OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term⋆

Subdwarf O Stars

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Abstract of Scientific Justification

The structure and evolutionary histories of subdwarf O stars are very poorly understood. The cooler subdwarf B (sdB) stars are known to be the helium burning cores of normal low mass red giants that were almost entirely stripped of their hydrogen envelopes, most likely due to binary processes. At least two thirds of sdB stars are found in non-interacting binaries. Subdwarf O (sdO) stars appear to be related to sdB stars based on their temperatures and gravities, but most have helium-rich atmospheres. Very few sdO's were believed to occur in binary systems prior to our recent discoveries. Up to now, the prevailing theory has been that sdO stars were created by mergers of low mass white dwarfs. While sdO stars sometimes have constant luminosities, they often exhibit small irregular luminosity variations. We recently observed unprecedented episodes in two sdO stars during which their luminosities decreased by roughly 10% for several hours while flickering irregularly, in the same manner as the light from an accretion disk in a cataclysmic variable (CV) in its low state. Furthermore, while normal sdO stars appear to have little or no radial velocity variations, we have caught a couple of them at apparently rare moments when their velocities were wildly different. It is not at all clear what these objects are (high mass-transfer accretion disks onto a compact companion? weak accretion disk around hot subdwarfs?) or what fraction of sdO's undergo these anomalous luminosity and RV events. The fraction could be quite large if highly elliptical orbits are common and mass transfer occurs near periastron. We request 61″/Mont4k nights for followup light curves of a sample of 60 sdO stars, and 90″/B&C time to characterize the radial velocity properties of about half of them.

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	grey	Sep–Dec	Sep–Dec	no	no
2	61”	f/13.5	Mont4k			5	bright	Sep–Dec	Sep–Dec	no	no
3	90”	f/9	B&C			10	bright	Sep–Dec	Sep–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We prefer to have nights spread over the whole semester. For the B&C, we request two or three nights at a time. Most targets are too faint to usefully observe within 3 nights of full moon on either telescope. We cannot observe Oct 10–15, Nov 24–29, or Dec 23–29.

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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	PG1708+602	17:09:15.9	+60:10:11	V=13.9
2	HS1741+2133	17:43:19.1	+21:32:38	V=14.0
3	2M1915+4256	19:15:18.9	+42:56:13	V=15.02
4	2M1931+4324	19:31:08.9	+43:24:58	V=14.11
5	LSIV+10_9	20:43:02.5	+10:34:21	V=12.05
6	PHL4	21:26:21.2	+00:58:34	V=14.34
7	Bal090900004	22:37:36.7	+22:44:13	V=12.87
8	GS259-8	22:47:56.5	+37:53:52	V=13.1
9	PG2321+214	23:24:27.5	+21:38:52	V=13.7
10	PHL687	00:08:17.8	+18:07:59	V=14.39
11	PG0011+221	00:14:19.4	+22:24:18	V=13.54
12	PG0039+135	00:42:16.6	+13:45:41	V=13.72
13	PG0108+195	01:11:03.8	+19:47:43	V=14.34
14	HS0222+2334	02:25:12.5	+23:48:21	V=14.0
15	PG0240+046	02:43:22.8	+04:50:35	V=14.12
16	KUV02445+3633	02:47:35.0	+36:45:51	V=13.5
17	HS0252+1025	02:55:33.3	+10:37:23	V=13.8
18	PG0314+180	03:17:46.3	+18:13:18	V=14.31
19	HZ1	04:50:13.5	+17:42:06	V=12.62
20	2M0450−0315	04:50:44.8	−03:15:18	V=13.4
21	Ton835	07:56:03.8	+22:26:31	V=14.0
22	PG0838+133	08:41:43.9	+13:04:31	V=13.64
23	PG0839+399	08:43:12.7	+39:44:51	V=14.39
24	2M0858+0210	08:58:51.1	+02:10:13	V=13.9
25	PG0934+553	09:38:20.3	+55:05:53	V=12.16
26	PG0942−029	09:45:11.8	−03:09:19	V=14.00

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

Hot subdwarf stars have often been considered one of the last frontiers of stellar evolution because their evolutionary origins are so poorly understood.

Subdwarf B (sdB) stars are evolved, low mass ($\sim 0.5\ M_{\odot}$), hot (20 000 – 40 000K), compact (log g = 5.0 – 6.2) stars associated with the extreme horizontal branch phase of stellar evolution, where they are now burning helium in their cores. They have lost (or were stripped of) all but a trace of their H-rich envelope near the tip of the first red giant branch. In nearly all sdB stars, the remaining hydrogen envelope floats up above most of the helium, resulting in mostly subsolar surface He abundances. Observational surveys show that a large fraction of sdB stars reside in close binary systems with white dwarf or M dwarf companions and orbital periods from hours to days (e.g. Maxted et al. 2001, Green et al. 2001), although there has never been any evidence of current interactions between the two components or mass transfer in any of these systems. It appears likely that the majority of sdB stars form via Roche lobe overflow and stable or unstable mass transfer near the tip of the red giant branch, resulting in common envelope evolution. Although the exact details are still being debated, various binary evolutionary scenarios proposed by Han et al. (2002, 2003) and others have been used to build synthetic binary populations that generally agree with the observed properties of typical sdB stars.

The hotter subdwarf O (sdO) stars remain a mystery. SdO stars have approximately the same range of surface gravities as sdB stars, but they are much hotter (see Figure 1). In contrast to sdB stars, sdO stars usually have He-rich atmospheres, *i.e.* the original H envelopes have somehow been almost entirely destroyed. There have been a number of different explanations for the origins of sdO stars, but none appear to explain all of their observed properties. Since Napiwotski et al's (2004, Ap&SS, 291, 321) discovery that very few, if any, sdO stars appear to be radial velocity variables, the preferred explanation has been that these stars are the result of mergers of low mass white dwarfs (Zhang & Jeffrey 2012, MNRAS, 419, 452).

Two years ago we used the 61″ Mont4k to conduct a search for rapid (100 sec) pulsators among sdO stars in the field, in the hope of finding bright analogs to the recently discovered sdO pulsators in the globular cluster Omega Cen (Randall et al 2009, A&A, 494, 1053; 2010, ApSS, 329, 55). After observing light curves of nearly 30 field sdO stars for 4 to 6 hours at a time over many months, we failed to find a single sdO pulsator. Curiously, however, we often observed occasional inconclusive instances of very small, irregular variations in luminosity that might conceivably have been due to atmospheric anomalies, except that the sky conditions usually didn't seem that bad. We reobserved a number of these stars, sometimes finding them to be very constant in luminosity and at other times not so constant.

Eventually we reobserved a He-rich sdO star that had been quite constant in luminosity a year earlier and found that it had dropped in luminosity by almost 0.1 mag (Figure 2) and was exhibiting low level irregular variations very closely resembling the "flickering" seen from the light of accretion disks in cataclysmic variables (CV's) in their low state. Within a few hours, the star had regained its previous luminosity and stopped flickering. A second sdO star, this time H-rich, was subsequently observed doing the same thing, dropping in luminosity and varying irregularly for a while. Normal stars do not decrease in luminosity over short periods like this, and particularly not hot subdwarfs, which are very slow rotators and have envelopes too thin to support any kind of turbulence, spots, etc.

The radial velocity behavior of sdO stars is equally interesting. When observed multiple times, instead of only two or three times each (Napiwotski et al 2004), many sdO stars appear to have small but signficant radial velocity variations (a few km/s). A few regularly exhibit much larger variations. Strikingly, we have twice observed anomalously large velocities. One sdO whose velocities normally varied by less than 15 km/s was seen to change by 75 km/s in under 20 minutes. In a more extreme case, four observations of a different sdO showed 50–100 km/s velocity variations over several years and then a fifth observation found a blue shift of 1600 km/s. A month later, the velocity had returned to near its previous level, implying a highly elliptical orbit around a compact object.

Although we have only seen anomalous luminosity and radial velocity events in a very few sdO stars, there is other evidence that a significant fraction of of sdO stars are in fact in binaries: J-H colors red enough to require a cool component, and emission cores in Balmer and helium lines potentially indicating mass

transfer.

Clearly, there are many sdO stars that were not produced by the merger of two low mass white dwarfs. However, at the moment, there are many more questions than answers. Do the anomalous light curves truly indicate variable accretion disks? If not, what else could possibly cause the observed luminosity variations? If there are accretion disks in these systems, the observed H/He absorption line spectra would seem to require optically thick, high temperature, accretion disks and extremely high rates of mass transfer onto, presumably, white dwarf primaries. However, our preliminary attempts to model a few sdO spectra as accretion disks indicate that this would only work if the disks were all nearly edge on, which is very improbable. A compact primary has always been considered necessary in order to have an accretion disk, but we don't know whether a weak accretion disk could occur in a binary with a hot subdwarf primary.

We are working on a two-pronged approach for further follow up: 1) obtain light curve data for more sdO stars over longer periods of time in order to get a better idea of the fraction of sdO stars that undergo these irregular light curve episodes, and how often they occur in individual stars, and 2) acquire multiple spectra of a sample of 20 to 30 sdO stars, over time scales of days, months and years, to better characterize their radial velocity behavior. Obtaining multiple light curves and velocities will take time, but that is the only way to follow up the rare events we have observed.

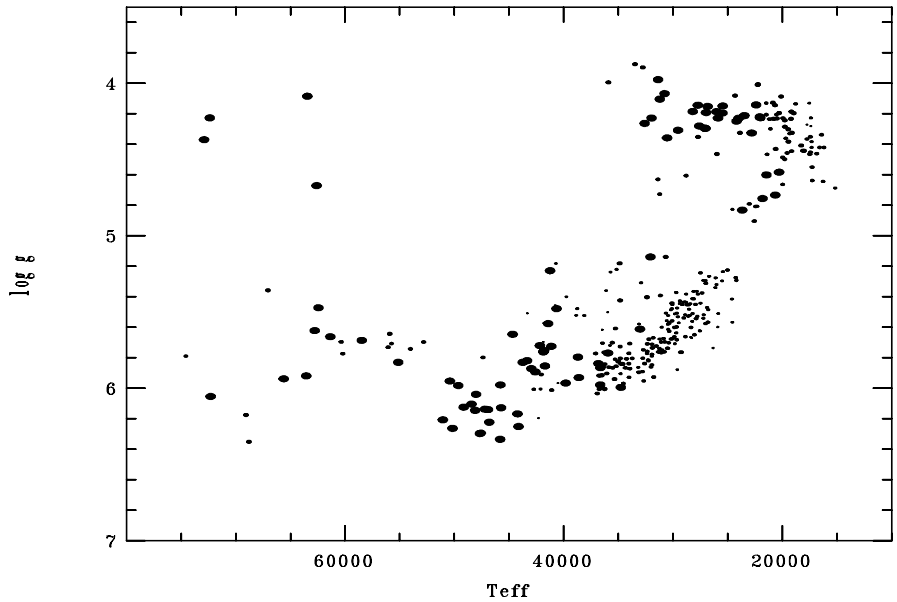

Fig. 1. A preliminary plot of *log g* vs T_{eff} from our homogeneous spectroscopic survey of hot stars. Point size is proportional to the surface helium abundance. Main sequence stars are toward the upper right. sdB stars have 23000 K $< T_{eff} <$ 38000 K and *log g* > 5.0. sdO stars extend from 38000 K to 80000 K, with gravities comparable to sdB stars, and usually much greater He abundances.

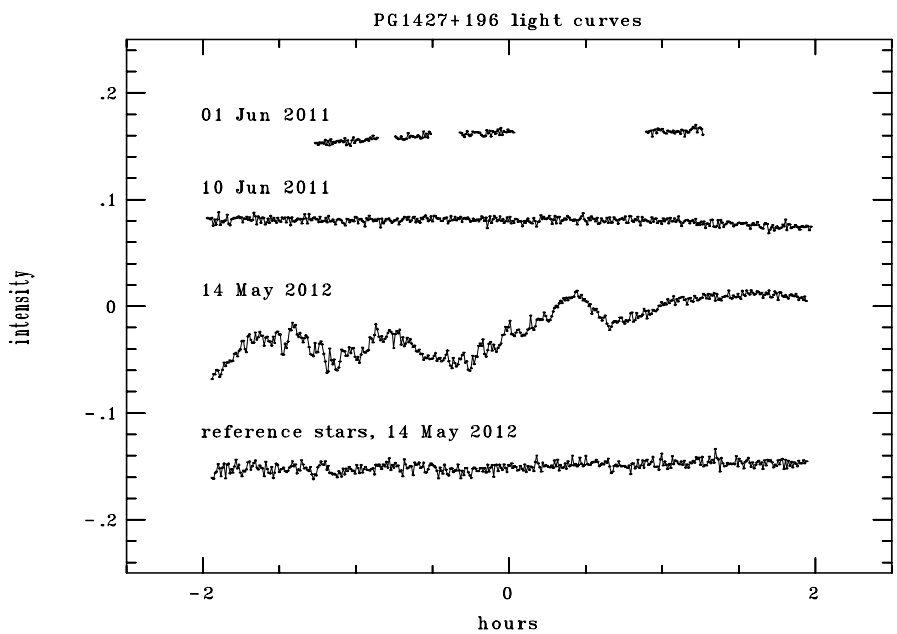

Fig. 2. Mont4k light curves for a He-rich sdO star observed on three different nights (arbitrarily shifted in the vertical direction for clarity; the first night was interrupted by clouds). The sdO luminosity at the end of the night of 14 May 2012 was the same, relative to the reference stars, as on 01 Jun and 10 Jun 2011. The bottom curve shows that the luminosity variations on 14 May 2012 were not due to the reference stars.

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 61″ Mont4k camera to obtain light curves as we did for Figure 2. So far, we have obtained one to three light curves for about 30 sdO stars. Over the next several years, we hope to get three or more light curves for about 60 of the brightest sdO stars.

We propose to use the 90″ B&C spectrograph with the 832/mm, 3762Å grating and 1.5″ slit to obtain 1.3Å resolution spectra covering 3675–4515Å, with a typical S/N of 60 to 100. 1.3Å is the highest longslit resolution possible with the B&C in the blue. For sdO stars, this allows us to achieve a radial velocity precision of $\sim$ 4 km/s. It is sufficient to satisfactorily resolve both the higher order Balmer lines and the (usually) somewhat narrower He lines for atmospheric modeling. On occasion we can also detect emission lines (presumably from weak accretion disks).

As we have done very successfully in the past for sdB stars, many of which are in close binaries, we will take multiple spectra of each sdO target at different times and on different nights, using shorter exposures to avoid smearing out the absorption lines due to possible orbital motion. The individual spectra will be shifted to the same radial velocity and combined into a single high S/N spectrum for further atmospheric analysis.

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 third proposal to follow up these sdO stars. Our first priority during the past few observing seasons has been to finish two critical asteroseismology campaigns on the 61″ and the spectroscopy needed to support those campaigns. We expect that it will take several years to obtain sufficient sdO light curves and radial velocities to get more quantitative estimates about the properties of these stars, both because it takes a lot of time to observe light curves and characterize orbits, and because our asteroseismology targets will have higher priority in some semesters.

We only have access to Arizona telescopes.

Our combined sdO spectra will be compared to grids of theoretical stellar spectra appropriate for hot sdO stars, and also with spectra of theoretical models of accretion disks. Our collaborators already have all the tools needed to do this. Fontaine, Brassard and colleagues have been at the forefront of the construction of model atmosphere grids appropriate for hot subdwarfs for many years now. They recently computed the first-ever NLTE model atmospheres with arbitrary amounts of metals included, as opposed to the pure H+HE atmospheres that have been used for nearly all other NLTE grids. Furthermore, in 2011, Fontaine and Brassard successfully proved that the alleged "first white dwarf pulsator found in the field of the Kepler satellite" was not a He-rich white dwarf at all, but a very rare Am CVn star (helium accretion disk) star. After failing to find any satisfactory match between our high S/N B&C spectrum and theoretical model atmospheres covering the entire range of white dwarf parameters, they constructed detailed models of He accretion disks that fit the observed spectrum very well.

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