Session 1

Photometric Systems

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Photometric Systems

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Abstract

Multicolour photometry has historically been carried out within a variety of standard systems. With the advent of new detectors with different wavelength sensitivities to those of the original system and the use of subsets of secondary standards, many subtle and not so subtle changes have occurred to the original systems. However, by reverse engineering, the passbands of the modified standard systems can be determined which enables good realisation of theoretical colours and better passband matching for CCD-based photometry. In this paper, the various photometric systems will be discussed and compared and strategies will be outlined for ensuring that precise relative photometry is maintained in the future, in particular from area detectors.

1. Introduction

More than any other aspects of astronomy the subjects of magnitude scales and photometric systems are encumbered by history. Early astronomers compared star with star, a procedure that still retains great benefits. The temperatures of common stars range from 30000K to 3000K. Their brightnesses cover a range of almost a factor of 10^{10}, from the sky background upwards. (this range does not include the sun). The majority of stars are constant in total light output and in temperature. They must all be observed through the Earth's atmosphere. No laboratory sources of light have energy distributions similar to those observed in stars and it is natural that astronomers seek to use the standard candles in the sky rather than inferior and technically complex ones in the laboratory. Photometric systems represent attempts to define standard bandpasses and sets of standard sources, measured with these bandpasses, that are well distributed about the whole sky. Different photometric systems measure different wavelength bands. All photometric systems enable the measurement of relative fluxes, from which can be inferred particular properties of the emitting object, such as temperature and luminosity, but different systems claim to do so more precisely, more quickly or more easily compared with other systems. Some are suited for hot stars, others for cool stars. Most of the systems were developed and modified by different astronomers over many years and the literature contains confusing versions and calibrations. Some people have despaired that it is so confusing we should start again with a well defined ultimate system, but recent analysis has shown that modern versions of the existing photometric systems can be placed on

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a firm quantitive basis and that more care with passband matching will ensure that precise and astrophysical valid data can be derived from existing, though imperfect systems. This is not to say that better systems will not be devised but they face strong competition from more precisely defined and better calibrated old systems. The zero point of the V (visual) photometric system has undergone much refinement over time and although it was officially set by the specified visual magnitudes of stars in the *north polar sequence* the magnitude scale of all systems today is established by the contemporary whole-sky standard star catalogues.

2. New systems from new detectors

Technological advances over the last 50 years have provided a series of light detectors of ever increasing sensitivity and wavelength coverage. The advent of photography in the late 19th century revolutionised astronomy as did the introduction of photomultiplier tubes with their light sensitive photocathodes in the mid 20th century and detectors such as silicon charge-coupled-devices (CCDs) and infra-red detectors over the last 10 years. Light intensities or magnitudes measured with these new detectors naturally differ from the visual magnitudes and depend on the colour of the objects. Initially, there was only the difference between visual magnitudes and 'blue' photographic magnitudes to be considered, but three factors resulted in a proliferation of different passbands and photometric systems. These were the extension of photographic and photocathode sensitivities to a wider wavelength range, and the use of coloured glass filters and interference filters to sample the starlight in narrower bands within the total wavelength sensitivity range of detectors.

3. Rationale for multicolour photometry

Photometry of astronomical objects is carried out in order to measure the apparent total brightness of objects and their relative brightnesses at different wavelengths i.e. their energy distribution. It is possible to characterize the temperature of most objects from the overall shape of their energy distribution, and to infer the metal content of stars from depressions in the energy distribution at particular wavelengths due to the absorption of flux by lines principally of Fe and Ti, which have very rich line spectra, Ca, Mg and the molecules CN and CH, which also have very strong lines in the blue-violet region of cool stars. There are many other molecular absorption bands, such as TiO,CO and H20 which depress the continuum in very cool stars and such molecular features are also used to provide information on the temperature, abundance and luminosity. The energy distributions of galaxies and star clusters can be analysed to extract the relative numbers of different kinds of stars making up the composite object. Red shifts of very distant QSOs can also be measured from the positions of depressions or peaks in their energy distributions.

Multicolour photometry is best thought of as very-low-dispersion spectroscopy. The entire high resolution spectrum of a star or cosmic object contains a large amount of information, but when dealing with extremely faint objects or large numbers of objects it is a great advantage to measure a small number of wavelength bands in as short a time as possible. Such a minimal technique is invaluable if it enables the derivation of many of the same parameters derivable from a complete (and very redundant) description of the spectrum. A great deal of effort therefore has gone into accurately measuring the calibrating colours and depressions in terms of temperatures, metal abundances and other parameters, and investigating which of competing minimal descriptions of a star's spectrum is the most accurate or most practical.

4. Photometric systems - natural systems, standard systems

A light detector, a telescope, a set of coloured filters, and method of correction for atmospheric extinction makes up a *natural photometric system*. Each observer therefore has their own natural system. The *standard* system is indirectly defined by a list of standard magnitudes and colours measured for a set of typical stars with the natural system of the originator. These are often called the *primary standards*. Later lists comprising more stars and fainter stars but based on the primary standards are called *secondary standards*. However, in the case of all photometric systems, recently published secondary standards effectively redefine the standard system because they tend to be more accurately measured than the primary lists and to represent contemporary detectors, filters and practice. The term 'colour' is an abbreviation for 'colour index' which is the difference between the apparent magnitudes in two different spectral regions. Photometry is generally published as a series of colours and single magnitude. The zero points of many colour systems are set so that Alpha Lyrae (Vega) has zero colours. In the southern hemisphere (where Vega is inaccessible, and often also in the north) the zero point is set by requiring that an ensemble of unreddened A0 stars have zero colours.

The most influential of the early works of photoelectric photometry were the so-called broadband Johnson UBVRI and Kron RI systems, which covered the wavelength region between 310nm and 900nm. The natural systems of Johnson, Kron and coworkers served as *standard* systems for many other users who attempted with varying success (due to differences in detectors, filters, telescopes and techniques) to duplicate the originators natural systems. That is, using their own detectors and filters, astronomers measured stars from the Johnson and Kron lists and linearly transformed their natural magnitudes and colours to be the same as the Johnson and Kron colours and magnitudes. They then applied those same linear coefficients to transform the colours and magnitude of unknown stars onto the Johnson or Dron system.

The original blue and yellow filters were chosen by Johnson from readily available glasses so that when used with the IP21 photomultiplier tube they approximated the ordinary blue photographic response (~436nm) and the visual response (~545nm). A more violet magnitude U(~367nm) useful for very hot stars, was obtained by using a common violet glass. In retrospect, these choices should have been based more on astrophysics and less on glass availability, but so much work has been done in UBV that the weight of history assures its continuation. Intercomparison of much

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of the published broad-band photometry, in particular photometry taken more than 15 years ago, often shows scatter of more than 0.03 magnitudes, but more recent photometry obtained using better equipment, better matched natural systems and better secondary standard stars agree to better than 0.01 magnitude or 1 percent. Plans for automatic telescope based photometric systems aim for precisions of 0.001 magnitudes or 1/10 of a percent.

The 1P21 phototube was a remarkable invention and its high blue sensitivity dominated the development of photometric systems for over 30 years. There were red-sensitive devices available but observations were only made for bright stars because for many years the red detectors were much less sensitive, noisier and less reliable than the 1P21. In the mid-70s new detector materials became available, in particular the gallium-arsenide and multi=alkali phototubes which provided high (>15%QE) sensitivity between 300nm and 860nm, and the infra-red sensitive InSb photodiodes together with low-noise preamplifiers which revolutionised photometry between 1000nm and 4000nm., Both developments enabled red photometry to be done on faint objects, hitherto the province of blue detectors.

Photometry done with the new red sensitive tubes was placed on either the Kron or the Johnson standard systems again with mixed success and it has only been in the last few years that the Cousins RI 'near-natural' standard system (based on the Kron System) has gained wide spread acceptance. It has also been very useful that the Cousins system R(~638nm) and I(~797nm) bands are similar to the contemporary photographic R and I bands.

Johnson also introduced the infrared alphabetic JKLMN (approximately 1.22mm, 2.19mm, 3.45mm, 4.75mm, and 10.4mm) system in the mid-60s using PbS detectors and bolometers. The water vapour in the earths atmosphere defines a series of wavelength bands (windows) through which observations from the ground can be made. Johnson used interference filters (and unfortunately the atmospheric H20 absorption bands) to define what he called JKLM and N bands. Glass (1974) in his early observations with an InSb detector used the additional band H(1.63mm) between J and K, and in his choice of filters attempted to match the other Johnson bands. All IR observers have proceeded in a similar fashion and have concentrated mainly on copying the Johnson K magnitude scale. Identical detectors have been used but slightly different filters, dewar windows, focal plane shutters and observing altitudes have produced subtly different systems. The publication of sufficient numbers of stars in common from the different natural systems has helped delineate the differences and transformations between the systems are now quite reliable (eg Bessell & Brett 1988; Leggett et al 1992; McGregor 1992).

5. Passbands or sensitivity functions of standard systems

The most important specifications of a photometric system are the passbands or sensitivity functions of its magnitudes. For a variety of reasons, technical and historical, the passbands of the broad-band photometric systems have not been known with certainty and this has inhibited close matching of natural systems and prevented

Figure 1. The passbands of the UBVRIJHKL system. The spectrum is of an AO star

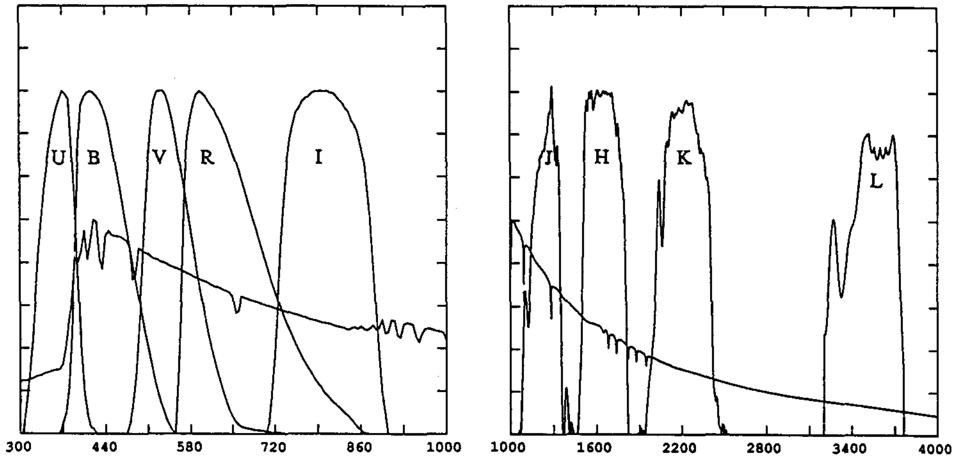

Table 1. Johnson-Cousins-Glass UBVRIJHKLM System

	U	B	V	R	I	J	H	K	L	M
λeff(nm)	367	436	545	638	797	1220	1630	2190	3450	4750
Δλ(nm)	66	94	88	138	149	213	307	390	472	460
$F_\nu(V=0)$ ($10^{-30}Wcm^{-2}hz^{-1}$)	1780	4000	3600	3060	2420	1570	1020	636	281	154

Table 2. Effective Wavelengths (nm) and FWHM Bandpasses (nm) for Selected Systems

		λeff	Δλ			λeff	Δλ			λeff	Δλ
Geneva	U	343.8	17.0	Walraven	W	325.5	14.3	Wash'ton	C	391	110
	B	424.8	28.3		U	363.3	23.9		M	509	105
	B_1	402.2	17.1		L	383.8	22.7		T_1	633	80
	B_2	448.0	16.4		B	432.5	44.9		T_2	805	150
	V	550.8	29.8		V	546.7	71.9				
	V_1	540.8	20.2								
	G	581.4	20.6								
Strömgren	u	349	30	DDO	35	349.0	38.3	Thuan-Gunn	u	353	40
	v	411	19(12)		38	381.5	33.0		v	398	40
	b	467	18		41	416.6	8.3		g	493	70
	y	547	23		42	425.7	7.3		r	655	90
	β_w	489	15		45	451.7	7.6				
	β_n	486	3		48	488.6	18.6				

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computation of accurate synthetic colours from theoretical spectra. The recent availability of spectrophotometry for many stars combined with the increased precision of second generation photometric catalogues has, however, enabled the passbands to be indirectly derived by computing synthetic colours from spectrophotometry of stars with well defined standard colours and adjusting the passbands until the computed and standard catalogue colours agree. This technique has enabled the passbands of the major systems to be well defined, which in turn has permitted filters to be designed which will still result in good passband matches with a variety of detectors. In addition, when it is not possible to exactly match passbands with detectors such as photographic plates it is possible to accurately predict the differences between photographic and p[hotoelectric magnitudes by computing the synthetic magnitudes.

The Vilnius optical spectrophotometry (Straizys & Sviderskiene 1972) has been used by Taylor (1986) and Bessell (1990) for passband analyses. Cousins (1987) uses spectra from Willstrop (1965). A more recent extensive catalogue of spectrophotometry is the Gunn- Stryker spectra (Gunn & Stryker 1983); corrections to these Gunn-Stryker absolute fluxes have been discussed by Rufener & Nicolet (1988) and Taylor & Joner (1990). The theoretical fluxes by Kurucz (1991) will also be extremely useful for passband analysis as well as calibration of colours. Excellent summaries of photometric systems are given by Lamla (1982) and Davis Philip (1979). More recent discussions of particular systems will be referenced individually below.

5.1 The UBVRIJHKL System

In Figure 1 the linear normalised passbands of the Johnson-Cousins-Glass UBVRIJHKL system are shown. The F_ν spectrum of an A0 star is shown for orientation. Table 1 lists the effective wavelength λ_{eff}, the approximate bandwidth $\Delta\lambda$, which is the full width at half maximum (FWHM) of the band, and the absolute calibration of this system, based on the flux of Vega, for a zero magnitude A0 star. Note that the effective wavelengths of the broad bands change with the colour of the objects. The λ_{eff} listed are for an A0 star.

There are two large sets of photometric standards which represent the contemporary UBVRI system. One is in the southern hemisphere E and F regions (Cousins 1973, Menzies et al 1989) the other in the equatorial regions (Menzies et al 1991). The equatorial stars were previously established independently by Landolt (1983, 1992). Menzies et al (1991) has outlined some systematic differences between these representations and these are discussed by Menzies (1992). These differences have almost certainly arisen through the slight differences in the passbands used (in particular the B band and the method of U-B standardisation) and a lack of very red standards. Differences in passbands and transformations between various UBVRI systems have been discussed by Bessell (1979, 83, 86ab), Taylor (1986), Taylor et al (1989), Joner & Taylor (1990) and Bessell & Weis (1987). The variety of IR JHKL systems alluded to above has been discussed by Bessell & Brett (1988) who also give transformations between the various systems. New transformations have been derived by Leggett et al (1992) and McGregor (1992). Better calibration will now be possible through the absolute IR spectrophotometry of Cohen et al (1992).

5.2 Other Photometric Systems

Real or perceived drawbacks in existing photometric systems (the UBV system in particular) stimulated the design of other photometric systems better suited for measuring temperatures, metal-line blanketing, effective gravity and interstellar reddening. Some of these systems used broad bands comparable to the UBVRI system, others used narrower bands defined by different mixes of glass filters or interference filters. Effective wavelengths and other details of some of the better known systems are given in Table 2 and discussed below.

The Stromgren 4-colour system: The uvby system was devised by Stromgren to better measure the Balmer discontinuity, the metallicity and the temperature of A, B and F stars. The bands are essentially separate unlike the UBV bands which overlap. Fig. 2 shows the passbands realised by Olson (1974).

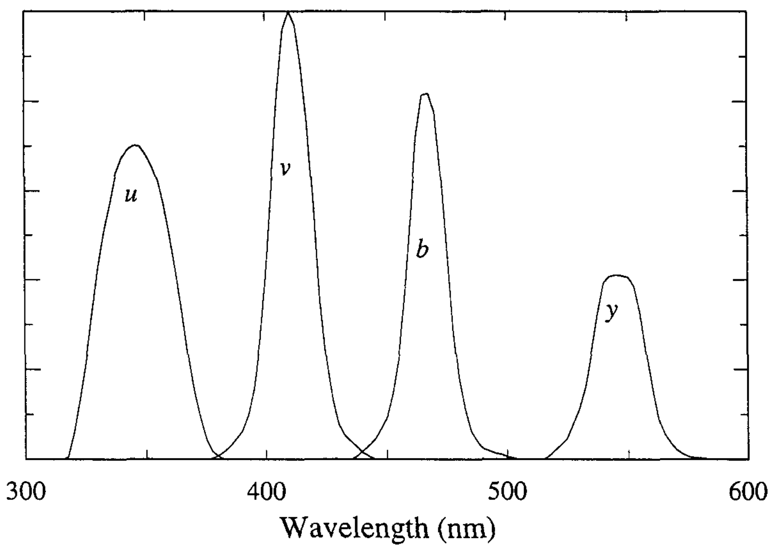

Figure 2. The uvby passbands of the Stromgren 4-colour system

The u band is completely below the Balmer jump; v measures the flux near 400nm, a region with much absorption due to metal-lines; b is centred near 460nm and is affected much less than B by metal-line blanketing; y is essentially a narrower V band. The u filter is coloured glass, the others are interference filters. Two special indices are derived m_1=(v-b)-(b-y), which measures metallicity and c_1=(u-v)-(v-y), which measures the Balmer discontinuity; (b-y) like B-V is used primarily as a temperature indicator. The system is capable of very high precision but unfortunately errors in the width of v filters manufactured some years ago resulted in non-standard

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filters being supplied to many users. Since then, published photometry has exhibited some systematic differences in c_1 and m_1 and there are difficulties in synthesizing c_1 and m_1 from theoretical spectra, particularly for cool stars. (For such late-standard catalogues (Olsen 1983, Cousins 1987) of new and more homogeneous observations are of high precision and internal consistency and it should now be possible to better define the v band; Cousins (1987) has investigated the theoretical realisation of the standard passbands for earlier stars than spectral type K. Systematic colour transformation effects are discussed by Manfroid and Sterken (1991, 1992). Anthony-Twarog et al (1991, 1992) discuss CCD photometry on the uvby system. Calibration of the Stromgren system for A, F and G supergiant stars is discussed by Gray & Olsen (1991) and Gray (1991).

Two additional interference filters (15nm wide and 3nm wide) centred on the $H\beta$ line are often used together with the 4 colours. The $H\beta$ index is used to derive luminosities in B stars and reddening in F and G stars (Crawford 1975). Some of the more recent $H\beta$ catalogues are Perry et al (1987), Cousins (1989, 90). The Stromgren system was one of the first photometric system devised to measure specific features in stellar spectra (eg Crawford 91). Because of the short wavelength range of its 4 colour filters, 1 percent photometry at least is required to realize the benefits the system has over the UBVRI system.

The DDO (35, 38, 41, 42, 45, 48) system: This system (also built around the sensitivity of the 1P21) was designed for the analysis of G and K dwarfs and giants. Figure 3 shows the passbands. The 35 filter is the u filter of the 4-colour system; the 38 filter is also a glass filter and better measures metal blanketing than the v filter, being further to the violet and wider; 41 measures the CN band; 42, 45 and 48 are continuum filters. The colour 35-38 (the 3538 index) measures the Balmer jump, 3842 the metallicity, 4245 and 4548 are used for gravity and temperature measurements. By restricting the measurements to the blue spectral region complicated blanketing corrections are necessary to derive temperatures and gravities. good results, especially for faint K stars, can be obtained by using V-I or R-I as the temperature indicator. Because of the narrow band width of the filters the DDO system has been mainly restricted to relatively bright stars. Standards are given by McClure (1976), Dean (1981) and Cousins (1992). The system is discussed by McClure (1976, 79) and Osborn (1979).

The uvgr system: This system was devised by Thuan & Gunn (1976) in the mid-70s from the UBVR system for use with an S20 detector and in order to avoid the strong Hg lines from city lights and [OI] lines in the night sky. The g and r bands are of similar width to the V and R bands while the u and v bands are about half

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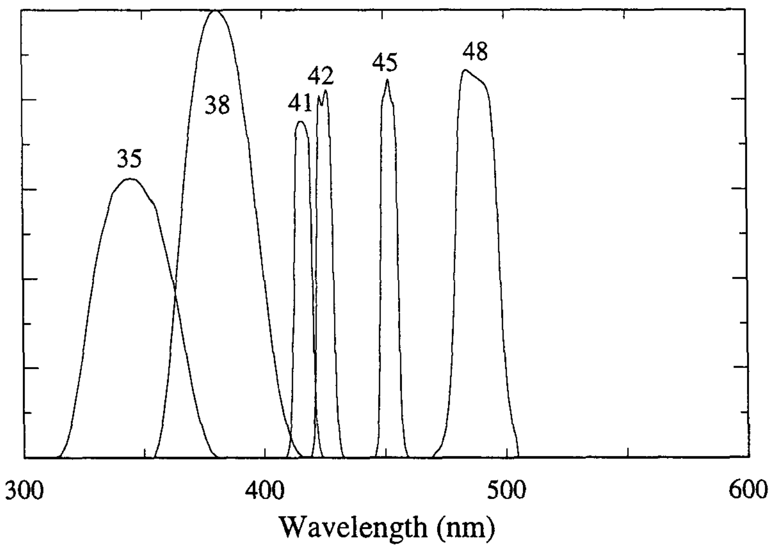

Figure 3. The passbands of the DDO system.

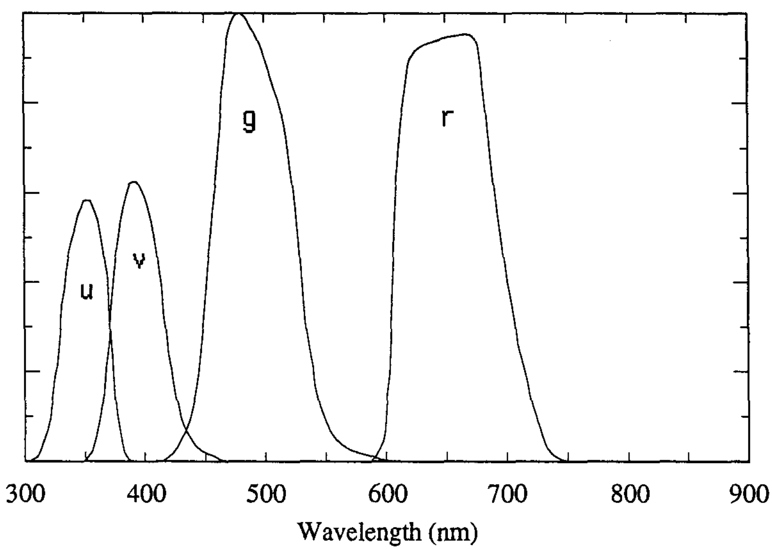

Figure 4. The passbands of the Thuan-Gunn uvgr system.

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the width of the U and B bands. Unlike other systems the zero points have been set by the FG subdwarf CD+174708, which by definition has g = 9.50; g-r = u-v = v-g = 0. The g-r colour has a longer baseline than V-R but they transform well. The r band has also been used for photographic and CCD photometry. The relation between r and R is $r = R + 0.35 - 0.148(R\text{-}I) + 0.122(R\text{-}I)^2 + 0.0118(R\text{-}I)^3$ for $(R\text{-}I) < 1.8$. The relation between g-r and V- R is $V\text{-}R = 0.29 + 0.585(g\text{-}r) + 0.060(g\text{-}r)^2$.

The Geneva ($UBB_1B_2VV_1G$) System: Difficulties with matching natural systems have been eliminated by the strategy employed by proponents of the closed Geneva ($UBB_1B_2VV_1G$) system. This multiband photometric system is supervised by a small group who control the instrumentation and supervise the data reduction and calibration. The 4th edition of the catalogue (Rufener 1988) containing data for 29400 stars and is also available from the Stellar Data Centre in Strasbourg. Cramer (1991) discusses more recent data. Rufener & Nicolet (1988) discuss the passbands and their absolute calibration and the theoretical calibration of some colours in terms of temperature and gravity. In practice, three colours $U\text{-}B_2$,$B_2\text{-}V_1$ and $V_1\text{-}G$ are used together with linear combinations which are reddening free for a standard extinction law and E(B-V)<0.4 mag. The combination indices are $d = (U\text{-}B_1)\text{-}1.430(B_1\text{-}B_2)$, $F = U\text{-}B_2) - 0.832\ (B_2\text{-}G)$, $g = (B_1\text{-}B_2) - 1.357(V_1\text{-}G)$ and $m_2 = U\text{-}B_1) - 1.457(B_2\text{-}V_1)$. The various Geneva indices have been well calibrated in terms of gravity, temperature and abundance (eg Golay 1980). The indices d and m_2 are clearly closely related to the $[c_1]$ and $[m_1]$ indices of the Stromgren system (eg Eggen 1977).

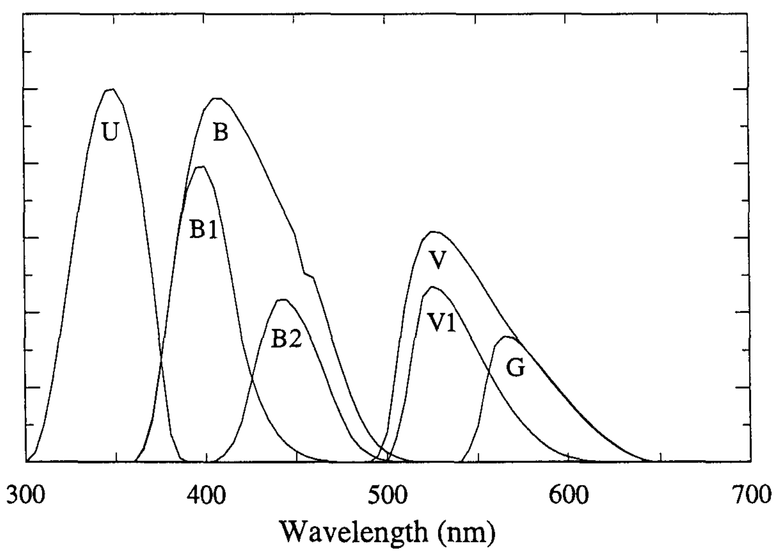

Figure 5. The isophotonic passbands of the Geneva system.

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The Vilnius (U P X Y Z V S) system: The intermediate band 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 (eg Straizys 1979). The colours are normalised by the condition U-P = P-X = X-Y = Y-Z = Z-V = V-S for unreddened O-type stars. Therefore all colours for all normal stars are positive. Reddening free indices are constructed as with the Geneva system and these are Vilnius system has now been used with CCDs (Straizys 1991,92) and has also been extended to the southern hemisphere (Dodd et al 1992).

Straizys (1979) has also utilized a 7 colour VILGEN system comprising passbands from the Vilnius (P Z S) and Geneva (U B_1 B_2 V) system. Its advantage is that it uses wider bands than the original Vilnius system yet scarcely compromises the selectivity of the indices.

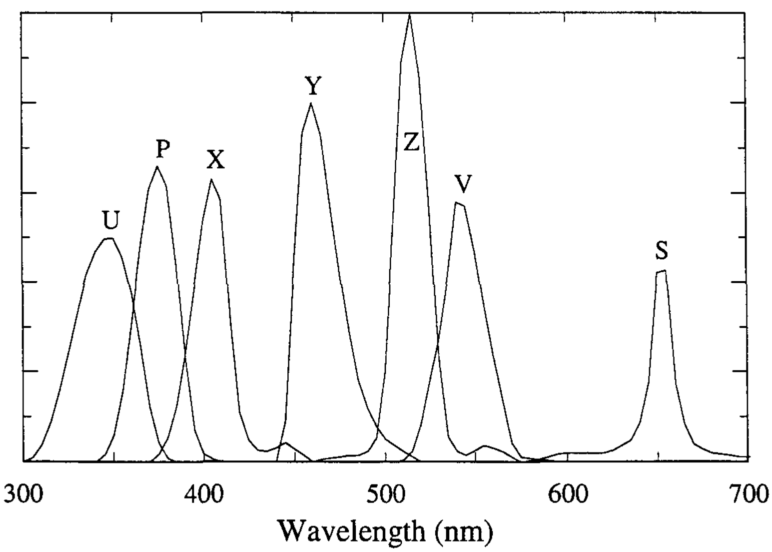

Figure 6. The passbands of the Vilnius system.

The Walraven (VBLUW) system: The properties of the system are described by Lub and Pel (1977). Unlike the other systems discussed here, Walraven photometry is obtained using a specially constructed spectrograph-photometer. Originally used in South Africa from 1960, the photometer was moved to La Silla in 1979 (Pel et al 1988). The VBUW bands are defined by a special filter of crystal quartz and 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 technique provides great stability of passbands which has helped Pel (1991,92) to discern small systematic errors with right ascension and declination in the V photometry of Landolt (1992) and Rufener (1988). Much of the work in the VLBUW system has

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been on cepheids and RR Lyrae stars (eg Lub 1979, Pel 1985). Comparison of the VLBUW colours of stars with synthetic colours from theoretical fluxes has proved to be a very precise test of the model atmospheres and fluxes (Pel 1992).

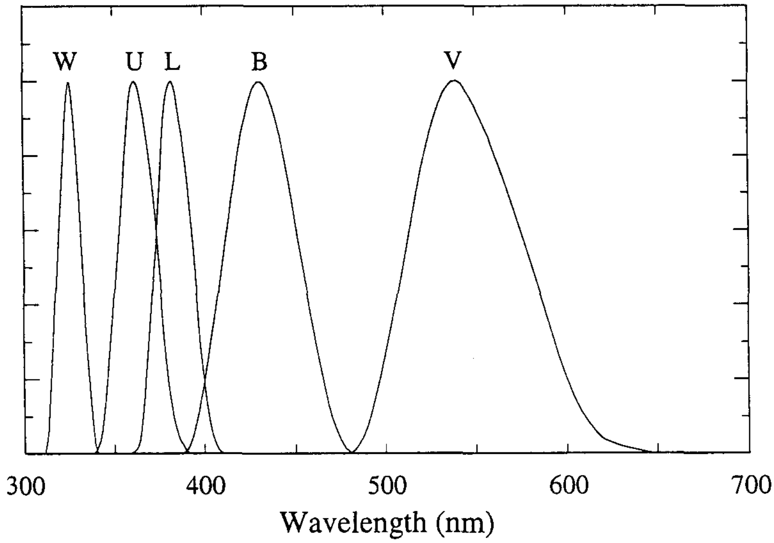

Figure 7. The passbands of the Walraven VLBUW system

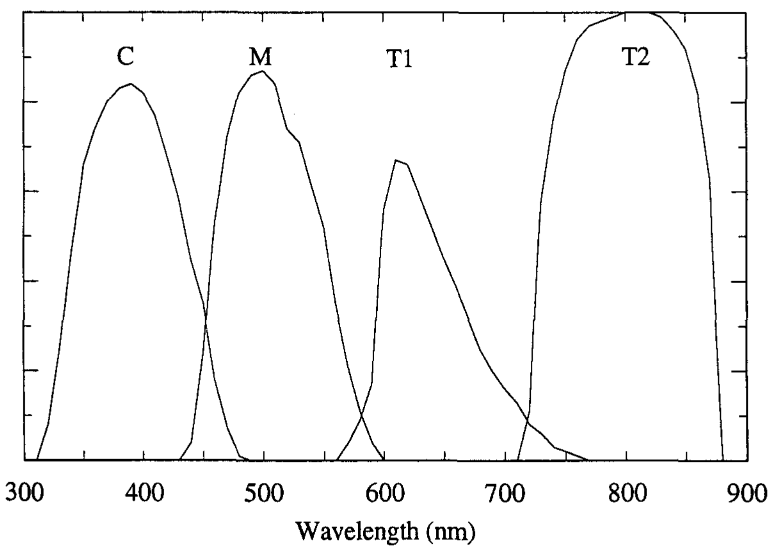

Figure 8. The passbands of the Washington CMT_1T_2 system

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The Washington CMT_1T_2 System: The Washington system is a very broad-band system which was devised to use the wideband sensitivity of the extended-red detectors, to improve the sensitivity of blue-violet colours to metallicity and gather more violet light in cool stars, and to try and separate the effects of CN from other metal lines. New standards are given by Geisler (1990) and revised calibrations are given by Geisler et al (1991) together with many references to the successful work that has been done on the abundances of faint K giants in globular clusters and in external galaxies. Tyson (1991) discusses CCD photometry. We have found that the violet C band is a very useful metallicity indicator for faint K giants but that the M band contains little more information for giants than does V; T_1 and T_2 have no advantages over R and I. We find that a minimal CVI system is very useful for metal-weak K stars. It takes advantage of C being better than U and B for a metallicity sensitive band and uses the larger baseline of V-I compared to T_1 - T_2 as a temperature index. Most importantly, it reduces the proliferation of additional bands.

Good transformations can be derived between the Washington indices and VRI indices.

$$R-T_1 = -0.012 + 0.046(T_1 - T_2) - 0.082(T_1 - T_2)^2$$
$$V - I = 0.003 + 1.794(T_1 - T_2) + 0.517(T_1 - T_2)^2 - 0.402(T_1 - T_2)^3$$
$$V - R = 0.008 + 1.016(V-T_1)$$
$$M - V = 0.006 + 0.240(V-I)$$
$$(M-T_2) - (V-I) = 0.242(V-I) + 0.018(V-I)^2$$

The Photographic systems: Originally photographic emulsions were only sensitive to light blueward of 490nm. These were to O emulsions. Different chemical sensitising shifted the red sensitivity cutoff to longer wavelength, G 580nm, D 650nm, F 700nm and N 880nm, approximately. By using blue cutoff glass filters and the red cutoff of the emulsions various photographic passbands were made. Photographic U used a violet filter for both blue and red cutoffs. The photographic colours were normally converted onto the photoelectric UBVR system but the accuracy of the conversions were restricted by limitations in iris photometry and poor matches of the bandpasses. The Basel RGU system (Buser 1979) was used quite successfully in studies of galactic structure. In recent years astronomical photography has undergone a renaissance caused firstly by the development of new fine grain emulsions (Kodak IIIaJ and IIIaF) and the utilization of methods of greatly increasing the sensitivities of the J and F emulsions using hydrogen gas and the IVN emulsions using silver nitrate solution, and secondly by the use of new scanning microdensitometers and better methods of intensity calibration. Averaging of several wide field Schmidt plates of higher scale prime-focus plates can now produce photometry to a few percent to very faint limits. Recent experiments to digitally combine 64 limiting exposure Schmidt plates (Hawkins 1992) has resulted in an increase in the limiting magnitude by about 2 magnitudes, a very impressive result. Theoretical investigation of bandpasses enables better filter design for bandpass matching or predicts the relevant transformations and systematic differences between photoelectric and photographic photometry. Photographic photometry these days is usually restricted to attempted matches to the Johnson U and B or the Thuan and Gunn g using IIIaJ plates; Cousins R or Thuan- Gunn r using IIIaF plates; and Cousins I using IVN plates. Direct photographic calibration from step-wedges is usually supplemented by direct magnitude measurements of stars in each field using a CCD array. A discussion of some of the new photographic passbands is given in Bessell (1986b).

CCD photometric systems: The high QE of CCDs and their inherent linearity has made them the detectors of choice for most area photometry, especially for colour- magnitude diagrams of clusters. Unfortunately the advantages of the CCDs were not initially fully attained because many users paid insufficient care in defining their passbands and in standardizing their photometry. This resulted in internally precise results but an inability to relate these results with much confidence to the photoelectric system data or to the theoretically derived magnitudes and colours. Most astronomers now realize the importance of matching the CCD passbands to the photoelectric passbands and measuring their instrumental passbands.

Standardization, at the time, was not made easy by a paucity of suitable standards for CCD photometry, namely stars that were faint enough, had a good range in colour and many of which could be observed on a single CCD frame. That problem has now been addressed by RCCD-sized fieldsS of UBVRI standards of Landolt (1992) and Jones (1992) and CMT_1T_2 standards of Geisler (1990). It would be very useful were these CCD fields to be standardized for JHKL, uvby, DDO and other systems as well.

There can be additional problems associated with interference filter photometry from imaging systems. Firstly, the filters need to have uniform transmission across the filters and to be specified as image quality from the manufacturer. Secondly, there are shifts in passbands associated with off-axis imaging and these shifts are more significant in narrow- band work. Photoelectric photometry is done on-axis and at long (f/18) focal ratios. Imaging is done at shorter focal ratios, f/8 at 1m class telescopes, f/3.5 at 4m class telescopes or with focal reducing cameras. In the collimated sections of cameras the passband shifts to the blue as one moves away from the field centre, whilst in short focal ratio telecentric sections the bandpass does not vary with field position but is distorted compared to that on-axis in a near-parallel beam. These complications can be accounted for, but users should be aware of such problems.

Broad band glass filter defined systems are advantageous for imaging photometry as they provide robust passbands together with a large range of possible aperture sizes and can be used to the faintest magnitude limits. Care must be taken however, to ensure that band passes of the broad-band CCD systems are good matches to the photometric system within which the standards were established so that astrophysically sound transformations can be made and so the same colour calibrations can be used. Bessell (1990) discusses these problems and suggests some glass mixes for UBVRI which are appropriate for some CCDs. The U and the B bandpasses are the most critical for most stellar work and the significant differences in the blue-violet sensitivities of coated, uncoated, thinned and coated, thinned and uncoated CCDs necessitate different glass mixes being designed for different CCDs. The stellar flux atlases and theoretical fluxes discussed at the beginning of section 5 are very useful for synthesizing colours from trial glass mixes with various CCDs when designing new filters which will enable best matches to the standard system colours.

One possible remaining problem with CCD bandpass matching concerns the I band. The photoelectric I band has a steep red cutoff due to the GaAs photocathode; however, the cutoff of the CCD is much less steep with the CCD sensitivity extending beyond 1m. This does not cause transformation problems for most stars, but cool, strongly banded stars such as late M and C stars will be affected. Walker (1991) also notes that the telluric emission is brightest beyond the cutoff of the photoelectric I band which will result in brighter sky backgrounds and possible problems with sky flat-fielding. He therefore recommends removing the extended red sensitivity tail of the CCD using an interference filter. One such filter (an infrared mirror No 60.5050) is readily available from the Rolyn Optics Company.

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Discussion

D. Crawford: *Strömgren and I talked about red extensions to uvby, but decided that the existing R and I were perfectly adequate for any who needed a red extension, (eg. for B,A and F stars). It was a conscious decision not to add two new filters; R,I are, in fact, very useful supplements to uvby for many applications.*

Bessell: That is interesting. But I feel it is likely that, because you and your collaborators have never combined the uvby and R,I systems in your published work, (unlike Eggen), it has inadvertently led others to neglect the possibility of using redder colours.

W.Z. Wisniewski: *H. Johnson was well aware how the UBV filters should match the solar spectrum. But after the Second World War the number of available filters was limited. One would have had to pay for development and there were severe financial limitations. We could afford to spend just a few hundred dollars.*

Bessell: As you have pointed out to me in the past, we should not judge the originators of photometry by modern criteria. But one should ensure that their inadequacies are not still evident in the modern secondary standards.

G. Szécsényi-Nagy: *As CCD's are mushrooming in astronomical observatories too and manufacturers offer a wide choice of ultraviolet and violet-blue sensitive coatings, do you see any possibility of standardizing the short wavelength sensitivity of thinned, back illuminated CCD's?*

Bessell: It is unlikely that the ultraviolet sensitivity of CCD's will be standardized in the near future; however as most of the flux in the U systems, (the flux which is astrophysically significant), lies redward of 350 nm, it is possible to get good transformations for unreddened stars by concentrating on matching the red side of the passband, and using standards with a good range of spectral types.

S.B. Howell: *What differences have you found between the manufacturers, supplied, 'generic' QE curves for CCD's and the actual curves? Also, can you comment on any problems when using a filter set designed for a specific CCD (type and QE curve) with another CCD of different type?*

Bessell: Alistair Walker can give you better information but I believe that the main differences between the manufacturers' curves and the actual curves occur shortward of 350 nm and longward of about 800 nm. The long wavelength response is the most temperature sensitive and this is usually set by observatory engineers to minimize the dark current and will be different from the temperature relevant to the manufacturers' curves.

One can reliably calculate the differences by convolving the different responses with the spectrophotometric atlases and plotting these differences against spectral type, luminosity etc.

R.F. Garrison: *The small differences in passband definition can be disastrous for unusual objects like supernovae, for which the emission lines develop and recede in addition to moving in radial velocity, so as to move in and out of the boundaries of the passbands. These differences can lead to differences of 0.4 magnitude or more which is not small for theoreticians.*

D.H.P. Jones: *About ten years ago the KPNO supervised a contract to buy in a uniform set of BVRI filters to be used at several observatories throughout the world. On La Palma we have three of these sets still in use. Does anyone else still use them?*

Bessell: It is now recognised that the rectangular bandpasses of the KPNO BVRI interference filter sets was very unfortunate. Although these filters have high throughputs, they provide very poor transformations to the BVRI system and with the paucity of suitable standards at the time they resulted in very poorly standardized photometry.

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