Photometric Calibrations for 21st Century Science

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*Work supported by the U.S. Department of Energy under contract No. DE-AC02-07CH11359.

February 15, 2009

1 Introduction

The answers to fundamental science questions in astrophysics, ranging from the history of the expansion of the universe to the sizes of nearby stars, hinge on our ability to make precise measurements of diverse astronomical objects. As our knowledge of the underlying physics of objects improves along with advances in detectors and instrumentation, the limits on our capability to extract science from measurements is set, not by our lack of understanding of the nature of these objects, but rather by the most mundane of all issues: the precision with which we can calibrate observations in physical units.

In principle, photometric calibration is a solved problem - laboratory reference standards such as blackbody furnaces achieve precisions well in excess of those needed for astrophysics. In practice, however, transferring the calibration from these laboratory standards to astronomical objects of interest is far from trivial - the transfer must reach outside the atmosphere, extend over 4π steradians of sky, cover a wide range of wavelengths, and span an enormous dynamic range in intensity.

Virtually all spectrophotometric observations today are calibrated against one or more stellar reference sources, such as Vega, which are themselves tied back to laboratory standards in a variety of ways. This system's accuracy is not uniform. Selected regions of the electromagnetic spectrum are calibrated extremely well, but discontinuities of a few percent still exist, *e.g.*, between the optical and infrared. Independently, model stellar atmospheres are used to calibrate the spectra of selected white dwarf stars, e.g. the HST system, but the ultimate accuracy of this system should be verified against laboratory sources. Our traditional standard star systems, while sufficient until now, need to be improved and extended in order to serve future astrophsyics experiments.

This white paper calls for a program to improve upon and expand the current networks of spectrophotometrically calibrated stars to provide precise calibration with an accuracy of equal to and better than 1% in the ultraviolet, visible and near-infrared portions of the spectrum, with excellent sky coverage and large dynamic range.

2 Science Requiring Precision Calibration

The following sections present four science investigations that already are or soon will be limited by the accuracy of photometric calibration. This list is not intended to be exhaustive.

2.1 Expansion history of the Universe using Type Ia supernovae

In 1998 we learned that the expansion of the universe is accelerating, implying the existence of a new component of the universe dubbed ”dark energy”. Precise measurement of the history of expansion and thus the properties of dark energy is a major science goal of the next decade. The Dark Energy Task Force (DETF) (Albrecht *et al.*, 2006) has identified Type Ia supernovae as being one of four principal methods for probing the expansion history.

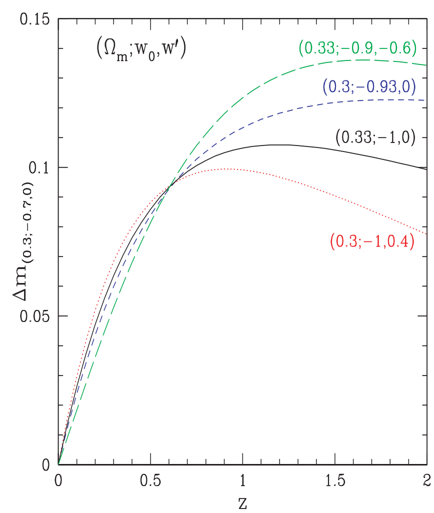

Figure 1: Differential magnitude-redshift diagram for dark energy models with Ω, w_0, and $w' = xw_a$. The difference between models is of order 0.02 magnitudes (or roughly 2%). Models from Huterer & Linder 2003.

Type Ia supernovae are thought to be “standardizable candles” - from observations of light curves and spectra, one can derive the luminosity of a supernova that is the same on average with a scatter of ≈15% for a single object. Cosmological and dark-energy parameters are determined from the shape, not the absolute normalization, of the Hubble brightness-redshift relationship. For each supernova, its rest-frame B-band flux is plotted against its redshift, z. Since the rest-frame B-band is seen in different bands at different redshifts, the relative zero-points of all bands from 0.35 μm to 1.7 μm must be cross-calibrated to trace the supernova from z = 0 to z = 1.7.

Planned dedicated experiments, including Pan-STARRS[1], the Dark Energy Survey (DES) (Abbott *et al.*, 2005), the Large Synoptic Survey Telescope (LSST) (Ivezic *et al.*, 2008), and the Joint Dark Energy Mission[2] (JDEM) and current and future observing programs using multipurpose facilities such as the Supernova Legacy Survey on CFHT (Astier *et al.*, 2006), SN programs using Hubble Space Telescope (Riess *et al.*, 2007) and James Webb Space Telescope (JWST) (Gardner *et al.*, 2006) are or will be focused on collecting accurate data for large numbers of supernovae, eventually leading to a data set containing thousands of objects ranging in redshift from 0 to 1.7.

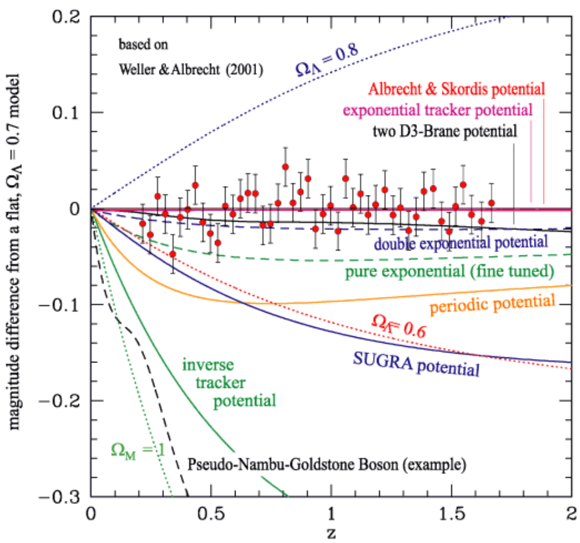

Figure 2: Simulated SNIa data from one version of a JDEM mission compared with predictions from a range of Dark Energy Models (Derived from Weller & Albrecht (2001)).

The power of using SNe Ia out to z$\sim$1.7 for measuring the cosmological parameters is demonstrated in Figure 2, which compares the expected (simulated) results of one version of a JDEM mission, to a range of possible dark energy models (Weller & Albrecht, 2001) . This calculation is based on 2000 SNe Ia measured in the range $0.1 \leq z \leq 1.7$, plus 300 low-redshift SNe Ia from, e.g., the Nearby Supernova Factory (Aldering *et al.*, 2002). The simulated data have a statistical accuracy that is capable of distinguishing models whose predictions differ by as little as 2% over the full range of redshifts.

However, to make full use of the data, systematic errors must be comparable to or smaller than the statistical errors. The NASA-DOE Joint Dark Energy Mission's Reference Mission specifies that, over the fullwavelength range of $0.35 < \lambda < 1.7\,\mu$m, a photometric uncertainty of 0.5% per octave is required for the mission to reach its target Figure of Merit. Achieving this level of precision at the (faint) flux levels of the redshifted SNe requires a transfer of the absolute calibration from bright standard stars to fainter calibration standard stars which can be directly observed by the DE missions.

2.2 Growth Of Structure

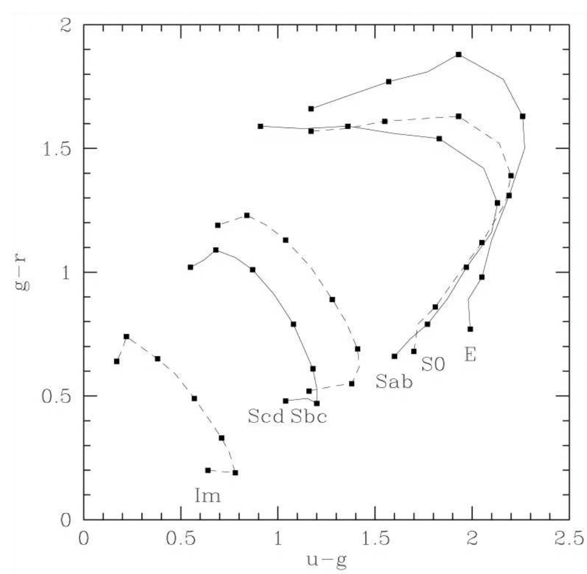

Figure 3: A figure demonstrating the technique of photometric redshifts. For each galaxy type, the dashed line joins together points that mark the colors at a particular redshift. From lower right to upper left, the redshift increases from 0 to 0.6 (Eisenstein et al. 2001).

A potentially powerful technique for measuring the growth of structure in the universe is to use gravitational weak lensing combined with photometric redshifts of galaxies to study

[1]http://pan-starrs.ifa.hawaii.edu/public/
[2]http://jdem.gsfc.nasa.gov/

the statistical properties of the mass distribution as a function of redshift. The history of growth of structure provides another approach to measuring the properties of Dark Energy. Current and future experiments that propose to collect data for such studies include Pan-STARRS, DES, LSST, and JDEM.

A simplified description of this approach is as follows. One identifies a set of galaxies at the same approximate redshift and measures the distortions in the shapes of these galaxies induced by gravitational lensing from the intervening mass distribution (such as clustering). A single set of galaxies measures the properties of the integrated mass distribution along a line of sight. By selecting a second set of galaxies at, *e.g.*, a higher redshift, and measuring the changes in lensing-induced shapes relative to the first set, one obtains information about mass structures in a slice of space between the two sets of galaxies. Thus, in a process analogous to tomography, one can build up a view of the mass structures and how they change as a function of redshift.

A key necessity in this approach is the use of multicolor, broadband photometry of galaxies as a "low-resolution spectrograph" to estimate redshifts (Fig. 3). Because the intrinsic spectral energy distribution of any galaxy is not known a priori, one must rely on matching a set of redshifted template spectra to the measured photometry of a galaxy and utilizing a "training set" of galaxies with known redshifts to calibrate the templates.

Spectrophotometric calibrations are used to convert the template spectra to predictions of galaxy magnitudes and colors. Ideally, the training set would span all of parameter space, but in reality there will always be galaxies that can be measured photometrically but are too faint to measure spectroscopically. Accordingly, the LSST project has developed a two-pronged approach to obtain photometric redshifts from its multicolor data set (Connolly *et al.*, 2006), and established a requirement on spectrophotometric calibration of 1% (1.5% in the UV), with design goals that are twice as good[3].

[3]www.lsst.org/Science/docs/SRD.pdf

2.3 Stellar Populations In Elliptical Galaxies

Although elliptical and S0 galaxies are only a small fraction of all galaxies, they are notable for having very similar stellar populations, as reflected in their uniformity of colors. With the advent of large, multicolor surveys using digital detectors, these objects can be identified over a range in redshift and used for cosmological studies. Thus, the red galaxy spectroscopic sample in SDSS has been used to detect acoustic baryon oscillations (Eisenstein *et al.*, 2005). Additionally, optical detection and measurement of galaxy clusters has seen a resurgence of interest due to the ability to identify galaxy clusters based on the "red sequence" of these types of galaxies. In low redshift clusters, the colors of early-type galaxies are remarkably uniform, showing a scatter of just 5% in colors such as SDSS $g-r$ and $r-i$ (Koester *et al.*, 2007). The SpARCS survey (Wilson *et al.*, 2008) has shown that clusters with similar galaxy content exist out to redshifts of at least 1.34. Galaxy clusters will be detected and measured by nearly every current and future imaging survey conducted for weak lensing. Galaxy cluster counts have been identified as a third method for measuring dark energy by the DETF.

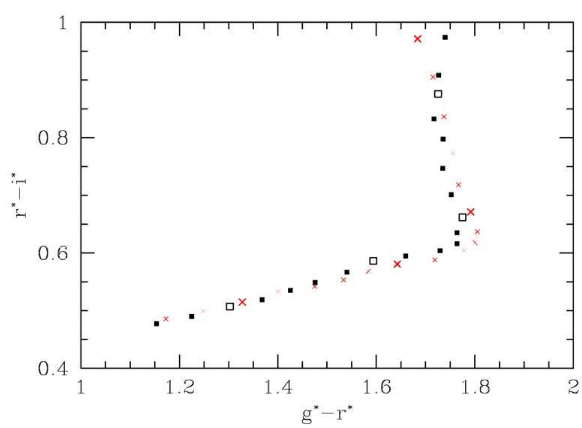

Figure 4: Black squares: colors of elliptical galaxies as a function of redshift; Red crosses: Passively evolving stellar population model (Eisenstein et al. 2001).

Since a cluster has anywhere from 10 to 100 members, the mean color of galaxies can be measured with extremely high precision. By comparing the colors over a range in redshifts, it should be possible to make accurate models of the stellar populations and infer their evolution over a significant fraction of the age of the universe. The limit on the accuracy of these models will be set by the ability to self-consistently calibrate the galaxy photometry over the optical and near-IR bands. Conceivably one could take advantage of data calibrated at better than 1% accuracy. Figure 4 demonstrates the precision with which elliptical galaxy colors can be measured and compared with stellar synthesis models.

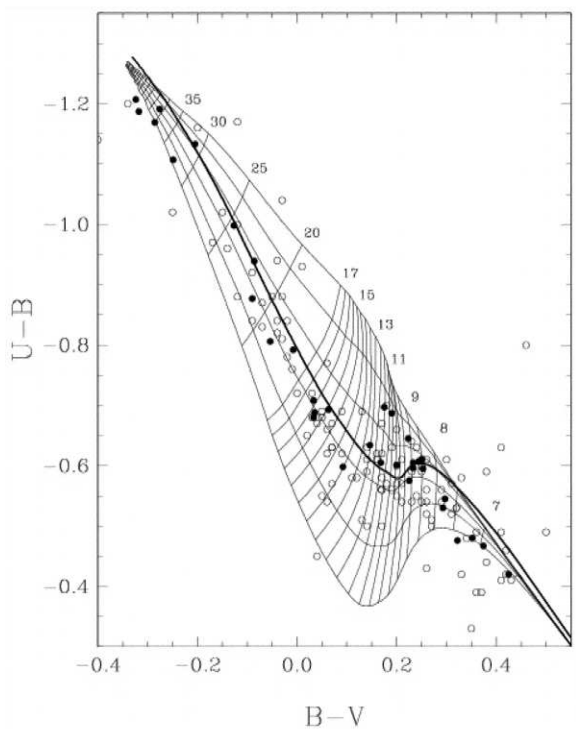

Figure 5: Color-color diagram for DA white dwarfs. Open and filled circles are observations of stars with measured distances. Solid lines are predictions from a grid of models with constant gravity or constant effective temperature (Holberg, J & Bergeron, 2006).

2.4 Stellar Structure

The fundamental parameters of stars, including mass, radius, metallicity, and age, are inferred by matching accurate models of stellar atmospheres to calibrated spectroscopic data and thus determining effective temperature, surface gravity, composition and, if necessary, interstellar reddening. For stars with relatively simple atmospheres such as hydrogen white dwarfs, atmosphere models are thought to be quite accurate and can be used to predict photometric parameters (Fig. 5) and, in combination with stellar interior models, the radii and absolute luminosities as well. By combining these data with photometric measurements, it is possible to predict distances. A comparison of these predictions with measured trignometric parallaxes for those stars with such measurements shows excellent agreement (Holberg *et al.*, 2008). If calibrations can be improved to the level of 1% and with more stars (such as will be measured with GAIA), it will be possible to make meaningful tests of 3-D spherical models, derive masses directly, and make more quantitative tests of evolutionary models.

3 Flux Calibration & Standardization

Ultimately, observed astrophysical fluxes must be converted to physical units. Three of the most common methods of determining the absolute fluxes are through comparison to standard stars (e.g. solar analog stars), stellar atmosphere models, and certified laboratory standards. But, the existing precision of each of these methods is inadequate to meet the requirements of the science described in the previous section.

3.1 Solar Analog Stars

Use of solar analog stars as a standard source relies upon the star having the same intrinsic SED as the sun. Unfortunately, no star is a true solar analog. Even G-type stars with the most-closely matching visible spectra can differ by a few percent. In addition, uncertainties in the solar SED itself are 2-3% (Thuillier *et al.*, 2003).

3.2 Stellar Atmosphere Models

UV and visible astrophysical fluxes are often normalized to an absolute flux using a set of hot, white dwarfs (WDs) whose models are tied to Vega's absolute flux at 5500 Angstroms, as determined through direct comparison to a black body reference.

Stellar atmosphere models are currently the preferred method for calibrating stellar fluxes due to the agreement between the models and the observations as well as the increased resolution of both the models and the data. Use of these pure hydrogen WD stars simplifies the computation and improves the precision by eliminating one of the most difficult steps in atmospheric modeling - that of including the blanketing from the plethora of metal lines.

To obtain the absolute flux and its uncertainty for an unreddened WD, medium-resolution high S/N (>50) observations of the Balmer lines are fit to model hydrogen line profiles to determine the effective temperature, the gravity, and the associated uncertainties (e.g., Finley *et al.*, 1997). Then, the best-fit model and the models at the extremes of the uncertainty in $T_{\rm eff}$ and $\log g$ determine the nominal flux and uncertainty in the shape of the flux distribution. These model fluxes are normalized to V-band Landolt photometry.

The three primary WD standards of *HST* CALSPEC network are internally consistent to an uncertainty level of 0.5% in the visible with localized deviations from models rising to $\sim$1% over the 4200$-$4700 Å spectral range, and a $\pm$1% uncertainty in the NIR (1$-$2 μm) (Fig. 6; Bohlin 2007). Current uncertainties in the extensive NIR ($1.0 < \lambda < 1.7\,\mu$m) network of standard stars are $\sim$2% (e.g. Cohen *et al.* 1992a,b, 2003; Cohen 2007).

Any systematic modeling errors that equally affect the shape of the flux distributions of all three WD stars cannot be ruled out and would make the actual error larger. Differences between the continua of the LTE and NLTE models place a lower limit of 2% on the uncertainty in the 0.35$-$1.7 μm range for these standards.

In the NIR, astrophysical fluxes are often normalized to A-star models, where the accuracy of the best A-star models rivals that of the pure hydrogen WD models. Absolute photometry of Vega is used to normalize the SEDs of these stars to an absolute flux scale. Rieke *et al.* (2008) tested the agreement of IR standard star calibrations and models based on direct absolute measurements of A0V stars versus the sun and examined the impact of extrapolating the IR data into the visible. The data were found to be consistent, permitting flux calibrations with an accuracy of $\sim$2% between 1 and 25 μm.

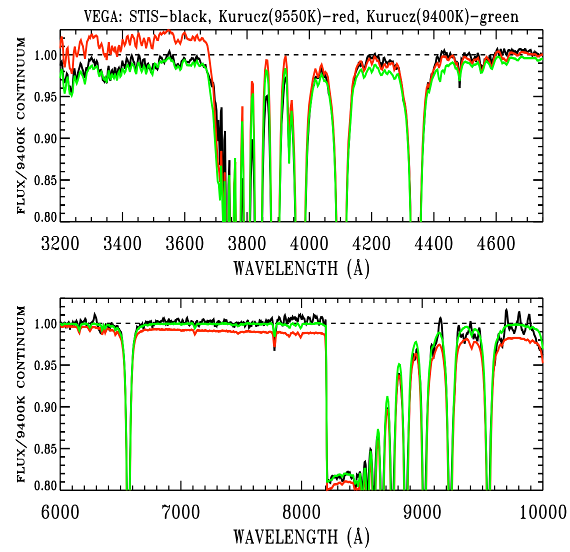

Figure 6: Uncertainties in the absolute flux for Vega: HST/STIS observations (black line: Bohlin 2007; Bohlin & Gilliland 2004), the Kurucz stellar model with T_{eff}=9400 K (green), and the Kurucz stellar model at 9550 K (red) are compared. The observations exhibit better agreement with the cooler model at the longer and shorter wavelengths. The hotter model agrees better with the measured flux by $\sim$1% at 4200–4700 Å.

3.3 Certified Laboratory Standards

Photometry of Vega has been absolutely calibrated against terrestrial observations of certified laboratory standards (e.g. tungsten strip lamps, melting point black bodies) to provide the normalization for the network of stellar models and templates that are used as practical absolute standards. These absolute calibrations to standard sources were difficult and subject to large systematic uncertainties due primarily to the large and variable atmospheric opacity.

Discrepancies of $>$10% in Vega's flux exist at 0.9$-$1 μm, whereas the measurements from 0.5$-$0.8 μm agree to $\sim$1% (Bohlin & Gilliland 2004; Hayes 1985). Beyond 1 μm, windows of low water vapor absorption have been used for absolute photometry (e.g. Selby *et al.* 1983; Mountain *et al.* 1985).

Currently, the uncertainty in the standard star flux calibration network relative to the fundamental laboratory standards exceeds 1%.

Certified Detectors: The calibration precision of photodetectors has greatly improved since early pioneering measurements (e.g. Oke and Schild 1970; Hayes & Latham 1975). Current NIST $\sim 2\sigma$ uncertainties in the absolute responsivity of standard detectors are $\sim 0.2\%$ for Si photodiodes and 0.5% for NIR photodiodes (Larason and Houston, 2008). This increased precision in the photodetector calibration, ease of use, and repeatability, now make standard detectors the calibrator of choice.

3.4 Extension to Standard Star Networks

The basic techniques and methodologies for extending one fundamental standard candle to a network of stellar standards are well established. This extensive network of stellar standards is fundamentally tied to the sun or to Vega, e.g SDSS successfully established a network of standard stars spanning the visible range from $0.3-1.0$ μm (Smith *et al.*, 2002) with absolute fluxes based on Vega using BD+17°4708 as an intermediate (V=9.5 mag) transfer standard (Fukugita *et al.*, 1996). Even the Cohen *et al.* (1992a) absolute standard models of Sirius are tied to Vega as the underlying standard.

Vega is far too bright to be observed directly by the current class of 4-m telescopes and even with most 2-m telescopes using state-of-the-art instruments. Its use as a standard is further complicated by its protoplanetary disk which contributes to IR flux measurements. In addition, as a pole-on rotator its surface temperature and gravity vary dramatically from the pole to equator (e.g. Aufdenberg *et al.* (2006)). This introduces complexity into accurately and precisely representing its flux with robust stellar atmosphere models. Furthermore, uncertainties in atmospheric corrections have resulted in wavelength dependent uncertainties in Vega's intrinsic flux. Thus, Vega is not suitable as a modern astrophysical flux standard.

NIST standards have been transferred to observations of other stars, but the level of uncertainty in the flux measurements have precluded their widespread use (e.g. HZ43 and G191B2B: $\sim$4% precision, Kruk *et al.* (1997)). An exception to this was the Midcourse Space Experiment (MSX) which observed eight standard stars, including Vega, in the infrared and directly tied these observations to inflight measurements of emmisive reference spheres (Price *et al.*, 2004). These measurements resulted in corrections (Sirius: 1%) and caveats (Vega: flux excess). These MSX observations were limited to bright, typically K III and M III, stars in six selected NIR/IR bandpasses. Thus, the need for a sample of absolutely calibrated astrophysical standards spanning a broad dynamic range in flux and wavelength (UV through NIR) persists.

Current astrophysical problems need a precise (better than 1%) network of astrophysical flux standards spanning a wide dynamic range. This enables scientists to take advantage of the capabilities of current and future telescopes and the instruments that were developed to address pressing scientific questions. New, direct measurements of standard stars tied directly to fundamental NIST standards are required.

3.5 Current Status & Future Prospects

Although the relative photometry of objects in a single CCD exposure can be better than 1%, this level of precision is not achieved for the relative fluxes of sources in different fields of view. Stubbs & Tonry (2006) reviewed systematic uncertainties that plague ground-based observations, discussed the challenges associated with characterization of atmospheric transmission and the removal of instrument artifacts, and presented a method for achieving photometry with fractional uncertainties. Using precisely calibrated photodiode detectors in concert with a wavelength tunable laser illumination source, Stubbs *et al.* (2007) demonstrated the success of their methodology in measuring the instrument transmission and established the capability of standard detectors as a fundamental metrology to achieve precise and accurate photometry.

Other programs are also making concerted efforts to characterize instrument performance (e.g ASTRA Adelman *et al.* (2007)), however, the need to monitor and correct for atmospheric transmission on short timescales persists. One approach (e.g. Pan-STARRS, LSST) uses a dedicated telescope to monitor the atmosphere throughout the night to enable corrections for science observations at the neighboring facility.

Direct, absolute calibrations of stellar fluxes measured above the Earth's atmosphere are also being pursued. A recently approved sub-orbital program, ACCESS: Absolute Color Calibration Experiment for Standard Stars (Kaiser *et al.* 2008, 2007), will transfer NIST absolute detector standards to additional standard stars with better than 1% precision over the $\sim$3500Å $-$ 1.7μm bandpass at a spectral resoloving power of $\sim$500. However, due to the limited time above atmosphere for rocket flights, these measurements will be limited to a few stars brighter than $\sim 10^{th}$ magnitude.

The scientific impact of a standard star network based on the absolute calibration of stars too bright to be observed with the premier telescopes needs to be addressed. A modern calibration program should extend direct flux measurements to fainter sources, encompass a broad spectral range (UV through the IR), ensure robust results through the support of independant calibration programs, and provide technology support to execute these programs.

In conclusion, we stress the need for a calibration program that supports the science of the 21st century.

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