OBSERVING REQUEST
University of Arizona Observatories

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

A Network of Photometric Standard Stars for LSST

P.I.: Jay Holberg (LPL; *holberg@vega.lpl.arizona.edu*; 621-4571)

CoI(s): E Olszewski (Steward), Tim Axelrod (SO), Gautham Narayan (NOAO), Abhijit Saha (NOAO), Tom Matheson (NOAO), Larry Camarota (LPL)

Abstract of Scientific Justification

Systematic uncertainties in existing phototometic calibrations are the dominant source of error in current type Ia supernova dark energy studies, as well as other forefront cosmology efforts, e.g. photometric redshift determinations for weak lensing mass tomography. Current and next-generation ground-based all-sky surveys require a network of calibration stars that 1) have known spectral energy distributions (SEDs) to properly and unambiguously account for differences in as-built filters, and 2) are on a common photometric zero-point scale. The observations proposed here represent the essential ground-based component of an ongoing HST program with the primary objective of establishing a consistent very high quality set of faint DA white dwarf standard stars. This set of stars is chiefly intended as primary photometric standards that meet the demanding absolute and relative calibration specifications of the LSST. However, these same stars also can meet the photometric or spectrophotometric needs of other large ground-based and space-based instruments or surveys. We are proposing MMT blue channel spectroscopy of these stars in order to obtain accurate effective temperatures and surface gravities which define the SEDs of each star. HST WFC3 multi-band photometry, which we already have for the 9 Cycle 20 stars, then places each star directly on the HST photometric scale. We received 18 orbits in HST Cycle 20 to observe 9 of these stars, and 60 more orbits in Cycle 22 for additonal observations of those nine, plus 14 more, plus 3 observations each of the fundamental HST standards. The weakest link is in obtaining spectroscopy: while we have Gemini time through HST, our experience at Gemini has been unsatisfying. Our 2014B MMT time was granted in mid August and was wiped out by the monsoon.

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	MMT	f/9	Blue			3	dark	Feb-May	Jan-June	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)*: None. We do not need all the nights in a single block.

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	full set of our 23 HST targets regardless of semester			
2	WD0100-006	01:03:22.191	-00:20:47.73	$g = 19.09$
3	WD0225-086	02:28:17.169	-08:27:16.41	$g = 19.97$
4	WD0245+335	02:48:54.96	$+33$:45:48.48	$g = 18.36$
5	WD0408-066	04:10:53.634	-06:30:27.75	$g = 19.09$
6	WD0554-165	05:57:01.300	-16:35:12.00	$g = 18.2$
7	WD0724+323	07:27:52.70	$+32$:14:16.10	$g = 17.98$
8	WD0812+076	08:15:08.90	$+07$:31:45.80	$g = 19.68$
9	WD1021-002	10:24:30.932	-00:32:07.03	$g = 18.88$
10	WD1108-168	11:10:59.43	-17:09:54.1	$g = 17.85$
11	WD1108+402	11:11:27.30	$+39$:56:28.00	$g = 18.40$
12	WD1204+023	12:06:50.41	$+02$:01:42.4	$g = 18.65$
13	WD1211+459	12:14:05.11	$+45$:38:18.50	$g = 17.71$
14	WD1300+104	13:02:34.441	$+10$:12:39.01	$g = 16.98$
15	WD1312-029	13:14:45.050	-03:14:15.64	$g = 19.05$
16	WD1511+009	15:14:21.273	$+00$:47:52.79	$g = 16.10$
17	WD1556+559	15:57:45.40	$+55$:46:09.70	$g = 17.45$
18	WD1635:+008	16:38:00.360	$+00$:47:17.80	$g = 18.83$
19	WD1719+297	17:21:35.98	$+29$:40:16.0	$g = 19.62$
20	WD1817+788	18:14:24.1	$+78$:54:02.90	$g = 16.50$
21	WD2034-053	20:37:22.17	-05:13:03.03	$g = 18.91$
22	WD2059-059	21:01:50.657	-05:45:50.97	$g = 18.66$
23	WD2327-000	23:29:41.325	$+00$:11:07.80	$g = 18.12$
24	WD2349+376	23:51:44.29	$+37$:55:42.6	$g = 18.06$

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
Larry Camarota	Jay Holberg		no	yes

Scientific Justification

This is a resubmission of a 2014B proposal granted two nights and wiped out by August 2014 monsoon. We were recently awarded 60 orbits with HST in Cycle 22, giving us 78 orbits in total.

The Problem: Sub-percent global standardization of photometric calibration in astronomy remains elusive. That said, the successes of major ongoing and planned astronomical surveys depend on attaining all-sky and band-to-band photometric accuracies to better than 1 percent. Among such projects are LSST, PanSTARRS, SDSS, the Dark Energy Survey with DECam, Skymapper, JWST, Galex and WISE. As a concrete science case example, consider the use of type Ia supernovae to probe the history of cosmic expansion and the properties of dark energy. Photometric calibration issues completely dominate the uncertainty budget of SN cosmology (e.g. Sullivan et al. 2011). Another example is weak lensing tomography with LSST, which demands sub-percent level accuracies in color for reliable photometric redshift determination.

The current best realization of an accurate and widely used photometric/spectrophotometric calibration is the HST photometric scale (Bohlin & Gilliland 2004), which is defined by HST spectra of Vega and Sirius(!!) (Bohlin et al 2014) at the bright end, and HST spectra of a handful of white dwarfs (11-15 mag) at the faint end. All of these stars would be saturated in individual LSST exposures. Our team (UofA, NOAO, STScI, CfA) have an on-going HST GO program (GO 12967 and now GO 13711 Saha, PI; Narayan is the postdoc) aimed at establishing a basic, 'all-sky', self-consistent set of faint stars (16-20 mag) directly related to the HST scale. Briefly, our current set of 23 calibration standards consists of 15 stars in the equatorial belt with roughly 2 hr spacing in RA and supplemented by eight stars in the northern hemisphere [the surveys needed to find such faint southern WD are either not existing or public at this time]. All stars are DA (pure H) white dwarfs and almost all have SDSS photometry and spectroscopy. The direct relation to the HST photometric scale is achieved through multi-band WFC3 photometry between 0.275 and 1.6 microns. Although primary motivation for the equatorial set of standard stars is to provide a nightly network of photometric LSST standard stars, the entire set of standards will also see wide spread use in many other sensitive surveys on the ground and in space, for which the current standards are too bright and not well-enough calibrated.

The importance of ground-based spectroscopy

The ground-based spectroscopy requested here plays a key role in photometric calibration technique we are using. Briefly, the observed HI Balmer profiles of the DA white dwarfs are fit using non LTE model atmosphere grids to jointly estimate the effective temperature and surface gravity. It should be noted that these parameters are independent of the slope of the stellar SED because the lines are extracted and flattened prior to analysis (see Fig 1 for one of our targets WD1021-002). From the T_{eff} and log g, a detailed model atmosphere spectrum is generated to represent the star. This model can then be convolved with filter response functions to generate synthetic multi-band magnitudes for each star. The method is essentially the synthetic photometry technique described in Holberg & Bergeron (2006). The critical step is to normalize the model atmosphere at six points using the WFC3 filters F275W, F336W, F475W, F625W, F775W, and F160W. The observed HST magnitudes are thus free from the uncertainties of atmospheric extinction and automatically on the HST scale.

Because our stars are fainter than 16th magnitude they have distances ranging from 400 to 2000 pc which means that they exhibit small (≤ 0.1 in E(B-V)) interstellar reddening. This needs to be accounted for in the process of matching our model SEDs to the observed SEDs. The method for doing this is described in Holberg, Bergeron & Gianinias (2008, HBG) and is illustrated in Fig 2. We estimate the multi-band absolute magnitudes for each star, as defined by its spectroscopic T_{eff} and log g, from the Montreal photometric tables [1]. Reddened distance moduli can then be obtained by differencing the synthetic absolute magnitudes with observed magnitudes to produce a vector of multi-band distance moduli. These distance moduli (Y-axis) are then a linear function of the band weighted extinctions scaled by E(B-V). A linear fit such as that shown in Fig 2 then gives the unreddened distance modulus (Y-intercept) and the slope (E(B-V)) for each star. In Fig 2 we use the existing SDSS ugriz magnitudes but our final result involves the much more accurate HST WFC3 filters that extend to 1.6 μ. Application of an appropriate reddening law (we use Fitzpatrick 2004, for R_V = 3.1) will result in a wavelength dependent reddening of the model spectrum.

[1] www.astro.umontreal.ca/~bergeron/Cooling_Models/

The need for MMT spectra

The current HST Cycle 22 program comes with an assignment of 2.6 nights of NOAO Coordinated Time with GMOS at Gemini South. Although this time should be sufficient, our bad experiences with Gemini from Cycle 20 (falling off queue, standards not observed, flatfields not obtained, etc) make us nervous about the set of Gemini spectra and make us wish to have a homogeneous set of spectra properly observed.

The HST TAC recognized the importance of our program for the future of reliable photometry in the era of large surveys. Given the excellent blue efficiency of MMT Blue Channel, increased wavelength coverage, and more precise control over the observing (all compared to Gemini GMOS, which has failed us at some level), we wish to use the MMT for this crucial part of the project. We can then place our primary reliance on user-validated (MMT) spectra and use the GMOS data as validating/check observations. The MMT spectra will ensure that all spectra are optimized to obtain the necessary Teff and log g with minimum observational uncertainties. Finally, our target list contains seven non-equatorial northern hemisphere stars that cannot be observed with GMOS on Gemini South.

The current status of our Program

We were awarded 18 orbits in Cycle 20 (G0 12967) which translates into WFPC3 observations of 9 separate targets, and have just been awarded 60 orbits in Cycle 22 (GO 13711). As of today, all of the HST Cycle 20 data have been obtained, reduced and magnitudes have been obtained for each star. We have just gotten some Cycle 22 data and Gautham will go to STSCI in October to work with STSCI on a new reduction procedure that bypasses DRIZZLE, does the best possible correction for CTE, and deals with cosmic rays in the best way. We have validated/questioned the zero points of the WFC3 filters. We have presented results for five stars (Narayan et al, 2014). We currently have complete GMOS spectra for eleven stars, only five of which are complete for the nine Cycle 20 HST targets. We are optimizing the fitting procedures and reddening estimates. With these existing data we have demonstrated our methods and estimated the ultimate error budget for our calibration program (Narayan et al 2014). Our MMT target list contains all 23 standards in our program. We are also in contact with a DES team finding southern white dwarfs for a possible Cycle 23 HST enhancement (there is no catalog of faint southern WDs, unfortunately).

The final deliverable for our program will be a set of faint DA white dwarfs that have been photometrically calibrated on the HST photometric scale system. Each star will be characterized by a noiseless flux model that can be specified at arbitrary spectral resolution over the entire optical and into the near IR (and the UV as well) at the top of the earth's atmosphere. As such this will meet the stringent photometric specifications of LSST (1% absolute and 0.5 % relative). This will also be a lasting astrophysical legacy will serve many other programs for decades to come, hence the need to do it correctly the first time. The link with the HST scale is critical since any subsequent adjustment in this scale (Vega fluxes are questionable in the IR) can be easily and unambiguously incorporated into our set of standard stars. Finally it could be argued that we will be relying on model fluxes and not 'absolute laboratory photometric standards'. However it has been shown by HBG that synthetic DA white dwarf fluxes can be used to estimate absolute stellar magnitudes that match the best trigonometric absolute magnitudes at the 1% level. Furthermore, recently, Bohlin (2014) has incorporated STIS observations of Sirius into the HST flux scale that minimizes reliance on Vega. In the next several years the European Space Agency Gaia mission will provide exquisitely accurate trigonometric parallaxes for each of our stars that will lead very precise absolute magnitudes that can be compared in detail with our models.

References

Bohlin, RC, & Gilliland, RL, 2004, AJ, 127, 3508 (BG04).

Bohlin, 2014, AJ, 127, 127.

Fitzpatrick, EL, 2004, "Astrophysics of Dust," ASP Conf Series, Vol 39, p33.

Holberg, JB, & Bergeron, P, 2006, AJ, 132, 1331.

Holberg, JB, Bergeron, P, & Gianninas, A, 2008, AJ, 135, 1239 (HBG).

Narayan, G, et al 2014, HST Summer 2014 Calibration Workshop (poster paper).

Sullivan, M, 2011, ApJ, 737, 102.

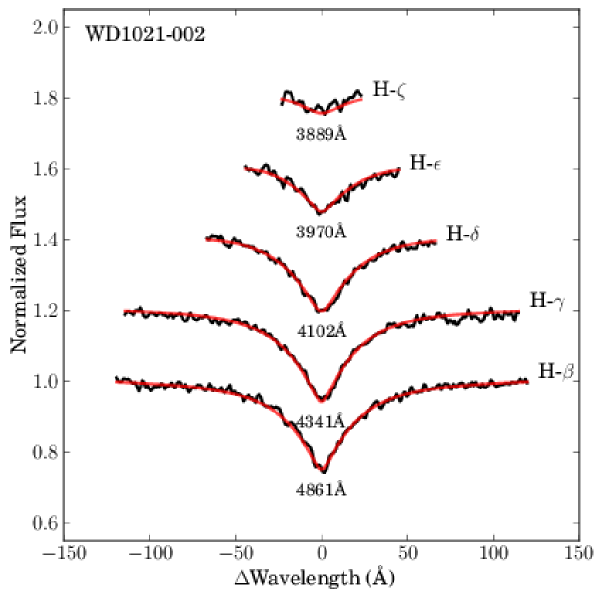

Figure 1: GMOS Balmer profiles for our target WD1021-002 fit to a model.

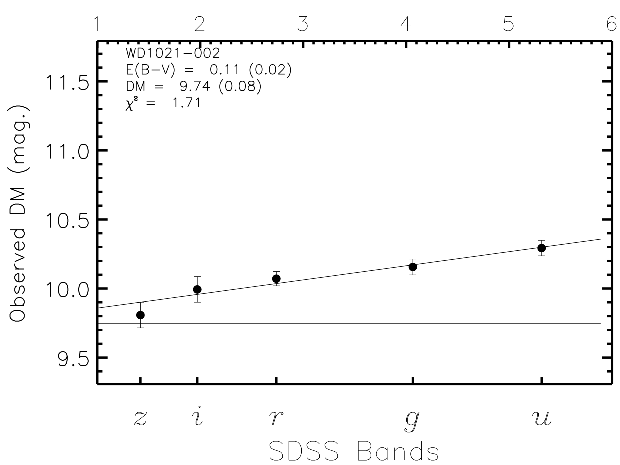

Figure 2: Determination of interstellar reddening for our target WD1021-002. The error bars are primarly due to the uncertainty in the observed SDSS photometry. Our ultimate result will use our HST magnitudes. The horizontal line is the unreddened distance modulus.

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)***

Again, our catalog on the second page gives our entire list of 23 stars. About half of the stars from that list are observable in 2015A.

We will use the MMT Blue Channel with the 300-line grating, observing from 3200-8800 $\AA$. (The Gemini data were not useful below 4000 $\AA$ because of the design of the instrument.) Holberg is one of the world experts in the fitting of model atmospheres to White Dwarf spectra, and requires S/N>50, at $\lambda 3800 \AA$, for each spectrum.

We estimate esposure times empirically in three ways: 1) from the Gemini spectra with corrections for aperture and QE; 2) from a large body of supernova spectra obtained at CFA (part of that team includes Narayan); 3) from scaling of the old-MMT spectrum (by Foltz on the MMT website) of Wolf 1342. All of these analyses agree reasonably and point to 4x1200s for the brighter stars and 4x1800s for the fainter stars. At an average of 1.7 hours per star and assuming 10 hours per night on average, and 15% for standards, we can observe 5 stars per clear night. Three clear nights will therefore give us the 2015A sample.

We will obtain spectra with a 1 arcsec slit, and much shorter-duration spectra with a wider slit. This will give us line profiles for the analysis, and spectrophometry (an added, not crucial, benefit) that we can compare to the models as another check. We will observe bright standard stars each night including the fundamental STIS standards that happen to be up.

Data redcution will largely be performed by Gautham Narayan (who is the postdoc on the HST grant)and Larry Camarota, and analysis, using Holberg's code, will be largely done by Narayan and Holberg.

We are asking for dark time because of the faintness of the stars, the need for high S/N, and the need to work as blue as $3750 \AA$ (well below Balmer ζ). If we are assigned gray time there will be an efficiency and time penalty, resulting in fewer stars.

We stress that there are a lot of details in obtaining sub-percent standards, and our HST Cycle 20 observations informed changes incorporated into Cycle 22. Our current weakest link is the Gemini spectroscopy, which we wish to supercede here.

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**)*

As noted above, we drew the short straw and got our two 2014B nights on Aug 21 and 22, and never even thought of opening the telescope.

We received HST time for this project in Cycle 20, and in Cycle 22. As stated above, the Gemini time attached to our HST data is not well calibrated (this is a peril of queue observing) and is complete for only 5 targets to date (after two years!). We will use the Gemini data as a check of the MMT data, there is no way it can stand alone or be properly calibrated with "short MMT spectra."

Our list of 23 targets cannot all be observed in this semester (about half can be). We will therefore apply for MMT time again for the B semester.

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)***

The only Steward time Jay Holberg has had in the past two years is the two August 2014 nights in support of this project. We never opened the telescope.

Holberg, however, has a good history of publishing his UAO spectra.

And, as noted above, we presented preliminary results (Narayan et al 2014) at the Summer 2014 HST Calibration Workshop.