A&A 437, L51–L54 (2005)
DOI: 10.1051/0004-6361:200500136

Astronomy & Astrophysics

Discovery of pulsation in a helium-rich subdwarf B star★

A. Ahmad and C. S. Jeffery

Armagh Observatory, College Hill, Armagh BT61 9DG, N. Ireland, UK
e-mail: amir@star.arm.ac.uk

Received 7 January 2005 / Accepted 1 June 2005

Abstract. Helium-rich subdwarf B (He-sdB) stars form a very small inhomogeneous group of subluminous stars showing varying degrees of helium enrichment. They have been found in the field of our galaxy as well as in globular clusters. Here we report the first discovery of pulsation in a He-sdB star – LS IV−14°116. Two pulsation periods can be clearly identified (1950 and 2900 s) and are more likely to be due to high-order non-radial g-mode oscillations than to radial or non-radial p-modes.

Key words. stars: chemically peculiar – stars: early-type – subdwarfs – stars: individual: LS IV−14°116 – stars: oscillations

1. Introduction

Pulsations in stars can arise when a local maximum in opacity is situated at an appropriate depth in the stellar atmosphere. Pulsations in subdwarf B (sdB) stars were first discovered by Kilkenny et al. (1997). They are thought to be driven by an opacity peak due to iron often referred to as the "Z-bump" (Charpinet et al. 1997). Such stars (EC14026 or V361 Hya variables) have pulsation periods of ~100–200 s and amplitudes of ~0.01 mag (Kilkenny 2002). More recently, Green et al. (2003) have reported another class of pulsating sdB star with periods of around 1 h and amplitudes of ≲0.05 mag (PG 1716+426 stars: Green et al. 2003). These pulsations were recently ascribed to non-radial g-modes with $l = 3$ or 4 with very high radial wavenumbers (Fontaine et al. 2003). Such stars are generally cooler than the V361 Hya variables.

Helium-rich sdB (He-sdB) stars have similar effective temperatures ($T_{\rm eff}$) to normal sdB stars but have generally lower surface gravities ($\log g$, Ahmad & Jeffery 2003). They roughly straddle the top of the V361 Hya instability zone and lie close to the bottom of the Z-bump instability finger for extreme helium stars (Fig. 1). With less hydrogen, which tends to damp oscillations, a systematic search for variability in He-sdB stars was suggested by Jeffery & Saio (1999). Results of an initial survey were inconclusive (Ahmad et al. 2004).

LS IV−14°116 was first listed in volume IV of the Luminous Stars in the Northern Milky Way catalogue (Nassau & Stephenson 1963). Kilkenny & Pauls (1990) later classified it as sdO from an optical spectrum. It was subsequently called sdO/He-rich (Viton et al. 1991) and was later included in a catalogue of helium-rich subdwarf B stars by Jeffery et al. (1996). Although the star shows significantly more helium ($n_{\rm He} = 0.21$, Ahmad et al. 2003) than other sdB stars, which generally show substantial depletions of helium ($0.001 < n_{\rm He} < 0.03$, Edelmann et al. 2003), LS IV−14°116 is not as extremely helium-rich as some other He-sdB stars (e.g. LB 1766, Kilkenny & Busse 1992). This is evident from the presence of strong hydrogen Balmer lines (see Ahmad et al. 2003). Nevertheless it is fair to refer to all sdB stars showing significantly more helium than normal as "helium rich".

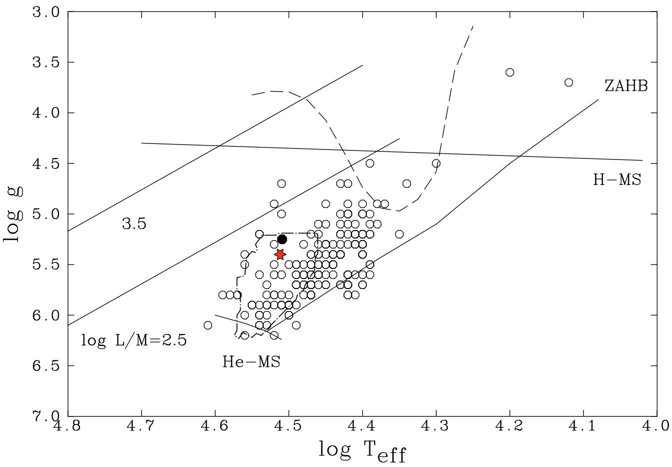

Fig. 1. Position of the He-sdB star – LS IV−14°116 (filled star) on the $\log g - T_{\rm eff}$ diagram in comparison to PG 1605+072 (filled circle) and other sdB stars (open circles). The dot-dash line around LS IV−14°116 represents the instability region where pulsating V361 Hya stars are found with $N \geq 5$ excited radial ($l = 0$) modes (Charpinet et al. 2001). The dashed line represents the instability boundary for low-mass (0.5 $M_\odot$), extremely helium-rich ($X = 0.00$) stars (Jeffery & Saio 1999).

In this paper we report photometry of LS IV−14°116 obtained in 2004 May as part of our systematic monitoring programme (Ahmad et al. 2004).

★ This paper uses observations made from the South African Astronomical Observatory (SAAO).

Table 1. Photometric observations of LS IV−14°116.

Night	Date	Run	UT Start	t_{exp}	N_{obs}
N1	2004 05 20	203	00:30:06	8	1269
N2	2004 05 21	304	00:23:31	11	238
N3	2004 05 22	403	00:22:42	7	2080
N4	2004 05 24	605	00:46:43	12	1065
N5	2004 05 25	703	00:03:14	15	942

Table 2. Stars present on the UCT CCD frame.

Star	α_{J2000}	δ_{J2000}	GS2.2 identifier	R mag
LS IV−14°116				
	20 57 38.9	−14 25 42.2	S3313303328	13.2
Comp 1				
	20 57 41.4	−14 26 11.4	S331330313746	14.1
Comp 2				
	20 57 41.6	−14 26 23.7	S331330313647	16.7

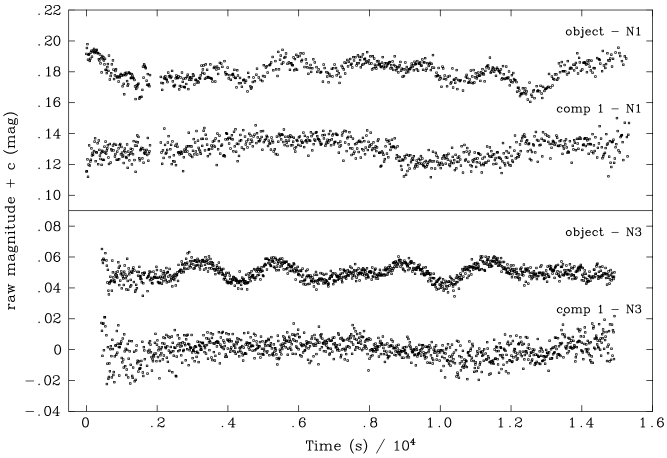

Fig. 2. Detrended nondifferential light curve of LS IV−14°116 and comparison 1 for nights one (N1) and three (N3).

2. Observations and data reduction

High-speed photometric observations of LS IV−14°116 were obtained with the Elizabeth Telescope (1.0 m) at the South African Astronomical Observatory (SAAO) on five separate nights in 2004 May as part of our follow-up observations of suspected pulsating He-sdB stars (Ahmad et al. 2004). LS IV−14°116 had earlier been monitored on two nights in 2003 April for ~2000 s, but no short-period oscillations had been detected. Hence the the star was not on the original list of follow-up targets. However, due to poor observing conditions at the telescope, LS IV−14°116 was selected for monitoring as it is relatively bright ($B \sim 13$ mag). Hints of variability were present in the light curve obtained on the first night. Observations were therefore made on four subsequent nights.

The 2004 observations were made with University of Cape Town (UCT) high-speed CCD camera operated in "frame-transfer" mode. In this mode data are acquired continuously since there is essentially no dead time for the CCD readout.

Weather conditions were not photometric on nights two, four and five. The integration time was adjusted on each night to ensure high signal-to-noise (S/N). No filter was used for the observations. A summary of the observations is shown in Table 1, which includes the run label, the start time, individual exposure time t_{exp} in seconds, and the number of observations N_{obs} for each night.

The raw CCD frames were bias subtracted and flat-fielded using standard procedures. The processed frames were then reduced in real-time using D.O'Donoghue's DuPhot routines (Schechter et al. 1993) available at the telescope. The raw magnitudes were extracted by fitting a Point Spread Function (PSF) to each star. Due to the small size of the UCT CCD ($109'' \times 74''$), only two nearby comparison stars could be observed (Table 2). Comparison 2 is quite faint hence only comparison 1 was used for the differential correction. Comparison 2 was checked against comparison 1 for variability.

Since the observing runs were quite long and no filter was used, the effects of atmospheric extinction are quite significant creating long term trends in the data. The data were detrended by dividing the reduced light curve from each individual night with a second order polynomial. Bad data points were removed from the final light curve. Detrended nondifferential light curve for two nights are shown in Fig. 2. The detrended and cleaned data from individual nights were then combined into a single light curve.

3. Is LS IV−14°116 variable?

The variability seen in LS IV−14°116 is intrinsically due to the star and not due to observing conditions, as Fig. 2 clearly shows short period variations (~1000 s) in LS IV−14°116 which are not present in the light curve of the comparison. Longer term variations (~10 000 s) apparent in both stars may be due to transparency fluctuations.

We computed Scargle periodograms (Fig. 3) from the light curve (Fig. 2) of LS IV−14°116 and comparison 1 for nights one (N1) and three (N3). Periodograms were also computed for the combined data from the two nights (N1+N3). If a period is present on individual nights and is still present in the combined data, then it is likely to be intrinsic to the object. Extrinsic factors (e.g. observing conditions) will normally, but not always, cancel when data from several nights are combined. In Fig. 3 we see that the frequency around 0.1 mHz is most likely to be due to long term atmospheric trends which are not completely removed by detrending as it is seen in all data. However the periods around 0.35 and 0.50 mHz are present *only* in the periodogram of LS IV−14°116 (N1, N3 and N1+N3) and *not* in the periodogram of the comparison. Differentially corrected, detrended and cleaned data from all five nights were combined into a single light curve. This final light curve was used for the frequency analysis. The periods in the raw light curve of LS IV−14°116 (N1, N3 and N1+N3) also appear in the periodogram of the final light curve.

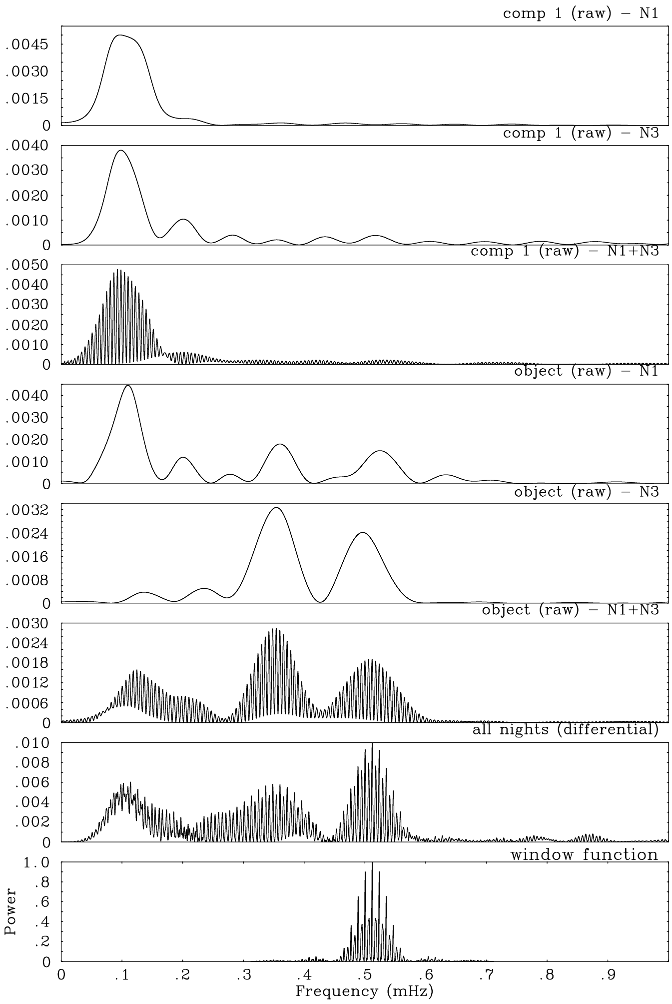

Fig. 3. Panels one to three show the Scargle periodogram of comparison 1 computed from the raw light curve for nights one (N1) and three (N3) and both nights combined (N1+N3). Panels four to six show the periodogram for LS IV−14°116 for N1, N3 and N1+N3. The second bottom panel shows the periodogram for the combined (differentially corrected) data from all five nights. The bottom panel shows the window function for the entire dataset shifted to the principal frequency.

Table 3. Results of frequency analysis as found while pre-whitening.

No.	μ [mHz]	A [mmag]	ϕ
1	0.5119 ± 0.0001	4.175 ± 0.248	4.175 ± 0.043
2	0.3484 ± 0.0001	3.917 ± 0.244	3.917 ± 0.048
Long term atmospheric trends			
	0.0927 ± 0.0001	3.904 ± 0.263	3.904 ± 0.046
	0.1308 ± 0.0001	2.863 ± 0.258	2.863 ± 0.069
	0.1782 ± 0.0001	1.900 ± 0.256	1.900 ± 0.097

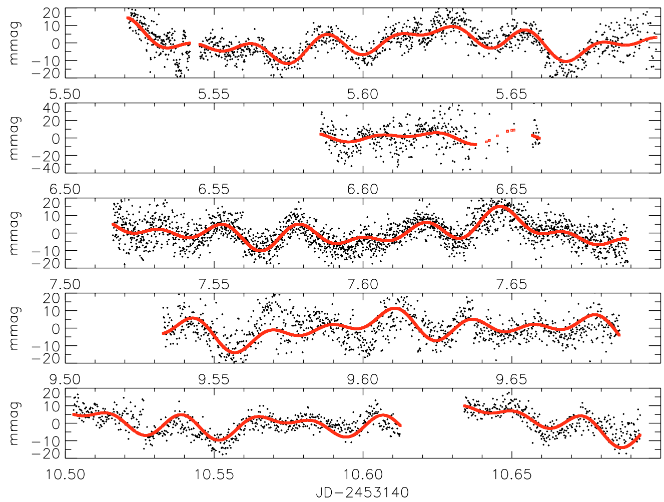

Fig. 4. Detrended differential light curve of LS IV−14°116 along with best fit model (solid line).

4. Frequency analysis

The final light curve was subjected to a formal frequency analysis assuming that the variations seen in the data comprise a multi-periodic sinusoidal oscillation. The discrete Fourier transform (DFT, Deeming 1975) was constructed. Although the data are well-sampled locally, the window function is complicated by the 1 cycle d^{-1} alias (0.011 mHz) and by the relative brevity of the time series (Fig. 3).

After selecting a number of frequencies from the DFT, a multi-parameter solution was obtained using a gradient expansion algorithm to compute a non-linear least squares fit in which the frequency, amplitude and phase of each independent sinusoid are free parameters. The resulting fit was subtracted from the original data and the DFT of the residual light curve was inspected.

The multi-parameter solutions would, on occasion, find inappropriate solutions in which one or more frequencies were considerably different from those provided as initial estimates. Such solutions would be rejected. A criterion for a good solution was that the inclusion or omission of any given frequency would not significantly affect the frequencies or amplitude of any stronger components of the solution. The persistence of significant power after the removal of five frequencies points to the need for more accurate photometry with a much cleaner window function.

A short section of very noisy data obtained early on 2004 May 21 was omitted from the final analysis; its inclusion had no effect on the frequencies identified, but a small effect on the amplitudes measured. The final solution is listed in Table 3 and shown in Fig. 4. Three low frequencies (Table 3) are also included in the final solution shown in Fig. 4, these are also seen in the periodogram of the comparison star (Fig. 3) and are most likely due to residual long term atmospheric trends which are not totally corrected by detrending.

5. Pulsations in LS IV−14°116

LS IV−14°116 is shown on the $\log g$ – $T_{\rm eff}$ diagram in Fig. 1, using $T_{\rm eff}$ = 32 500 ± 700 K, $\log g$ = 5.4 ± 0.1 (Ahmad & Jeffery 2003). The contour around LS IV−14°116 marks the region of instability where most V361 Hya stars are found with typical periods of ~100–250 s (Charpinet et al. 2001). The periods seen in LS IV−14°116 (1953–2870 s, Table 3) are very long, even in comparison with PG 1605+072 (295–573 s, Kilkenny et al. 1999) which lies very close to LS IV−14°116 on the $\log g - T_{\rm eff}$ diagram (Fig. 1) and is the V361 Hya star with the longest periods. However, they are much shorter than those seen in the non-radially pulsating low-mass helium-rich star HD 160641 (8.2–41 h, Lynas-Gray et al. 1987).

We can compare the pulsations in LS IV−14°116 with those in PG 1605+072. If, for the sake of argument, the longest period seen in each star belongs to the fundamental radial mode, then we can compare their mean radii using the period-mean density relation (Cox 1980). Since we also know their surface gravities, we can eliminate mass to obtain $R \propto P^2 g$. For LS IV−14°116, $P_{\rm LS} = 2870$ and $\log g_{\rm LS} = 5.4 \pm 0.1$. For PG 1605+072, $P_{\rm PG} = 573$ and $\log g_{\rm PG} = 5.25 \pm 0.1$. Hence $R_{\rm PG}/R_{\rm LS}$ would be $\sim 0.03 \pm 0.01$ and, since $M \propto P^4 g^2$, the corresponding mass ratio ($\sim 6 \pm 3 \times 10^{-5}$) would be unphysical. Hence the assumption of oscillations in the fundamental radial mode is untenable. V361 Hya stars are primarily p-mode oscillators, including modes with $l = 0$. With such long periods, it therefore seems likely that LS IV−14°116 shows non-radial g-modes, possibly as seen in the the cooler PG 1715+426 stars. Fontaine et al. (2003) compute periods for g-modes in sdB stars; at the observed periods in LS IV−14°116, the radial order must be high, increasing from $k \sim 4$–12 at degree $l = 0, 1$ to $k > 10$ for $l = 3, 4$. However, although excited in PG 1716+426 stars, these modes are *stable* at $T_{\rm eff} \gtrsim 25\,000$ K (Fontaine et al. 2003). No other published pulsation studies successfully account for the variability observed in LS IV−14°116. Pulsation calculations including an appropriately helium-enriched envelope have still to be undertaken.

6. Conclusions

In the course of systematic monitoring of helium-rich subdwarf B stars, we have found the moderate He-sdB LS IV−14°116 to show multi-periodic photometric variability. On the basis of a comparison with the V361 Hya star PG 1605+072 we argue that the variability is due to non-radial g-mode oscillations of high radial order. Current theory suggests that such modes should be stable. These observations therefore offer a new challenge to stellar pulsation theory.

Meanwhile, with two modes clearly present, and more likely to be found in a sustained multi-site observing effort, LS IV−14°116 offers many opportunities for further study. Ultimately, direct measurements of mass and radius will allow an informed discussion of its evolutionary origin and an explanation for its unusual surface helium abundance. In the longer term they may help to explain the connection, if any, between the normal and the helium-rich subdwarf B stars.

Acknowledgements. This research is supported by the UK Particle Physics and Astronomy Research Council through grants PPA/G/S/2002/00546 and PPA/G/O/2003/00044 and by the Northern Ireland Department of Culture, Arts and Leisure (DCAL). This research has made use of NASA's ADS. Contructive comments from two referees are appreciated.

References

Ahmad, A., & Jeffery, C. S. 2003, A&A, 402, 335
Ahmad, A., Jeffery, C. S., Solheim, J.-E., & Østensen, R. 2004, Ap&SS, 291, 435
Charpinet, S., Fontaine, G., Brassard, P., et al. 1997, ApJ, 483, L123
Charpinet, S., Fontaine, G., & Brassard, P. 2001, PASP, 113, 775
Cox, J. P. 1980, Theory of Stellar Pulsation (Princeton: Princeton Univ. Press)
Deeming, T. J. 1975, Ap&SS, 36, 137
Edelmann, H., Heber, U., Hagen, H.-J., et al. 2003, A&A, 400, 939
Fontaine, G., Brassard, P., Charpinet, S., et al. 2003, ApJ, 597, 518
Green, E. M., Fontaine, G., Reed, M. D., et al. 2003, ApJ, 583, L31
Jeffery, C. S., & Saio, H. 1999, MNRAS, 308, 221
Jeffery, C. S., Heber, U., Hill, P. W., et al. 1996, in Hydrogen Deficient Stars, ed. C. S. Jeffery, & U. Heber, ASP Conf. Ser., 96, 471
Kilkenny, D. 2002, in Radial and Nonradial Pulsations as Probes of Stellar Physics, ed. C. Aerts, T. R. Bedding, & J. Christensen-Dalsgaard, ASP Conf. Ser., 259, 356
Kilkenny, D., & Pauls, L. 1990, MNRAS, 244, 133
Kilkenny, D., & Busse, J. 1992, MNRAS, 258, 57
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
Lynas-Gray, A. E., Kilkenny, D., Skillen, I., & Jeffery, C. S. 1987, MNRAS, 227, 1073
Nassau, J. J., & Stephenson, C. B. 1963, Hamburger Sternw. Warner & Swasey Obs., 0
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Viton, M., Deleuil, M., Tobin, W., Prévot, L., & Bouchet, P. 1991, A&A, 242, 175