Observational Asteroseismology of Hot Subdwarf Stars with the Mont4K/Kuiper Combination at the Steward Observatory Mount Bigelow Station

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Abstract. In the last few years, we have carried out several extensive observational campaigns on pulsating hot subdwarf stars using the Mont4K CCD camera attached to the 1.55 m Kuiper Telescope on Mount Bigelow. The Mont4K is a joint partnership between the University of Arizona and Universit\'e de Montr\'eal. It was designed and built at Steward Observatory. Using the Mont4K/Kuiper combination, we have so far, and among others, gathered high-sensitivity broadband light curves for PG 1219+534, PB8783, HS 0702+6043, and Feige 48. We report very briefly on some of the most interesting observational results that came out of these campaigns.

1. The Mont4K Instrument

The Mont4K (as in Montr\'eal 4K × 4K CCD Imager) is an instrument that has been developed and built at Steward Observatory thanks, in part, to a Canadian Foundation for Innovation grant awarded to G. Fontaine. E.M. Green at Steward has been the main driving force behind this project. This partnership between the University of Arizona and Universit\'e de Montr\'eal has been extremely fruitful and has allowed us to gather high S/N light curves of pulsating hot subdwarf and white dwarf stars. The instrument has also proved itself to be an excellent imager in standard mode.

The CCD has a response of more than 95% in the blue, ideal for studying pulsating hot subdwarf and white dwarf stars. A wheel containing six 5” × 5” filters (currently \textit{U, B, V, R, I}, and either F555W or Schott 8612) can be used. The Mont4K is mounted exclusively at the 1.55 m Kuiper Telescope on Mount Bigelow near Tucson. More details about the instrument can be found at the following web address, http://james.as.arizona.edu/~psmith/61inch/CCD/CCDmanual.html
2. The Campaigns

We have taken advantage of the Arizona-Montréal partnership to periodically secure huge blocks of observing time on the 1.55 m Kuiper Telescope, a privilege seldom granted on other telescopes of this class. We selected targets deemed of particular interest, fociussing mostly on pulsating hot subdwarfs, but also including pulsating white dwarfs. Although hugely successful, we have yet to exploit the results of most of these campaigns because our collective attention over the last few years has been diverted primarily on results obtained with the Kepler satellite.
Table 1. Campaigns on Hot Subdwarfs with the Mont4K/Kuiper Combination

| Dates          | Target                  | Type       | Length (hr) | Duty cycle (%) | Resolution (µHz) | Sampling time (s) | Noise level (%) |
|----------------|-------------------------|------------|-------------|----------------|------------------|-------------------|-----------------|
| 19/12/06-24/02/07 | PG0911+456             | sdBV_r     | 57.1        | 3.5            | 0.17             | 38.30             | 0.0063          |
| 03/02/07-03/05/07 | PG1219+534             | sdBV_r     | 198.7       | 9.3            | 0.13             | 19.44             | 0.0043          |
| 17/09/07-04/12/07 | PB8783                 | sdBV_r,s   | 182.5       | 9.8            | 0.15             | 21.20             | 0.0035          |
| 01/11/07-14/03/08 | HS0702+e043            | sdBV_m     | 415.7       | 12.9           | 0.086            | 49.66             | 0.0044          |
| 01/03/09-17/05/09 | Feige 48               | sdBV_m     | 399.1       | 12.2           | 0.085            | 34.00             | 0.0035          |
| 10/11/09-10/03/10 | KPD0629−0016           | sdBV_m     | -228        | ...            | ...              | ...              | ...             |
| 10/11/10-10/02/11 | LSIV-14 116            | He-sdBV    | 53.5        | 4.6            | 0.24             | 51.78             | 0.0180          |
| 12/03/13-ongoing | PG1605+072             | sdBV_r     | ...         | ...            | ...              | ...              | ...             |

The vital statistics of the campaigns carried out so far on pulsating hot subdwarfs (including one in progress and another one planned for the fall of 2013) are listed in Table 1. We use the nomenclature proposed by ? to designate the various types of pulsators that were considered. Note, in particular, the excellent temporal resolution achieved and, above all, the rather remarkably low noise level reached after our longest campaigns. This is the mean noise level computed after prewhitening in the relevant frequency interval where power was detected. This unique combination of resolution and sensitivity from ground-based observations has allowed us to circumvent most of the usual difficulties associated with short observing runs carried out at a single site.

Figure 1 illustrates the locations of our hot subdwarf targets in relation to other known pulsators in the effective temperature-surface gravity domain. Along with three “classic” sdBV_r stars, PG0911+456, PG1219+534, and PB8783 (but see below), we have also dedicated long campaigns on the first-discovered hybrid (sdBV_m) pulsator HS0702+6043 and on the long suspected pulsator of the same kind, Feige 48. Furthermore, a campaign on the long-period sdBV_s pulsator KPD0629−0016 was carried out in 2009-2010 to back up a run that was obtained on the satellite CoRoT in 2010 March (?). Another similar campaign was carried out the following season, but the data remain to be analyzed. Although the difficulties of exploiting asteroseismology for long-period pulsating hot subdwarfs observed from the ground have been well documented in ?, it is hoped that the combination of space and ground based data will help testing and improving the seismic model of KPD0629−0016 proposed by ?. Also, we are hoping that the difficulties mentioned in ? will be largely alleviated during our next effort, planified for the fall of 2013, and dedicated to the sdBV_s pulsator PB5450, since this object is the most compact of its class (see Fig. 1) and, consequently, exhibits the shortest and more easily characterized g-mode periods.

In addition to the above, a relatively short campaign was carried out in 2010 on the unique and puzzling He-sdBV star LSIV-14 116 (?). Finally, a campaign is currently being pursued on another challenging object, PG1605+072, possibly the most intensely observed pulsating hot subdwarf star, but which has so far resisted detailed interpretation. The latest word on that target is provided by ?.

In the remainder of this article, we provide some additional details on four of our campaigns. In each case, we provide, on the exact same scale, an example of a
representative light curve obtained with the Mont4K/Kuiper pair in order to facilitate the comparisons (Figs. 2, 3, 4, and 5).

2.1. PG1219+534

This target was selected in order to test, and ultimately improve, the seismic model proposed by ?. That model had been developed on the basis of the discovery of nine distinct pulsation modes during a single superlative night at the CFHT as reported by these authors. Previous to that effort, only four modes were known for that pulsator. We thus hoped that more modes still would be uncovered after an extensive campaign with our setup on Mount Bigelow.

The campaign was somewhat disappointing in the sense that no new \((k,l)\) modes were discovered beyond the nine \(p\)-modes already reported by ?. However, two of the nine redetected modes show obvious multiplet structure, best explained in terms of rotational splitting. In particular, the second highest peak corresponding to a central period of 133.52 s in the Fourier transform appears to be made of a quintuplet. This mode stands out compared to the others as it shows relatively large and complex amplitude and phase variations on a nightly basis. These variations are well explained in terms of internal beating between the components of the multiplet. Interpreted as rotational...
splitting, and using the seismic model of ?, this leads to a preliminary estimate of the (uniform) rotation period of 35.61 d for PG1219+534.

2.2. HS0702+6043

The first hybrid (sdBV$_{ns}$) hot subdwarf pulsator was discovered by ?. Although not particularly bright at $V = 15.10$, its light curve shows large amplitudes and the very nature of the object makes it an intrinsically interesting target to study. The observations of ? indicated that the light curve of HS0702+6043 is dominated by a single mode, which made it an attractive target in the context of the EXOTIME project to search for planets orbiting around pulsating hot subdwarfs. The data that we gathered were used extensively by Ronnie Lutz in his Ph.D. thesis. A recent summary of the EXOTIME efforts has been presented by ?.

In our quest to ultimately exploit the seismic potential of HS0702+6043, our campaign turned out to be quite promising. Indeed, our preliminary reduction has led to the detection of a total of 13 $p$-modes and 10 $g$-modes (+3 nonlinear peaks) with amplitudes larger than 4$\sigma$. Interestingly, no sign of rotational splitting is found, despite a total baseline of 134.6 d. This suggests that HS0702+6043 rotates really slowly.
2.3. PB8783

PB8783 is one of the original four hot subdwarfs that were discovered to pulsate (??). Quite bright at $V = 12.32$, ?? demonstrated early on its potential for seismology. They uncovered 11 pulsation modes after a two-week campaign. These modes belonged to 7 distinct complexes, including multiplets best explained in terms of rotation.

Despite rather small amplitudes (see Fig. 4), the light curve of PB8783 is rich with many oscillations. And indeed, our effort has led to the detection of some 63 pulsation modes with amplitudes larger than $4\sigma$ in that star. Contrary to HS0702+6043, however, PB8783 shows clear evidence of rotational splitting as first suggested by ??, and many of the detected modes are part of rotational multiplets. In particular, we find a magnificent quintuplet, and an incomplete nontuplet. The latter may be yet the best observational evidence in favor of a $l = 4$ mode in a pulsating hot subdwarf. Using the average spacing between the multiplet components, and in the absence of a detailed seismic model for that star, we find a rotation timescale of 12.1 d for PB8783.

It is not completely clear yet if PB8783 is a $\sim 36,000$ K sdBV, star or a much hotter $\sim 50,000$ K sdOV because its spectrum is heavily polluted by the presence of a main sequence companion, and it is consequently difficult to infer the atmospheric properties of the pulsating hot subdwarf component of the binary system. ?? has recently argued that PB8783 is a hot sdO star, unrecognized as such since the discovery of its pulsation in 1996. If correct, this implies that PB8783 may be the first field equivalent of the
2.4. Feige 48

The primary objective of this campaign is to test ultimately the seismic model of Feige 48 proposed by ?. The latter is based on only four multiplet structures associated with rotationally-split \( p \)-modes, and it was hoped to detect many more modes from a long ground-based effort at Mount Bigelow. In addition, we had secured \textit{FUSE} observing time on Feige 48 to be gathered in early 2009 when we scheduled our ground-based campaign. The idea was to assemble together as many observational constraints as possible and, in the case of the contemporary \textit{FUSE} observations, to exploit the amplitude-color relation (FUV vs optical) in order to identify or constrain the \( l \) index values for at least the dominant modes. Very unfortunately, the \textit{FUSE} satellite ceased to operate in October 2008, just before the beginning of our planned campaign.

The failed \textit{FUSE} component of our program was certainly a major disappointment to us. However, our ground-based observational campaign has been most successful on the front of uncovering new pulsations in Feige 48, with the firm detection of 15 \( g \)-modes and 31 \( p \)-modes (+2 nonlinear peaks). The detection of \( g \)-modes for the first time in that star makes it a hybrid pulsator. This discovery should not be too surprising in view of the location of Feige 48 in the effective temperature-surface grav-
ity plane (see, e.g., Fig. 1). We also find that rotational splitting is present, but it is complicated due to the mixed character of the modes of interest.

An interesting bonus of our observations is the realization that Feige 48 is part of a reflection effect binary. Its companion is not a white dwarf as previously believed (?), but a very cool main sequence star. Radial velocity measurements carried out by E.M. Green at the MMT have led to a very precise determination of the orbital period for the Feige 48 system: 8.2466210.00001 h (see the paper by Latour et al. in these proceedings). We find a peak at that period in our photometric data, thus proving that there is a reflection effect in the system. Since such an effect cannot be caused by a tiny white dwarf, the culprit must be a cool main sequence companion.

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