OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jul **Proposal type:** short-term

High precision asteroseismology of the pulsating sdB star in the eclipsing binary system PG 1336-018

P.I.: B. Green (SO; *bgreen@as.arizona.edu*; 520-621-1144)

CoI(s): S. Charpinet (Inst. Recherche Astr. et Planet., Toulouse, France), G. Fontaine (Université de Montréal), V. Van Grootel (U. de Liège, Belgium)

Abstract of Scientific Justification

PG 1336−018 is a compact sdB+dM eclipsing binary system whose primary, the sdB star, is a short-period nonradial p-mode pulsator of the V361 Hya type. This extremely rare configuration allows the stellar properties to be derived by completely independent techniques. PG 1336−018, the only currently known example, is therefore a Rosetta stone for asteroseismology. For this star alone, the external accuracy of asteroseismic measurements can be tightly constrained, making possible stringent calibrations of the constitutive microphysics in stellar models. To achieve this goal, we propose to use the proven, very efficient Mont4K/61″ for an extended photometric light curve campaign on PG 1336−018 in order to improve to the limit of what is currently possible the precision at which seismic and orbital constraints can be determined. These data will constitute a very important legacy to the field. **N.B. 16 of the requested nights will come out of G. Fontaine's guaranteed 61″ time.**

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	61”	f/13.5	Mont4K			5	gray	Jan–Jan	Jan–Jan	no	no
2	61”	f/13.5	Mont4K			12	all	Feb–Feb	Feb–Feb	no	no
3	61”	f/13.5	Mont4K			12	all	Mar–Mar	Mar–Mar	no	no
4	61”	f/13.5	Mont4K			12	all	Apr–Apr	Apr–Apr	no	no
5	61”	f/13.5	Mont4K			8	all	May–May	May–May	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We request 8 dark guaranteed nights in each of March and April. All Jan nights should be at end of the month. Moon is too bright/close on Feb 6–11, Mar 5–10, Apr 1–7, Apr 30–May 5, and May 27–Jun 1. Cannot observe March 29–Apr 1. The asteroseismology requires that there not be any gaps longer than 2.0 to 2.5 weeks between the scheduled nights.

no text past this line

A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	PG1336−018	13:38:48.1	−02:01:49	V=13.44

Approval for Instrument Use from PI: ____________________

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis

Scientific Justification

Subdwarf B (sdB) stars are compact stars of approximately half a solar mass associated with an intermediate stage of stellar evolution when helium is burning in the core. These stars are observed to lie on the so-called Extreme Horizontal Branch (EHB) – a blue extension of the normal Horizontal Branch (HB). SdB stars remain hot ($T_{\rm eff} \simeq$ 20,000–40,000 K) and compact ($\log g$ = 5.0–6.2) throughout their He-burning evolution and beyond, until they reach a later stage of the white dwarf cooling track (see, e.g., Heber 2009, ARA&A, 47, 211 for a review). Most are believed to be post-RGB stars. However, in order to become an sdB instead of a normal HB star, a red giant must undergo enormous mass loss, expelling almost entirely its hydrogen-rich envelope and leaving its helium core barely hidden under an extremely thin layer of residual hydrogen atmosphere (less than 0.01 $M_\odot$). How this happens is still not well understood, although the large fraction of sdB stars ($> 60\%$; Green et al. 2008, ASPCS, 392, 65) found in compact binary systems strongly suggests that binary evolution, through various channels involving stellar and possibly substellar companions, is very likely involved (Han et al. 2003, MNRAS, 341, 669; Charpinet et al. 2011, Nature, 480, 496).

The thin stable envelopes of sdB stars set the stage for diffusive phenomena, leading heavy metals (in particular iron) to accumulate in a region of partial ionization, sustained by radiative levitation, where the gas opacity is strongly increased (the so-called Z-bump in the Rosseland mean opacity). As a consequence, pulsational instabilities develop in these stars through a kappa-effect. These are manifested as rapid p-mode oscillations with periods from 80 to 600 seconds in a fraction of the hotter sdB stars (the V361 Hya stars with $T_{\rm eff} \geq$ 29,000 K; Charpinet et al. 2001, PASP, 113, 775; Kilkenny et al. 1997, MNRAS, 285, 640) and as slower g-mode pulsations with periods between 45 minutes and several hours in most of the cooler sdB stars (the V1093 Her stars with $T_{\rm eff} \leq$ 30,000 K; Fontaine et al. 2003, ApJ, 597, 518; Green et al. 2003, ApJ, 583, L31).

More than a hundred sdB stars pulsating in p-modes or g-modes (and rarely both) have now been identified. Very often they exhibit a rich distribution of nonradial oscillations, making them targets of choice for asteroseismology. This powerful technique exploits the fact that oscillation modes detected as periodic brightness modulations at the stellar surface can propagate deep inside the star. The observable properties (such as the pulsation periods) are therefore influenced by the structure and dynamics of internal regions that would otherwise remain hopelessly out of reach. Since the He cores of sdB stars, inherited from the red giant progenitor near the He flash, are essentially identical to the He cores of all low-mass He-burning stars, this not only gives us a chance to clarify the still uncertain history of sdB stars alluded to above (see Fontaine et 2012, Van Grootel et al. 2014, ASPC, 481, 229), but also provides a tremendous and unique potential for probing stellar stucture and rotation during the intermediate evolutionary phase of low mass stars, and opens the door to test the constitutive physics of He-burning cores.

Asteroseismology has been successfully applied to 15 **p-mode** sdB pulsators so far (see Fontaine et al. 2012, A&A, 539, 12 and reference therein), leading to precise determinations of key structural parameters. The results are generally, although not entirely, consistent with currently available predictions from stellar evolution. Among the stars analyzed in this manner, one stands out for its rare but essential properties: PG 1336−018 (a.k.a. NY Virginis) is one of the very few known sdB + dM close eclipsing binaries, and one of only two such objects where the sdB component is a pulsator (Kilkenny et al. 1998, MNRAS, 296, 329). The other, 2M 1938+4603, is an eclipsing **g-mode** sdB+dM pulsator in which most of the pulsational periods are nearly as long as the 4 hour orbital period. In the latter star, internal rotation can no longer be treated as a small perturbation on the pulsations, and it is not possible to model the pulsational instabilities. This leaves PG 1336−018 as a unique Rosetta stone with which the determination of sufficiently precise stellar parameters (orbital modeling, asteroseismology, and spectroscopy) can be used to tightly constrain the different approaches. One can therefore check the reliability of the methods and models, as well as the presence (or lack thereof) of biases in the derived quantities. This very rare opportunity provides a critical check on the external accuracy of the results, as opposed to the usual case when only the internal precision of the measurements can be determined.

The data obtained for PG1336−018 in the past, namely multicolor photometry with ULTRACAM at the VLT (5 hours during a single night), radial velocity curves with UVES at the VLT (9 hours during a single night;

Vuckovic et al. 2007, A&A, 471, 605), and multisite white light photometry from the Whole Earth Telescope (WET) (172 hours over 14 nights; Kilkenny et al. 2003, MNRAS, 345, 834) have made it possible to begin to exploit the possibilities offered by this very singular object (Charpinet et al. 2008, A&A, 489, 377; Van Grootel et al. 2013, A&A, 553, 97). These analyses showed, among other results, that the mass of the sdB star determined independently from both asteroseismology and the orbital lightcurve and eclipse properties is accurate to within the achieved precision (1%), a very important result for assessing the reliability of the mass distribution of sdB stars derived from asteroseismology (Fontaine et al. 2012). Van Grootel et al. (2013) and Charpinet et al. (2014, ASPC, 481, 105) experimented further with changes in the constitutive microphysics in the stellar models and their influence on the values derived from seismology, demonstrating that even more profound tests of stellar physics would be possible with an object like PG1336−018.

In order to do so, further progress has to be made on the observational side in order to achieve the highest possible precision for the various parameters of this system (both from the orbital lightcurve analysis and asteroseismology). We propose to use the proven, very efficient Mont4K on the 61″ to conduct an extended photometric light curve campaign on the relatively bright (V=13.4) star PG 1336−018 to monitor both its short period p-mode oscillations and its 2.42 h periodic orbital modulations (including eclipses). Although the data available from the WET campaign are the best to date for asteroseismology of this star, the higher efficiency of the Mont4K, the homogeneous data set, and the considerably longer time total baseline will translate into a considerable gain in sensitivity and precision for the measured periodicities (orbital and pulsations), allowing for much more stringent tests. The Mont4K/61″ combination is in fact the only foreseeable possibility to achieve this objective, as there is currently no possibility for PG1336−018 to be observed from space. (It will definitely not be observed during the Kepler 2 mission). Considering the utmost importance of PG1336−018 as a key object to calibrate asteroseismology and stellar models, the proposed data will be a very important legacy in the field.

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science. (**up to one page**)*

The 1999 multi-site WET campaign for PG 1336−018 (Kilkenny et al 2003, MNRAS 345, 834), remains the largest and most comprehensive asteroseismology campaign ever carried out for this star. It resulted in the identification of 28 periodicities extracted from $\sim$ 172 hours of observations over the course of 14 days. However, the precision of the data was clearly limited by the available technology at the time. Most of the contributing observatories used three channel photometers; nearly 30 hours of the total 172 hours of data were observed with a single channel photometer, and only 29 hours came from observatories using CCD's. The 4σ noise level in the combined Fourier transform achieved a very modest precision of 0.33%.

During nine previous asteroseismology campaigns with the Mont4k/61″, we have obtained light curves for various p-mode sdB pulsators with total observation times ranging from 57 hours to more than 400 hours, depending on the target. The Mont4K was designed and built specifically to maximize the potential of our asteroseismic campaigns. We use a "white light" Schott-8612 filter and 3x3 binning, enabling us to sample the pulsation periods 3 to 6 times per cycle. Table 1 of Fontaine et al. (2014, ASPC, 481, 83) summarizes our results so far and also shows that we require at least 200 hours of light curves in a single campaign, and optimally 225 to 250 hours, to reduce the noise in the Fourier Transform to approximately 0.005%. This would be an improvement of more than a factor of six in S/N over the existing asteroseismic data for PG 1336.

The three primary requirements of a suitable asteroseismology campaign are: 1) to obtain the longest possible start-to-finish time baseline in order to measure the pulsational frequencies as precisely as possible, 2) to obtain relatively continuous coverage over the entire campaign to avoid cycle count ambiguities, and 3) to obtain a total of 200 to 250 hours of lightcurves as described above.

PG 1336, whose Declination is $\sim -2^{\circ}$, can be observed up to 7.5 hours per night from Mt. Bigelow between the end of January and the end of May, a total time baseline of four months (compared to the previous 14 days). Its pulsational periods are relatively short (95 to 205 s) even for p-mode pulsators and thus we would need to avoid any gaps in the observations greater than 2 to 2.5 weeks. Assuming that 70% of the nights will be clear enough to observe, we would require 49 nights, distributed as follows, to obtain the approximately 225 hours of light curves (324 x 0.7 = 227) required to meet our goal:

end of Jan: 5 nights, 5.0 hours/night
Feb: 12 nights, 6.25 hours/night
Mar: 12 nights, 7.5 hours/night
Apr: 12 nights, 7.5 hours/night
May: 8 nights, 5.5 hours/night

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is our first proposal to obtain light curves for asteroseismology of PG 1336−018, the only known eclipsing sdB p-mode pulsator.

The Mont4K on the 61″ is the only ground-based instrument/telescope combination that has ever proven its ability to reach the needed asteroseismic precision.

All of the observations must be completed in a single observing season. If there are any gaps in the observations longer than about 2 to 2.5 weeks, the ambiguity in cycle count becomes too large to make sense of the data.

We expect that the proposed campaign for this unique target is most likely to be possible during spring 2015. The observations require the 61″ telescope, and the chances of getting the required minimum number of nights during a single observing season (45–50 nights) will almost certainly decrease significantly in the future once the 61″ has been reconfigured for remote and/or queue observing.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with `\related` command). **(up to one page)***

90″ B&C: **2013:** 01–04 Jan,01–03 Apr, 01–04 May, and 03, 26, 27, 30 Jun, 01 July, 03–06 Sep; **2014:** Apr 3–6, 30, May 1–4, Jun 17, 20–22. 14 papers have been published so far based on our high S/N, 90″ B&C survey results, including most recently:

"*A preliminary look at the empirical mass distribution of hot B subdwarf stars*",⋆ Fontaine et al 2012, A&A, 539, 12
"*Third generation stellar models for asteroseismology of hot B subdwarf stars. A test of accuracy with the pulsating eclipsing binary PG 1336-018*", Van Grootel et al 2013, A&A, 553, 97
"*Improved Determination of the Atmospheric Parameters of the Pulsating sdB Star Feige 48*", LaTour et al 2014, ApJ, 788, 65

90″ B&C: **2013:** 20–22 and 28–30 Jan, 19–20 and 28–30 Feb, 01 and 19–20 Mar, 27–28 May, 22–23 Nov, 06–07 Dec, **2014:** Mar 8–10, Apr 19–20, Jun 6, 17, Sep 2–4, 12–15, for exploratory near-UV spectra of field sdO stars to follow up our recent discovery of potential accretion disks. We have discovered unexpected RV variations in a number of sdO stars, but haven't yet acquired sufficient orbital coverage to derive unique periods.

⋆ **61″ Mont4K**: **2013:** 03–07 and 11–12 Jan, 01–02 and 15–16 Feb, 10–14 Mar, 13–18 May, 14–16 Jun, 14 and 16–17 and 20 Sep, 14 and 20 and 23–24 Oct, 12–13 and 16 and 22–23 Nov, 11-14 and 19–21 Dec; **2014:** Jan 1–8, 10–12, 24–28, Feb 2, 4–7, 9–10, 17, 19–20, 23–24, 27, Mar 3, 5, 22-24, 26–27, 30–31, Apr 1–3, 8–9, 15–20, May 5–7, 16–19, 23–28, Jun 5–8, 12–13, 16–17, Sep 2, 12–13, 16–18, 20, 24–25, 28–30, Oct 1–3, 12–15, 31, Nov 1, 10–15, for light curves of sdO stars, the sdB pulsators PB 5450 and PG 1047+003, and a few white dwarf ZZ Ceti candidates:
"*Observational Asteroseismology of Hot Subdwarf Stars with the Mont4K/Kuiper Combination at the Steward Observatory Mount Bigelow Station*", Fontaine, G., Green, E.M. et al 2013, arXiv1307.6112
"*High-speed photometric observations of ZZ Ceti white dwarf candidates", Green, E.M. et al 2015, paper presented at "The 19th European Workshop on White Dwarfs" in Montreal, August 11–15, 2014*
"Photometric Survey to Search for Field sdO Pulsators", Johnson, C. et al 2015, in preparation
"Surprising Evidence for Binarity in sdO Light Curves", Green, E.M. et al 2015, in preparation

MMT Blue*: TBS nights 29–30 Apr 2012: spectra for a second evolved star with "deep-fried" planets and for the first member of a new class of BHB g-mode pulsators:*
"KIC 1718290: A Helium-rich V1093-Her-like Pulsator on the Blue Horizontal Branch", Østensen, R. H., Degroote, P., Telting, J. H., Vos, J., Aerts, C., Jeffery, C. S., Green, E. M., Reed, M. D., Heber, U. 2012, ApJ, 753, L17
"Kepler detection of a new extreme planetary system orbiting the subdwarf-B pulsator KIC 10001893", Silvotti, R. et al 2014, A&A, accepted