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# HS 0702+6043: a star showing both short-period *p*-mode and long-period *g*-mode oscillations*

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## ABSTRACT

*Context.* The hot subdwarf B star HS 0702+6043 is known as a large-amplitude, short-period *p*-mode pulsator of the EC 14026 type. Its atmospheric parameters place it at the common boundary between the empirical instability regions of the EC 14026 variables and the typically cooler long-period *g*-mode pulsators of the PG 1716 kind.

*Aims.* We analyse and interpret the photometric variability of HS 0702+6043 in order to explore its asteroseismological potential.

*Methods.* We report on rapid wide band CCD photometric observations to follow up on and confirm the serendipitous discovery of multiperiodic long-period luminosity variations with typical time scales of ~1 h in HS 0702+6043, in addition to the two previously known pulsations at 363 s and 383 s. In particular, we isolate a relatively low-amplitude (~4 mmag), long-period (3538 ± 130 s) light variation.

*Results.* We argue that the most likely origin for this luminosity variation is the presence of an excited *g*-mode pulsation. If confirmed, HS 0702+6043 would constitute a rare addition to the very select class of pulsating stars showing simultaneously parts of their pressure and gravity mode pulsation spectra. The asteroseismological potential of such stars is immense, and HS 0702+6043 thus becomes a target of choice for future investigations. While our discovery appears consistent with the location of HS 0702+6043 at the common boundary between the two families of pulsating sdB stars, it does challenge theory's current description of stability and driving mechanisms in pulsating B subdwarfs.

**Key words.** stars: subdwarfs – stars: horizontal branch – stars: individual: HS 0702+6043 – stars: oscillations

## 1. Introduction

Subdwarf B stars populate the extreme horizontal branch (EHB) in the effective temperature range of 22 000 to 40 000 K and have surface gravity values from $\log g = 5.0$ to 6.2 in cgs units. The masses of these hot, evolved objects should cluster around 0.5 $M_\odot$ as suggested by evolution theory (Han et al. 2003). Indeed, masses between 0.457 and 0.49 $M_\odot$ have been derived recently for four EC 14026 stars by asteroseismology (Charpinet et al. 2005). They are believed to be core helium-burning but with hydrogen envelopes too thin to sustain H-shell burning. Standard tracks of stellar evolution do not cross the EHB region since they do not produce inert hydrogen envelopes, but the high fraction of binaries among the sdB stars suggests that close binary evolution may play an important role in their formation. The relative importance of several proposed feeder channels remains unclear.

To learn more about sdB structure and hence their evolutionary history, asteroseismology is one of the important methodical approaches, made possible due to short-period oscillations exhibited by a fraction of sdB stars (called sdBVs). To the group of pulsating sdB stars known as V631 Hya variables (more commonly referred to as EC 14026 variables) which show periods of the order of a few minutes, Green et al. (2003) have recently added a longer-period group (tentatively called lpsdBV) for which the prototype is PG 1716+426. In the short-period sdBVs, a $\kappa$ mechanism drives the low-order *p*-modes, where the required opacity bump is due to iron accumulated by diffusion (Charpinet et al. 1996). According to Fontaine et al. (2003), the same $\kappa$ mechanism can also drive high-order *g*-modes in the long-period sdBVs that have periods of the order of about an hour.

The $m_B = 15$ star HS 0702+6043 was identified as a member of the EC 14026 group in a search program by Dreizler et al. (2002, hereafter DR02). Its effective temperature was

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* Based on observations collected at the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, operated jointly by the Max-Planck Institut für Astronomie and the Instituto de Astrofísica de Andalucía (CSIC), and at the Bok Telescope on Kitt Peak, operated by Steward Observatory (University of Arizona).

**Table 1.** Frequencies extracted from the February 2004 data.

| | Frequency [$\mu$Hz] | Period [s] | Amplitude [mmi] |
|---|---|---|---|
| $f_1$ | 2754 (9) | 363.1 | 21.7(5) |
| $f_2$ | 2606 (9) | 383.7 | 4.6(5) |
| $f_3$ | 283 (9) | 3538. | 3.7(5) |

determined to be 28 400 K, its surface gravity $\log g = 5.35$. These spectroscopic parameters place it at the cool end of the EC 14026 instability region. The main pulsation period was found to be 363 s at a relatively large amplitude of 29 mmag. A second period of 382 s has been shown to be present at a much smaller amplitude of 3.8 mmag. This paper reports on the discovery of additional variations at a longer time scale of ~1 h, and addresses in particular the implications resulting in the case of an interpretation of the period as a stellar oscillation.

## 2. Discovery and follow-up observations

Photometric observations of HS 0702+6043 were obtained on three consecutive nights in December 1999 using the Calar Alto 1.2 m telescope. Details of the set-up, the observing log and the data reduction may be found in DR02. The light curve has an average cycle time of 18 s and was taken in white light. The analysis of the relative light curve obtained from aperture photometry yielded two periods in the range of 360–390 s as detailed in the previous section.

While testing a new set of time-series analysis tools (Huber et al., in preparation), we discovered a ~1 h variation in the residuals of the discovery light curve of HS 0702+6043. These data are however of insufficient quality to conduct a false alarm probability analysis. In order to confirm the variation, we reobserved the star during two nights using the Steward Observatory 2.3 m Bok telescope.

These observations, obtained in February 2004, span roughly 6 h on both nights. A relative light curve was extracted from images that have an average cycle time of 86 s and were taken through a F555W filter. As in DR02, the two shorter periods (see Table 1) were prewhitened from the data. Note that the value DR02 have identified for their tentative second short period is separated by a one-day alias from the more reliable result for $f_2$ from the new data.

Both the full light curve and the residual after subtraction of $f_1$ and $f_2$ are shown in Fig. 1. The frequency spectrum of the full data is displayed in Fig. 2. A false alarm probability analysis of the residual (see DR02 for details of our implementation of this method) for the peak near 271 $\mu$Hz in Fig. 2 indicates that it is real with a significance well above $5\sigma$. Moreover, there is significant residual power left around this peak after prewhitening of $f_3$. Regardless of ambiguities in the prewhitening due to one- and two-day aliases, this is already evident in the original frequency spectrum as a “shoulder” or “hump” to the right of the main peak. Since this sub-structure is not resolved from what we have identified as $f_3$, we do not however attempt to assign any further frequency detections to it.

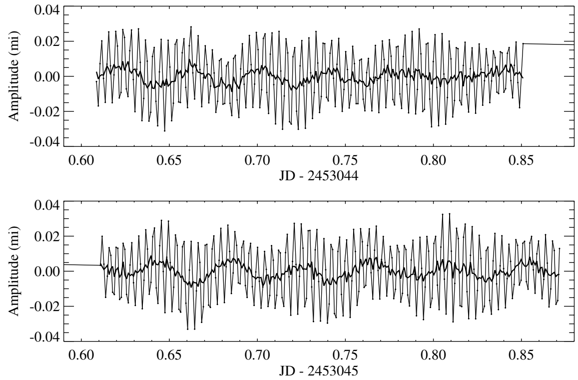

**Fig. 1.** Original data points (dots joined with a line), and residuals (thick line) after subtraction of two short-period frequencies $f_1$ and $f_2$: the variability pattern of the residuals strongly resembles the multi-period brightness changes observed in lpsdBV stars.

## 3. What is causing the variation?

There are three possible interpretations of the low-frequency variation: binarity (reflection effect or ellipsoidal variation), a rotating star spot, or pulsation. Its coherence and persistence over four years rules out normal sky or transparency variations.

### 3.1. The binary hypothesis

From the uncontaminated optical spectrum of HS 0702+6043, we can easily exclude a potential F- or G-type main sequence companion. Because the star is relatively faint, *2MASS* photometry is only accurate enough to require that any hypothetical companion must be later than K-type. At the supposed 1 h orbit, the Roche geometry marginally allows to fit an object near the minimum of the mass-radius relation, i.e. an old massive brown dwarf. However, all systems containing an sdB plus low-mass companion show a substantial reflection effect. The amplitude of the observed variation is quite low when compared with known sdB plus M-dwarf close double stars. HW Vir was the first such system discovered, with peak-to-peak amplitudes of ~0.26 mag in $V$ (e.g. Kiss et al. 2000), as well as eclipses, while the most recent discovery is that of HS 2333+3927 (Heber et al. 2004), a system with peak-to-peak amplitudes of 0.33 mag in $R$. Another system, PG 1017−086, shows a lower amplitude of 0.083 and a period of 1.75 h (Maxted et al. 2002), however this variation is still ~22 times larger than the one we see in HS 0702+6043. One possible way to explain a very low-amplitude reflection is by assuming a low inclination angle, i.e. so that the system is virtually seen pole on; this is also the only way to prevent eclipses in very tight configurations.

If the 1 h variation we see in HS 0702+6043 is due to an ellipsoidal distortion of the star by a compact companion, then we would expect that the actual orbital period of the system is twice that of the intensity variation. There are two known sdB plus white dwarf systems showing an ellipsoidal effect, KPD 0422+5421 (Koen et al. 1998) and KPD 1930+2752 (Billères et al. 2000; Maxted et al. 2000). These stars show intensity variations of 0.0148 mag and 0.013 mag, respectively, and both are seen almost edge on (with inclinations ≳80°). Feige 48, an EC 14026 star with parameters very similar to

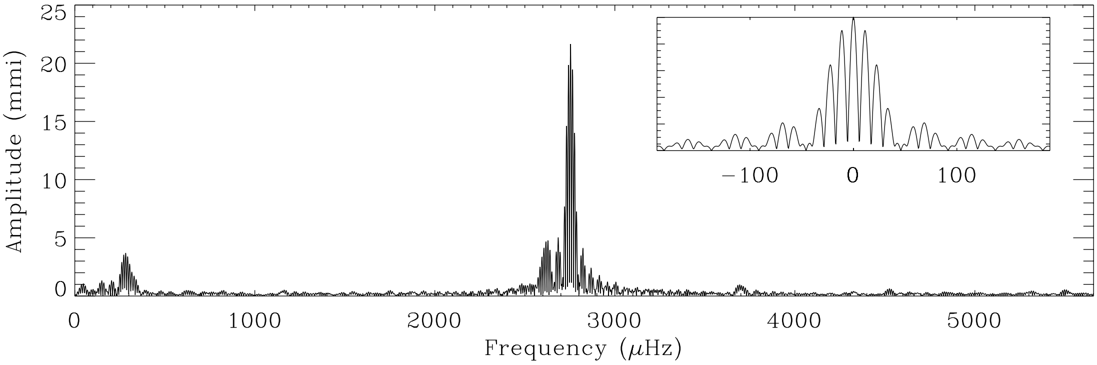

**Fig. 2.** Discrete Fourier transform of the full light curve, with the window function for the two-night data set displayed in the inset panel in the upper right corner (frequency in $\mu$Hz as in the main plot, the amplitude scaling is arbitrary). $f_1$ and $f_2$ clearly stand out slightly below 3000 $\mu$Hz, as does the unresolved $f_3$ conglomeration near 300 $\mu$Hz. Note the "shoulder" of that feature towards higher frequencies which is responsible for significant residual power after prewhitening of one low-frequency period.

HS 0702+6043, was found to be a sdB plus white dwarf system of low inclination with a period of 9 h (O'Toole et al. 2004). If such a system were reduced to a 2 h orbital period, ellipsoidal variations might become apparent. In addition to the inclination, the size of the variation depends on how much of its Roche lobe the sdB fills. These relaxed constraints on the amplitude together with a larger possible orbit (due to the twice as long orbital period) to accommodate a second component that is more compact make it harder to rule out the sdB plus white dwarf scenario.

However, if we examine the light curve after the two higher pulsational frequencies have been subtracted (the thick line in Fig. 1), it becomes quite evident that the amplitude of the variation is changing. This strongly suggests that the variation is not due to binary motion.

### 3.2. A rotating star spot?

Another possible cause to be considered as the origin of the variation in HS 0702+6043 is a rotating star spot. Although single sdBs do not generally rotate very rapidly, with only one possible exception (PG 1605+072, but see Kuassivi et al. 2005), the following scenario can be constructed around this possibility. Assuming that the 1 h period corresponds to the rotational period of the star, the variation would then be caused by an inhomogeneous surface temperature distribution (possibly resulting from a magnetic field). The variation has been seen at the same period in two observations taken four years apart, a time scale that is probably much longer than the typical life time of a star spot. However, newly appearing star spots are bound to result in the same rotation period determination, only with arbitrary phase discontinuities. Furthermore, differential rotation could explain the variation in the period ("multiperiodicity") when a single spot drifts, or when several spots are present simultaneously.

For the frequencies in the *p*-mode domain, substantial rotational splitting due to the fast rotation would have to be taken into account for all $l \neq 0$ modes. For a hypothetical $l = 1$ mode $f_0$ at a suitable geometric orientation, the two $m = \pm 1$ frequencies could be observable and would lie at about $f_1 = f_0 + \Delta f$ and $f_2 = f_0 - \Delta f$, where $\Delta f$ would correspond to the rotational frequency. Using $f_1$ and $f_2$ from Table 1 and $f_0 = (f_1 + f_2)/2$, $\Delta f$ would amount to 74 $\mu$Hz, only a fraction of $f_3$.

The fact that no frequency splitting at the large value of $f_3$ (or multiples of it) is seen does not automatically rule out this interpretation, but, together with the unusually high rotation rate implied, makes it relatively unlikely.

### 3.3. The long-period pulsation hypothesis

The final possible cause of the observed variation is pulsation. Green et al. (2003) first detected oscillations in several sdBs with periods from around 30 to 80 min. The periodicity we observe lies within this range, and the amplitude is also very comparable to that of the lpsdBVs. As noted in the previous sections, the data imply multiperiodicity, a strong indicator for a pulsational origin of the variation. This might already be seen in the light curve, especially in the top panel of Fig. 1, where the amplitude in the second half of the curve appears to reduce almost to zero – suggesting beating between several modes. The unresolved multiperiodicity becomes particularly evident after the highest peak in the low-frequency domain ($f_3$) has been removed: after this additional prewhitening of the strong variation, there is significant residual power remaining, above the $3\sigma$ level derived from a false alarm probability analysis.

It is also interesting that the low frequency we measure is very close to, but not exactly, the difference between the two higher frequencies presented in Table 1. This near-resonance is striking, and again indicates that the variation is most probably not due to rotation or orbital motion. If either of these were the case, we would expect exact resonance. All of this together suggests the very exciting possibility that HS 0702+6043 shows both *p*-modes *and* *g*-modes simultaneously.

## 4. Implications for asteroseismology

Stars that show observable multimode pulsations in both *p*- and *g*-modes have an enormous potential for asteroseismology since modes on the acoustic and gravity branches, respectively, probe different regions in the depth-dependent stellar structure. HS 0702+6043 is probably one among very few objects to fall

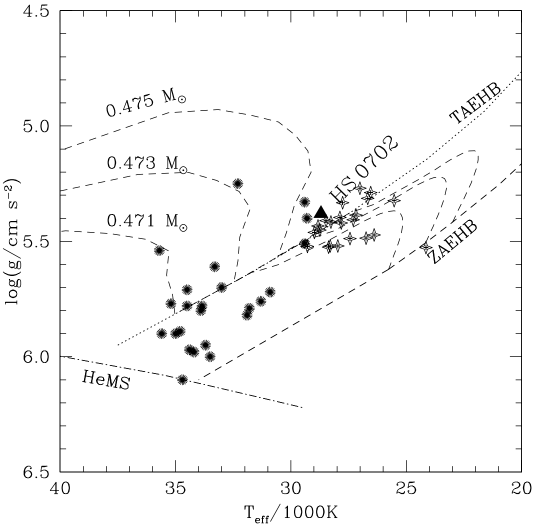

**Fig. 3.** Known sdBV and lpsdBV pulsators in the log $g$–$T_{\rm eff}$ diagram: sdBV populate the higher-temperature, lpsdBV the lower-temperature region. The helium main sequence (HeMS), zero (ZAEHB) and terminal (TAEHB) age extended horizontal branches are marked; also shown are evolutionary tracks off the extended horizontal branch by Dorman et al. (1993). The position of HS 0702+6043 is indicated.

into this class of hybrids. Not only does the range of its long period(s) and the magnitude of the corresponding amplitude match what is expected for $g$-mode pulsators, its stellar parameters also place it at a position at the edge of both of the empirical instability regions in the $T_{\rm eff} - \log g$ diagram (see Fig. 3). In fact, from its position in Fig. 3, which shows the two groups of hot, short-period pulsators, and the cooler, long-period pulsators, one could argue that $g$-mode pulsations should almost be *expected* in HS 0702+6043 (although it should not be forgotten that both types of pulsators among sdB stars co-exist with a larger fraction of non-pulsating sdBs in the same areas).

A second candidate for the class of sdBV / lpsdBV hybrids established through the initial announcement of our discovery (Schuh et al. 2005) has recently been published by Baran et al. (2005): Balloon 090100001 (Oreiro et al. 2004). It is striking that there appears to be a gap along the EHB, so that the four coolest sdBVs (Feige 48, HS 2201+2610, Balloon 090100001 and HS 0702+6043) are closely connected in parameter space to the lpsdBVs rather than to the rest of the sdBVs. In fact, two of them are hybrid (HS 0702+6043 and Balloon 090100001), so what about Feige 48 and HS 2201+2610? If attempts to detect long-period variations remain unsucessful, the latter two stars would belong to the sdBs in the lpsdBV regions that do not show $g$-mode pulsations. From a theoretical point of view, it is a challenge to drive both $p$- and $g$-modes simultaneously in this object; future models will have to account for the existence of HS 0702+6043.

On the main sequence, where the sdBV / lpsdBV groups might have an analogy in the $\beta$ Cep / [SPB] variables, potential hybrid stars include two objects presented by Jerzykiewicz (1993) and Handler et al. (2004). The class of $\gamma$ Dor / $\delta$ Scu hybrids are discussed in Handler et al. (2002), Dupret et al. (2005), and Henry & Fekel (2005).

## 5. The future

The amplitude variability observed in HS 0702+6043 is highly suggestive that the 1 h variation is not due to binary or rotational motion, and results from $g$-mode pulsations instead.

To resolve the suspected several low-frequency modes of HS 0702+6043, longer observations are clearly required. To this end, we have recently completed a 10-day-multisite campaign to observe HS 0702+6043 photometrically that we will report on in a forthcoming paper.

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