Long-term photometric monitoring of the hybrid subdwarf B pulsator HS 0702+6043

R. Lutz\textsuperscript{1,2}, S. Schuh\textsuperscript{1}, R. Silvotti\textsuperscript{3}, R. Kruspe\textsuperscript{1}, and S. Dreizler\textsuperscript{1}

\textsuperscript{1} Institut für Astrophysik, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany
\textsuperscript{2} Max-Planck-Institut für Sonnensystemforschung, Max-Planck-Straße 2, 37191 Katlenburg-Lindau, Germany
\textsuperscript{3} INAF - Osservatorio Astronomico di Capodimonte, via Moiariello 16, 80131 Napoli, Italy

Abstract

Pulsating subdwarf B stars oscillate in short-period \textit{p}-modes or long-period \textit{g}-modes. HS 0702+6043 is one of currently three objects known to show characteristics of both types and hence is classified as hybrid pulsator. We briefly present our analysis of the \textit{g}-mode domain of this star, but focus on first results from long-term photometric monitoring in particular of the \textit{p}-mode oscillations. We present a high-resolution frequency spectrum, and report on our efforts to construct a multi-season O–C diagram. Additionally to the standard (although nontrivial) exercise in asteroseismology to probe the instantaneous inner structure of a star, measured changes in the pulsation frequencies as derived from an O–C diagram can be compared to theoretical evolutionary timescales. Within the EXOTIME program, we also use this same data to search for planetary companions around extreme horizontal branch objects.

Session: STARS - opacity driving, levitation, opacity data
Individual Objects: HS 0702+6043, HS 2201+2610

Introduction

Subdwarf B stars (sdB stars) populate the extreme horizontal branch (EHB) at effective temperatures between 20,000 and 40,000 K and surface gravities \( \log(\text{cm s}^{-2}) \) between 5.0 and 6.2. They are believed to be core helium-burning objects of half a solar mass with remaining hydrogen envelopes too
thin to sustain H-shell burning. The reason for losing almost all of their original hydrogen envelope in earlier stages of their evolution is still unknown. The high fraction of binaries among the sdB stars suggests that close binary evolution may play an important role in their formation. The discovery of a planetary companion to HS 2201+2610 (Silvotti et al. 2007), the only case where the necessary kind of measurements for such a discovery are available so far for an sdB star, now revives the idea that planets in wide orbits may also play a role in the formation of these stars.

A fraction of the sdB stars shows pulsations. Variable subdwarf B stars (sdBV stars) can be divided into the classes of rapid $p$-mode pulsators (sdBV$_p$) and slow $g$-mode pulsators (sdBV$_g$), with three objects known so far to belong to both classes simultaneously (hybrid pulsators, sdBV$_{pg}$). These are of particular interest since the two mode types probe different regions within the star. Both types of pulsations are driven by a $\kappa$-mechanism where the required opacity bump is due to iron and nickel accumulated by diffusion, resulting in phase-stable pulsational behaviour (Charpinet et al. 1997; Fontaine et al. 2003; Jeffery & Saio 2006).

The $p$-mode pulsators show low amplitudes (few ten mmag) and short periods (few minutes) at higher temperatures (roughly 30 000-35 000 K). In contrast, the $g$-mode pulsators have even lower amplitudes (few mmag) and longer periods (30 to 90 min) at lower temperatures (roughly 25 000-30 000 K). In a log $g$–$T_{\text{eff}}$ diagram, the hybrids are located at the interface of the $p$-mode and $g$-mode instability regions (see Figure 1 in Lutz et al. 2008a). The class prototypes are EC 14026-2647 (Kilkenny et al. 1997) and PG 1716+426 (Green et al. 2003), respectively. The known hybrids are HS 0702+6043 (Schuh et al. 2006), Balloon 090100001 (Oreiro et al. 2005; Baran et al. 2005) and HS 2201+2610 (Lutz et al. 2008b). Asteroseismology has been one of the important tools to constrain the evolutionary history of subdwarf B stars. While an asteroseismological solution provides an instantaneous “snapshot” of the interior stellar structure, extended monitoring of changes over several years in the short, stable $p$-mode pulsation frequencies allows to directly measure evolutionary timescales $\dot{P}$ which can be compared to predictions from evolutionary models. $\dot{P}$ can be measured from O–C diagrams, which will at the same time reveal the presence of potential planets that may in turn have influenced the previous evolution.

EXOTIME

EXOTIME is the abbreviation of EXOplanet search with the TIming MEthod. This program is led by Roberto Silvotti and Sonja Schuh. Being a collaborative long-term campaign, it involves a substantial number of observers and telescopes all over the world which perform ground based time-series photometry.
Table 1: Photometric data of HS 0702+6043. CA: Calar Alto, T: Tübingen, SB: Steward Bok, G: Göttingen, L: Loiano, MB: Mt. Bigelow.

| Date       | Site | Length | Date       | Site | Length |
|------------|------|--------|------------|------|--------|
| Dec 1999   | CA   | 1.2m   | Feb 2008   | T    | 0.8m   |
| Feb 2004   | T    | 0.8m   | Feb 2008   | G    | 0.5m   |
| Feb 2004   | SB   | 2.2m   | Mar 2008   | G    | 0.5m   |
| Jan 2005   | CA   | 2.2m   | Mar 2008   | L    | 1.5m   |
| Dec 2007   | T    | 0.8m   | Nov 07 - Mar 08 | MB | 1.55m |
| Dec 2007   | G    | 0.5m   | May 2008   | G    | 0.5m   |

Basic information (target objects, observing schedule etc.) can be found on the program’s webpage http://www.na.astro.it/~silvotti/exotime/. While most of the more than 300 exoplanets are found around main sequence host stars, EXOTIME searches planets orbiting evolved sdB pulsators, i.e. extreme horizontal branch objects. Currently the target list consists of five pulsating sdB stars, HS 0702+6043 and HS 2201+2610 being two of them. The search for exoplanets is performed with the timing method or O–C analysis, which also allows to derive evolutionary timescales (described on the example of HS 2201+2610 in a following section). Closely related to the search for exoplanets orbiting sdB stars are evolutionary aspects of sdB stars, late-stage or post RG evolution of planetary systems and the question if planets could be responsible for the extreme mass loss of sdB progenitors.

HS 0702+6043

The sdB pulsator HS 0702+6043 was first identified as a variable in a search program by Dreizler et al. (2002). Its spectroscopic parameters place it at the common boundary of the $p$- and $g$-mode instability regions and as mentioned above, Schuh et al. (2006) indeed first revealed this object to be a hybrid pulsator. This detection triggered extensive follow-up observations which are listed in Table 1. There are photometric data available going back to 1999, but unfortunately with large gaps in between. A regular monitoring was not performed until the end of 2007.

$p$-modes

The short-period $p$-modes are the relevant ones for the construction of a multi-seasonal O–C diagram. From all the data until Feb 2008 (MB not included),
Long-term photometric monitoring of the hybrid subdwarf B pulsator HS 0702+6043

Figure 1: Periodogram of HS 0702+6043 showing the two main pulsation periods $f_1$ and $f_2$. The inset window is a zoom into the main-peak.

we derived the high-resolution frequency spectrum displayed in Figure 1, which shows the two dominant frequency features $f_1$ and $f_2$ at frequencies of $2753.9 \mu$Hz (363.1 s) and $2606.1 \mu$Hz (383.7 s), respectively. The corresponding amplitudes are 26.6 and 5.5 mmag. Due to the large gaps in our data archive, we cannot present a meaningful O–C analysis for HS 0702+6043 yet, but with a regular EXOTIME monitoring we are confident that this will be possible within the next two years.

$g$-modes

The Jan 2005 run (see Table 1) was initiated in order to resolve the low frequency $g$-mode regime in HS 0702+6043 and indeed, three features could be identified in the data at frequencies of $271.7 \mu$Hz, $318.1 \mu$Hz and $206.3 \mu$Hz (61.3 min, 52.4 min, 80.8 min) with amplitudes of 1.8 mmag, 1.3 mmag and 0.9 mmag, respectively. A periodogram can be found in Lutz et al. (2008a).
HS 2201+2610

HS 2201+2610 is so far the only EXOTIME target for which an extended O–C analysis could be executed (Silvotti et al. 2007). Regular data sets are available since 2000.

O–C Analysis

An O–C (Observed minus Calculated) analysis is a way to measure the phase variations of a periodic function. The observed times of the pulsation maxima (or minima) of the single runs of an observational season are compared to the calculated ephemeris of the whole data set (see e.g. Kepler et al. 1991). Different shapes in the O–C can be identified with different situations: a parabolic shape indicates a linearly changing period, whereas a sinusoidal component can
be interpreted by cyclically advanced and delayed timings of the pulsation maxima (or minima) due to the presence of a low-mass companion, which causes the pulsator to wobble around the common barycenter. Figure 2 shows the O–C analysis for the main pulsation period of HS 2201+2610, which is around 350 s at an amplitude of about 10 mmag. The parabolic shape of the O–C diagram in the top panel of Figure 2 indicates a linearly changing period of $P = 1.46 \cdot 10^{-12}$. Since this is a positive value, one can infer that this object is expanding, i.e. cooling. The evolutionary timescale can be calculated as $P/P = 7.6$ Myr, consistent with theoretical predictions (Charpinet et al. 2002). The bottom panel of Figure 2 displays the sinusoidal residuals which are induced by the gravitational influence of a planetary mass body. Some system parameters that can be derived are the companion’s mass of 3.2 Jupiter masses (still with an uncertainty due to the unknown inclination), an orbital period of 1170 days, an orbital separation of 1.7 AU, a star projected orbital velocity of 99 m/s or a planet orbital velocity of 16 km/s. For more system parameter and a detailed description of the applied assumptions refer to Silvotti et al. (2007).

Acknowledgments. RL thanks the organizers for financial support. The authors thank all observers who contributed observations to the HS 0702+6043 and HS 2201+2610 data archive.

References
Baran, A., Pigulski, A., Koziel, D., et al. 2005, MNRAS, 360, 737
Charpinet, S., Fontaine, G., Brassard, P., et al. 1997, ApJ, 483, L123
Charpinet, S., Fontaine, G., Brassard, P., & Dorman, B. 2002, ApJ, 140, 469
Dreizler, S., Schuh, S., Deetjen, J.L., et al. 2002, A&A, 386, 249
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. 2006, MNRAS, 372, L48
Kepler, S.O., Winget, D.E., Nather, R.E., et al. 1991, ApJ, 378, 45
Kilkenny, D., Koen, C., O’Donoghue, D., & Stobie, R.S. 1997, MNRAS, 285, 640
Lutz, R., Schuh, S., Silvotti, R., et al. 2008a, ASPC, 392, 339
Lutz, R., Schuh, S., Silvotti, R., et al. 2008b, A&A, submitted
Oreiro, R., Pérez Hernández, F., Ulla, A., et al. 2005, A&A, 438, 257
Schuh, S., Huber, J., Dreizler, S., et al. 2006, A&A, 445, L31
Silvotti, R., Schuh, S., Janulis, R., et al. 2007, Nature, 449, 189