J08069+1527: A newly discovered high amplitude, hybrid subdwarf B pulsator

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ABSTRACT
We present our discovery of a new hybrid pulsating subdwarf B star, J08069+1527. The effective temperature and surface gravity of 28,500±400 K and 5.37±0.04 dex, respectively, place this object inside the instability strip and also among other pulsating hot subdwarfs of a hybrid nature, right next to another fascinating star: Balloon 090100001. From this proximity, we anticipated this star could pulsate in both high and low frequency modes. Indeed, our analysis of photometric data confirmed our prediction. We detected two peaks in the high frequency region and two other peaks at low frequencies. In addition, the amplitude of the dominant mode is very high and comparable to the dominant peaks in other hybrid subdwarf B stars. Since this star is bright, we performed time-series low resolution spectroscopy. Despite a low signal-to-noise (S/N) ratio, we were able to detect the main peak from these data. All our results strongly indicate that J08069+1527 is a high amplitude pulsating hot subdwarf B star of hybrid nature. By analogy to the other pulsating sdB star, we judge that the dominant mode we detected here has radial nature. Future stellar modelings should provide us with quite good constrains as p- and g-modes presented in this star are driven in different parts of its interior.

Key words: stars: subdwarfs, asteroseismology.

1 INTRODUCTION
Hot subdwarf B (sdB) stars are horizontal branch stars with masses about 0.5 M⊙ and very thin, in mass, hydrogen envelopes. Their average effective temperature and surface gravity are about 30 000 K and log g ∼ 5.5, respectively. Although the future evolution of the sdB stars to the white dwarf cooling track is generally accepted, their formation prior to the sdB stage is under debate resulting in several mechanisms that involve single-star or binary evolution (e.g. D’Cruz et al. 1996; Han et al. 2002, 2003).

The detection of pulsations in sdB stars opened a way to study their interiors and may help to understand their evolution prior to the horizontal branch. First, short period oscillations were found by Kilkenny et al. (1997) in EC 14026-2647 (now officially named V391 Hya). According to theoretical models, these pulsations are attributed to pressure modes and are driven in the outer part of the star (Charpinet et al. 1997). Several years later, Green et al. (2003) announced another kind of variability in sdB stars. In this case, however, the pulsations were identified with gravity modes. Following Fontaine et al. (2003) they are driven deeper in the sdB stars than the pressure ones. Short-period sdBV (sdB Variable) stars are located at higher, while long-period sdBV stars at lower effective temperatures.

The pulsation modes of the two kinds of sdBVs probe different regions, and stars displaying both types are particularly interesting since their interiors can be better constrained. Such hybrid pulsations were first found in DW Lyn (Schuh et al. 2006) and another three objects with clear pulsations at both short and long periods have so far been recognized; Balloon 090100001 (Baran et al. 2005; Oreiro et al. 2005), V391 Peg (Lütz et al. 2009) and RAT 0455+1305 (Baran & Fox-Machado 2010). Another star, CS 1246, has similar log T eff and log g and one high amplitude short periodicity detected. Unfortunately, because of noisy data, the detection threshold in the low frequency region is too high. The best data are in the r’ filter, and the amplitude spectrum calculated from these data contains some excess signal in the low fre-
servations of CS 1246. Extremely high precision photometry obtained with the Kepler spacecraft has revealed several long period sdBs. An unusual hybrid pulsator in an eclipsing binary, 2M1938+4603, was found to show an exceptionally low duty cycle, which is surprising as the peaks are detected in a very small range, but for the other sdBs observed during the search program. The derived effective temperature of 28,877(±202) K and surface gravity of 5.34(±0.03) dex along with its encouraging brightness made it a priority target for the next observing season. Recently, Vennes, Kawka & Németh (2010) have published their first results from a survey of UV-excess stars in the GALEX archive, and J08069+1527 is included in their sample. Their determination of $T_{\text{eff}}$ and log g is fully consistent with ours, within the errors.

3 TIME SERIES PHOTOMETRY

3.1 Discovery data

We performed time-series photometry of J08069+1527 on 30 December 2009 using the KPNO 2.1 m telescope. We used an Apogee CCD with a BG40 filter (wide band covering UBV filters range) with 12 sec exposure times. Seeing conditions allowed us to set up a single exposure per night as long as possible. In total we collected 4 hours of data. The derived effective temperature of 28,877(±202) K and surface gravity of 5.34(±0.03) dex along with its encouraging brightness made it a priority target for the next observing season. Recently, Vennes, Kawka & Németh (2010) have published their first results from a survey of UV-excess stars in the GALEX archive, and J08069+1527 is included in their sample. Their determination of $T_{\text{eff}}$ and log g is fully consistent with ours, within the errors.

### Table 1. Observational Log.

| Date [UT] | hours | exposure | filter | site | observer |
|-----------|-------|----------|--------|------|----------|
| 30 Dec 2009 | 4.0 | 12s | BG40 | KPNO | ASB,JTG |
| 10 Jan 2010 | 5.4 | 30s | BG40 | Baker | LH,MDR |
| 11 Jan 2010 | 7.0 | 31s | B(Geneva) | Mercator | KS |
| 12 Jan 2010 | 6.2 | 31s | B(Geneva) | Mercator | KS |
| 20 Jan 2009 | — | 600s | spectrum | NOT | RO |
| 07 Jan 2010 | 6.6 | 30s | spectra | NOT | JHT |

As was shown by Baran & Fox-Machado (2010), for hybrid stars the dominant modes in both frequency domains appear at very similar frequencies. These are $\sim 0.3$ Hz for gravity modes and $\sim 2.8$ Hz for pressure modes. As for gravity modes, it may not be so surprising as the peaks are detected in a very small range, but for the pressure modes it is more astonishing. This may indicate that these stars are alike in internal structure and/or evolutionary status on the horizontal branch. In this paper we present our discovery of a new hybrid sdBV star with a high amplitude short period mode. We obtained data on four nights, including the discovery one.

### Figure 1

Light curve in a BG40 filter obtained in December 2009 at KPNO.

### Figure 2

All data obtained on J08069+1527. The first night was taken at KPNO, while the second at Baker and the last two at Mercator. Note that data from the third one was taken in a BG40 filter while during the last two we used a B filter (Geneva system). Each set of points stands for one night. Two vertical lines indicate coverage of spectroscopic data.

Typical amplitudes of sdBV stars showing high frequency oscillations are below 1%, which corresponds to 10 mmag. Most hybrid stars have unusually high amplitudes (few per cent), making them extremely desirable. Since sdBV stars tend to be faint ($V > m_{\text{V}} > 17$ mag) high amplitude pulsators are easier to observe, even with 1 m class telescopes.

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### J080656.7+1527

The target J08069+1527, has UV magnitudes $FUV = 13.68$, $NUV = 13.86$ in the GALEX All-sky Imaging Survey. (Martin et al. 2005). AIS) observation obtained on February 2, 2006. After comparing the UV magnitudes with visual photometry in the NOMAD survey ($B = 13.88$, $V = 14.23$, $R = 14.83$), we flagged the target as a likely sdB star, and it entered a list of bright spectroscopy targets that served as a poor weather backup for a photometric observation run in the NOT search for pulsating sdBs in January 2009 (Østensen et al. 2010b). The extracted spectrum was fitted to a model atmosphere spectrum, using the same procedure as for the other sdBs observed during the search program. The derived effective temperature of 28,877(±202) K and surface gravity of 5.34(±0.03) dex along with its encouraging brightness made it a priority target for the next observing season. Recently, Vennes, Kawka & Németh (2010) have published their first results from a survey of UV-excess stars in the GALEX archive, and J08069+1527 is included in their sample. Their determination of $T_{\text{eff}}$ and log g is fully consistent with ours, within the errors.
 telescope on La Palma. At Baker Observatory we used a Photometrics RS-1340 CCD with a BG40 filter. Exposure times were set to 30 sec along with 1 sec readout time. At the Mercator telescope we used the Merope CCD camera, which was recently upgraded with a new E2V frame transfer CCD with 2048 pixels (Østensen 2010c). Here we used a B filter (Geneva system) with a new E2V frame transfer CCD with 2048 pixels (Østensen 2010c). Here we used a B filter (Geneva system) setting the data cadence period to about 31 sec. We include all this information in Tab.1.

We calibrated all star images for instrumental effects (bias, dark, flat field) and extracted brightnesses of target and field stars. In the next step we calculated differential photometry using a few comparison stars. All these tasks were done by means of the Daophot package (Stetson 1987) with a graphical user interface (FinRed, developed by ASB). Because the field of view only covers a few-arcminutes on the sky, the first order extinction (differential extinction) was negligible and long term variations (on the scale of run duration) were de-trended by subtracting a cubic spline curve. We assume here that any change in brightness, on time scales of about 6 hours or longer, is not intrinsic to the star and is likely caused by non-perfectly removed extinction, either first or second order or other atmospheric effects.

In the next step, treating all nights separately, we transformed all brightnesses to fluxes and subtracted a mean value. Resulting fluxes were then centered around zero. Next, we analyzed these data by means of a Fourier analysis. We present our discovery light curve of J08069+1527 obtained at KPNO on 30 Dec 2009 in Fig.1. One can note that besides short period variability some long term variability is also present in the light curve. We present all data in Fig.2.

3.3 Amplitude spectrum

Although we have data taken with three different telescopes, we decided not to combine them all together. It is because data from KPNO and Baker, taken in the same filter, are 10 days apart. When combining such data, we arrived with a higher noise level in the amplitude spectrum and a very complex window function. In the case of data from Baker and Mercator, although collected on consecutive nights, they are not in the same filter. As a result, during the pre-whitening process, we can obtain residual (fake) peaks caused by different amplitudes and perhaps phases of modes observed in different filters.

Since the telescope at KPNO is the biggest among those we used, data collected on that site are characterized by the smallest noise level in their amplitude spectrum. These data allow us to detect the highest number of peaks at S/N > 4 used as our threshold. We detected two peaks in the high frequency region and two in the low frequency region. The dominant peak has a high amplitude and a frequency similar to some other sdBV stars discovered so far. Baran & Fox-Machado (2010) showed that all hybrid sdBV stars detected from ground have a main dominant high frequency peak at similar frequencies around 2.8 mHz. The main peak in J08069+1527 is also located in the same region. What is more, its effective temperature and surface gravity is almost the same as other hybrids, particularly Balloon 090100001. In addition, we found two peaks in the low frequency region. Precise estimation of their significance is rather hard since not all the signal can be pre-whitened from that frequency region. This increases the real noise level. A detection threshold used in our analysis is an average through all frequencies in the amplitude spectrum, which might be a source of underestimation in the low frequency region. To estimate the noise level in that region more reliably, we used the adjoining 0.35–1 mHz region and assumed it to be valid for those two peaks. Although the detection threshold increased, they still remained significant. Amplitude spectra with all pre-whitening steps calculated from KPNO data are shown in Fig.3.

In pre-whitening data taken at Baker, we could safely secure only one peak at the same frequency (within errors) as the dominant one from analysis of KPNO data. Others, if present are below the detection threshold. Only one peak detected here should not be surprising as the average noise level reaches 0.7 mma so only peaks higher than 2.8 mma could be detected with sufficient confidence. Looking at the result from KPNO, none but the dominant peak sat-
though here we have better resolution and more points collected, we  
satisfies this condition. An amplitude spectrum as well as the residual  
one is shown in Fig[4].  
To Mercator we obtained data on two consecutive nights. Al-
though here we have better resolution and more points collected, we  
could not detect more peaks compared to the KPNO data. There is  
some signal excess in the low frequency domain. Unfortunately, the  
noise level is too high to confirm any peaks in this region. We can  
only confirm two peaks in the high frequency region. The dominant  
peak we detected here has the same frequency as the one detected  
in KPNO and Baker data while the other has a similar frequency  
but barely exceeds the error limits. However, apart from amplitude  
errors, frequency errors are sensitive to the length of observations.  
That is why we may consider the frequencies derived from Merca-
tor data as the more precise ones. On the other hand, after removing  
the dominant peak, the residual amplitude spectrum still contains  
a small peak at the frequency of the removed one (Fig[5]). It can  
mean that this peak is physically unstable, or there may be a mode  
beating, or some instrumental effects that cause either frequency,  
or amplitude to be different on each night. From Tab[2] we can see  
that frequencies are not changing within the given errors. Compar-
ing amplitudes is harder since at Mercator we used a different filter.  
By comparing KPNO and Baker data, which were obtained in the  
same filter we can conclude that the amplitude has not changed over  
10 days (or is changing with periodicity of about 10 days). Trying to  
solve this issue we chopped Mercator data into nightly chunks and  
Fourier analyzed them separately. From the Fourier solution, we  
found that timing issues between nights is not bigger than 0.5 sec.  
However, the amplitudes from these two nights are substantially  
different. We derived 25.72(42) mm and 29.12(42) mm on the  
first and second nights, respectively. Since the residual of the pre-
whitened data roughly equals the difference of the amplitudes from  
the two nights, we can conclude that the cause is the change in  
amplitude.

4 TIME-SERIES SPECTROSCOPY

We performed time-series spectroscopy on the night starting on  
7 Jan 2010. We used ALFOSC at the Nordic Optical Telescope  
(NOT) to obtain 472 low resolution spectra. We used grism#16 and,  
for all but the first few exploratory spectra, we used a 1.3 - arcsec  
wide vertical slit. Our dataset spans a total of 6 hours and 40 min-
utes.

We used a small window and $2 \times 2$ binning in the spatial  
direction to minimize readout-overheads; the window allowed for  
28 arcseconds of sky on either side of the stellar spectrum. To  
avoid under-sampling and to not smear the dominant variability too  
much, we set the exposure time to 30 sec, achieving a 42 - sec cycle  
time. In the course of our run we obtained spectra of a helium arc  
lamp to calibrate the wavelength.

Unfortunately, since the brightness of this star is about 14 mag  
in the B filter only, we could not achieve very high S/N ratio. For  
single spectra we had typical S/N $\sim$ 15 in the 440-480 nm re-
ion, while we reached S/N $\sim$ 150 in the average spectrum shown  
in Fig[6].

We used standard IRAF procedures to reduce and calibrate the  
spectra, leading to 472 extracted spectra. We normalized the average  
spectrum to unity, using a low-order polynomial fit. The result-
ning spectrum was then fitted with a model spectrum, and the  
resulting model spectrum was used for guidance in the final normal-
ization of the average spectrum. The stellar parameters we derived  
from the average spectrum ($T_{\text{eff}}$, $\log g$ and $\log He$) were  
consistent for different normalization/rectification methods that  
either employ straight-line fits around each Balmer line or a multi-
order polynomial fit that rectifies the complete spectrum at once.  
Then all individually extracted spectra were rectified using the fit  
that was needed to normalize the average spectrum. Finally the in-
dividual spectra were scaled to get their continuum at unity, using  
a simple parabolic fit in the regions with no absorption lines.

We derived $T_{\text{eff}} = 28,063 \pm 163$ K, $\log g = 5.39 \pm 0.02$ and  
$\log He/H = -2.971 \pm 0.064$ dex. These values are different than  
those derived from spectrum taken in January 2009 so we adopt  
an average value for all three parameters: $T_{\text{eff}} = 28,500 \pm 400$ K,  
$\log g = 5.37 \pm 0.05$ dex and $\log He/H = -2.96 \pm 0.10$. The reader  
should be aware, though, that systematic effects from the model  
grid can give shifts on the order of 2000 K and 0.2 dex in $T_{\text{eff}}$ and  
$log g$, respectively.

To look for radial velocity (RV) displacements we used the  
IRAF cross-correlation routine FXCOR, finding the radial-velocity  
shift of each individual spectrum with respect to that of the aver-
gage spectrum. We included only the wavelength regions around 7  
Balmer lines (H-$\beta$-H10) in the cross-correlation. We fitted a Gauss-
ian function to find the center of the cross-correlation function,  
which we adopted as a measure of the radial-velocity shift. As a  
result we obtained Heliocentric Julian Date along with RV shifts  
and their errors. We present the radial velocity curve in Fig[8]. This  
result was subject to Fourier analysis in order to extract any period-
icity from the data. The amplitude spectrum is shown in Fig[12]. By  
means of non linear least square fitting, we detected only one peak  
which satisfies S/N$>4$. Its frequency, amplitude and phase with er-
rors are: 2.8202(42) mHz, 6.1(1.0) km/s and 5.69(17) rad, respec-
tively. The phase is given at HJD = 2455204.577483. We present  
the radial velocity curve folded with the period obtained in our anal-
ysis in Fig[10]. The periodicity detected in a Fourier space barely  
meet our significance level as S/N $= 4.55$.  

Figure 5. Amplitude spectrum with pre-whitening steps calculated from  
data taken at Mercator. The solid horizontal at 1.65 mma line represents  
S/N = 4.
**Figure 6.** Average spectrum of J08069+1527 obtained at NOT and calculated from 472 single low resolution spectra. Magenta line represents a model spectrum used for the final normalization.

**Figure 7.** Fits to the line profiles of hydrogen and helium lines in the spectrum taken in January 2009 (on the left) and the mean spectrum of recent time-series spectroscopy (on the right) with RV fixed at 335 km/s. Cited errors are the formal fitting errors between the observed and model spectra.
### Table 2

Results of the pre-whitening process of all data treated separately by site. The phases are given at mean epoch (HJD) of each night: 2455195.960754, 2455206.844458 and 2455209.065208 for KPNO, Baker and Mercator, respectively. The numbers in parentheses are the errors of the last digits. Gaps in the cells mean that no signal was detected either in Baker or Mercator data at frequencies detected in KPNO data.

| Mode | f [mHz] | A [mma] | Phase [rad] | f [mHz] | A [mma] | Phase [rad] | f [mHz] | A [mma] | Phase [rad] |
|------|---------|---------|-------------|---------|---------|-------------|---------|---------|-------------|
| f_A  | 0.2926(47) | 1.68(18) | 3.74(12) | f_B    | 0.3577(53) | 1.63(17) | 1.63(12) | f_1    | 2.81862(28) | 22.06(16) | 2.237(7) |
| f_2  | 2.6059(31) | 1.98(16) | 4.45(8) | f_A    | 0.2926(47) | 1.68(18) | 3.74(12) | f_B    | 0.3577(53) | 1.63(17) | 1.63(12) | f_1    | 2.81862(28) | 22.06(16) | 2.237(7) |
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#### 5 SUMMARY AND CONCLUSION

In this paper we presented our discovery of a new hybrid pulsating subdwarf B star, J08069+1527. Effective temperature and surface gravity place this object in the instability strip among other hybrid subdwarfs. From our analysis of photometric data we detected four peaks, including two in the low frequency domain, confirming our prediction. As the star is relatively faint, spectroscopic data is not sufficient to detect more than just the dominant mode we found in the discovery data. However, it proved that time-series spectroscopy at 2 m class telescope can support our analysis with radial velocity shifts down to 14 mag hot subdwarf stars, particularly when data are taken over several nights.

As it turns out, physical parameters are not the only similarities J08069+1527 has to other hybrid sdBV stars. As shown in Baran & Fox-Machado (2010), some hybrids share a common frequency for their dominant variation and J08069+1527 also has this characteristic. It might be that these stars are in very similar evolutionary state and/or have very similar stellar structure. If so, we could use the result obtained by Baran & Fox-Machado (2010) to constrain the degree of the dominant mode to \( \ell = 0 \). Balloon 090100001 has photometrically constrained pulsation modes using multiplets (Baran et al. 2009). The dominant periodicity in Balloon 090100001, associated with an \( \ell = 0 \) mode, has a photometric amplitude in a B filter of 53 mma and a radial velocity (RV) amplitude of 19.2 km/s. The amplitude ratio of RV/B is 0.362. The dominant periodicity in J08069+1527 has an amplitude of 27 mma and RV = 6.1 km/s which results in a ratio of 0.226. The difference in ratio is substantial, however, the amplitude spectrum of J08069+1527 might be unresolved and the amplitude of the dominant mode affected by poor resolution. More data of J08069+1527 taken over several days may help to better compare results on these two interesting stars.

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