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STANDARD PHOTOMETRIC SYSTEMS

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■ **Abstract** Standard star photometry dominated the latter half of the twentieth century reaching its zenith in the 1980s. It was introduced to take advantage of the high sensitivity and large dynamic range of photomultiplier tubes compared to photographic plates. As the quantum efficiency of photodetectors improved and the wavelength range extended further to the red, standard systems were modified and refined, and deviations from the original systems proliferated. The revolutionary shift to area detectors for all optical and IR observations forced further changes to standard systems, and the precision and accuracy of much broad- and intermediate-band photometry suffered until more suitable observational techniques and standard reduction procedures were adopted. But the biggest revolution occurred with the production of all-sky photometric surveys. Hipparcos/Tycho was space based, but most, like 2MASS, were ground-based, dedicated survey telescopes. It is very likely that in the future, rather than making a measurement of an object in some standard photometric system, one will simply look up the magnitudes and colors of most objects in catalogs accessed from the Virtual Observatory. In this review the history of standard star photometry will be outlined, and the calibration and realization of standard systems will be examined. Finally, model atmosphere fluxes are now very realistic, and synthetic photometry offers the best prospects for calibrating all photometric systems. Synthetic photometry from observed spectrophotometry should also be used as a matter of course to provide colors within standard systems and to gain insights into the spectra and colors of unusual stars, star clusters and distant galaxies.

1. INTRODUCTION

1.1. Background

One of the major achievements of 20th century astrophysics has been the unravelling of the evolution of stars and the understanding of the creation of elements in stars and in supernova explosions. Another highlight has been work on the formation and evolution of galaxies stimulated by cosmological n-body simulations and large telescope observations of distant galaxies. Central to all this work is the quantitative photometry and spectroscopy of stars and stellar systems.

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For historical reasons, these brightness measurements are normally given in magnitudes (an inverse logarithmic scale) and magnitude differences between different wavelength regions are called colors.

Much of astrophysics revolves around the position occupied by stars in the luminosity versus temperature plane known as the Hertzsprung-Russell (HR) diagram. The life history of a star is traditionally described by the path it traces in the HR diagram. The observational version of the HR diagram is the Color-Magnitude diagram. The integrated magnitudes and colors of star clusters and galaxies are often analyzed in similar diagrams for integrated systems. Much effort, observational and theoretical, goes into converting, for example, the visual magnitude and color of a star into its total absolute flux (bolometric magnitude) and effective temperature (related to the surface temperature) in order to derive the mass, composition and age of the stars. This involves empirical relations derived from stars with known luminosities and measured radii together with theoretical model atmosphere computations.

The integrated magnitudes and colors of star clusters are also of great interest as they can be used to derive the age and composition of the constituent stars. Similarly, the integrated magnitudes and colors of galaxies can be analysed in order to determine the nature and proportion of their constituent stars and gas and study galaxy evolution. Such population synthesis is a powerful tool in the study of the distant universe as well as the local system (for example, Lançon & Rocca-Volmerange 1996; Ng 1998).

Common to all these endeavors is the necessity to place the measurements onto a standard physical flux scale by removal of the absorption by the Earth's atmosphere and the calibration of the sensitivity of the photometric/spectroscopic equipment at different wavebands. For mainly historical reasons, but also for good practical reasons, astronomical photometric observations are calibrated through the use of networks of constant brightness stars, rather than laboratory based calibration lamps of constant temperature. These networks of stars comprise the various standard star systems that this review will examine.

Three significant papers on photometry have been published in this journal. Oke (1965) outlined the AB (absolute) photometric system of pseudo monochromatic photometry in which the fluxes are on an absolute flux scale and the magnitude differences (colors) are directly related to flux ratios. This system is the basis of all spectrophotometric calibrations.

In a very influential and forward looking paper Johnson (1966) described the *UBVRIJHKLMN* system of broad-band photometry extending from 300 nm to 10 μ that he had established. This system forms the basis of all subsequent broad-band systems and initiated IR astronomical research. Fluxes in the Johnson system are normalized to that of Vega, so conversion of Johnson magnitudes to absolute fluxes requires multiplication by the flux of Vega. Johnson provided tables of intrinsic colors for dwarf and giant stars, temperature-color calibrations and bolometric corrections for stars with different color with which to derive total flux from their measured *V* magnitude.

In the same volume, Strömgren (1966) outlined the intermediate-band uvby system that he had devised to better measure the temperature, gravity and reddening of early-type stars. This system revolutionised quantitative photometry by providing more precise estimates of temperature, gravity, metallicity and interstellar reddening for stars hotter than the sun. It also stimulated the establishing of other systems better suited for studying cooler stars.

Wider discussions of photometry and photometric practice are provided in the following selected books. *Problems of Calibration of Multicolor Photometric Systems*: Philip (1979); *High Speed Astronomical Photometry*: Warner (1988); *Astronomical Photometry—A Guide*: Sterken & Manfroid (1992); *Multicolor Stellar Photometry*: Straizys (1992); *Handbook of Infrared Astronomy*: Glass (1999); *Handbook of CCD Photometry*: Howell (2000). The Web also provides access to course notes and other useful photometric information some of which is described below.

Since the last reviews, there have been great changes in detectors and a proliferation of photometric systems, some related, some different. There are at least three outstanding photometric questions for astronomers that this review will help answer. These are: What are the precisions of the different photometric systems? What are the conversions between the magnitudes and colors in the different photometric systems and how reliable are they? How well are the passbands known and can the extant standard systems be theoretically realised using model atmosphere fluxes and observed spectra?

1.2. The Worldwide Web Resources

The advent of the worldwide Web has opened up the way for ready access to standard star and standard bandpass databases. As with much on the Web it is necessary to have a reasonable appreciation of what one is viewing, in this case standard star systems, their limitations and strengths, because most database providers are collectors rather than censors and the quality of the content is mixed.

There is also the problem with referring to WWW sites that the address may subsequently change; however, the advantages of ready access to digital data outweigh the frustration of the nonexistent address and often a similar or updated document can be found from higher in the tree or with the help of a search engine.

The Asiago database of photometric systems was recently established (http://ulisse.pd.astro.it/Astro/ADPS/). Moro & Munari (2000) provided a compilation of basic information and reference data for 201 photometric systems. Fiorucci & Munari (2003) added a further 17 systems and provided homogeneous band and reddening parameters for all systems with known band transmission profiles. Future papers will deal with calibration of the systems in terms of the basic physical stellar parameters (temperature, gravity, metallicity, reddening) and transformations between the systems.

The Lausanne Photometric Database (http://obswww.unige.ch/gcpd/gcpd.html) also provides catalogs and details of the *UBV*, *uvby*, Geneva, Vilnius, Walraven, DDO, Washington, and gnkmfu systems. Photometric calibrations are referenced in http://obswww.unige.ch/gcpd/calibration.html.

Standard Objects for Astronomy (http://sofa.astro.utoledo.edu/SOFA/photo metry.html) has links to the other two databases and provides lists of standard star photometry in the optical and IR for many systems.

All the major observatories also provide Web access to lists of standard stars, zeropoint calibrations and transformation coefficients for their instrumental systems.

The Space Telescope Science Data Analysis System (STSDAS) synthetic photometry (synphot) package (http://stsdas.stsci.edu/documents/SyG_95/SG_1.html) is an IRAF (Image Reduction and Analysis Facility)-based suite of tasks designed to simulate photometric and spectrophotometric data resulting from *Hubble Space Telescope* (HST) observations. In addition to the HST instrument filters, it also contains throughput data for several conventional photometric systems, such as Johnson-Cousins *UBVRI*, Strömgren uvby, and Walraven *VBLUW*.

1.3. Basic Astronomical Photometry Assumptions

To assist those new to the arcane study of astronomical photometry, it is useful to mention a few of the usual assumptions and some of the vocabulary. If N_B is the total number of electrons detected from a source above the background sky in t seconds through a filter B, the measured instrumental B_i magnitude is $B_i =$ const -2.5 log $10(N_B/\mathrm{t})$. That is, for two stars with fluxes N_1 and N_2 the magnitude difference between them is

$$B_1 - B_2 = -2.5 \log 10(N_1/N_2).$$

A star overhead in the zenith suffers the least absorption from the atmosphere. At positions away from the zenith, the absorption or extinction is greater as the path length through the atmosphere is longer. The normalized path length is called the airmass. The airmass is 1 at the zenith and is 2 at a zenith distance of 60 degrees (Z = 60). The airmass is approximated by sec Z. In the optical part of the spectrum extinction is a combination of continuous absorption from Rayleigh scattering of gas molecules and mainly neutral absorption from dust and aerosols. Rayleigh scattering varies with wavelength^{-4} and is high in the UV and blue. There is in addition, some absorption at specific wavelengths mainly due to O_3, O_2, CO_2 and H_2O. Ozone is responsible for the atmospheric cutoff in the UV and H_2O severely affects the transmission in the IR. The continous absorption is proportional to airmass, whereas the specific molecular absorption is non-linear with airmass and in the case of H_2O can vary with time as well as airmass. The wavelength dependent extinction is quite steady throughout the night and even from month to month so it is usually possible to adopt mean extinction values and simply solve for the neutral component that can and does change nightly. Extinction is generally measured by observing pairs of standard star fields, one in the meridian, the other at high airmass. And because the extinction varies appreciably across some of the broad photometric bands, especially in the blue and violet, red and blue extinction stars are observed to solve for the color term in the extinction.

Using *B* as an example, the extinction in the *B* band k_B is therefore generally given as k_1-k_2(*B*-*V*) to allow for the fact that in the broad *B* band, a blue star will suffer more extinction than a red star as its light is concentrated toward the high extinction side of the band. The extinction coefficients are normally expressed in magnitudes per airmass. In the optical part of the spectrum the observed instrumental magnitudes (B_i) are corrected to outside the atmosphere (B_{i0}) by extrapolating to zero airmass and $B_{i0} = B_i - k_B$(airmass). However, as will be discussed later, such extrapolation is not possible for existing IR systems. Strategies to minimize problems with extinction generally involve interspersing observations of unknown objects with standard objects and ensuring that the standards are observed at airmasses similar to those of the program objects. In this way extinction correction is a second-order effect.

To put one's observations onto a standard system, one derives the differences between the extinction corrected instrumental values B_{i0} and the standard B value. These differences are then regressed against one or more standard colors to see the trends and determine the transformation equation. If an observer's instrumental system is close to the standard system a simple linear relation, with a small color term, should be derived. That is, $B_{i0} - B = \mathrm{ZP} + \mathrm{a}(B\text{-}V)$ where a should be smaller than ± 0.05. ZP is the zeropoint constant that includes any neutral extinction residual, aperture correction and so forth. If there are systematic deviations from a linear fit, two lines can sometimes be used or the deviations can be regressed against another color that better correlates with whatever in the spectrum (perhaps the Balmer or Paschen Jump) is causing the deviation. The closer the color term is to zero, the less likely that systematic errors will be made in measuring the magnitude and colors of stars and galaxies whose energy distributions differ significantly from those of the ensemble of stars in the standard list.

Finally, if observers are undertaking a large photometric program with the same equipment, it is best to maintain one's extinction corrected instrumental system magnitudes for the duration and not transform onto the standard system nightly (except perhaps for the zeropoint). That way one is less likely to introduce uncertainties and systematic differences that can occur from using standards with a restricted color range or a subset of less well defined standards on some nights. Better combine all the standards from all the nights to determine the color term in the transformation equation once.

1.4. The Nature of Standard Systems

A standard photometric system is defined by a list of standard magnitudes and colors measured at specific bandpasses for a set of stars that are well distributed around the sky. Observed magnitudes are corrected for the attenuation of the Earth's atmosphere away from the zenith, and the data is then normally extrapolated to zero airmass (outside of the atmosphere). The method of correcting for extinction is an integral part of the standard system (Cousins & Caldwell 1998, 2001). However, most of the infrared (IR) broad bands are difficult to extrapolate to zero airmass because of the nonlinear behavior with airmass of the H_2O absorption (Manduca & Bell 1979) compared to the linear behavior of dust, aerosols and Rayleigh scattering, the major components of optical extinction. New IR bands have been devised to address this problem (Young, Milone & Stagg 1994; Simons & Tokunaga 2002; Milone & Young 2005).

Many astronomical photometric systems have been established over the years by different observers with a variety of detectors and passbands. Different standard photometric systems usually measure different wavelength bands. All photometric systems enable the measurement of absolute fluxes, from which can be inferred particular properties (such as temperature, gravity, and metallicity) of the emitting object, but different systems claim to do it more precisely or more efficiently than other systems and some are better suited for hot stars and others for cool stars.

Photometric systems are usually divided into broad band ($\Delta\lambda < 1000$ Å), intermediate band (70 Å $< \Delta\lambda <$ 400 Å), and narrow band ($\Delta\lambda < 70$ Å). Another category, the ultra–broad band, has been recently proposed to encompass those survey systems, such as Sloan and Hipparcos, whose bandwidths are wider than the well-known BVRI broad-band system. In the following sections we will discuss many of the well-established photometric systems within these three usual bandwidth divisions.

Another important difference between systems relates to whether they are closed or open. An open system is one whose originators encourage others to duplicate the passbands and detector system and to use the originator's standard stars and reduction system for their photometric programs. A closed system is one where a small group of people control the instrumentation and data reduction and only encourage others to use the results but not to attempt to duplicate the system and observe stars for themselves. For obvious reasons, systematic errors and the quality of the data are better controlled in a closed system than an open system. In the past, the main disadvantage of a closed system was that your particular star of interest was often not in the catalog. However, with the advent of large-scale sky surveys to faint magnitudes, it is likely that, in the future, photometry for most objects of interest will be provided by closed photometric systems.

Most of the older systems were developed and modified over many years as detectors with greater sensitivity and wider wavelength response were used in place of the original detectors; different filters than those specified by the originators have also been used. This has resulted in the literature containing slightly different versions of some standard system, such as the *UBV* system, which is confusing. But in general, modern versions of most of the well-established photometric systems can be homogenized and placed on a firm quantitative footing and, provided care is taken with passband matching, precise and astrophysically valid data can be derived by observers for most passbands and for most kinds of stars.

However, some systems, notably the Strömgren system, have proven very difficult to homogenize, and the standard system is not really well defined for some kinds of stars such as supergiants. This has arisen from systematic variations in photometry between different observers with different photometers owing to the great sensitivity of the photometry to the placement and widths of some of the passbands (Manfroid & Sterken 1987, 1992).

1.5. The Development of Standard Systems—Changes in Detectors and Wavelength Coverage

1.5.1. OPTICAL WAVELENGTHS A good summary of the history of photometry is given by Hearnshaw (1996) and the nature of multicolor photometry by Straižys (1992), but a few comments concerning detector advances and the resultant development of standard systems are useful here. Whitford (1940) was one of the first astronomers to show the advantages of photoelectric photometry. Important contributions were made by Stebbins, Whitford & Kron in the 1940s at the Washburn and Lick Observatories (Stebbins & Whitford 1943, Kron 1946) using early photocells. But it was the introduction of the cooled blue sensitive RCA 1P21 photomultiplier tube in the mid-1940s and the development of low-noise amplification techniques that provided a huge impetus to accurate photometry (Johnson 1948; Dewitt & Seyfert 1950; Stebbins, Whitford & Johnson 1950). An informal collaboration was agreed upon between the major photometrists at the time to establish a sequence of standard stars in the Northern Hemisphere but Johnson (Johnson & Morgan 1951, Johnson 1952) preempted this agreement and published his version that formed the basis of the *UBV* system (Johnson & Morgan 1953, Johnson & Harris 1954, Johnson 1955). The high sensitivity and reliability of the blue photomultipliers were also utilized by Strömgren (1951, 1957, 1966) and McClure (McClure 1976, McClure & Forrester 1981) for the archetypal intermediate-band uvby and DDO system, respectively.

In the early 1950s a red-sensitive photocell was used by Kron and collaborators to set up the 6-color system (Stebbins, Kron & Smith 1950) and the Kron *RI* system (Kron, White & Gascoigne 1953) but the low gain and high dark current of the photocell restricted work mainly to bright stars. But by the end of the 1950s, Kron (1958) reported the usefulness of the first red-sensitive S1 photomultiplier tubes. An S1 tube was used by Johnson and collaborators to set up the Johnson *RI* system defined by the bright star photometry in Johnson et al. (1966). Eggen (1975) also used an S1 tube for his broad-band *RI* photometry as did Oke (1964) and Wing (1967) for red spectrophotometric observations.

Johnson was also one of the early pioneers in IR observations using a lead sulfide cell for *JK* photometry and a germanium bolometer for longer-wavelength *LMN* studies. Johnson observed many different kinds of stars with his *UBVRIJKL* photometric system and his review article (Johnson 1966) was extremely influential for stellar photometry and astrophysics. However, the low precision of the *RI* catalog and the unreliability of the S1 detectors compared to the blue sensitive S5 and S11 photomultiplier tubes inhibited widespread use of *RI* photometry.

All this changed with the development of the multialkali extended-red response photomultiplier (S25) and, more importantly, the GaAs photomultiplier tubes.

These tubes, which were more sensitive than 1P21s, also had high gain, low dark current, and were very reliable. For the first time wide-band photomultiplier tubes were available that enabled observations from *U* to *I* to be done with the same detector (Bessell 1976). Many people took advantage of this (for example, Fernie 1974, Canterna 1976, Eggen 1977, Weis 1981, Sandage 1997), but it was Cousins (1976) who revolutionized broad-band photometry by providing lists of extremely precise photometric standards showing that low precision per se was not associated with broad bandpasses.

The precise Southern Hemisphere *E* and *F* region *UBVRI* standards were an excellent representation of the Johnson *UBV* system and related linearly to the Kron *RI* system. Cousins (1980a,b) also provided photometry of more northern stars and stars covering a wider range of temperature and luminosity useful as secondary standards. Using the Cousins primary and secondary *VRI* standards, Landolt (1983) set up *UBVRI* photometric standards around the equator thus opening up the northern hemisphere to accurate *UBVRI* photometry. Unfortunately, the *U* and *B* filters available to Landolt (1973, 1983) were not as good a match to the Johnson system as those used by Cousins, resulting in some systematic differences in some colors between the Landolt and Cousins *UBVRI* systems, especially for reddened *A* stars (Menzies et al. 1991).

CCDs have now almost completely replaced photomultiplier tubes as the photometric detectors of choice. This has resulted in some complications for photometry. As most of the passbands of intermediate band standard systems are defined by interference filters, their use for off-axis imaging puts more stringent conditions on both the interference filters' construction and the camera optics to ensure that the same passband and image quality are provided across the field. In the case of broad-band imaging using colored glasses, the uniformity of passbands is generally not the issue but rather the requirement to mimic the standard photoelectric passbands as closely as possible. This has generally been successfully accomplished except for the *U* band where large differences between CCDs make it very difficult to achieve a good match (Bessell 1995, Sung & Bessell 2000). Landolt (1992) extended his standard photometry to close groups of stars suitable for CCD imaging, and Stetson (2000) provided homogeneous CCD *BVRI* data for more than 15,000 standard stars based on the Landolt standards.

The transition from photomultiplier tubes to CCDs is almost complete. It is very difficult now to find an observatory that still supports photoelectric photometry for visitors. The downside of this transition has been a lowering of the photometric accuracy, in particular for standardized photometry. This is due to several effects—passband mismatches, lack of faint standards suitable for CCDs, lack of standards with a good range of color, and reluctance of observers to observe many individual standards because of slow readout times of CCDs. All these problems are being addressed. More care is now taken with passband matching, new secondary standards appropriate for CCDs are being established and, with the availability of CCDs capable of being readout in 10–20 seconds, there is nothing to inhibit taking short exposures of many individual standard stars.

1.5.2. INFRARED WAVELENGTHS The detector revolution has been even more dramatic for IR astronomy. Commencing in the 1960s with single-element, high dark-current detectors—PbS photocells, InSb photovoltaic and Ge bolometers—pioneering work was done by Johnson (Johnson 1962, 1966; Johnson & Mendez 1970), Glass (Glass 1973, 1974) and Spinrad & Wing (1969). The last 10 years have seen a rapid advance in the fabrication of large 2D focal plane arrays in IR-sensitive semiconductors. These photon detection devices have read noises approaching those of optical CCD systems (8–15 e) and dark-current levels between 0.1 and 1 e/sec. A useful summary of 2D detector development is given at http://www.nomic.net/ ∼tplagge/norton-arrays.pdf. The original arrays were developed for military applications, but much of the latest IR detector development is underwritten by NASA for future space and ground based large telescope instrumentation (http://irtek.arc.nasa.gov/ARCS&T.html). Details of the latest IR technologies are given in http://www.rockwellscientific.com/imaging/products.html and http://www.raytheon.com/products/astronomy_sensors/.

The main IR standard photometry system is the Johnson-Glass *JHKLMN* broadband system, devised to measure the integrated flux in windows in the Earth's atmosphere away from the H_2O absorption. A summary of the Johnson-Glass broad-band system was given by Bessell & Brett (1988). The original *K* bandpass has been modified in an attempt to minimize the sky and telescope emission in the original band (Wainscoat & Cowie 1992), while problems associated with residual atmospheric absorption in all bands have been addressed by Young, Milone & Stagg (1994) and Simons & Tokunaga (2002) by designing new bandpasses. Not only will the new bands permit more accurate photometry but they will enable better extrapolation for outside-atmosphere magnitudes. Standards in the new *MKO*-IR bands are given by Hawarden et al. (2001) (*JHK*) and Leggett et al. (2003) ($L'M'$).

Space-based instruments have made remarkable contributions to the IR observations of stars and galaxies. Dedicated experiments, such as *Infrared Astronomical Satellite* (IRAS), *Infrared Space Observatory* (ISO), and *Midcourse Space Experiment* (MSX), have explored mainly at very-long wavelengths inaccessible or barely accessible from the ground. The KAO (Kuiper Airborne Observatory) similarly has concentrated on the longest wavelengths. The HST does near-IR imaging with NICMOS (near infrared camera and multi-object spectrometer) and the *Spitzer Space Telescope* (formerly SIRTF) is doing 2–30 μ wavelength IR imaging with large-array detectors and 3–700 μ imaging and spectroscopy with small-array detectors.

2MASS (Two Micron All Sky Survey) (*JHK*) (http://www.ipac.caltech.edu/2mass/overview/about2mass.html) and DENIS (Deep Infrared Survey of the Southern Sky) (*iJK*) (http://www-denis.iap.fr/presentation/presentation.html) are two ground-based surveys that are providing a wealth of photometric data on stars and galaxies. The limiting magnitudes of the surveys are: 2MASS—*J*: 15.8, *H*: 15.1, *K*: 14.3; DENIS—*i*: 18.5, *J*: 16.5, *K*: 14.0.

Martin Cohen and collaborators have made immense contributions to the photometric calibrations of all the IR space experiments as well as to ground-based

IR spectrophotometry and imaging (e.g., Cohen et al. 1992a,b, IRAS; Schaeidt et al. 1996, ISO; Fouquét et al. 2000, DENIS; Cohen, Wheaton & Megeath 2003, 2MASS; Cohen et al. 1999, IR spectrophotometric standards; Cohen et al. 2003, stellar calibration in the IR).

1.6. Synthetic Photometry

Synthetic photometry is the name given to magnitudes and colors derived by convolving model atmosphere fluxes or observed spectrophotometric fluxes with standard passbands. Synthetic photometry is discussed by Cousins & Jones (1976), Buser (1986), Straižys (1996), and Cohen et al. (1996). The passband or response function of a standard system is normally obtained by multiplying together the filter transmission, the reflectivity of the telescope mirror, the transmission of the camera optics, and the quantum efficiency of the detector used. For ground-based work, this should then be multiplied by the transmission of the Earth's atmosphere for an airmass of (at least) 1.0. Generally, the atmospheric correction is usually only done for broad UV bands like *U*, where the extinction is large and varies significantly across the passband, and for the far-red and IR bands that contain significant molecular (for example, H_2O and O_2) absorption. At other wavelengths the atmospheric extinction variation across the passband is so small that it will not cause an effective wavelength shift but only change the zeropoint. For most purposes the passbands are generally normalized rather than using the absolute values.

Most past computations of synthetic photometry convolved the f_λ spectrum of a star in energy units by the bandpass sensitivity function. That is, the energy measured across a bandpass *X* is

$$\int f(\lambda) R_X(\lambda)\, d\lambda, \quad \text{where } R_X(\lambda) \text{ is the response function of the system.}$$

But if photometry is done by counting the number of detected photons across the passband *X*, that number is

$$\int [f(\lambda)/h\nu] R_X(\lambda)\, d\lambda = \int [\lambda f(\lambda)/hc] R_X(\lambda)\, d\lambda.$$

This in essence weights the fluxes by the wavelength. The net effect is to shift the apparent effective wavelength of a passband slightly to the red. By rearranging the above equation as follows,

$$\int [f(\lambda)/h\nu] R_X(\lambda)\, d\lambda = (1/hc) \int f(\lambda)[\lambda R_X(\lambda)]\, d\lambda,$$

one sees that it is possible to modify the bandpass responses rather than modify the stellar fluxes, often making it simpler to compute.

Modern detectors are all photon-counting detectors, unlike most photomultiplier tubes that were originally used as energy integrating devices, so it is generally correct to modify the resultant passbands to account for these photon-counting observations. As noted above, it is common to use normalized response functions and to obtain the zeropoint of the synthetic photometry from the primary standard star, normally Vega or some other spectrophotometric standard with accurately known standard magnitudes and colors. The *UBVRI* system's magnitude zeropoints were set by defining Vega to have colors of zero. The V magnitude being +0.03 mag means that Vega is 0.03 mag in all bands. Where there was doubt about Vega having an IR excess beyond *K*, Sirius was used (Cohen 1998; see also Price et al. 2004). Setting the zeropoints for the *UBVRIJHKL* system is discussed in an appendix of Bessell, Castelli & Plez (1998) and by Cohen et al. 1992.

When exploring the realization of a standard system it is necessary to have a set of stars that cover a wide color range and have accurate spectrophotometry from which to derive synthetic photometry. It is best for those stars to have established standard colors and magnitudes for the system in question, but if that is not possible, then it is acceptable to compare synthetic photometry relations from observed fluxes or model atmosphere fluxes with observed relations from standard stars. That is, if exploring the synthetic Sloan Digital Sky Survey (SDSS) g band using the Vilnius fluxes (averaged spectral and luminosity types) for which one does not have SDSS photometry, one can regress synthetic g-V against synthetic *V-I* for the Vilnius stars and compare this with the observed relations for nearby unreddened Population I stars. This presupposes that the *V* and *I* passbands, in this case, are well established. One then changes the *g* passband and recomputes the synthetic magnitude until the synthetic and observed regressions agree.

2. BROAD-BAND PHOTOMETRIC SYSTEMS

The passbands of some of the various systems are shown in Figure 1. The effective wavelengths and FWHMs are given in Table 1.

2.1. The Johnson-Cousins UBVRI System

One of the earliest and most used of the standard photoelectric photometric systems is the *UBV* system. The *B* band was devised to approximate the raw photographic magnitude (less the UV), whereas the *V* band was to approximate the visual magnitude system. The *U* band provided the important additional band between *B* and the atmospheric cutoff. Perceived problems with the original system were the short-wavelength cutoff of the *U* band being provided by the atmosphere (and the glass optics of the photometer and the 1P21 glass envelope), while the long-wavelength cutoff of the *V* band was provided by the detector. This resulted in the atmospheric extinction becoming an integral part of the *U* band, and the *V* band cutoff was a function of the temperature of the photomultiplier tube and the specific photomultiplier selected. Additional problems arose as different observers used different kinds of glass filters with different thicknesses and S11 photocathodes rather than the S5 photocathode of the 1P21. The different natural systems

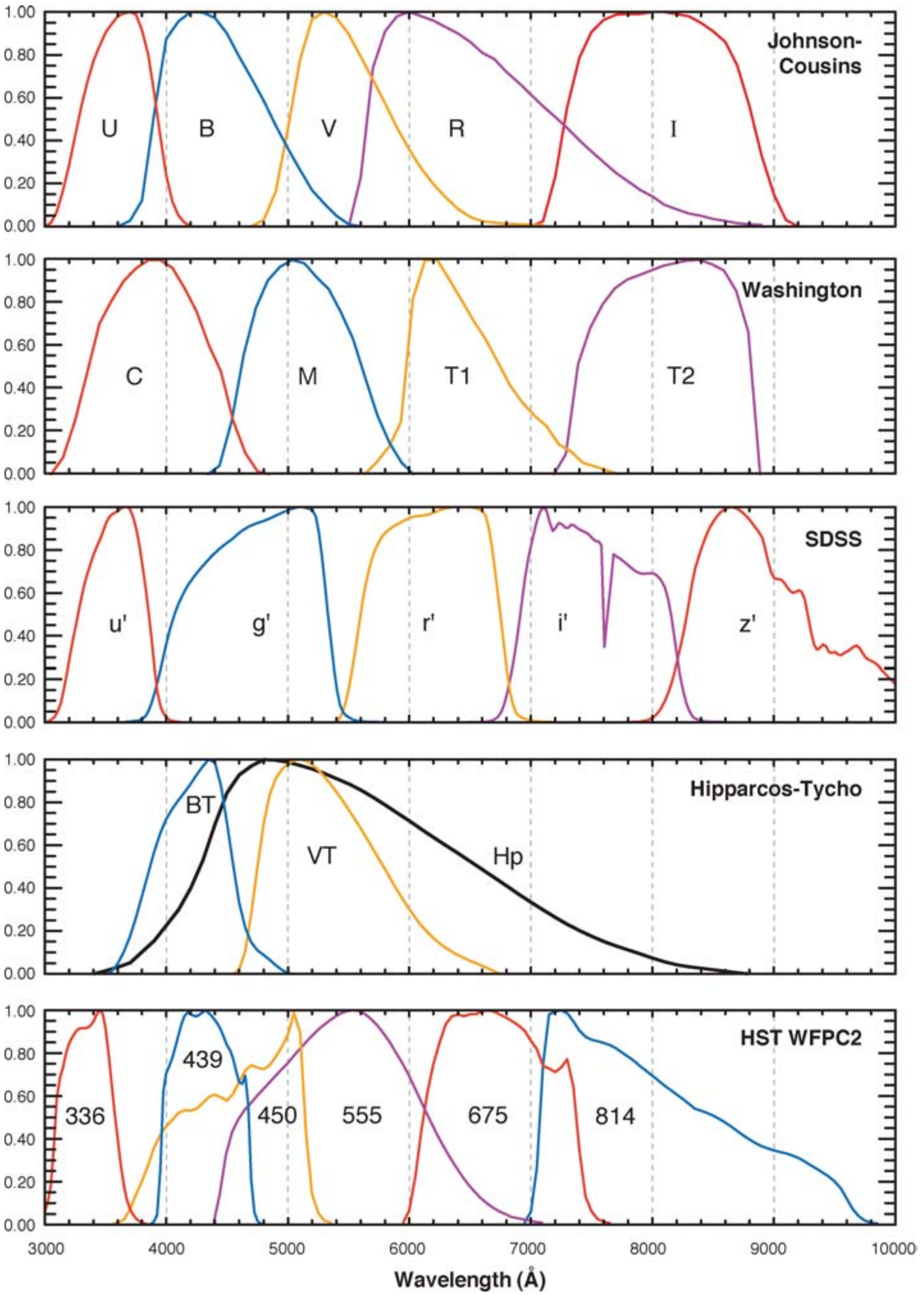


Figure 1 Schematic passbands of broad-band systems.

TABLE 1 Wavelengths (Å) and widths (Å) of broad-band systems

UBVRI			Washington			SDSS			Hipparcos			WFPC2		
	λeff	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**
U	3663	650	C	3982	1070	u'	3596	570	H_P	5170	2300	F336	3448	340
B	4361	890	M	5075	970	g'	4639	1280	B_T	4217	670	F439	4300	720
V	5448	840	T_1	6389	770	r'	6122	1150	V_T	5272	1000	F555	5323	1550
R	6407	1580	T_2	8051	1420	i'	7439	1230				F675	6667	1230
I	7980	1540				z'	8896	1070				F814	7872	1460

thus defined resulted in poor standardized photometry and systematic differences for unusual stars or for stars of a kind (such as highly reddened or metal-deficient) not represented in the standard lists.

There are good contemporary photoelectric catalogs of *UBV* standards. Cousins (1973, 1983, 1984) established accurate *UBV* photometry in the E-regions and the equatorial regions by carefully transferring the original Johnson standards to the south. Landolt (1973, 1983) independently established equatorial *UBV* standards from the Johnson standards. Cousins (1984) noted differences between contemporary northern hemisphere *U-B* systems and that of the Cape. These systematic differences need not affect derived astrophysical quantities as long as observers identify if they are using Landolt or Cousins standards. Unreddened stars can accurately be transformed between the two systems at the (generally) extreme color ranges where they differ. Menzies et al. (1991) also commented on these systematic differences resulting from different filters used and different transformation techniques. Systematic differences can be introduced into standard *U-B* and *B-V* photometry by whether or not the transformation equations use a *B-V* term instead of or as well as a *U-B* term.

The *UBV* system originated with the 1P21 and although the *B* and *V* bands have been well duplicated using redder and more sensitive detectors, the *U* band has provided difficulties. The quartz windows of many of the substituted phototubes permitted too much UV light compared with the glass envelope of the 1P21, and the effective wavelength moved too far to the UV (see Landolt 1983, figures 4, 5, 6, and 7), while most CCDs, having low UV response, often produced an effective wavelength too far to the red (Sung & Bessell 2000) when the same photoelectric filters were used. Menzies (1993) details the transformation procedures and the linear and nonlinear relations involved in converting from the natural photometry system (in *UBV* and *RI*) to the standard Cousins system at Sutherland.

There have been several attempts to realize the *UBV* passbands (Matthews & Sandage 1963; Ažusienis & Straižys 1969; Buser 1978; Bessell 1986:*U*, 1990:*UBVRI*). The agreement for *B* and *V* is good but there is still some disagreement and uncertainty associated with the *U* band, the major effect of which is to require adjustment of the *U* zeropoint for different temperature ranges (see appendix 3.1 in Bessell, Castelli & Plez 1998).

The red bands could not be measured with the 1P21, so a variety of photomultiplier tubes were used with mixed success and limited usefulness until the extended-red S20 and GaAs tubes were developed as discussed in Section 1.3. Bessell (1983) discussed in detail differences between the original Johnson *RI* system developed using an S1 phototube and later observers claiming to be observing on the Johnson system. One of the problems was the fact that Johnson published *R* and *I* passbands for his system that were about 200 Å further to the blue than indicated by the colors of stars in his catalog (Johnson et al. 1966). The low precision of many of the Johnson *RI* catalog stars made it time-consuming to observe a sufficient number of standard stars to ensure that the same standard system was defined each observing run and, as a result, it often was not.

Independently, Kron & Smith (1951), Kron et al. (1953), and Kron, Gascoigne & White (1957) established the Kron *RI* system using a Continental Electric CE25A/B tube that did not extend as far to the red as the S1 tube and, as a consequence, the *R* and *I* bands of Kron were not the same as the Johnson *RI* bands. As the extended-red S20 and GaAs tubes also did not extend as far to the red as the S1 tube, their natural photometric systems were more closely related to the Kron system. Weis (for example, 1983, 1996) developed a precise contemporary version of the Kron system using a GaAs tube (Bessell & Weis 1987). Weis' version is an excellent representation of the Eggen-Kron RI system (Eggen 1975).

Cousins (1976) established a stand-alone *RI* system in the *E*-region using the GaAs tube and noted (Cousins 1980b) that it was similar to the Kron and Eggen system for the hotter stars but diverged for the redder stars. Bessell (1979) also compared the new Cousins *VRI* system photometry with Johnson et al. (1966), Kron et al. (1953, 1957), and some other systems and provided transformations between the different systems. Bessell & Weis (1987) updated and refined the transformations between the Kron system and the Cousins system.

The Cousins system *UBVRI* standards are defined by the Menzies et al. (1989) E-region list of 570 stars with magnitudes in the range $2 < V < 11$ supplemented by the Kilkenny et al. (1998) list of stars with the most extreme blue and red colors. Landolt (1983, 1992) very usefully provided many faint photoelectric standards in small areas suitable for CCD imaging; however, it must be remembered by CCD observers that the catalog measurements refer to apertures of 14 arcsec centered on the individual stars and the same aperture (including background stars) needs to be measured with the CCD. Stetson (2000) provides homogeneous multiple CCD magnitudes in *BVRI* for all these Landolt fields including values for many additional stars. These magnitudes are based on small synthetic apertures for bright isolated stars and profile-fitting photometry (corrected by growth curves) for fainter stars or those with companions within a few arcsecs. The large deviations between some of Stetson's and Landolt's values must result from the different apertures used.

As the Johnson *RI* system is little used now, *UBVRI* normally refers to the Johnson-Cousins *UBV* system and the Cousins *RI* system. Sometimes people refer to the Johnson-Landolt *UBV* system to distinguish between the Landolt (1973, 1983, 1992) version of the *UBV* system and the subtly different Cousins E-region and equatorial version. Taylor (1986) provides transformations between many sets of *VRI* photometry.

The *VRI* passbands of Bessell (1990) are a good representation of the Cousins system. Model atmosphere temperature calibrations and bolometric corrections for the *UBVRI* system were provided by Bessell et al. (1998) and Houdashelt, Wyse & Gilmore (2000). VandenBerg & Clem (2003) provide empirical *BVRI* temperature relations. Mélendez & Ramírez (2003) recently provided an *IRFM* temperature calibration for the *RI* system. Ramírez & Mélendez (2004) also provide an *IRFM* temperature calibration for *V-K* for solar-type stars. Bergeat, Knapik & Rutily (2001) provide a temperature calibration for carbon stars.

The color *V-K* or *R-K* is probably the best color for use in determining the effective temperature of all but the hottest stars. This is particularly pertinent now that 2MASS and DENIS *K* magnitudes (see Sections 5.5 and 5.6) are available for a large number of stars. Not only is the color quite insensitive to metallicity, but the large baseline of the color means that reasonably large uncertainties in the *K* magnitude, for instance, will not greatly affect the derived temperature. For late-M and L dwarfs *I-K* is the best color to use. If near-IR magnitudes are not available, *V-I* is the best color to use. It has half the baseline of *V-K*. It should also be noted that for stars hotter than the sun, *V-I* is between two and three times more sensitive to temperature than is *b-y*.

Isochrones and evolutionary tracks in *BVRI* are provided by VandenBerg et al. (2000), Bergbusch & VandenBerg (2001), Lejeune & Schaerer (2001), and Girardi et al. (2002). Bessell, Castelli & Plez (1998) (appendix D) discuss bolometric corrections and provide the flux calibration of the *UBVRIJHKL* system (table A1). (Note that the magnitude zeropoints in Table A1 for f_λ and f_ν are erroneously reverse labelled.)

2.1.1. S20–S25–BASED VRI SYSTEMS Sandage (1997, 2001) discusses the *UBV*(*RI*) Mount Wilson photometric system derived using an extended-red S20 phototube. This *VRI* system is closely related to the Cousins *VRI* system as seen in the derived transformation coefficients, so precise astrophysically valid transformations to the Cousins system should be possible for most halo stars. Menzies (1993) discusses in detail the systematic differences that exist between a natural extended-red S20 *RI* system and the natural GaAs *RI* system with the same filters. For stars earlier than M, the transformations are single-valued and robust, but differences exist for M supergiants, M giants, M dwarfs, and carbon stars owing to the different red cutoffs of the tubes and the different strength TiO and CN bands in the stars.

2.1.2. CCD-BASED VRI SYSTEMS The *V* and *R* passbands are generally well reproduced by most CCD users, but the CCD *I* bandpass, more often than not, extends further to the red than the standard *I* band. This is because in the standard GaAs system, the cutoff of the GaAs tube defines the cutoff of the *I* band and unless this cutoff near 8800 Å is mimicked by an interference edge coating on the *I* filter, the CCD I band continues out beyond 10,000 Å. Fortunately, this does not seem to cause a transformation problem for most stars that are smooth in the far-red region, but when there are significant nongrey variations in the flux beyond the 8800 Å cutoff of the standard system, systematic differences will occur between the standard system and the natural CCD I system. The least that needs to be done is to ensure that the change in slope of the transformation equation is well defined for the latest spectral-types. Small systematic differences will also be evident for the hotter *ABF*-type stars owing to the Paschen line contribution. Photometry of emission line objects such as SN will also be a problem with even small differences in bandpasses, as seen by I band observations of SN1987a with different detectors.

The inclusion in the SDSS system of a Z band situated approximately between the cutoff of the standard I band and the cutoff of the CCD near 11,000 Å also makes it important to cut off the CCD I band with an edge coating.

2.2. The Washington CMT_1T_2 System

The broad-band Washington system of photometric standards was established by Canterna (1976) and Geisler (1990). The Washington system was devised to use the wideband sensitivity of GaAs phototubes and CCDs and makes use of the sensitivity of blue-violet colors to metallicity and gathers more violet light in cool stars. Most of its colors can be well transformed into related colors in the Cousins *BVRI* system; some transformations were given in Bessell (1992). An empirical abundance calibration was originally provided by Geisler (1986), and a revised calibration of the system was given by Geisler, Claria, & Minniti (1991). Bessell (2001) revised the passbands of the Washington system and computed theoretical colors using the Castelli (1999) model atmospheres of Kurucz. The Washington system, supplemented by the DDO 51 filter, is being used in the Spaghetti Survey (Morrison et al. 2000, 2001; Dohm-Palmer et al. 2000) to identify and measure the distances and abundances of K giants. Isochrones are provided by Girardi et al. (2002).

2.3. The Sloan Digital Sky Survey ugriz System

This revolutionary project, by providing an unprecedented database of photometric observations of stars and galaxies, has essentially made its bandpasses the de facto standard for all future photometric surveys and most future photometric imaging. Much effort is going into calibrating the SDSS system and providing transformation to other systems for particular kinds of stars. Two data releases have been made (Abazajian et al. 2003, 2004) and although the final SDSS system passbands are still to be determined, preliminary passbands—labelled u', etc. (http://home.fnal.gov/dtucker/ugriz/index.html)—enable synthetic photometry to be done and isochrones in SDSS magnitudes and colors to be computed (Girardi et al. 2004).

The original g,r,i,z passbands were produced by using Schott GG, OG, and RG glasses to define the blue edges and a multilayer interference edge coating to provide the red edge. Sets of nominally identical filters were also made for use on other telescopes to provide calibrating standards. Unfortunately, the Survey telescope filters were used in a vacuum and the layers in the interference filter coatings shrank slightly, shifting the red edge blueward by an amount approximately 1% of the wavelength (50–100 Å). The set of filters provided for the U.S. Naval Observatory (USNO) 1m telescope and used for the standards were not stored in a vacuum and did not suffer the same shifts, however this means that the two systems are not identical and the consequences of this are being reviewed. The 158 standard stars that define the $u'g'r'i'z'$ photometric system are given by Smith et al. (2002) together with transformations between the SDSS system and *UBVRI*. The revised absolute flux distribution of the fundamental SDSS standard $BD + 17°4708$ is given by Bohlin & Gilliland (2004).

In some ways it is unfortunate that the SDSS bandpasses were chosen basically to provide photometric redshifts for galaxies, rather than to isolate relevant stellar absorption features in particular bands or to match existing broad-band systems. It is also unfortunate that the SDSS bandpasses have been altered by the red edges shifting blueward from their designed placement, as this will cause uncertainty as to whether others should copy the originally specified SDSS bandpasses or the actual shifted bandpasses.

While considering that question, it is also pertinent to consider modifying the ultraviolet and blue-green bands for stellar photometric purposes by placing the UV band below the Balmer Jump (like the Strömgren *u*) and by introducing a violet band sensitive to metallicity in cool stars and hydrogen lines in hot stars (like the DDO 38 band or the Walraven L band). For higher velocity resolution of nearby galaxies it would also be useful to break the *g* band into two.

2.4. The Hipparcos-Tycho $H_pB_TV_T$ System

The European Space Agency's (ESA) Hipparcos mission provided parallaxes of unprecedented precision and accuracy for nearby stars and also produced exceedingly precise magnitudes for hundreds of thousands of stars (Hipparcos and Tycho Catalog: Perryman et al. 1997; Tycho2 Catalog: Høg et al. 2000).

The main Hipparcos detector was an unfiltered S20 image dissector scanner that provided the H_P magnitudes. Most stars brighter than 8.5 were measured with a precision of a few tenths of a millimagnitude. In addition, light from the star mapper area was divided by a dichroic beam splitter onto two photomultiplier tubes, providing simultaneously measured B_T and V_T magnitudes. The Tycho catalog provides magnitudes for a larger number of stars, but for the fainter stars the precision is lower than the Hipparcos catalog. For the brighter stars it is comparable. This wealth of accurately calibrated and precisely measured photometric data covers the whole sky, north and south of the equator. This enables intercomparison of many of the ground-based standard photometric systems and a search to be made for systematic differences with right ascension and declination.

The Hipparcos catalog provided tables and equations for relating Johnson-Cousins *B* and *V* magnitudes with H_P, B_T, V_T based on pre-flight calibrations. However, Bessell (2000) discovered small systematic differences between these tables and values measured using precise *E*-region stars. The catalog passbands were adjusted slightly until synthetic photometry indicated a good match to the observations. The biggest effect was for the H_P passband, which seemed to require a significant redward shift to the blue edge of the bandpass. The Hipparcos spacecraft suffered on-going damage from regular passage through the Van Allen radiation belts, which must have affected the detector response. The redward shift of the blue edge of the H_P passband to fit the observations may be an oversimplification of the actual damage but is an acceptable fix until more information is available. Grenon (M. Grenon, 2002, private communication) considered the complete loss of sensitivity as adopted was unlikely and favored a more complicated depression of the blue.

Platais et al. (2003) discuss *V-I* colors and issues concerning the Hipparcos and Tycho data for very red stars, in particular the carbon stars.

2.5. The HST WFPC2 160w, 336, 439, 450, 555, 675, 814 System

WFPC2 has 38 filters comprising 18 broad-band, 5 intermediate-band, 13 narrow-band (mostly for emission-line work), and two long-pass red filters. Five of the broad bands, F336W, F439W, F555W, F675W, and F814W, were designed to be closely related to the *UBVRI* bands. The system was calibrated from the ground before the flight and regular in-flight observations of standards are made. Holtzman et al. (1995) present an in-depth analysis of the WFPC2 photometric bands, their zeropoints and transformations to the *UBVRI* system. Details of the synthetic photometric comparisons are shown. However, the authors caution users of the danger of transforming WFPC2 magnitudes onto the *UBVRI* system for stars that are not representative of those for which the standardization transformation equations were derived. They also suggest caution with respect to reddening corrections.

The synthetic photometry comparisons indicate good agreement except for F336W and *U*, where there were significant deviations for hot stars. They suggested that the *U* bandpass was probably at fault rather than F336W. Synthetic photometry has been computed using the Vilnius (Straižys & Sviderskiene 1972) and Pickles (1985) spectrophotometric catalogs with the F336W passband from the WFPC2 Web site and the UX90 passband from Bessell (1990). The agreement was much closer (within 0.1 mag) with this *U* bandpass than that used by Holtzman et al. (1995) (0.4 mag), but the character of the AB star deviations could only be duplicated by shifting the F336W bandpass about 100 Å to the red. Adjusting the *U* bandpass could not effect the required change. However, for ground-based work the atmosphere greatly affects the effective F336W passband compared to that in space; consequently the ground-based tests are probably not indicative of the true bandpass.

Figure 2*a* shows the synphot passband (*magenta line*) and the modified F336 band that has been bodily shifted to the red (*green line*) together with the UX90 passband (*blue line*), a modified UX90 band (*orange line*; blue edge shifted

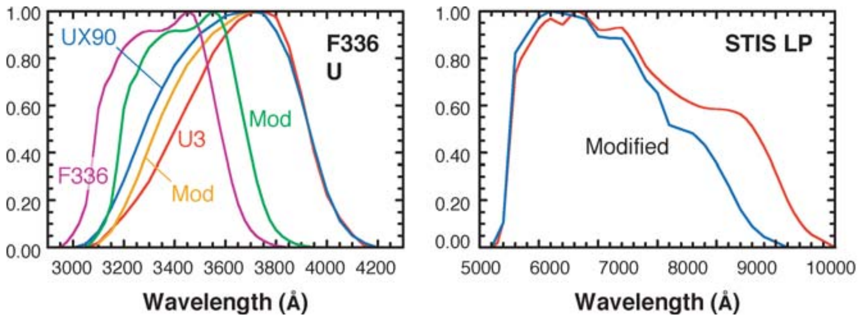


Figure 2 Schematic passbands of intermediate-band systems.

50 Å to the red), and the U3 band of Buser (1978) (*red line*) that is recommended in synphot for the *U* band. Bessell, Castelli & Plez (1998) discuss synthetic *U-B* colors based on their model atmospheres in an appendix and show that *U-B* using the UX90 passband fits the Landolt *U-B* colors reasonably well, while the synthetic Cousins *U-B* colors require a scaling of 0.96, equivalent to shifting the blue edge of UX90 by about 50 Å, as shown in Figure 2*a*.

The far UV bandpass filter F160BW is discussed by Watson et al. (1994) and Keller, Bessell & Da Costa (2000), the latter of whom also provided theoretical F160BW-F555W colors and showed the excellent temperature sensitivity of F160BW-F555W for very hot stars. Isochrones in HST bandpasses have been computed by Girardi et al. (2002).

Much information on standards and other information relevant for photometry with HST can be found on ftp://ftp.stsci.edu/cdbs/cdbs8/synphot_tables/. WFPC2 calibration data is regularly updated on the WFPC2 Web site (www.stsci.edu/instruments/wfpc2/wfpc2_resources.html). Details of the photometric zeropoints for the Space Telescope Science Institute–specified WFPC2 bands are given at http://www.stsci.edu/instruments/wfpc2/Wfpc2_dhb/wfpc2_ch52.html#1902184. It is suggested that the passbands and zeropoints for F336W should be reassessed and the *UBVRI* passbands of Bessell (1990) be used in place of the synphot-recommended *UBVRI* bands.

2.5.1. THE HST SPACE TELESCOPE IMAGING SPECTROGRAPH (STIS) *LP* BAND An arbitrary shift in the synphot *LP* bandpass was also needed to get agreement between synthetic photometry and globular cluster giant observations in F814-LP and F606-LP. This was described by Houdashelt, Wyse & Gilmore (2001) in an appendix. In 2000 Bessell trialed variations in the bandpass and an acceptable fit was obtained by suppressing the extended red tail of the band, thus effectively shifting the synphot *LP* passband beyond 8000 Å by about 80 Å to the blue. These synphot passband (*red line*) and arbitrarily modified *LP* passband (*blue line*) are also shown in Figure 2*b*. Table 2 lists the UX90, U3 and modified *U*, F336 and *LP* passbands.

TABLE 2 Modified passbands

Wave	UX90	Umod	F336mod	U3	Wave	LPmod
3050	0.016	0.000	0.000	0.000	5200	0.000
3100	0.068	0.016	0.059	0.020	5400	0.105
3150	0.167	0.068	0.182	0.077	5600	0.822
3200	0.287	0.167	0.582	0.135	5800	0.899
3250	0.423	0.287	0.732	0.204	6000	0.974
3300	0.560	0.423	0.844	0.282	6200	1.000
3350	0.673	0.560	0.896	0.385	6400	0.990
3400	0.772	0.673	0.917	0.493	6600	0.980
3450	0.841	0.772	0.918	0.600	6800	0.966
3500	0.905	0.841	0.948	0.705	7000	0.893
3550	0.943	0.905	1.000	0.820	7200	0.886
3600	0.981	0.943	0.912	0.900	7400	0.885
3650	0.993	0.981	0.658	0.959	7600	0.807
3700	1.000	1.000	0.395	0.993	7800	0.710
3750	0.989	0.989	0.185	1.000	8000	0.653
3800	0.916	0.916	0.074	0.975	8200	0.517
3850	0.804	0.804	0.029	0.850	8400	0.499
3900	0.625	0.625	0.009	0.645	8600	0.482
3950	0.420	0.420	0.000	0.400	8800	0.432
4000	0.238	0.238		0.223	9000	0.356
4050	0.114	0.114		0.125	9200	0.264
4100	0.051	0.051		0.057	9400	0.162
4150	0.019	0.019		0.005	9600	0.090
4200	0.000	0.000		0.000	9800	0.045
					10000	0.023
					10200	0.000

3. INTERMEDIATE BAND SYSTEMS

Real and perceived problems with the placement and definition of the bands in the *UBV* system led to the development of intermediate band photometric systems. Figure 3 illustrates schematically the passbands for five of the most widely used of these systems. Table 3 lists the nominal central wavelengths and full width half maximum (FWHM) of the passbands.

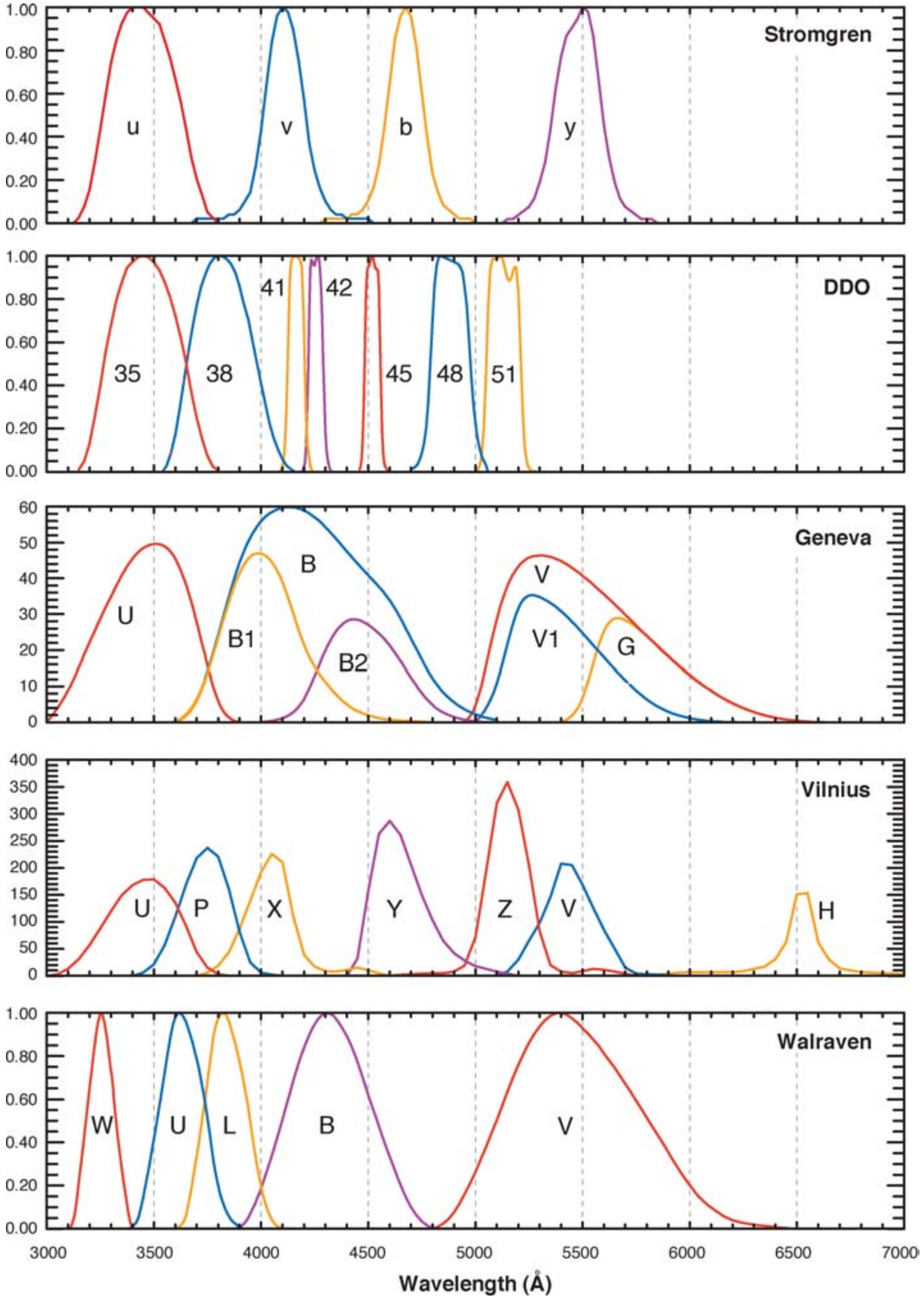


Figure 3 Modified passbands for F336, *U*, and STIS *LP* compared to the synphot passbands.

TABLE 3 Wavelengths (Å) and widths (Å) of intermediate-band systems

Strömgren			DDO			Geneva			Vilnius			Walraven		
	λeff	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**		**λeff**	**Δλ**
u	3520	314	35	3460	383	*U*	3438	170	*U*	3450	400	*W*	3255	143
v	4100	170	38	3815	330	*B*	4248	283	*P*	3740	260	*U*	3633	239
b	4688	185	41	4166	83	*B*1	4022	171	*X*	4050	220	*L*	3838	227
y	5480	226	42	4257	73	*B*2	4480	164	*Y*	4660	260	*B*	4325	449
β_w	4890	150	45	4517	76	*V*	5508	298	*Z*	5160	210	*V*	5467	719
β_n	4860	30	48	4886	186	*V*1	5408	202	*V*	5440	260			
			51	5132	162	*G*	5814	206	*S*	6560	200			

3.1. The Strömgren Four-Color *uvby* System

The system was specifically devised by Strömgren (1951) for B, A, and F stars, although it was extended later to other kinds of stars. Several indices are derived: $m_1 = (v\text{-}b)\text{–}(b\text{-}y)$ to measure the depression owing to metal lines around 4100 Å, $c_1 = (u\text{-}v)\text{–}(v\text{-}b)$, which measures the Balmer discontinuity, and $\beta = \beta_w - \beta_n$ to measure the strength of the $H\beta$ line.

Reddening independent indices [m_1] and [c_1] are also often used (Strömgren 1966). The *y* magnitude is defined to be essentially the same as *V* for non-M stars and *b-y* is a color like *B-V* but less sensitive to metallicity. Surprisingly, *b-y* also transforms extremely well to *V-I*. From all the E-region stars Cousins (1987) derives

$$b\text{-}y = 0.000 + 0.481(V\text{-}I) + 0.161(V\text{-}I)^2 - 0.029(V\text{-}I)^3$$

$$V\text{-}I = -0.002 + 2.070(b\text{-}y) - 1.113(b\text{-}y)^2 + 0.667(b\text{-}y)^3.$$

The system has been extended to white dwarfs, K giants and dwarfs, and FGK supergiants but problems have occurred in the standardization owing to differences in filters (especially the *v* filter) and the restricted color, reddening, and spectral-type range of the original standards. Manfroid & Sterken (1987, 1992), Eggen (1976), and Olsen (1995) discuss some of these problems. Extensive photometry has been published by Crawford, Olsen, and collaborators (Gronbech & Olsen 1977; Olsen 1983, 1984, 1988, 1994; Olsen & Perry 1984; Perry, Olsen & Crawford 1987). The Hauck & Mermilliod (1998) homogenized catalog contains data for 63,313 stars and is available through the VizieR interface as are other *uvby* catalogs.

Some of the transformation problems have also arisen from the initial prescriptions of photometric reduction procedures. Rather than standardizing the basic bands *u*,*v*,*b*,*y* or the colors *u-v*, *v-b*, users were instructed to standardize the derived quantities m_1 and c_1 along with *b-y*. Because few standard stars have extreme values for m_1, it was impossible to properly determine secondary color terms. In the case of c_1, nonstandard *v* filters resulted in systematic differences between B and F stars with the same standard c_1 value. Cousins (1986, 1987, 1989, 1990) established excellent secondary standards in the E-regions by standardizing the intermediate colors *u-v*, *v-b* and *b-y* directly. Ironically, CCD observations and data reductions are forcing more scientific standardizing procedures based on the individual bands (Grundahl, Stetson & Andersen 2002) so better standardized Strömgren photometry can be expected in the future.

Although the transformation problems discussed above have made it difficult to define the *uvby* system precisely for all spectral types and luminosity classes, a subset of the published photometry has been made with tightly controlled instrumental systems and a restricted set of photometric standards by Schuster and Nissen and their collaborators (Schuster & Nissen 1988; Schuster et al. 2004). These observations have been made on the 1.5 m telescope at the Observatorio Astronómico Nacional at San Pedro Mártir, Baja California, México, and on the Danish 1.5 m telescope, at La Silla, Chile, using simultaneous *uvby/Hβ* photometers with the bandpasses defined by spectrograph exit slots combined with interference filters (Nielsen 1983). From these data it should be possible to realize the current standard uvby system and compute theoretical *uvby* colors for all stars. The precise Strömgren CCD photometry of Grundahl, Stetson & Andersen (2002) indicates that good standard *uvby* photometry is possible using CCDs and good standards. However, they note from their standard star comparisons an increased scatter for the *u* and *v* filters owing to the bands of CN and NH in some stars and the slightly different passbands of the Schuster & Nissen photoelectric system and the CCD system.

Theoretical Strömgren colors for a grid of model atmospheres have been calculated by Clem et al. (2004) using the original filter passbands of Crawford & Barnes (1970). No adjustments to the raw colors were made. Rather than use these passbands, I suggest that it is better to use the passbands of Helt, Florentin Nielsen & Franco (1987) which seem identical to those used by Schuster at San Pedro Mártir and on which the uvby system for metal-deficient stars is now based. The normalized and smoothed response functions, including atmospheric extinction, are given in Table 4. These passbands need small color terms to realize the *uvby* system, similar to those given by Schuster & Nissen (1988) (Table 1). The exact color terms are currently being assessed using MARCS models.

Empirical calibrations for color excesses, E(*b-y*), photometric metallicities, [Fe/H], and absolute magnitudes, M_V, are provided by Schuster & Nissen (1989) and Nissen & Schuster (1991) and reviewed by Nissen (1994). Arellano Ferro et al. (1990) provide a catalog of F-K supergiants photometry. Gray & Olsen (1991) also discuss the calibration of the Strömgren system for A, F, and G supergiants. Reddening is often better measured through uvby photometry than *UBV* photometry, although for O and B stars the *UBV* reddening-free Q index [$Q = (U\text{-}B) - 0.82(B\text{-}V)$; $(B\text{-}V)_0 = Q/3$] is still a powerful tool.

TABLE 4 Passbands of the *uvby* system (including atmosphere)

Wave	*u*	Wave	*v*	Wave	*b*	Wave	*y*
3320	0.000	4000	0.000	4560	0.000	5340	0.000
3340	0.349	4020	0.427	4580	0.304	5360	0.389
3360	0.492	4040	0.754	4600	0.576	5380	0.672
3380	0.581	4060	0.884	4620	0.906	5400	0.912
3400	0.687	4080	0.979	4640	0.994	5420	1.000
3420	0.789	4100	0.995	4660	1.000	5440	0.982
3440	0.835	4120	1.000	4680	0.969	5460	0.953
3460	0.879	4140	0.996	4700	0.921	5480	0.913
3480	0.926	4160	0.942	4720	0.871	5500	0.850
3500	0.960	4180	0.742	4740	0.864	5520	0.798
3520	0.982	4200	0.440	4760	0.804	5540	0.759
3540	0.992	4220	0.219	4780	0.522	5560	0.725
3560	1.000	4240	0.000	4800	0.186	5580	0.631
3580	0.996			4820	0.000	5600	0.424
3600	0.991					5620	0.213
3620	0.973					5640	0.000
3640	0.934						
3660	0.816						
3680	0.356						
3700	0.000						

Although the *uvby* system is well established and well calibrated empirically, it does require high precision photometry, generally better than 0.01 mag, to deliver precision in the derived temperatures, gravities, and metallicities. Broad-band *V-I* or *V-K* can provide temperatures with 3 or 6 times (repectively) greater sensitivity in the color than *b-y*, and for the metallicity indicator in GK stars, the Washington *C-M* or *C-V* index or the DDO/Cousins 38-V color is also more sensitive than m_1. For that reason, as well as for reaching fainter magnitudes in a given time, when CCD observations are to be undertaken, it is often advantageous to measure broad band and wider baseline colors rather than *uvby*.

3.2. The DDO 35, 38, 41, 42, 45, 48 System

Another very useful intermediate band system is the DDO system that was devised to work principally with GK giants and dwarfs. Because it has not been used as a general photometric system, the standard system is robust and well established (McClure 1976, McClure & Forrester 1981, Cousins 1993, Cousins & Caldwell 1996). An homogenized catalog of 6139 stars was prepared by Mermilliod

& Nitschelm (1989). The 35 filter is the same as the Strömgren u; the 38 filter is more sensitive to metal-line blanketing than the Strömgren *v* filter; the 41 filter measures the CN band; 42, 45, and 48 are pseudo-continuum filters; and the 51 filter measures the MgH feature in KM dwarfs. The color 35-38 (the 3538 index) measures the Balmer jump; 3842, the metallicity; 4245 and 4548 are used for gravity and temperature measurements; and 4851 separates K dwarfs from K giants. Combining some of the DDO magnitudes or indices with broad-band magnitudes such as R-I or M-51 (Geisler 1984) has proved very effective for metallicity estimates and halo GK giant selection (Norris, Bessell & Pickles 1985; Morrison et al. 2001), especially for faint stars.

Recent calibrations of temperatures and metallicity are given by Piatti et al. (1993); Claria, Piatti & Lapasset (1994); Claria et al. (1994); Claria, Piatti & Osborn (1996); and Mélendez & Ramirez (2003) [IRFM (infrared flux method) temperatures]. Absolute magnitude calibrations are discussed by Høg & Flynn (1998).

3.3. The Geneva ($UBB_1B_2VV_1G$) System

The best known of the closed photometric systems, the Geneva system, is supervised by a small group at the Geneva Observatory. VizieR contains the updated version of the 29,397 stars in the Geneva Catalog (Rufener 1999); the Lausanne photometric database contains data for 43,931 stars (http://obswww.unige.ch/gcpd/ph13.html). In practice, three colors, U-B_2, B_2-V_1, and V_1-G, are used together with linear combinations that are reddening free for a standard extinction law and E(B-V) < 0.4 mag (Golay 1972). The combination indices are $\mathrm{d} = (U\text{-}B_1) - 1.430(B_1\text{-}B_2)$, $\mathrm{F} = (U\text{-}B_2) - 0.832(B_2\text{-}G)$, $\mathrm{g} = (B_1\text{-}B_2) - 1.357(V_1\text{-}G)$, and $\mathrm{m}_2 = (U\text{-}B_1) - 1.357(V_1\text{-}G)$. The indices d and m_2 are closely related to the [c_1] and [m_1] indices of the Strömgren system. Nicolet (1996) has derived the natural system's passbands. Kunzli et al. (1997) provide a model atmosphere calibration for Geneva photometry. Mélendez & Ramirez (2003) have provided an IRFM temperature calibration for the Geneva system.

3.4. The Vilnius (UPXYZVS) System

The Vilnius system was developed independently from the Geneva system but for similar reasons, namely, to derive temperatures, luminosities, and peculiarities in reddening and composition from photometry alone (Straižys 1979). The colors are normalized by the condition $U\text{-}P = P\text{-}X = X\text{-}Y = Y\text{-}Z = Z\text{-}V = V\text{-}S$ for unreddened O-type stars. Therefore all colors for normal stars are positive. Reddening free indices are constructed as for the Geneva and Strömgren systems.

Straižys, Boyle & Kuriliene (1992) and Boyle et al. (1996) discuss transformations between the CCD and standard Vilnius system. Standard stars for CCD photometry are given by Cernis et al. (1997), and a photometry catalog of 7445 stars observed in the Vilnius system is given by Straižys & Kazlauskas (1993). Straižys et al. (1993b) provide a new calibration for temperature and gravity of B stars updated by Straižys, Kazlauskas & Bartasiute (1999). Mélendez & Ramírez

(2003) provide IRFM temperatures for the Vilnius system. Forbes, Dodd & Sullivan (1993, 1997) have established Southern Hemisphere E-region standards. Philip et al. (2003) and Kazlauskas et al. (2003) discuss the seven-color Stromvil system.

3.5. The Walraven WULBV System

The most interesting of the closed photometric systems is the Walraven system. Theodore Walraven and Gerry Kron are two of the most underappreciated contributors to accurate astronomical photometry who made innovative instruments and ground-breaking experiments with detectors. The Walraven photometer (Walraven & Walraven 1960) is a specially-built simultaneous photometer with the passbands defined by a special filter of crystalline quartz and Iceland spar (calcite) polarization optics and separated geometrically by a quartz prism spectrograph. The *L* band is taken from a beam that does not pass through the spectrograph. This innovative technique provides great stability of passbands that enabled Pel (1991) to discover small systematic errors in four other photometric systems, a feat that was not possible with any other ground-based systems. Used at the Leiden Southern Station in South Africa until 1979, the photometer was moved to the Dutch Telescope at La Silla in 1979 (Pel, Blaauw & Trefzger 1988). Much of the work in the *VLBUW* system has been on cepheids and RR Lyrae stars (Pel 1985) and halo stars (Pel, Blaauw & Trefzger 1988; Trefzger, Pel & Gabi 1995).

The properties of the system are described by Lub & Pel (1977). Calibrations of Teff, log g, and [Fe/H] for F-G stars are given by Trefzger, Pel & Gabi (1995), who estimate precisions of 50 K in Teff and 0.1 dex in [Fe/H] and log g from Walraven photometry.

4. NARROW-BAND PHOTOMETRIC SYSTEMS

4.1. The Oke AB Magnitude System

The Oke spectrophotometric system is specified on a relative absolute (AB) flux scale, $AB = -2.5 \log F\nu + 48.60$ (Oke 1965, Oke & Gunn 1983). The system is based on the absolute flux of α Lyrae. There were some uncertainties concerning standard lamps and horizontal extinction correction in the earliest measurements of the absolute flux of α Lyrae (Hayes, Oke & Schild 1970; Tüg, White & Lockwood 1977). The original standards were a set of bright A and B stars (Oke 1964) with measurements made over 50 Å bands at 30 wavelengths between 3390 Å and 10,800 Å avoiding the hydrogen lines. These were later supplemented by fainter FG subdwarfs and white dwarfs (Oke & Gunn 1983, Oke 1990) measured over 40 Å bands at 68 wavelengths between 3080 Å and 12,000 Å.

A significant impetus for the initial Oke spectrophotometric system was the provision of theoretical model atmosphere fluxes by Mihalas (1965a,b), which offered the prospect of the derivation of temperatures and gravities from the observed energy distributions of stars. At the time it seemed impossible to obtain this quantitative information with sufficient precision from existing photometric systems. The restricted wavelength response of photographic emulsions and severe difficulties of extracting relative absolute quantitative information from photographic spectra also contributed to the development of photoelectric spectroscopy.

This initial enthusiasm faded somewhat as the rapid development of the Strömgren intermediate band system and the provision of empirical and theoretical calibrations provided quantitative astrophysical data for A and B stars, thus undermining one of the reasons for obtaining energy distributions. In addition, because specialized instrumentation was required for photoelectric spectrophotometry, it was restricted to bright stars with single-channel systems or to only a few observatories with expensive multichannel systems. However, there has been a renaissance in spectrophotometry with the provision of two-dimensional detectors on spectrographs. Originally restricted to those observatories with two-dimensional photon counting systems such as the Image Dissector Scanner (IDS) (Robinson & Wampler 1972), Image Photon Counting System (IPCS) (Boksenberg 1977), and Photon Counting Array (PCA) (Schectman 1984), the introduction of low noise CCD systems on all spectrographs these days means that every spectrograph is now capable of accurate spectrophotometric observations.

Spectrophotometric catalogs have been published by several authors (Breger 1976, Burnashev 1996). The latest standard catalogs provide fluxes with a continuous wavelength coverage. One of the more useful recent lists of spectrophotometric standards are those of Hamuy et al. (1992, 1994). Bessell (1999) discusses removal of the atmospheric features from the Hamuy standards and other techniques to enable better flux calibration.

Several astronomers have provided digital spectral atlases for individual or averaged spectra for a range of spectral and luminosity classes. These are very useful for synthetic photometry: Straižys & Sviderskiene (1972); Bartkevicius & Sviderskiene (1981); Gunn & Stryker (1983); Jacoby, Hunter & Christian (1984); Pickles (1985); Silva & Cornell (1992); Danks & Dennefeld (1994); Knyazeva & Kharitonov (1996). Valiauga, Vansevicius & Straižys (1996) describe some intercomparisons, and Taylor & Joner (1990) outline some systematic corrections to the Gunn-Stryker data.

4.2. The Wing Eight-Color System

A very important far-red narrow-band system was developed by Wing to investigate late-type stars, especially M stars and carbon stars (Wing 1967, Wing & White 1978, White & Wing 1978, Wing & Yorka 1979). The eight-color system measured magnitudes with 40–70 Å bandpasses at specific far-red wavelengths to define pseudo-continuum colors, together with TiO, VO, and CN band indices or depressions. It provides an excellent quantitative framework for MK spectral and luminosity classes for M giants, supergiants, and dwarfs. An additional passband at 6880 Å to measure CaH is also very useful for identifying KM dwarfs and subdwarfs (Mould & McElroy 1978). Lists of standard KM giants and supergiants were provided by Wing (1978, 1979). Wing (RF Wing 1979, private

TABLE 5 Characteristics of the Wing bands

Band	λ_{eff} Å	FWHM Å	Primary function	Contaminant
	6880	60	CaH, KM dwarfs	
1	7120	60	TiO $\gamma(0,0)$	CN
2	7540	50	Continuum, K4-M6	wk CN
3	7810	40	Continuum, G,K,C	TiO M
4	8120	50	CN $\Delta\nu = +2$	wk TiO
	9910	50	FeH, late M dwarfs	
5	10395	50	Continuum, all	
6	10540	60	VO	
7	10810	60	Continuum	HeI
8	10975	70	CN (0,0)	

communication) also provided data for 56 standard M dwarfs as measured by Wing & Dean.

Table 5 lists the Wing bands and their functions. Originating as selected passbands from the 27-color photoelectric scanner program (Wing 1967), the eight-color system was developed using interference filter–defined passbands with S1 and GaInAsP phototubes.

In the Wing system, the continuum level is defined by fitting a Planck function to bands 2 and 5. This also defines the color temperature. The TiO $\gamma(0,0)$ band index D1 is then defined as the depression in magnitudes of band 1 below the continuum level at that wavelength. Similar indices are defined for the other molecular features measured. Wing used the TiO D1 index as a proxy spectral type and correlated it against the Keenan K and M spectral-type standards (Keenan & McNeil 1995, Keenan & Barnbaum 1999). Because D1 is a continuous variable, the spectral type derived from D1 should also be continuous, so Wing further divided his spectral-type divisions, which resulted in spectral types such as M3.3.

Observations of the bands and continuum colors were used to derive abundances for metal-rich globular clusters (Mould & Siegel 1982) and for studies of M supergiants (White & Wing 1978). More recently, Wing's quantitative spectral types and band indices provided invaluable calibration of observations of Magellanic Cloud M giants and miras (Wood, Bessell & Fox 1983) and M dwarfs (Bessell 1991) using IDS and CCD spectrophotometry.

5. INFRARED STANDARD SYSTEMS

5.1. Introduction

The subject of IR standard systems and IR flux calibration deserves a separate review and can only be briefly covered here. Advances in IR technologies over the past 10 years or so have brought near-IR photometry and spectroscopy to the same magnitude limits and observational limitations as the optical. Ground-based adaptive optics techniques have opened up the near-IR and the mid-IR to higher spatial resolutions than in the optical, and space-based missions have provided unprecedented mid-IR flux calibrations and mid- and far-IR sky surveys of the obscured parts of the Milky Way and the inner parts of external galaxies. The all-sky 2MASS (*JHK*) and southern sky DENIS (*iJK*) surveys have stimulated the study of the astrophysics of brown dwarfs and low mass stars, as well as red giant temperatures and galaxy luminosity functions. The United Kingdom Infrared Telescope (UKIRT) Infrared Deep Sky Survey is planned to extend the SDSS (*iz*) and 2MASS (*JHK*) surveys to fainter magnitudes and with higher precision.

5.2. Infrared Spectrophotometry

Pioneering work by Cohen, Walker & Witteborn (CWW; 1992) and their collaborators (Cohen et al. 1992, 1995, 1996) provided primary and secondary star IR spectrophotometric fluxes based partly on model atmosphere flux calibrations of Vega and Sirius. The spectral templates between 1.2 and 35μm (Cohen et al. 1999, 2003) have been confirmed between 4 and 24μm by the spectacularly successful MSX flux calibrations of Price et al. (2004) that also verified the CWW adopted fluxes for Vega up to 4 μm and measured Vega's IR excess at 12, 15, and 21 μm of $\sim$4%, 4%, and 17%, respectively, from a cool dust disk. The MSX calibration experiment confirms the scale of zero magnitude fluxes proposed by Cohen et al. (1992) but points to the need to slightly brighten their adopted fluxes for Sirius by 1%, within their estimated 1.46% assigned uncertainty. IR fluxes are now extremely well established and calibrated, and synthetic photometry can be used with confidence to realize IR photometric systems.

5.3. The Johnson/Glass *JHKLMN* System

The Johnson/Glass *JHKLMN* system was the original of the IR photometric systems and is related to all the broad-band systems since. Limitations with interference filter manufacture for the IR made it difficult to obtain well-matched passbands with different filter orders and manufacturers. The original bands were also wider than the atmospheric windows, which meant that atmospheric H_2O absorption defined at least part of the band with some filters, and so the passband varied at some sites with the seasons. There were also different detectors used, with different spectral responses and, as a result, there developed similar but subtly different natural *JHK* systems. Unlike in optical photometry, most observers did not use color terms when standardizing their photometry and simply applied average zeropoint corrections for each band. Bessell & Brett (1988) compared the IR systems then in use based on their bright standard lists and derived a homogenized system that was closely related to the Johnson and South African Astronomical Observatory (SAAO) systems but which had its zeropoints set by adopting Vega to be 0.03 mag in each band. Carter (1990) (SAAO) and van der Bliek et al. (1996) [European Southern Observatory (ESO)] also derived transformations between systems. The passbands of the Bessell & Brett homogenized *JHK* system together with the *I* passband of the Cousins system, the Z' passband of the SDSS system, and the K_p passband of Wainscoat & Cowie (1992) are shown at the bottom of Figure 4.

The advent of area detectors required fainter standards that were provided by Carter & Meadows (1995), SAAO (JHK: $8 < K < 10$); Persson et al. (1998), Las Campanas Observatory (LCO) (JHKK$_s$: $10 < K < 12$); Hawarden et al. (2001), UKIRT (JHK: $10 < K < 15$); and Leggett et al. (2003), Mauna Kea Obervatory (*MKO*) ($L' : L' \sim 10$; $M' : 4 < M' < 7$). Transformation equations between the different IR systems were also derived.

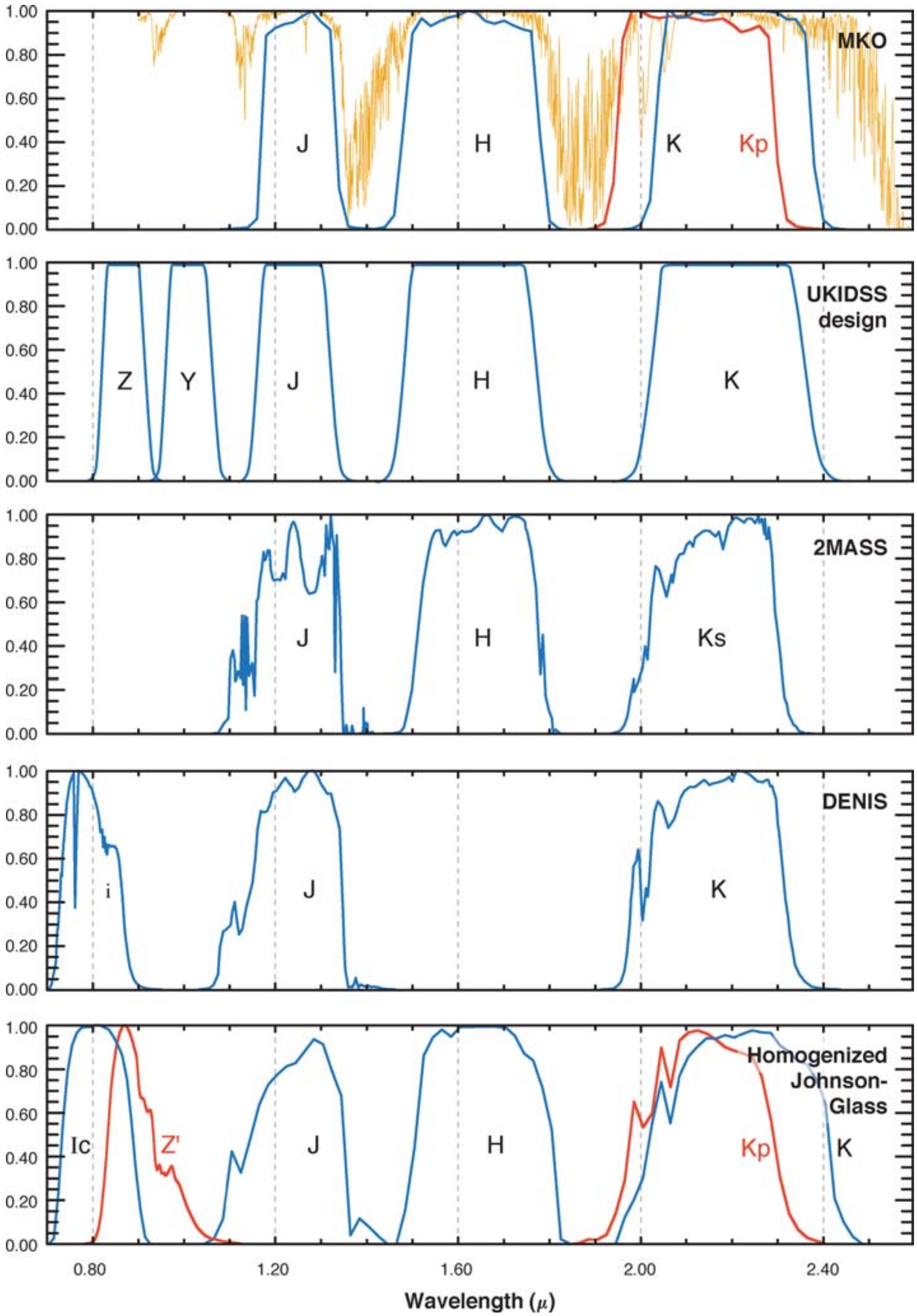
5.4. The MKO JHKL′M′ System

As mentioned earlier, the large atmospheric H_2O absorption in the edges of the original *J*, *H*, and *K* bands as well as in the center of many *J* bands led to lower precision photometry as the H_2O content of the atmosphere changed. It also resulted in large uncertainties with extrapolating to zero airmass for outside-atmosphere magnitudes for comparison with theoretical fluxes. Young, Milone & Stagg (1994) initiated the study of better-defined passbands and, finally, Simons & Tokunaga (2002) and Tokunaga, Simons & Vacca (2002) defined some optimal $JHK_s K_l L' M'$ filters that have been accepted by the community as the new standard passbands. Most observatories are now using these filters, called the *MKO*-NIR filter set. Transformations between the older UKIRT passbands and the new *MKO* bands are given at http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/phot_trans.html. Stephens & Leggett (2004) provide transformation coefficients between the *MKO* system and most other IR systems.

In Figure 4 the designed filters are shown in juxtaposition with an atmospheric transmission of near and far infrared radiation (ATRAN) (Lord 1992; Gemini Observatory) atmospheric transmission spectrum for a 1.6-mm water vapor column. The longer wavelength bands are shown in Tokunaga, Simons & Vacca (2002).

5.4.1. THE UKIDSS SYSTEM (DESIGN) UKIRT uses the *MKO* JHK_s bands together with new *Z* and *Y* bands for their Infrared Deep Sky Survey (UKIDSS) that will commence in 2005. The *Z* and *Y* band avoid the atmospheric H_2O band around 0.93–0.97 μm that affects the SDSS *Z* band and other *Z* bands that rely on the CCD response to define the red edge of the band. The UKIDSS *Z* magnitude will be very close to the SDSS magnitude. The *Y* band is centered near 1.1 μm and should be a continuum point in almost all stars.

Figure 4 Passbands and filter transmissions of IR systems. The atmospheric transmission of an ATRAN model is shown in the *top panel*. The filter transmissions only are shown for the *MKO* and UKIDSS systems. For 2MASS, DENIS, and the homogenized *JHK* system, the actual normalized bandpasses including the filters, the atmospheric transmission, camera optics, and detector responses are shown. The Cousins *I*, the Sloan Z', and the K_p bands are also shown in the *bottom panel* for comparison.


MKO
J
H
K
Kp
UKIDSS design
Z
Y
J
H
K
2MASS
J
H
Ks
DENIS
i
J
K
Homogenized Johnson-Glass
Ic
Z'
J
H
Kp
K
1.00
0.80
0.60
0.40
0.20
0.00
0.80
1.20
1.60
2.00
2.40
Wavelength (μ)

5.5. The 2MASS JHK System

This outstanding all-sky survey commenced in 1997 in the north and in 1998 in the south (http://www.ipac.caltech.edu/2mass/overview/about2mass.html). Its passbands are shown in Figure 4 (Cohen, Wheaton & Megeath 2003). The 2MASS was designed to obtain answers to questions on the large-scale structure of the Milky Way and the Local Universe but was also to provide basic data on stars and galaxies for the IR space missions, HST/NICMOS, *Spitzer*, and the *James Webb Space Telescope*. Its limiting magnitudes were J: 15.8, H: 15.1, and K: 14.3, and JHK were obtained simultaneously with three separate HgCdTe detectors. There have been two data releases so far.

Carpenter (2001) has compared the 2MASS photometry with many other IR systems and has provided color transformations for the AAO (Anglo-Australian Observatory), ARNICA (Arcetri Near Infrared Camera), CIT (California Institute of Technology), ESO, LCO (Las Campanas Observatory), MSSSO (Mount Stromlo and Siding Spring Observatories), SAAO, and UKIRT as well as the Bessell & Brett and Koorneef homogenized photometric systems. For the homogenized *JHK* system that is used for Bessell, Castelli & Plez (1998) theoretical colors,

$$(K_s)_{2MASS} = K - 0.044$$

$$(J\text{-}H)_{2MASS} = 0.980(J\text{-}H) - 0.045$$

$$(J\text{-}K_s)_{2MASS} = 0.972(J\text{-}K) - 0.045$$

$$(H\text{-}K_s)_{2MASS} = 0.996(H\text{-}K) + 0.028.$$

Ramírez & Meléndez (2004) have derived the transformation between the TCS *JHK* photometry in Alonso, Arribas, & Martínez-Roger (1994) and 2MASS. Cohen, Wheaton & Megeath (2003) in paper XIV of their series derived the passbands and carried out synthetic photometry to determine the absolute calibration of 2MASS. The 2MASS data now support the development of faint calibrators for the *Spitzer* IRAC (infrared array camera) camera.

5.6. The DENIS iJK System

The DENIS passbands are shown in Figure 4 (Fouqué et al. 2000). The instrument is used at the Cassegrain focus of the ESO 1-m telescope at La Silla Observatory (Chile). Dichroics split the three beams. The i beam passes through a Gunn *i* filter before being imaged onto a Tek CCD, the *J* and K_s beams pass through *J* and K_s filters before being imaged onto NICMOS3 HgCdTe arrays. The DENIS limiting magnitudes are *i*: 18.5, *J*: 16.5, *K*: 14.0. The final transformation equations for the DENIS passbands will not be available until the survey is completed, but Fouqué et al. (2000) provide interim absolute calibrations and discuss the DENIS normalized response functions. Carpenter (2001) provided a tentative transformation between DENIS and 2MASS but on the basis of more than 26,000 stars in common, Cabrera-Lavers & Garzón (2003) find $(J\text{-}K)_{2MASS} = (1.020 \pm 0.025)(J\text{-}K)_{DENIS} - 0.009$. The DENIS data releases are slow but DENIS has found many red objects, including some of the very first brown dwarfs.

5.7. Space-Based IR Photometric and Spectrophotometric Systems

5.7.1. THE IRAS MISSION IRAS (http://irsa.ipac.caltech.edu/IRASdocs/exp.sup/index.html) conducted a sensitive and unbiased survey of the sky in four wavelength bands centered at 12, 25, 60, and 100 μm. The resolution of the instrument varied between about 0.5′ at 12 μm to about 2′ at 100 μm. This resulted in confusion in fields near the galactic plane and in the Magellanic Clouds. Launched in January 1983, IRAS ceased operations in November 1983 after successfully surveying more than 96% of the sky. A tremendous amount of information was obtained about cool giants, circumstellar dust, and the general interstellar medium in galaxies. Cohen et al. (1992) discuss the IRAS broad-band calibration.

5.7.2. THE ISO MISSION The ESA's ISO (Kessler et al. 1996) was an astronomical satellite that was operational between November 1995 and May 1998. It operated at wavelengths from 2.5 to 240 μm (http://www.iso.vilspa.esa.es/manuals/HANDBOOK/gen_hb/gen_hb.pdf). At 12 μm, ISO was one thousand times more sensitive and had one hundred times better angular resolution than IRAS. An excellent summary of the ISO, its instruments and results is given by Kessler (2001).

The ISOCAM instrument (Cesarsky et al. 1996) was designed to map selected areas of the sky in the spectral region from 2.5 to 18 μm at various spatial and spectral resolutions. It provided imaging capabilities across a field of view of up to 3 arcmin in diameter. The short wavelength channel operated between 2.5 and 5.2 μm; the long wavelength channel between 4 and 18 μm. Each channel included lenses covering a range of magnifications (yielding fields of view having 1.5, 3, 6, and 12 arcsec per pixel), fixed filters, and continuously variable filters (CVFs). The detectors were 32 $\times$ 32 IR arrays. In addition, there was also a Long Wavelength Spectrometer (43–196 μm), a Short Wavelength Spectrometer (2.3–45 μm), and an Imaging Photo-Polarimeter, ISOPHOT.

ISOPHOT's four principal modes were single-detector–element aperture photometry (3–120 μm), array imaging (40–240 μm), polarimetry (25, 170 μm), and spectrophotometry (2.5–12 μm).

Details of the calibration and performance of the ISO instruments are given at http://www.iso.vilspa.esa.es/users/expl_lib/performance.html. Schaeidt et al. (1996) and Swinyard et al. (1996) describe the calibration of the short and long wavelength channels respectively. Cohen (2003) details how emergent fluxes from Kurucz stellar atmospheric models for Vega and Sirius were used to underpin IR photometry and spectroscopy in the 1–35 μm range and extended to 300 μm in support of the ISO imaging photopolarimeter (ISOPHOT).

5.7.3. THE MSX MISSION The MSX satellite (http://www.ipac.caltech.edu/ipac/msx/msx.html), launched in 1996, had IR instruments that spanned the range 4.2–26 μm. The focal plane arrays included five radiometer bands (8.3, 4.3, 12.1, 14.7, and 21.3 μm) with a beam-size 35 times smaller than IRAS, resulting in images with excellent spatial resolution. The cryogen phase of the mission ended on 26 February 1997. A full set of experiments mapped the Galactic Plane, the IRAS gaps, the zodiacal background, confused regions away from the Plane, deep surveys of selected fields at high galactic latitudes (such as the LMC), large galaxies, asteroids, and comets. Price et al. (2004) detail the calibration of the mid-IR bands.

5.7.4. THE ***SPITZER SPACE TELESCOPE*** *Spitzer* (http://www.spitzer.caltech.edu/) has two imaging cameras, IRAC and MIPS (Multiband Imaging Photometer for SIRTF). IRAC is a 4-channel camera that images a 5.2 $\times$ 5.2 arcmin field simultaneously in broad bands centered at 3.6, 4.5, 5.8, and 8 μm with InSb arrays with 1.2 arcsec pixels. MIPS has three detector arrays: a 128 $\times$128 arsenic-doped silicon (Si:As) array at 24 μ with a 5 arcmin field; a 32 $\times$ 32 gallium-doped germanium (Ge:Ga) array for 70 μ and a 5 arcmin field; and a 2 $\times$ 20 Ge:Ga array for 160 μ with a field of 0.5 $\times$ 5 arcmin. These images are also obtained simultaneously.

Cohen and colleagues (Cohen 2003, Cohen et al. 2003) are working to provide faint stellar calibrators for the IRAC bands using the Cohen et al. (1999) and Cohen, Wheaton & Megeath (2003) template spectra and a fainter sample of stars of similar spectral types (A0-5V and K0-M0III) and matched optical and near-IR colors.

6. OBSERVATIONAL COMPLICATIONS WITH STANDARD PHOTOMETRY

Caveats have been given throughout this review, however it is worthwhile to revisit the complications and problems that can occur with standard photometry. The first complications arise from the observers' equipment and observing procedures. A long-standing source of problems are the observers' passbands which may not be a close match to that of the standard system. Unfortunately, for visiting astronomers this is often out of their control. Nevertheless, it is important to stress that provision of a more closely matched passband will minimize the likelihood of systematic errors. Another problem arises from not observing standards with a large enough range in color to encompass the color of all the objects of interest, or not observing enough standards during the night to monitor the changing conditions. Although some of the recent standard star fields suitable for CCD observations contain many stars, which are good for determining accurate zeropoints, the color range of these stars is often quite restricted and inadequate for establishing the transformation equation for all stars (especially reddened stars, M stars, emission-line stars and galaxies).

Other problems are associated with the use of large CCD and IR detectors. Depending on the f/ratio of the telescope and the optics of camera, the changing field angle through an interference filter can cause the bandwidth of the passband to change across the field introducing systematic differences in photometry. The slow speed of some large shutters may also introduce variations in intensity across the field that are evident in short exposures. Shutter timing controls may also provide exposure times that are uncertain or non-linear. This will introduce systematic errors in photometry, especially when the standards are measured with much shorter exposures than the program objects (Stetson 2005).

There are problems associated with the standard lists themselves. Already mentioned is the fact that standard stars often are very restricted in the kinds of stars that are represented. Another problem is that most of the well established standard systems have standards that were measured using ground-based photoelectric photometry. The standard lists may contain stars that are systematically different by being measured at large zenith distance, by being measured at different times of the year and by being associated with particular parts of the galaxy where the reddening is high. Objects measured against a small subsection of standards may therefore be systematically different from those measured using another subset. This problem can be minimized by using standard stars covering a wide range of RAs, Decs and magnitudes.

Finally there are problems associated with aperture or diaphragm sizes. Photoelectric photometry required the use of quite large diaphragms to minimize fluctuations in light with seeing variations and telescope movement. In the case of Landolt (1983, 1992) standards, these are between 14 and 27 arcsec. When using these standards for CCD observations, such large apertures must also be used to ensure that the same area (including background stars) is measured. Sometimes data reduction software does not even permit such a large aperture to be used. The way around this is to use the Stetson (2000) secondary standards where the Landolt stars have been corrected to a small aperture relevant to CCD photometry.

However, observers should be more aware of and sensitive to the problem of seeing on their photometry. King (1971) discussed the profile of a star image and measured it out to a radius of 6 degrees. Kormendy (1973) actually made use of the large stellar point spread functions (PSF) to calibrate the surface brightness of galaxies. Howell (1989) developed the use of CCD "growth curves" to extract optimal magnitudes from 2D aperture photometry from CCD images. This is an extremely useful technique to use for the standard stars. The widely used DAOPHOT (Stetson 1987) and DOPHOT (Schechter, Mateo & Saha 1993) do excellent analyses of PSF in crowded fields. Nevertheless, in conditions of poor and variable seeing, in the absence of local standards (standards in the same field as the program objects), zeropoint errors of several percent are common. In this context, the network of Tycho B_T and V_T stars will prove invaluable for monitoring observational photometry and tying together the zeropoints of subsequent ground-based photometric surveys such as SkyMapper (http://www.mso.anu.edu.au/skymapper). Tycho 2 provides a catalog of more than 2 million stars brighter than 11th magnitude with photometric errors of 0.10 magnitude overall and better than 0.013 mag for stars brighter than 9th mag. The average density of Tycho 2 stars is 150, 50 and 25 stars per square degree at galactic latitudes of 0, 30 and 90 degrees, respectively.

7. COMPLICATIONS TO THE REALIZATION OF STANDARD SYSTEMS

7.1. Standard Systems May No Longer Represent Real Natural Systems

There is a fundamental concern associated with the theoretical realization of the older evolved standard photometric systems in order to produce synthetic photometry from theoretical and observational fluxes. The technique used is to reverse engineer the standard system's passband sensitivity functions by comparing synthetic photometry with observations (for example, Straižys 1996; *UBVRIJHKL* system: Bessell 1990; Bessell & Brett 1988). That is, commencing with a passband based on an author's prescription of detector and filter bandpass, synthetic magnitudes are computed from absolute or relative absolute spectrophotometric fluxes for stars with known standard colors. By slightly modifying the initial passband (shifting the central wavelength or altering the blue or red cutoff) and recomputing the synthetic colors, it is usually possible to devise a bandpass that generates magnitudes that differ from the standard magnitudes within the errors by only a constant that is independent of the color of the star. It is usually taken for granted that such a unique passband exists and that, given a large enough set of precise spectrophotometric data and sufficient passband adjustment trials, it can be recovered. However, there are several reasons why this may not be the case, at least not across the complete temperature range.

Whilst the original system may have been based on a real set of filters and detector, the original set of standard stars would almost certainly have been obtained with lower precision than is now possible and for stars of a restricted temperature and luminosity range. The filters may also have been replaced during the establishment of the system and the later data linearly transformed onto mean relations shown by the previous data. In addition, the contemporary lists of very high precision secondary standards that essentially define the "standard systems" have all been measured using more sensitive equipment with different wavelength responses. Again, rather than preserve the natural scale of the contemporary equipment the measurements have been "transformed" to some mean representation of the original system by applying one or more linear transformations or even non-linear transformations (Menzies 1993). To incorporate bluer or redder stars than those in the original standard lists (Kilkenny et al. 1998), extrapolations have also been made and these may have been unavoidably skewed by the imprecision of the original data and the small number of stars with extreme colors in the original lists. As a result, the contemporary standard system, although well defined observationally by lists of stars with precise colors and magnitudes, may not represent any real system and is therefore impossible to realize with a unique passband that can reproduce the standard magnitudes and colors through a linear transformation with a slope of 1.0.

In fact, perhaps we should not be trying to find a unique passband with a central wavelength and shape that can reproduce the colors of a standard system but rather we should be trying to match the passbands and the linear (but nonunity slope) or nonlinear transformations used by the contemporary standard system authors to transform their natural photometry onto the "standard system." That is why it is important for photometrists to publish the full details of their transformations and other details of their data reductions, such as extinction corrections. The revised realization of the Geneva photometric system by Nicolet (1996) demonstrates this philosophy and it is the one we are using to realize the *uvby* system.

8. CONCLUDING REMARKS

Standard photometric systems were developed in order to provide an empirical calibration of the measurement of magnitudes and colors (magnitude differences) for stars and galaxies across the whole sky. The better established standard photometric systems permit precisions down to 1 millimag to be obtained in multiple observations. However, systematic errors in standard photometry are commonly more than an order of magnitude higher than this, owing to poorly matched passbands and a too restricted sample of standard stars across the HR diagram.

Most sets of standard stars comprise little reddened Pop 1 B-G dwarfs and G and K giants. Supergiants, metal-deficient stars, O and M stars, white dwarfs, carbon stars, highly reddened stars, and emission-line objects are usually poorly represented in standard star lists because the stars are faint, rare, or variable. If the passbands are not identical, although the standard stars may define precise transformation relations, these may be different for supergiants, metal-deficient stars, etc., and give rise to systematic differences when the normal star transformation equations are applied to the photometry of such stars.

Clearly, it is best to match the standard passbands closely, but as explained above, the manufacturing processes for filters and detectors invariably produce unavoidable differences in passbands. Under these circumstances it is essential to measure the actual filter transmissions, the detector response, and the transmission of the telescope and camera optics so that one can calculate an accurate passband for the instrumental system. With this knowledge, one can conduct synthetic photometry using observed spectrophotometry and model atmosphere fluxes to predict the behavior of the instrumental system for the unusual stars and to provide an absolute calibration for the system. It is also important to publish the transformation equations used to standardize one's photometry so others can reproduce your system and understand any possible systematic effects.

As more and more photometry is being done either in service mode or by means of dedicated photometric surveys, the responsibility is with the instrument scientists to provide the relevant passband information and for the time assignment committees (TACs) to provide adequate calibration time. The Space

Observatories are very good at doing this; the ground-based observatories are getting better.

The situation for faint star photometric standards still requires work, especially for systems other than *BVRI*. Stetson (2000) provides excellent *BVRI* data based on Landolt standards for many faint stars with multiple observations; however, Saha et al. (2004) find differences between Stetson's and their photometry of the same globular cluster fields in *BVRI*. Stetson (2005) convincingly shows that this results from small standard samples and possible problems with short exposure times.

It is essential for those doing standardized CCD photometry to understand that photoelectric standard star photometry was necessarily obtained using apertures with diameters of 14 arcsec (Landolt 1992), 16–27 arcsec (Landolt 1983), and 40 arcsec (Cousins 1983). If 14-arcsec apertures cannot be used for the Landolt (1992) standards, then those standards with background stars evident within a 7-arcsec radius should be rejected, or the Stetson (2000) values for those stars used. Stetson's CCD photometry was obtained using small synthetic apertures or via profile fitting. Inversely, those using Tycho and Hipparcos photometry to standardize ground-based photometry need to check for nearby companions in the Tycho catalog that would be combined under ground-based seeing conditions.

The SDSS passbands are likely to become the new standard for optical broad-band photometry. As mentioned above, the placement and width of the *u* and *g* bands are not ideal for stellar work and steps are underway to design two or three different bands in the ultraviolet and blue that will enable the Balmer Jump, the metallicity and the hydrogen lines to be better measured. The passbands for the Global Astrometric Interferometer for Astrophysics (GAIA) satellite are also under active consideration and their finally adopted passbands will also greatly influence others.

The large size of filters in the new survey telescopes (>300 mm) is a serious problem with regard to the design of filters and their construction. Schott will not make UG and BG glasses larger than 165 × 165 mm, and interference coatings are either extremely expensive or currently impossible to make with a uniform passband across fields as large as 310 × 310 mm. The manufacturers recommend making mosaic interference filters to obtain the required uniformity but this obviously creates problems with vignetting. Filter cost is not an issue for space missions but it is for most ground-based projects.

There is good news for near-IR photometry. The adoption of new improved Z, J, H, K, L, M passbands is welcome and long overdue. The accompanying lists of faint photometric standards are also very important.

The provision of excellent faint spectrophotometric standards in the optical (Hamuy et al. 1992, 1994) and now in the near-IR, mid-IR, and far-IR (Cohen et al. 1999, 2003) is also an important development. Observers should flux calibrate their spectra as a matter of course, and spectroscopic observations should be taken using an atmospheric dispersion corrector (http://www.ctio.noao.edu/www/spectrographs/hydra/4mtelescope/refraction.html) or observed with the atmospheric dispersion tracked along the slit during the exposure to ensure that UV light is not preferentially lost on the slit jaws. Far-red spectra should be divided through by "smooth spectrum" halo GK stars (Bessell 1999) and IR spectra divided by "smooth spectrum" A-G dwarfs (Vacca, Cushing & Rayner 2003) to remove atmospheric H_2O and other molecular absorption (telluric) features.

Finally, the latest generation of model atmospheres (for example, MARCS: Plez, Brett & Nordlund 1992; Jørgensen, Johnson & Nordlund 1992; Edvardsson et al. 1993; ATLAS9: Zwitter, Castelli & Munari 2004) produce extremely realistic fluxes for a wide range of temperatures, gravities, scaled solar abundances, and enhanced carbon and other abundances. These fluxes can be used to check observed spectrophotometry and to compute synthetic photometry for calibration of standard systems in the UV, optical, and IR. As there will be much use made of transformations between the new survey photometry system colors and the old *UBVRI* system and other optical standard system colors, synthetic photometry will be indispensable in predicting the differences (if any) between the transformations derived from the normal Population I standard stars and other stars such as highly reddened stars and metal-deficient stars.

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