OBSERVING REQUEST
University of Arizona Observatories

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

A homogeneous spectroscopic survey of a complete sample of 2MASS-selected blue stars

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Abstract of Scientific Justification

During the last 12 years, we have used the 90$''$ B&C spectrograph to conduct the first complete, magnitude-limited survey characterizing moderately bright subdwarf O and B stars in the field. This survey is now 95% finished. Targets were selected from the 2MASS survey ($9.5 < J < 15.1$, $J - H < 0.00$, $J - K <$ –0.03, with Dec $> -5°$ and $\mid l \mid > 25°$). We have also included all $\sim$ 62 known hot subdwarf p- and g-mode pulsators brighter than V = 16 that are observable from the northern hemisphere, and a few important fainter ones. Our spectra have already turned out to be extremely valuable for studies of binary sdB evolution and asteroseismology of sdB/sdO pulsators, mostly due to their homogeneity and high S/N, but also because the relatively bright stars in our survey are the most useful for further in-depth investigations. A surprising number of bright and very interesting sdB and sdO stars were undiscovered until identified in this survey. The completed sample will be used to test a variety of evolutionary formation scenarios in addition to providing atmospheric parameters for individual stars. We observed 156 survey targets during April–June last year, and have only 84 of the faintest candidates remaining, most of which have 14:00 < RA < 18:30. We request gray nights in April and June and gray or dark nights in May to observe the remaining targets and finish our survey. Due to expected plans to use the majority of 90$''$ time for 90Prime observing in the future, and/or to move or replace the B&C spectrograph, it is critical for the homogeneity of our survey that we complete the remaining observations while the B&C spectrograph is still available on the 90$''$.

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	90”	f/9	B&C			3	gray	Apr–Apr	Apr–Apr	no	no
2	90”	f/9	B&C			3	dark	May–May	May–May	no	no
3	90”	f/9	B&C			3	gray	Jun–Jun	Jun–Jun	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Targets are best positioned in the sky at the end of April, any time in May, and in the first half of June. B&C nights in the first half of May (before May 16) must not conflict with nights for Green's PG 1336−018 observing on the 61$''$. This proposal might possibly share nights with the Astronomy Camp in June if there is no conflict with Fontaine's VATT run.

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A $\star$ appended to the proposal type indicates a continuation proposal; a $\star$ 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	2M1041+1842	10:41:30.4	+18:42:09	V=13.13
2	2M1123+2336	11:23:50.6	+23:36:45	V=14.28
3	2M1213+5303	12:13:24.6	+53:03:57	V=14.31
4	2M1240+5116	12:40:38.2	+51:16:00	V=13.73
5	2M1306+4850	13:06:15.5	+48:50:20	V=13.83
6	2M1408+5940	14:08:32.2	+59:40:25	V=13.52
7	2M1440−0308	14:40:52.8	−03:08:52	V=13.77
8	2M1456−0314	14:56:17.9	−03:14:25	V=14.33
9	2M1526−0412	15:26:21.2	−04:12:16	V=14.12
10	2M1601+5311	16:01:12.1	+53:11:51	V=14.39
11	2M1622+1213	16:22:03.8	+12:13:33	V=14.55
12	2M1625+0017	16:25:55.1	+00:17:02	V=14.36
13	2M1634+0201	16:34:08.1	+02:01:43	V=14.61
14	2M1637+0140	16:37:33.4	+01:40:37	V=14.48
15	2M1649+2915	16:49:26.2	+29:15:57	V=14.58
16	2M1659+0501	16:59:03.2	+05:01:38	V=14.74
17	2M1702+0856	17:02:33.3	+08:56:12	V=14.66
18	2M1707+0936	17:07:59.4	+09:36:38	V=14.64
19	2M1718+2207	17:18:44.6	+22:07:41	V=13.99
20	2M1725+3703	17:25:32.0	+37:03:02	V=14.01
21	2M1737+3347	17:37:08.1	+33:47:48	V=14.51
22	2M1741+3152	17:41:05.5	+31:52:09	V=14.55
23	2M1753+4906	17:53:21.0	+49:06:06	V=14.50
24	2M1802+4631	18:02:12.5	+46:31:17	V=14.25
25	2M1823+7038	18:23:14.4	+70:38:05	V=14.57
26	N6791/1812	19:20:20.2	+37:46:28	V=17.8

Approval for Instrument Use from PI: N/A

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

We have been observing homogeneous spectra of evolved hot subdwarf O and B stars (sdO and sdB) with the 90″ B&C spectrograph for over 12 years. The original purpose was to obtain low resolution, high S/N spectra for known hot subdwarf pulsators, in order to fit the Balmer lines and derive atmospheric parameters ($T_{\rm eff}$, log g, and H/He) needed as input to asteroseismic analyses. Once the empirical temperature and gravity boundaries of the subdwarf pulsation regions were better determined, we broadened our target list to search for additional pulsation candidates, especially brighter subdwarfs for which we could obtain extremely precise differential light curves using the 61″ Mont4k camera. After we had obtained spectra for a number of hot subdwarfs in the Palomar-Green Survey (R. Green, Schmidt, & Liebert, 1986, ApJS, 61, 305) down to $V \approx 14.5$, it became apparent that all previous surveys of hot subdwarfs are very incomplete due to significant selection effects, especially as a function of effective temperature. Theoretical models of the various evolutionary channels that could potentially produce hot subdwarfs by Han et al. (2002, MNRAS, 336,449 ; 2003, MNRAS, 341, 669) predict distributions of different types of sdB systems that are inconsistent with the numbers that we have observed. Han et al. (2003) attribute the inconsistencies to selection effects in published observational samples. However, the selection effects required to validate their models are considerably larger than those suggested by our current spectroscopic sample. What is needed is a sample of hot subdwarfs complete over the entire range of effective temperature, surface gravity and envelope composition.

Six years ago, we used the 2MASS survey to select a complete sample of about 1600 moderately bright, very blue, northern hemisphere stars ($9.5 < J < 15.1$, $J - H <$ 0.00, $J - K <$ –0.03, Dec $> -5°$, and $|$ galactic latitude $| > 25°$) covering the color range of single hot subdwarfs, sdB+WD binaries and sdB+dM binaries. We have acquired B&C spectra to identify a complete sample of hot subdwarfs (always using the same spectroscopic setup), while eliminating contamination from main sequence B and A stars, blue horizontal branch stars, post-asymptotic giant branch stars, white dwarfs, cataclysmic variables, etc.

We have so far identified many previously unknown hot subdwarfs and have established a worldwide reputation as a source for the best available hot subdwarf spectra and their derived atmospheric parameters. The relatively bright subdwarfs in our survey are the most valuable for detailed followup asteroseismic and binary investigations since they provide the most precise light curves, radial velocities, and heavy element abundances. Other surveys that could conclusively identify hot subdwarf stars are either incomplete on the sky (e.g. the Palomar-Green Survey), already saturated for the brighter magnitudes that are most useful for followup light curve investigations (brighter than $V \approx 14.5$ or $J \approx 15.1$, e.g. SDSS and Galex), and/or insufficiently accurate to distinguish between hot subdwarfs and other hot stars like main sequence or blue horizontal branch stars (e.g. grism surveys such as the FBS survey).

Our spectroscopic sample of hot subdwarfs has already turned out to be extremely valuable. 1) To date, asteroseismology of subdwarf B stars has been more successful than for any other class of evolved pulsating stars, and **all** of the dozen or so published p-mode sdB asteroseismic analyses have been accomplished using atmospheric input parameters derived from our spectra (Fontaine et al. 2012, A&A, 539, A12; Van Grootel et al. 2008, A&A, 488, 685; Charpinet et al. 2008, A&A, 489, 377; and references therein). 2) Subdwarf targets from our 2MASS-selected B&C survey were observed by FUSE after its gyros began failing and it could only observe objects with declinations north of +60°; ours was the only survey to have identified usefully bright hot subdwarf candidates with declinations $>$ +70°. 3) The COROT satellite project sent us lists of the pulsators they find with modal frequency characteristics appropriate for hot subdwarfs, for spectroscopic followup to determine whether they are in fact subdwarf stars, rather than delta Scuti or other types of pulsating variables. 4) We identified several of the brightest and most interesting subdwarf targets for the Kepler satellite prior to launch, including 2M1938+4603, the second known subdwarf B pulsator/eclipsing sdB+dM binary ever discovered. The Kepler satellite subsequently found it to be a unique hybrid pulsator exhibiting a large number of both p-modes and g-modes. This star will eventually become a Rosetta stone for g-mode asteroseismology once it becomes possible to construct theoretical models capable of describing the pulsational behavior in the presence of full internal rotation (not merely a perturbation). 5) We possessed the only existing high S/N spectrum of KPD 1946+4340 when Kepler found that it to be the first sdB+WD binary showing relativistic beaming effects, and were able to provide realistic temperature and gravity estimates for the modeling. Similarly, 6) the first successful analysis of a g-mode sdB pulsator (once again a Kepler target) was able to proceed right away because we already had a spectrum suitable for deriving the necessary temperature and gravity inputs for asteroseismology. We have already published two papers on this star, the initial asteroseismic analysis from the first Kepler data release and a second paper in Nature in which we announced the first planetary candidates discovered by the light signature from their heated faces. 7) When Kepler identified what was first thought to be the first pulsating white dwarf in its field of view, we obtained a flux-calibrated, relatively high S/N spectrum at the very end of an otherwise very bright night, from which Fontaine and our collaborators were able to prove that the light came from an AM CVn accretion disk, and not a white dwarf after all. Fontaine and Brassard were subsequently able to model the AM CVn star using the combined, high S/N B&C spectrum. More recently, we have 8) conducted the first empirical mass distribution of sdB stars, 9) evaluated third-generation stellar models for asteroseismology, and 10) determined improved atmospheric parameters for another rare p- and g-mode hybrid sdB pulsator using low resolution spectra from our survey.

We wish to build on this success by completing our homogeneous observations for the remaining candidates in our survey. The complete sample will allow us to analyze the systematic properties of hot subdwarfs in order to constrain the evolutionary channels in a way that has never before been possible.

We have so far observed about 94% of our 2MASS-selected sample, including all of the fall and winter targets and all of the brighter spring/summer objects that can usefully be observed during bright nights.

A rather large fraction ($\approx 80\%$) of the blue targets brighter than $J = 14.1$ turn out to be much more luminous main sequence B and A stars (and occasionally blue horizontal branch stars or white dwarfs), even though our survey includes only candidates more than $25°$ from the galactic plane. Increasingly larger fractions of hot subdwarfs are found away from the plane at fainter magnitudes, up to 35–45% of very blue stars at $J = 15.1$. Such stars are still quite bright enough to obtain excellent light curves, radial velocities, etc. It is therefore extremely important for us to complete our sample all the way down to the faint limit – the fainter stars are the critical for obtaining a complete sample for statistical purposes.

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**)*

We propose to use the 90″ B&C spectrograph with the 400/mm, 4800Å grating and 2.5″ slit to finish our low resolution (7Å), moderate S/N ($\sim$ 60–70/pix) sdOB survey by observing the few remaining candidates in our 2MASS-selected sample. Our spectra cover the wavelength region from the Balmer jump at 3600Å to just redward of Hα at 6900Å. This spectroscopic setup is the same as we used to obtain spectra for hot pulsating subdwarfs and white dwarfs in the *Kepler* field, and, before that, a survey of sdB candidates brighter than V = 14.3 (Green et al. 2008, ASPC, 392, 75) from the Palomar-Green Survey. As before, Fontaine will fit the Balmer lines in our flux-calibrated spectra to unique state-of-the-art diffusion-dominated NLTE H+He+metals atmospheres to determine effective temperatures, surface gravities and He abundances, in order to discriminate between subdwarf B stars and horizontal branch stars, sdO stars, post-asymptotic giant branch stars, white dwarfs, etc. Although the spectra of all of these stars are dominated by hydrogen Balmer lines, the derived temperatures and gravities show that sdB and sdO stars can be reliably isolated from other types of stars in the T_{eff} vs log g diagram, as long as the S/N per pixel is larger than about 60–70. Cooler stars can easily be distinguished from sdB stars by their flux distributions blueward of the Balmer jump, but relatively high S/N is crucial for deriving surface gravities sufficiently precise to distinguish sdB stars from fast-rotating broad-lined main sequence B stars of the same temperature. When hot subdwarfs are identified, we observe them 3–4 additional times with longer exposures, in order to achieve the high S/N ($>$200/pixel) required to derive the atmospheric $T_{\rm eff}$ and log g to the accuracy needed for asteroseismic analyses and to compare the distribution of different types of subdwarfs with the predictions of theoretical evolution models.

Even though our subdwarfs are relatively bright in an absolute sense, we require gray or dark time in order to get very high S/N (about 300 per resolution element) to define the extreme wings of the ultraviolet Balmer lines sufficiently to determine precise surface gravities of these hot stars. Discriminating evolved subdwarfs from main sequence OBA and cooler BHB stars depends on measuring the gravities extremely precisely, much better than 0.1 dex. Furthermore, about half of hot subdwarfs are pulsators for which the asteroseismology analyses require log g to be measured to better than 0.05 dex.

We have completed 94% of the observations remaining in our survey, including repeat observations to obtain high S/N for the identified hot subwarfs. All of the remaining targets are observable in April, May and June. A median $V = 14.2$ magnitude blue star requires a 15 minute exposure plus 9 minutes of overhead during dark gray conditions for S/N of 60–70, and thus (with clear skies and reasonably good seeing) we can observe about 20 faint targets per night in May. The ones that turn out to be hot subdwarfs are reobserved with longer 25 minute exposures. We therefore estimate that our $\sim$84 remaining targets will require about 6–7 more clear nights. The 9 requested nights allow for a weather factor.

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**)*

We have so far spent a total of 140 nights (of which approximately 97 were clear) during the last 12 years observing targets for this survey. We have completed the observations of all but the faintest stars in our sample (the largest proportion of hot subdwarfs are found at fainter magnitudes). The fainter stars are critical in order to obtain a complete magnitude-limited sample.

We have completed the observations for all targets with $0^{\rm h} < {\rm RA} < 11^{\rm h}$ and ${\rm RA} > 19^{\rm h}$. Last season, we observed almost 2/3 of the then-remaining targets during 20 allocated nights (including 6 TBS). We now request 12 nights to finish the last third in 2015.

All of the observations for this survey must be obtained with the B&C spectrograph on the 90″, partly because our collaborators do not have access to another suitable telescope/instrument, but mainly because homogeneity is one of the most important aspects of this survey. Homogeneous atmospheric parameters are particularly critical for constraining evolutionary formation scenarios and determining the temperature and gravity boundaries of the various types of evolved pulsators.

We must finish this survey in 2015 before DESI crowds out the B&C spectrograph on the 90″ and/or before the B&C gets moved to another telescope or otherwise replaced according to the Observatory's ongoing plans.

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**)*

$\star$ **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