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Photometry of balloon 090100001 with the Himalayan Chandra Telescope

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Abstract. About one tenth of all hot subluminous B stars pulsate non-radially with periods of 80 – 600 s; the oscillations are identified with pressure modes. At lower effective temperatures, another group pulsates non-radially with periods $>$ 3 000 s; these oscillations have been identified with gravity modes. If sufficient modes can be identified, such oscillations can provide information about the interior of a star. One pulsating sdB star – balloon 090100001 – lies at the boundary of the hot and cool groups, and shows both short and long-period oscillations. To study its interior structure in detail, we carried out a multi-site observing campaign in 2005 August in order to obtain a very precise light curve and hence to identify the modes of oscillation. This campaign involved four telescopes including the Himalayan Chandra Telescope (HCT), the William Herschel Telescope (in La Palma), the Canada France Hawaii Telescope and the Faulkes Telescope North (both in Hawaii). Here we report the HCT observations of balloon 090100001.

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1. Introduction

Stellar pulsations occur at various locations across the Hertzsprung-Russell diagram and are important in many branches of astronomy. Pulsations can arise when a local maximum in opacity is situated at a depth in the stellar interior such that the thermal timescale in that layer is similar to the dynamical timescale of the star. This resonance leads to pulsations driven by the opacity– or κ– mechanism. Such pulsations may be radial or non-radial and enable us to measure the global properties of stars directly, and to test models for the structure and evolution of stars. This paper describes the background to a project to study the internal structure of a pulsating subdwarf B star, balloon 090100001 (Section 2), and the observations obtained at the Himalayan Chandra Telescope as a part of this project (Section 3). It briefly assesses the quality and the information that can be obtained from these single-site data (Section 4) and draws some general conclusions (Section 5). The final results will be discussed elsewhere in combination with data from other telescopes.

2. Pulsations in subdwarf B stars

The sdB stars are thought to be extended horizontal-branch stars. That is, they are helium-burning cores of $\sim 0.5\,M_{\odot}$ with a very thin hydrogen-rich surface (Heber 1986). Their hot high-gravity surfaces provide ideal conditions for radiative and gravitational competition to produce chemically stratified envelopes (Heber 1986). In turn, this stratification appears to have created conditions where non-radial pulsations are excited, providing a unique opportunity to look inside the star and to determine their internal chemical structure (Brassard et al. 2001) and rotation properties directly. Further background may be found in reviews by Charpinet et al. (2001), Kilkenny (2002), and Jeffery (2005, 2007).

The first group of pulsating sdB stars (Kilkenny et al. 1997) to be discovered are generally known as EC14026 or V361 Hya variables, or as sdBV stars. Most show multiple pulsation modes with periods in the range $\approx 60 - 600$ s and amplitudes ~ 0.01 mag (Kilkenny 2002). They generally have temperatures and gravities in the range, 29 000 K $< T_{\rm eff} <$ 36 000 K and $5.2 < \log g < 6.1$. A second group of pulsating sdB stars was subsequently discovered by Green et al. (2003). Known as PG 1716+426 variables, these have longer periods of around 1 hr, amplitudes ≤ 0.05 mag, and temperatures and gravities in the ranges 25 000 K $< T_{\rm eff} <$ 30 000 K and $5.4 < \log g < 5.8$. At the boundary between these two distinct classes of sdB pulsators lie two hybrid pulsators – balloon 090100001 and HS 0702+6043 – which exhibit both short and long period pulsations (Schuh et al. 2006).

Balloon 090100001 (= BAL090100001, TYC2248 − 1751 − 1) was identified to be a hot subdwarf in a high galactic latitude survey of far-ultraviolet excess objects (Bixler et al. 1991). It was first identified as a bright (V = 12.1 mag) high-amplitude short-period variable by Oreiro et al. (2004). Subsequently it was found to also exhibit long-period variability (Oreiro et al. 2005, Baran et al. 2005). Together, these authors have identified over 13 independent pulsation periods with between 210 s and 360 s (short) and between 2 700 s and 6 300 s (long) and amplitudes from 75 milli-magnitudes (mmag) down to < 1 mmag.

2.1 Pulsations and asteroseismology

It is generally accepted that the short period pulsations in EC14026 variables are associated with radial and non-radial *p*-modes (pressure being the restoring force: Charpinet et al. 1997) driven through the κ mechanism by Z-bump opacity. In order to excite pulsations, the local opacity in the driving region must be enhanced compared with that found in stellar material of normal metallicity. This enhancement can be produced in the high-gravity radiative envelopes of sdB stars because the timescales for radiative levitation and gravitational settling are such that ions will diffuse through the envelope and accumulate in regions of high specific opacity (Chayer et al. 1995) – producing an opacity multiplier in the Z-bump domain. This opacity excess has been modelled and used successfully to interpret the *p*-mode oscillations in EC14026 variables (Charpinet et al. 2001).

With periods substantially longer than anticipated for the fundamental radial mode, the pulsations seen in PG 1716+426 variables have been associated with non-radial *g*-modes (gravity being the restoring force). Such modes have been shown to be unstable in models with chemically stratified envelopes in which the iron abundances in the driving zone is enhanced for $T_{\rm eff} < 24\,000$ K (Fontaine et al. 2003). Jeffery & Saio (2006a,b) have shown that this limit can probably be raised to $T_{\rm eff} < 28\,000$ K by adopting more up-to-date opacity tables and including the contribution of nickel.

While there remains room for improvement in the theoretical models, the fact that there remains a gap between the low-temperature limit of the theoretical *p*-mode regime and the high-temperature limit of the theoretical *g*-mode regime is at variance with the existence of hybrid pulsators which exhibit *both* types of behaviour. Therefore it will be important to obtain observations of these stars of sufficient quality to identify the pulsation modes uniquely, and to determine the total mass, the hydrogen-envelope mass, and the stellar radius and luminosity. In turn these will enable the theoretical models to be developed so as to understand better the mechanisms driving both the pulsation and the chemical stratification in these stars.

These primary quantities may be learned using the combined techniques of high-precision spectroscopy and asteroseismology. The latter relies on combining a precise knowledge of the pulsation frequencies observed at the stellar surface with those predicted by models of its interior. It is also useful to be able to identify the pulsation mode associated with each frequency, as characterized by its radial order, spherical degree and

Table 1. HCT observing log.

Date	Start (UT)	End (UT)	No. of frames*
2005 08 12	15:27:03	22:46:55	445
2005 08 13	15:12:19	23:08:59	517
2005 08 14	15:18:31	22:31:00	467
2005 08 15	21:43:04	22:52:11	62
2005 08 16	16:13:51	22:34:40	345

*The exposure times for the individual frames are not necessarily the same.

azimuthal wavenumber. In order to measure precise frequencies, it is necessary to obtain photometry over as long a time base as possible, with as much precision as possible and with as few gaps in the data as possible. In order to identify at least one characteristic of each mode (generally the spherical degree ℓ), it is useful to be able to observe either the amplitude of the light curve at different wavelengths, or to obtain some other measurement which can be reduced to a differential function of limb angle (e.g. line profile).

2.2 Objectives

With these principles in mind, a collaboration was established to obtain high-quality multicolour observations of a hybrid pulsator from two 4m-class telescopes – to allow mode identification – and to supplement these with high-quality photometry from two other sites – to maximise the frequency precision. Thus balloon 090100001 was chosen as the primary target for a campaign to address the following goals: (1) to measure accurate frequencies and identify the spherical degree (l) of non-radial modes using the amplitude-ratio method (e.g. Jeffery et al. 2004, Tremblay et al. 2006) and to test models for the deep interior of the sdB star and the prediction that sdB g-mode instabilities occur only for $l > 2$ (Fontaine et al. 2003); (2) to derive a full p-mode frequency spectrum down to amplitudes ~ 0.1 mmag, more sensitive than any previous sdB analysis; (3) obtain identifications for modes with amplitudes > 1 mmag; (4) to detect and resolve multiplets in order to the measure of rotation period in the envelope (p-modes) and in the interior (g-modes) and show whether rotation is rigid or differential (Kawaler & Hostler 2004); (5) to use the coexistence of p- and g-modes seen in balloon 090100001 as a very strong constraint on the global properties of the star, the structure and chemical stratification of the stellar envelope and on the details of the excitation mechanism of the g-modes.

3. Observations

Asteroseismology requires data with a high frequency resolution and a high signal-to-noise ratio. Frequency resolution $\Delta\nu$ is inversely proportional to the length of a data sequence, and is adversely affected by aliasing due to gaps in the data sequence. Therefore the

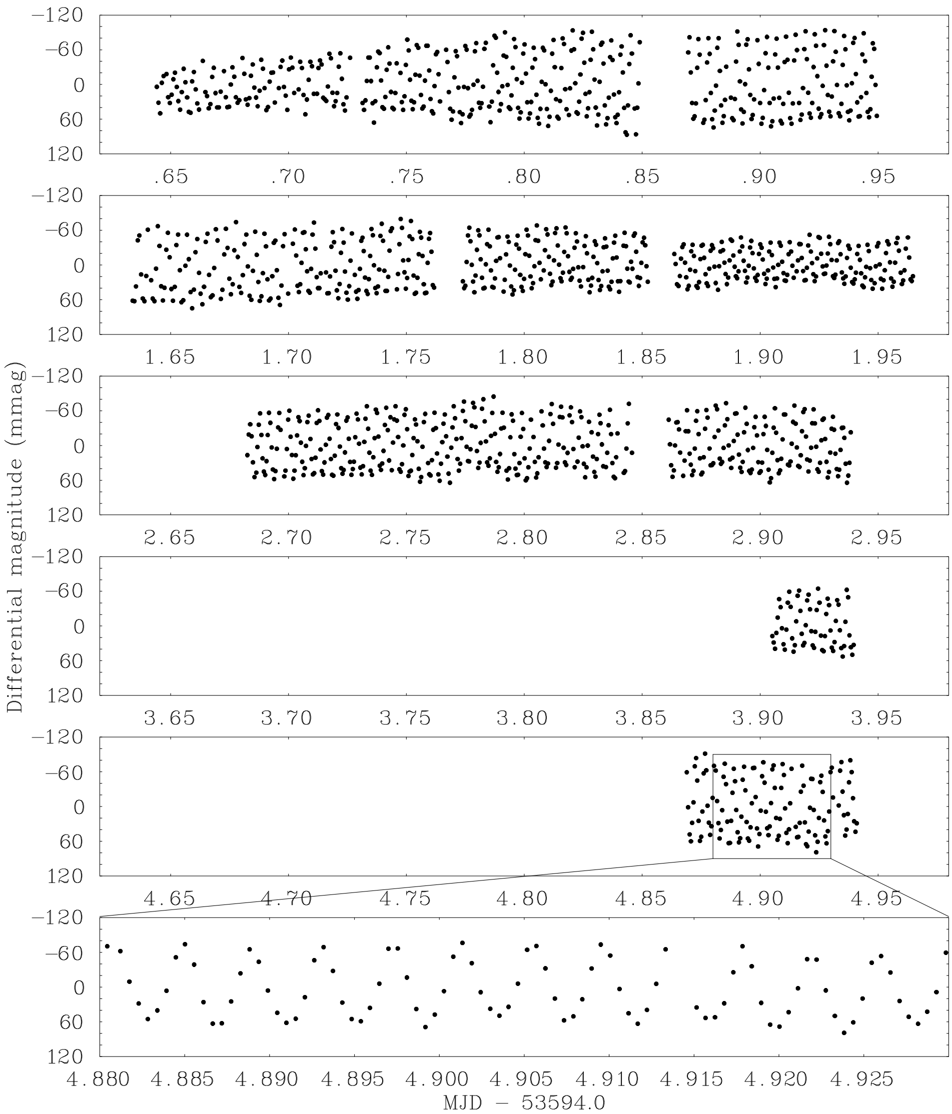

Figure 1. Light curve of balloon 090100001 obtained in 2005 Aug with the HCT. The bottom panel represents an expanded section.

science goals required near-continuous high-quality data over an interval of several days. To reduce aliases due to data gaps introduced by the Earth's rotation, observations were obtained from three sites, namely the Himalayan Chandra Telescope (HCT: 32°N 78°E), the Canada France Hawaii Telescope in Hawaii (CFHT: 20°N 155°W), and the

William Herschel Telescope in La Palma (WHT: 29°N 17°W). With eight hours observing available, these three sites potentially offer near continuous 24 hr coverage. Observations were also obtained at the Faulkes Telescope North (also in Hawaii) to extend the overall duration of the run.

Observations were scheduled in the middle of 2005 August. This reduces the available time for balloon 090100001 ($\alpha_{2000.0} = 23\,15\,21.48$, $\delta_{2000.0} = +29\,05\,01.4$) by about one hour, giving 6.5 hrs per night with the star at air mass less than 1.5 at the HCT. The observations were carried out with the Bessell B filter using the Hanle Faint Object Spectrograph Camera (HFOSC) (Anupama 2000) on the nights of 2005 August 12 to 16 (Table 1). The HFOSC CCD is not optimized for high-speed observations. However, by reducing the area of the CCD to be read out, repeat observations were obtained with a cycle time of about one minute. The integration time for the observations ranged from 5 – 20 s with decreasing altitude of the star. The total dead time for each observation was 41.6 s including 20.8 s for pre-clearing and 20.8 s for readout of the CCD window.

No autoguider was available at the telescope during the observing run. Hence the pointing of the telescope had to checked every 10 – 15 min. The telescope pointing with no autoguider was still found to be very accurate as the drift was usually of the order of a few pixels over the 10 – 15 min period. Sky flats were obtained (weather permitting) at the beginning and end of each night. A few bias frames were obtained every hour.

The data were reduced using the latest version of ULTRACAM data reduction pipeline (Marsh & Dhillon 2006) adapted by us for the HFOSC CCD. The observations were bias and flatfield corrected in the usual way and aperture photometry was carried out. Differential photometry was performed using a bright nearby comparison star (TYC2248−63 − 1). No extinction correction was applied to the data. The final light curve is shown in Fig. 1.

The dominant oscillation at 2.8076 mHz is clearly visible, as is the contribution from the long-period oscillations. The modulation of the overall amplitude due to closely spaced frequencies around 2.8 mHz is also clearly evident.

4. Analysis and Results

The HCT light curve of balloon 090100001 was subjected to a formal frequency analysis. First we constructed a Discrete Fourier Transform (DFT, Deeming 1975) (Fig. 2) and measured the frequency corresponding to the highest peak in the transform. We then computed a non-linear least-squares fit in which frequency, amplitude and phase of a sinusoid are free parameters, although the frequency found in the previous step is used to seed the solution. The resulting fit was subtracted from the original data and the DFT of the residual (or pre-whitened) light curve was inspected to identify additional frequencies. These were combined with the frequencies previously identified and a multiple sinusoid

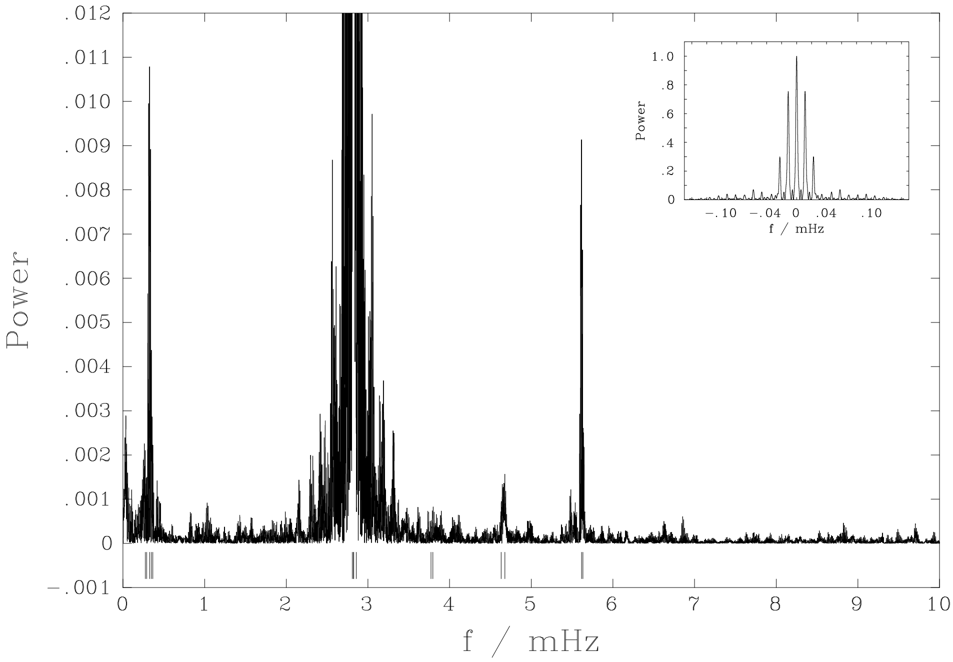

Figure 2. Lomb-Scargle periodogram of the lightcurve. The periods listed in Table 2 are marked with vertical lines shown under the periodogram. The window function is inset.

fitted to the original light curve. The process was repeated until all the significant peaks were removed from the periodogram and no significant power remained (*i.e.* no peaks $> 4\sigma$). In total we subtracted 15 frequencies from the power spectrum. The frequencies and amplitudes are listed in Table 2.

The frequencies and amplitudes measured from HCT data alone are comparable with those reported by Baran et al. (2005), with four long periods and two short periods in common, four short-periods approximately the same, and two of the same combination frequencies (see Table 2). The Baran et al. (2005) identifications are indicated in the table. Although we cannot hope to emulate the frequency resolution of the earlier work, it is satisfactory that from just five nights observing, of which two were partial, we have been able to recover photometry of very high quality, to achieve a frequency resolution of ~ 0.0067 mHz ($2.5/T$), and detect signals with an amplitude ~ 1 mmag or less. We note that observing overheads due to the CCD camera control software led to a duty cycle generally less than 20%. Since it should be possible, at least in principle, to reduce these overheads by at least 50%, substantially better performance is feasible. Alternatively, increased observing efficiency would make it possible to use more than one filter and hence to attempt mode identification using the colour-amplitude ratio method (Dupret et al. 2003).

Table 2. Frequency analysis of balloon 090100001. Note that the two frequencies 2.8224 mHz and 2.8253 mHz, measured in our frequency analysis using a non-linear least-squares fit are too close to be resolved by our data ($\Delta\nu \sim 0.0067$ mHz) and may therefore not be very reliable.

Frequency (mHz)	Amplitude (mmag)	Baran et al. (2005)
0.2733 ± 0.0011	1.796 ± 0.957	f_A
0.2902 ± 0.0018	1.145 ± 0.960	$\sim f_G$
0.3258 ± 0.0003	6.273 ± 1.046	f_C
0.3472 ± 0.0019	1.039 ± 1.086	
0.3658 ± 0.0006	2.806 ± 0.935	f_B
2.8076 ± 0.0000	49.113 ± 1.014	f_1
2.8224 ± 0.0004	9.171 ± 1.345	f_2
2.8253 ± 0.0002	14.141 ± 1.261	f_3
2.8572 ± 0.0007	2.531 ± 0.938	f_6
3.7724 ± 0.0017	0.934 ± 1.059	$\sim f_8$
3.7956 ± 0.0012	1.308 ± 1.057	f_{10}
4.6317 ± 0.0012	1.173 ± 0.926	
4.6764 ± 0.0007	1.961 ± 0.929	
5.6154 ± 0.0003	5.268 ± 0.927	$2f_1$
5.6330 ± 0.0006	2.543 ± 0.927	$f_1 + f_4$

*

5. Conclusion

We have carried out time series photometry of the pulsating subdwarf B star balloon 090100001 with HCT/HFOSC in August 2005. These observations complement observations obtained contiguously at the WHT and CFHT with the goal of studying the interior structure of this star using the tools of asteroseismology. The results presented here demonstrate the quality of the HCT site and the performance of the HFOSC instrument. The high quality of the frequency spectrum obtained from this short run reflects the quality of the site and the aperture of the telescope. The data will be especially useful in conjunction with data from other sites. With a little effort the camera control software could be modified to deliver greater observing efficiency and concomitantly greater scientific return.

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