THE FUTURE OF PHOTOMETRIC, SPECTROPHOTOMETRIC AND POLARIMETRIC STANDARDIZATION
ASP Conference Series, Vol. 999, 2007
C. Sterken

Historical View of the $u'g'r'i'z'$ Standard System

J. A. Smith[1], D. L. Tucker[2], S. S. Allam[2,3], Ž. Ivezić[4], B. Yanny[2], J. E. Gunn[5], G. R. Knapp[5], D. Eisenstein[6], D. Finkbeiner[7] and M. Fukugita[8]

[1]*Department of Physics & Astronomy, Austin Peay State University, Clarksville, TN 37044,*
[2]*Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510,*
[3]*Department of Physics & Astronomy, University of Wyoming, Laramie, WY 82071,*
[4]*Department of Astronomy, University of Washington, Seattle, WA 98115,*
[5]*Princeton University Observatory, Princeton, NJ 08544,*
[6]*Steward Observatory, 933 N. Cherry Ave., University of Arizona, Tucson, AZ, 85721,*
[7]*Department of Astronomy, Harvard University, 60 Garden St., Cambridge, MA 02138,*
[8]*Institute for Cosmic Ray Research, University of Tokyo, 5-1-5 Kashiwa, Kashiwa City, Chiba 277-8582, Japan*

Abstract. We describe the $u'g'r'i'z'$ standard star system developed to support the Sloan Digital Sky Survey (SDSS) and how it is used. Issues related to the SDSS will be discussed including; the offset between $u'g'r'i'z'$ and $ugriz$, the offset to the AB system, and the overall calibration of the SDSS. We will describe the northern hemisphere primary standard system, the southern hemisphere extension, and the current observational program designed to enhance the system.

1. Early History

The Sloan Digital Sky Survey (SDSS) (see York et al. 2000, for a technical overview) is a five-filter imaging survey of roughly 25% of the visible sky, centered on the northern Galactic Cap, and a follow-on spectroscopic survey of roughly 1.3 million objects — mostly galaxies and quasars. The primary science drivers of the SDSS are extra-galactic. Details of the imaging camera are given by Gunn et al. (1998), the telescope is described by Gunn et al. (2006), the photometric system is defined by Fukugita et al. (1996), the original standard star network is given by Smith et al. (2002), and the data releases to date are EDR: Stoughton et al. (2002); DR-1: Abazajian et al. (2003); DR-2: Abazajian et al. (2004); DR-3: Abazajian et al. (2005); DR-4: Adelman-McCarthy et al. (2006); and DR-5: Adelman-McCarthy et al. (2006).

The spectroscopic target selection for the Luminous Red Galaxies, the Quasars, and the Main Galaxy sample are discussed by Eisenstein et al. (2001);

Richards et al. (2002); Strauss et al. (2002) respectively. All of these works, and the ongoing stellar and supernovae programs in the SDSS extension, depend critically upon the calibration of the survey data. This in turn depends critically upon the standard star network.

1.1. The Telescopes

When originally conceived, it was planned that the SDSS would operate with two telescopes: the main 2.5-m survey instrument and a smaller 0.6-m monitor telescope (MT). The purpose of the MT was to provide extinction and photometric zeropoint measurements each night the main telescope was in operation. The MT was equipped with a single CCD camera and operated in the traditional "stare" mode while the 2.5-m operated in a "drift-scan" mode. The time required to complete the extinction and zeropoint operations would necessitate the use of calibration patches (secondary tie patches in SDSS terms) placed in each of the planned survey stripes, roughly one-hour of RA apart. Using this plan the secondary patches did not have to be observed simultaneously with the main imaging scan; however these patches did need to be completed prior to (or at the same time as) the imaging scan since they were critical to the photometric calibration required for the spectroscopic target selection. This was viewed as a critical path item in early survey planning.

The MT was brought to the observing site (Apache Point Observatory; APO) early in the survey (1996). Prior to starting the secondary patch work, it was to be used to develop the SDSS standard star network. Due to development issues a decision was made to replace the 0.6-m MT with the 0.5-m PT (photometric monitor telescope). The primary impact of this change was a loss of approximately one-year of development time for the standard star system. To minimize the survey time impact one of the partner institutions (the U.S. Naval Observatory) made time available to develop the standard stars on the 1-m telescope at the Flagstaff, Arizona station. While this saved time, it added a complication to the overall survey calibration plan. This telescope was used to build the $u'g'r'i'z'$ standard star network (Smith et al. 2002), where the prime marks denote the USNO 1-m system. The survey data from the 2.5-m telescope is given in the $ugriz$ system. The slight differences between the two systems are discussed by Tucker et al. (2006).

1.2. Network Development

The standard-star network is based on the filter system defined by Fukugita et al. (1996). It is zero-pointed to the spectral energy distribution (SED) of the sdF star BD+17°4708 which has spectrophotometry with respect to Vega. The photometric system is defined to be a broadband AB system as developed by Oke & Gunn (1983). This is *not* a Vega magnitude system.

The 2.5-m survey data are tied to the night extinction and zeropoints via "secondary" patches observed by the PT. The original plan called for observations of six extinction stars and 2 secondary fields per hour. This plan drove a bright magnitude range for the standard stars in order for all of them to be observed to a high S/N by the PT in the time allocated.

The end goal of the SDSS was 2% photometry at r and in $g-r$ and $r-i$; 3% in $u-g$ and $i-z$. To meet this goal, the standard star network needed to

be better than 1% in r', $g' - r'$ and $r' - i'$; and better than 1.5% in $u' - g'$ and $i' - z'$. This was half of the total error budget of the SDSS. The extra-galactic nature of the SDSS placed a restricted color range on the original standard star network. An emphasis was placed on blue stars and the red end cut off was about dM0.

Several papers using preliminary SDSS data or test data have appeared in press. These used an asterisk (i.e. $u^*g^*r^*i^*z^*$) to indicate a preliminary magnitude which was tied to the synthetic system developed by Fukugita et al. (1996). This system was discontinued as of DR-1.

Software for developing the standard star network was built into the primary survey MT reduction software suite `mtpipe` (see Tucker et al. 2006, for complete software details). Two independent programs were developed to run in this environment. In addition to this software, the standard star network reductions were checked using three additional sets of independent code.

2. The Original System

Because of the limited time to develop the standard network we made use of previous standard star work such as Landolt (1992). This work has existing $UBVRI$ magnitudes which allowed us to estimate our expected values and, most importantly, had identified variable stars in several of our candidate fields. This allowed us to make fewer observations in these fields and concentrate on the newer or less observed areas, thereby maximizing the number of observations in fields where we needed to identify variable stars. This dependence on the equatorial stars of Landolt (1992) would be beneficial for future expansion into the southern hemisphere. The equatorial stars were supplemented with stars from other standard star works to provide coverage across the northern hemisphere.

Observations to develop the original standard system spanned 183 nights. Of these, 61 were usable in total or in part (more than three hours at a stretch). Since the standard star network had to be bright, as driven by the need for observations with the 0.5-m PT, most of the available time was bright, generally centered on the full Moon. This drove a target selection plan to avoid observing within 30° of the Moon, but did not affect any other aspect of the system setup.

Since we began the observing campaign with a list of about 250 candidate stars to standardize, usually with only one or two stars per field, the exposure times were tailored to each field and optimized for the few stars of interest. This tailoring of exposures led to higher uncertainties for the blue or red stars in some of the fields where these stars were the fainter of the two (or three) candidates in each field.

The data were collected using a Tek-1k CCD operating with an inverse gain of 7.43 e/ADU and 6 electrons read noise. The system used a 15-bit A/D converter and showed a stable linear response region up to 15,200 ADU with a second linear correctable region up to 27,500 ADU. Observations greater than this were discarded as the detector became non-linear above this point. The pixels had an angular size of $0\farcs68$ and the system had an $11\farcm5$ field of view. Data extraction was based on a $24''$ diameter aperture which allowed us to slightly defocus some of the brightest candidates.

The original standard star system (Smith et al. 2002) contains 158 stars, with the photometric zeropoints tied to BD+17°4708. The synthetic magnitudes for this star in each of the five pass-bands is given by Fukugita et al. (1996). The magnitude range of the stars was $8.8 < r' < 14.7$ although only eight of the stars are fainter than $r' = 13.0$.

3. The Southern Extension

Due to the nature of the SDSS the standard star system was essentially a northern hemisphere network. Near the end of its completion, we began receiving requests for $u'g'r'i'z'$ standard stars in the southern hemisphere. These requests were primarily driven by a few small programs using the SDSS filters, but plans for large surveys were emerging. It seemed an obvious project to extend the standard star system into the southern hemisphere. About this time, the National Optical Astronomical Observatories (NOAO) announced the creation of a new category of observing proposals – Surveys Programs. The extension project seemed to be a natural fit and we were awarded 84 nights of time spread over 4 years on the Cerro Tololo Inter-American Observatory (CTIO) 0.9-m telescope. A National Science Foundation grant was secured to support the work.

Our initial plan was to follow a similar development pattern as we had with the northern system: that is we would make use of previous standard star works to help identify non-variable stars. Most of the northern network stars were too bright for use with large telescopes and we were not bound by a specific survey goal (extra-galactic in the SDSS case). Therefore, an additional need in the southern extension was to include fainter and redder stars in the candidate list. After consultations with several potential users of the proposed standards we concluded that a grid of fields across the sky with a large magnitude range of standards would be the best solution.

Observations were obtained using the CTIO 0.9-m telescope and a UV-AR coated Tek2k CCD operating in four-amplifier read mode. The approximate inverse gain was 3.0 e/ADU for each of the amplifiers with five electrons read noise. The CCD was controlled using the CTIO Arcon software and the CCD was linear up to 62,000 ADU. The instrument had a $13\farcm5$ field-of-view at $0\farcs4$ per pixel. Data reduction used the `mtpipe` software and an extraction aperture of $7\farcs43$ radius was used. This smaller aperture was used because we did not need to defocus the telescope for bright stars in this effort. This aperture size was not randomly chosen but is instead used when zero-pointing the 2.5-m instrumental photometry to the PT calibrations in the survey secondary patches. The size was chosen after several tests showed it will reproduce the standard network magnitudes.

We established a grid of candidate field spaced roughly every 2 hours of right ascension at declinations $\delta = -30$ deg and -60 deg and used the E-region fields at $\delta = -45$ deg (Graham 1982) to form the basis of the grid system. This was supplemented with fields from Alvarado et al. (1995), Bok & Bok (1969), and Landolt (1983). To aid in comparisons between the $u'g'r'i'z'$ and the $UBVRI$ filter systems a few additional fields were added (Landolt, private communication). Finally, a few special fields were added to provide local standards in areas of interest. These were the Chandra Deep Field south (CDFS) and some of the

Deep Lens Survey (DLS; Tyson, private communication) fields. The southern extension was tied to the existing northern standards via the equatorial standards.

Preliminary results from this project are described by Smith et al. (2003) for the CDFS. While this work shows the magnitudes that will be reached in the final network some of the sources suffered from extra-galactic contamination: that is, there are some galaxies or quasars in the list. Version 1 of the southern extension stars is available at our project web site `www-star.fnal.gov` and the paper with full details of the program is in preparation at this time.

4. Current Work

Development of the standard network continues as interest in the *ugriz* filter system grows. Part of this work was to expand the software capability of `mtpipe` to output magnitudes in both the $u'g'r'i'z'$ and the *ugriz* systems. There are three main thrusts of the current work – faint standards in the Equatorial stripe of the SDSS, reanalysis of the original northern images, and new northern observations. We summarize each of these three below.

4.1. Stripe 82, the Equatorial Stripe

For part most part, the SDSS scans each area of the sky once with minimal overlap of adjacent areas. Therefore, there are not enough observations of any particular area to search for variable stars or conversely, to develop standard stars. The exception is the equatorial stripe which has now been scanned up to thirty or more times in some areas.

Within the SDSS, three groups began working toward developing faint standard stars in this area. The three groups had different goals which drove their needs for faint standards: calibration of the Large Synoptic Survey Telescope (LSST), calibration of the SDSS Supernova scans, and calibration of the Dark Energy Survey, in addition to development of a set of faint standard stars.

These groups have since begun working together in an effort led by Ž. Ivezić: see the paper in these proceedings. The preliminary data show that we will have approximately 700,000 candidate standard stars in the right ascension range from $20^{\rm h}\ 34^{\rm m}$ to $4^{\rm h}\ 00^{\rm m}$ and with a declination range of $\pm 1\overset{\circ}{.}266$. This set of stars have random errors less than $0\overset{\rm m}{.}01$ at (19.5, 20.5, 20.5, 20, 18.5) in *ugriz*. It includes many of the Landolt (1992) *UBVRI* equatorial standards, making the set of stars extremely valuable for use in comparing filter systems. A paper describing the results is in preparation.

4.2. Re-analysis of the Original Stars

We are re-reducing the original USNO observations to extract all stars in each of the fields. The goal of this effort is to produce some fainter and redder standards in the existing northern fields. Since the original images are being used, we still suffer from the problem of the tailored exposures for each field so the faint limit will probably not be increased in this effort. Since we now have a standard system in place, we are able to recover some partial nights in this effort which were not used in the original work.

For this effort we reran all of the reduction steps. We used the smaller extraction aperture of the SDSS operations and southern extension work (7.″43 radius). Software changes which enhance this effort are variable star search (rejection) routines, an improved cosmic ray reject scheme, better combine routines for the output magnitude files, and use of SExtractor for star-galaxy separation. We estimate there will be several hundred standards produced in this effort.

4.3. The New USNO Program

We have also begun a series of new observations with the USNO 1-m. The drivers for this new program are redder and fainter standards, well-characterized star clusters for use in calibration, and an attempt to develop a photometric-metallicity standard system to aid in filter system transformations and identify gross metallicity using the SDSS filters. Based on preliminary studies, we estimate the classification will be possible to ± 0.5 dex based on photometry alone.

These new observations are planned to go 2–3 magnitudes deeper in existing fields, two magnitudes fainter in some of the PT secondary fields, and a grid of new fields. These are supplemented with some special fields – M 31, center of the proposed Kepler mission field, and northern DLS fields. The photometric-metallicity system uses targeted observations of stars with high-resolution spectroscopy.

5. Issues

As the SDSS filter system gains wider acceptance, some issues come to light which need to be emphasized again, or merit further study.

First, $u'g'r'i'z'$ is not the same as $ugriz$. They are close and they use the same filters, but the zeropoints are slightly different. The $u^*g^*r^*i^*z^*$ designation is no longer used, and when it was, it was a preliminary estimate only.

Transformations between filter systems, especially $u'g'r'i'z'$ and $UBVRI$ are currently being investigated. A few papers in this area have appeared in press dealing with stars, galaxies, quasars. Karaali et al. (2005) recently studied the ugr to/from UBV transformations and concluded two color terms were needed for proper transformations between these systems. Rodgers et al. (2006) agreed with the need for two color-terms for the bluer filters and found a luminosity-class dependence. A recent work (Jordi, Grebel, & Ammon 2006) derives empirical color transformations between $ugriz$ and $UBVRI$ and the RGU filter systems finding a linear transform is sufficient between $UBVRI$ and $ugriz$. Further, they note a slight metallicity dependence in the SDSS filter system.

Other areas which still require investigation for the $ugriz$ filters are the effects of age and environment on the filter pass-bands and the effect of the water-vapor absorption band on the z-filter photometry. We are actively pursuing the offsets from the SDSS $ugriz$ photometry to a true AB system. The current best estimates are $(-0.04, -0.01, 0.00, +0.015, +0.03)$ for $ugriz$ respectively to fit $\mathrm{m}_{AB} = \mathrm{m}_{\mathrm{SDSS}} + \mathrm{constant}$.

The other main issues are the red leak which is present in the SDSS u filter which shows a $u - i$ and $u - z$ dependence. A further complication with the $ugriz$ filters is that the z filter is open ended on the red end. This could lead to complicated transformations for different CCDs.

6. Summary

The $u'g'r'i'z'$ filter system designed for use with the SDSS continues to be improved and expanded. The standard network has been extended into the southern hemisphere and a set of faint standards are being developed along the equator. There are several areas which still merit investigation. We have requested an IAU acronym to designate standard stars on the $u'g'r'i'z'$ system: `ugriz Jhhmmss.s±ddmmss`. The locations of the northern and southern fields is shown in Figure 1. The official web site for the $u'g'r'i'z'$ standard star network and extensions is `www-star.fnal.gov`.

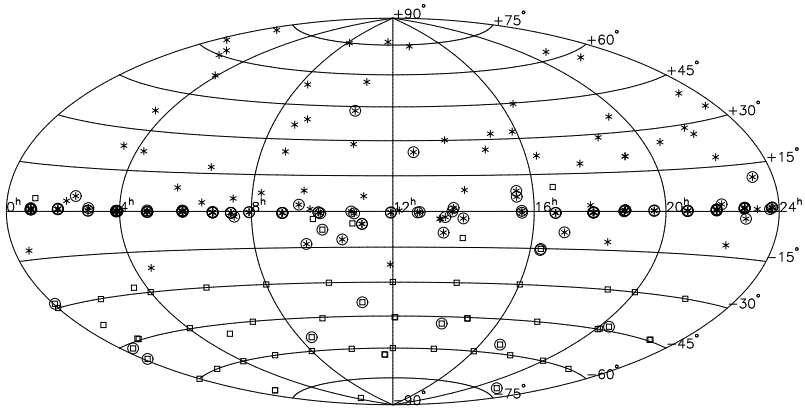

Figure 1. Locations of all current $u'g'r'i'z'$ standard star fields. The original network fields are shown as asterisks and the southern extension fields are shown as squares. Fields with complementary $UBVRI$ data from Landolt are circled. $UBVRI$ data also exists for the E-region fields at $-45°$ declination.

Acknowledgments. JAS, DLT, and SSA acknowledge support from NSF Grant No. AST 00-98401 and the support of the NOAO Surveys Program. JAS and DLT acknowledge the U.S. Naval Observatory and staff for use of the 1-m telescope. DLT and BY acknowledge support from DOE Grant DE-AC02-76CH03000. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is `http://www.sdss.org`. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions. The Participating Institutions are the American Museum of Natural History, Astrophysical Institute Potsdam, University of Basel, Cambridge University, Case Western Reserve University, University of Chicago, Drexel University, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Joint Institute for Nuclear Astrophysics, the Kavli Institute for Particle Astrophysics and Cosmology, the Korean Scientist Group, the Chinese Academy of Sciences (LAMOST), Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, Ohio State University, University of Pittsburgh, University

of Portsmouth, Princeton University, the United States Naval Observatory, and the University of Washington.

References

Abazajian, K., Adelman-McCarthy, J.K., Agüeros, M.A. et al. 2003 AJ, 126, 2081
Abazajian, K., Adelman-McCarthy, J.K., Agüeros, M.A. et al. 2004 AJ, 128, 502
Abazajian, K., Adelman-McCarthy, J.K., Agüeros, M.A. et al. 2005 AJ, 129, 1755
Adelman-McCarthy, J.K., Agüeros, M.A., Allam, S.S. et al. 2006 ApJS, 162, 38
Adelman-McCarthy, J.K., Agüeros, M.A., Allam, S.S. et al. 2006 ApJS, submitted
Alvarado, F., Wenderoth, E., Alcaíno, G., & Liller, W. 1995, AJ, 110, 646
Bok, B. J., & Bok, P. F. 1969, AJ, 74, 1125
Eisenstein, D.J., Annis, J., Gunn, J.E. et al. 2001 AJ, 122, 2267
Fukugita, M., Ichikawa, T., Gunn, J.E. et al. 1996 AJ, 111, 1748
Graham, J. A. 1982, PASP, 94, 244
Gunn, J.E., Carr, M., Rockosi, C. et al. 1998 AJ, 116, 3040
Gunn, J.E., Siegmund, W.A., Mannery, R.E. et al. 2006 AJ, 131, 2332
Jordi, K., Grebel, E.K., & Ammon, K. 2006 A&A, in press
Karaali, S., Bilir, S., Tunçel, S. 2005, PASA, 22, 24
Landolt, A. U. 1983, AJ, 88, 853
Landolt, A. U. 1992, AJ, 104, 372
Oke, J.B., & Gunn, J.E. 1983 ApJ, 266, 713
Richards, G.T., Fan, X., Newberg, H.J. et al. 2002 AJ, 123, 2945
Rodgers, C. T., Canterna, R., Smith, J. A., et al. 2006, AJ, 132, 989
Smith, J.A., Tucker, D.L., Kent, S. et al. 2002 AJ, 123, 2121
Smith, J.A., Tucker, D.L., Allam, S.S., & Rodgers, C.T. 2003 AJ, 126, 2037
Stoughton, C., Lupton, R. H., Bernardi, M. et al. 2002 AJ, 123, 485
Strauss, M.A., Weinberg, D.H., Lupton, R.H. et al. 2002 AJ, 124, 1810
Tucker, D.L., Kent, S., Richmond, M.W. et al. 2006 AN, 327, 821
York, D.G., Adelman, J., Anderson, J.E. et al. 2000 AJ, 120, 1579

Discussion

Kidger: Do you have any means of checking water vapour during the observations (bearing in mind the z' problem)? We use the 940-nm water-vapour line to measure the water-vapour column at La Palma and have, in an extreme case, seen a variation of more than a factor of 10 in around 2 hours!

Smith: We are also concerned, but have no direct way of measuring it at CTIO or USNO. At Apache Point, we use a $10\,\mu$m IR camera which has been calibrated, and CTIO is considering adding a $10\,\mu$m camera to support the DES.

Holberg: What is the motivation for extending SDSS standards to the southern hemisphere, since the SDSS survey does not cover that part of the sky?

Smith: Even though the SDSS does not go to the southern hemisphere, several surveys are planned there which will use some or all of the SDSS filters. (Deep Lens Survey, COMBO-17 survey, OmegaCAM, Dark Energy Survey, LSST). So we decided it would be a good project for the community. By doing the initial work, we made use of the same software, observers, and observing techniques as the northern network, thereby minimizing any differences in the extension.