Magnitude Scales and Photometric Systems

More than any other aspects of astronomy, the subjects of magnitude scales and photometric systems are encumbered by history. The intensity of light from stars and other cosmic objects is usually expressed in magnitudes, an inverse logarithmic scale that confuses physicists who work in SI units, but that is practical for astronomers. The apparent magnitude of an object is a measure of the intensity of radiation within a particular wavelength interval received from that object at the Earth. The absolute magnitude is the magnitude that the object would have were it situated at a distance of 10 parsecs (pc, about 32.6 light-years (ly)) from the Sun. The relation between apparent magnitude m and absolute magnitude M is $m - M = 5 \log d - 5$, where the distance d is in parsecs.

The total energy, integrated over all wavelengths, received at the Earth from an object is also expressed as a magnitude, the bolometric magnitude. The difference between the bolometric magnitude M_{bol}, and the magnitude m_{A} in bandpass A is called the bolometric correction BC_{A}. BC without a qualifier normally refers to the correction to the visual magnitude; BC or BC_{V}. The zero point of the bolometric magnitude scale is usually set by adopting $M_{\mathrm{bol}}(\mathrm{Sun}) = 4.75$, which implies $\mathrm{BC}_{\mathrm{Sun}} = -0.07$.

Early astronomers compared star with star, a procedure that still retains great benefits. The surface temperatures of common stars range from 30 000 K down to 3000 K, and their apparent 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 and as no laboratory lamps have energy distributions very similar to those observed in stars it is natural that astronomers seek to use the standard candles in the sky. 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 (such as temperature) of the emitting object, but different systems claim to do it more precisely or more efficiently than other systems. Some 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 too confusing and have suggested that 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 a firm quantitative basis and that more care with passband matching will ensure that precise and astrophysically valid data can be derived from existing, although imperfect, systems.

Several recent large-scale astronomical projects are providing significant new magnitudes for large numbers of a wide range of astronomical objects. Firstly, the gravitational lensing projects, such as MACHO, EROS, OGLE and AGAPE, are identifying a range of variable stars and measuring light curves in the GALACTIC BULGE and the MAGELLANIC CLOUDS; secondly, wide-field survey projects, such as the SLOAN DIGITAL SKY SURVEY, are measuring the magnitudes of all objects above a certain brightness in the northern sky. Finally, the remarkable astrometric satellite HIPPARCOS measured extremely precise magnitudes for more than 118 000 stars, mostly brighter than 9th magnitude, over the whole sky and from outside the atmosphere. These projects are indicative of the quality and quantity of data that are becoming available and that will be a great challenge for standard magnitude calibrations.

The magnitude scale of Hipparchus; the intensity scale of Pogson

In the earliest recorded star catalog, HIPPARCHUS (2nd century BC) divided the stars in the sky into six groups. Twenty of the brightest stars that could be seen were called first-magnitude stars and those at the limit of visibility were called sixth-magnitude stars. Intermediate-brightness stars were put in intermediate magnitude classes. In the 18th century, astronomers were using telescopes and had begun to measure the light intensities of stars by closing down the telescope aperture until the image of the star under study just disappeared (the disappearance aperture). By taking the ratio of the squares of the disappearance apertures of two different stars, the relative intensity of the stars' light could be calculated. This was the beginning of astronomical visual photometry. Norman R Pogson (in 1856) at the Radcliffe Observatory compared his measurements of stellar brightness with stellar magnitudes given in contemporary star catalogs (such as those of Stephen Groombridge and the zone observations of Friedrich Argelander and Friedrich Wilhelm Bessel) and suggested the simple relationship $m = 5 \log a + 9.2$ to relate the magnitude m of a star and the disappearance aperture a (in inches). This relation implies a coefficient of 2.5 for the relation between magnitude and the logarithm of the intensity as $I \propto a^2$. Around that time, Gustav Theodor Fechner and Wilhelm Edward Weber (1859) were investigating the response of the eye to light and proposed the following psychophysical law: $m - m_0 = s \log I/I_0$, where m is a perceived brightness and the constant s defines the scale. Pogson's work implied a scale of −2.50 for astronomical visual (eye) photometry, and we thereby have the basis for the inverse logarithmic scale. There was continuing disagreement concerning the adoption of this exact scale of 2.5 and it was not until almost 30 yr later, after the Harvard photometry results were published in 1884, that adoption was ensured. The constant m_0, which defines the zero point, has undergone much refinement since Pogson's estimate and was officially set by the specified visual magnitudes of stars in the 'north polar sequence'. The early photometry catalogs are based on this sequence but the magnitude scale today is established by the contemporary whole-sky photometric standard star catalogs.

New magnitudes from new detectors

Technological advances over the last 100 yr have provided a series of light detectors to supplement the eye. These detectors, in general, respond differently to light of different wavelengths from the eye; that is, they are more sensitive to blue light or to red light than is the eye. The advent of photography in the late 19th century revolutionized astronomy, as did the introduction of photomultiplier tubes with their light-sensitive photocathodes in the mid-20th century and sensors such as silicon charge-coupled devices (CCDs) and infrared detectors over the last 20 yr. Light intensities, or magnitudes, measured with these new detectors naturally differ from the visual magnitudes and depend on the color of the star. Initially, there was only the difference between visual magnitudes and 'blue' photographic magnitudes to be considered, but several factors resulted in a proliferation of different passbands and photometric systems: the extension of photographic and photocathode sensitivities to a wider wavelength range, the use of colored glass filters and interference filters to sample the starlight in narrower bands within the total wavelength sensitivity range of the detectors and, more recently, the requirements of survey instruments to provide maximum sensitivity for the detection of faint objects.

Rationale for multicolor photometry

Much photometry of astronomical objects is carried out in order to measure the apparent total brightness of objects and their relative brightnesses at different wavelengths, that is, their energy distributions. It is possible to characterize the temperatures of most objects from the overall shapes of their energy distributions. It is also possible to infer the metal content of stars from depressions in their energy distributions at particular wavelengths. These depressions (absorption lines) are due to the absorption of flux, principally by Fe and Ti (which have very rich line spectra), Ca, Mg and the molecules CN and CH (which have very strong lines in the blue–violet region of cool stars). There are many other molecular absorption bands (such as TiO, CO and H_2O) that depress the continuum in very cool stars; such molecular features are also used to provide information on the temperature, chemical composition and luminosity. The energy distributions of galaxies and star clusters can be analyzed to extract the relative numbers of different kinds of stars making up these composite objects. REDSHIFTS of very distant galaxies and quasi-stellar objects can also be measured from the positions of depressions or peaks in their energy distributions. These are called photometric redshifts and have been used very successfully with data from the Hubble Space Telescope and the Sloan Digital Sky Survey.

Multicolor photometry is best thought of as very-low-dispersion spectroscopy. The entire high-resolution spectrum of a star or other cosmic object contains a large amount of information, but, when dealing with extremely faint objects or with 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 obtainable from a complete (and very redundant) description of the spectrum. A great deal of effort therefore has gone into accurately measuring and calibrating colors 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.

Finally, GRAVITATIONAL LENSING results in changes in the brightness of the object independently of the color measured. Most intrinsically variable stars, however, have different amplitudes in red and blue light. Consequently, gravitational MICROLENSING surveys are efficiently carried out by splitting the light between a blue and a red channel for simultaneous direct comparison. Equal-amplitude variations in blue and red channels imply a lensing event, not a variable star.

Photometric systems: natural and standard

A light detector, a telescope, a set of filters and a method of correcting for atmospheric extinction make 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 colors that have been measured for a set of typical stars, using 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 'color' is an abbreviation for color index, which is the difference between the apparent magnitudes in two different spectral regions. Photometry results have generally been published as a series of colors and a single magnitude. The zero points of many color systems are set so that α Lyrae (Vega) has zero colors. 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 colors of zero magnitude. (See also STELLAR PHOTOMETRY.)

The original standard systems

The most influential of the early works of photoelectric photometry were the broadband Johnson UBVRI and Kron RI systems, which covered the wavelength region between 310 and 900 nm (3100 and 9000 Å). The natural systems of

Harold L Johnson and of Gerald E Kron and coworkers served as 'standard' systems for many other users who attempted with varying success (owing 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 colors to be the same as the Johnson and Kron colors and magnitudes. They then applied those same linear coefficients to transform the colors and magnitudes of unknown stars onto the Johnson or Kron system. The original blue and yellow filters were chosen by Johnson from readily available glasses so that when used with the 1P21 photomultiplier tube they approximated the ordinary blue (B) photographic response (∼436 nm) and the visual (V) response (∼545 nm). A more violet magnitude U (∼367 nm), which is 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 this UBV system that the weight of history ensured its continuation. Intercomparison of much of the published broadband photometry (in particular, photometry carried out more than 15 yr 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 agrees to better than 0.01 magnitude, or 1%.

The 1P21 phototube was a remarkable invention and its high blue sensitivity dominated the development of photometric systems for over 30 yr. There were red-sensitive devices available but observations were made only for bright stars because for many years these devices were much less sensitive, noisier and less reliable than the 1P21. In the mid-1970s new detector materials became available; in particular, the gallium arsenide and multialkali phototubes, which provided high (≫15% quantum efficiency) sensitivity between 300 and 860 nm, and the infrared-sensitive InSb (indium antimonide) photodiodes together with low-noise preamplifiers, which revolutionized photometry between 1000 and 4000 nm. Both developments enabled photometry to be done on faint stars that had hitherto been the sole province of the blue-sensitive detectors. Photometry done with the new red-sensitive tubes was placed on either the Kron or the Johnson standard system, again with mixed success, and it has only been in the last 10 yr that A W J Cousins' RI 'near-natural' standard system (based on the Kron system) has gained widespread acceptance. It has also been very useful that the Cousins system's R (∼638 nm) and I (∼797 nm) bands are similar to the contemporary photographic R and I bands.

Johnson also introduced the infrared alphabetic JKLMN (approximately 1.22, 2.19, 3.45, 4.75 and 10.4 μm) system in the mid-1960s, using PbS (lead sulfide) detectors and bolometers. The water vapor in the Earth's 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 H_2O absorption bands) to define what he called the J, K, L, M and N bands. Ian S Glass, in his early observations with an InSb detector, used the additional band H (∼1.63 μm), between I and K, and in his choice of filters attempted to match the other Johnson bands. All infrared observers have proceeded in a similar fashion and have concentrated mainly on copying the Johnson K magnitude scale. Identical detectors have been used but a range of slightly different filters and observatory 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.

Passbands or response functions

The most important specifications of a photometric system are the passbands or response functions of its magnitudes. For a variety of reasons, technical and historical, the passbands of the original broadband photometric systems have not been known with certainty and this has inhibited close matching of natural systems and has prevented computation of accurate synthetic colors from theoretical spectra. The recent availability of spectrophotometry for many stars combined with the increased precision of second-generation photometric catalogs has, however, enabled the passbands to be derived indirectly by computing synthetic colors from spectrophotometry of stars with well-defined standard colors and adjusting the passbands until the computed and standard catalog colors agree. This technique has enabled the passbands of the major systems to be well defined, which in turn has permitted filters to be designed that still will result in good passband matches with a variety of detectors. In addition, when it is not possible to match passbands exactly with some detectors, such as photographic plates, it is possible to predict accurately the differences between photographic and photoelectric magnitudes by computing the synthetic magnitudes using the different passbands.

In figure 1 the normalized passbands of the Johnson-Cousins UBVRI system are shown plus an added Z band for CCD observations. The F_ν (flux per unit frequency interval) spectrum of an A0 star is shown for orientation. Table 1 lists the effective wavelengths $\lambda_{\rm eff}$, the approximate bandwidth $\Delta\lambda$, which is the full width at half-maximum of the passband, and the absolute calibration of the UBVRIJHKL 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 color of the objects. The effective wavelengths listed are for an A0 star.

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

Table 1. Johnson–Cousins–Glass UBVRIJHKLM system.

	U	B	V	R	I	J	H	K	L	M
λ_{eff} (nm)	367	436	545	638	797	1220	1630	2190	3450	4750
$\Delta\lambda$ (nm)	66	94	85	160	149	213	307	39	472	460
F_ν ($V = 0$) (10^{-30} W cm^{-2} Hz^{-1})	1790	4063	3636	3064	2416	1589	1020	640	285	154

Table 2. Effective wavelengths (nm) and FWHM bandpasses (nm) for selected photoelectric systems.

	λ_{eff}	$\Delta\lambda$		λ_{eff}	$\Delta\lambda$		λ_{eff}	$\Delta\lambda$
Geneva U	350	47	Walraven W	323.3	15.4	Washington C	391	110
B	424	76	U	361.6	22.8	M	509	105
B_1	402	38	L	383.5	21.9	T_1	633	80
B_2	448	41	B	427.7	49.0	T_2	805	150
V	551	67	V	540.6	70.3			
V_1	541	44						
G	578	47						
Strömgren u	349	30	DDO 35	349.0	38.3	Thuan–Gunn u	353	40
v	411	19	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			

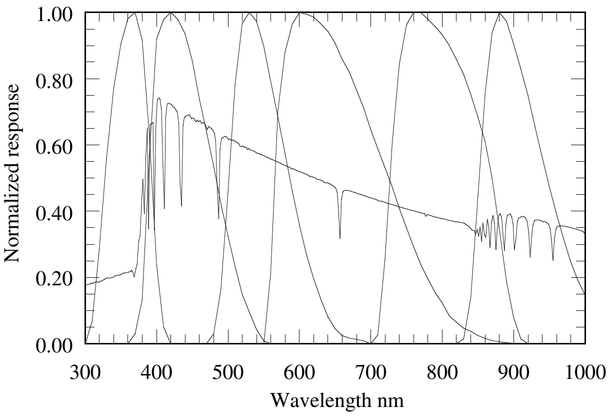

Figure 1. The passbands of the standard UBVRI system.

gravity and interstellar reddening. Some of these systems used broad bands comparable with the UBVRI system, while others used narrower bands defined by different mixes of glass filters or interference filters. Effective wavelengths and other specifications of some of the better-known systems are given in table 2 and are discussed below.

Geneva and Walraven systems

Difficulties with matching natural systems have been eliminated by the strategy employed by proponents of the Geneva ($UBB_1B_2VV_1G$) and Walraven (VBLUW) systems. The latter takes its name from Th and J H Walraven. These multiband photometric systems are supervised by small groups who control the instrumentation and supervise the data reduction and calibration. The colors have been well calibrated in terms of gravity, temperature and abundance. Such closed systems have excellent precision but not necessarily greater than that possible from the open Cousins UBVRI system with careful bandpass matching.

Washington system

This CMT_1T_2 system was devised to use the wideband sensitivity of the extended-red detectors, to improve the sensitivity of blue–violet colors to metallicity and gather more violet light in cool stars and to try to separate the effects of CN from other metal lines. 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 than does V; T_1 and T_2 have no advantages over R and I. The minimal CVI system is very useful for metal-weak K stars.

Strömgren four-color system

The uvby system was devised by Bengt Strömgren to measure better 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. The u band is completely below the Balmer jump; v measures the flux near 400 nm, a region with much absorption due to metal hnes; b is centered near 460 nm and is affected much less than B by metal-line blanketing; y is essentially a narrower V band. The u filter is colored 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. The index $b - y$, 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 nonstandard 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 computing these colors from theoretical spectra, particularly for cool stars. Recent standard catalogs of new and more homogeneous observations are of high precision and internal consistency and it should now be possible to define better the v band. Two additional interference filters (15 and 3 nm wide) centered on the Hβ line are often used together with the four colors. The Hβ index is used to derive luminosities in B stars and reddening in F and G stars. The Strömgren system was the first photometric system devised to measure specific stellar features. Because of the short-wavelength baseline of its four color filters, 1% photometry at least is required to utilize the system's advantages over the UBVRI system.

DDO (35, 38, 41, 42, 45, 48) system

This system (also built around the sensitivity of the 1P21 photomultiplier) was designed for the analysis of G and K dwarfs and giants. The 35 filter is the u filter of the four-color 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 color 35–38 (the 3538 index) measures the Balmer jump, 3842 measures the metallicity and 4245 and 4548 are used for gravity and temperature measurements. By restricting the measurements to the blue spectral region, complicated corrections for spectral line blanketing are necessary to derive temperatures and gravities. Good results, especially for faint K dwarfs, can be obtained by using $V - I$ or $R - I$ as the temperature indicator. Because of the narrow bandwidth of some of the filters, the DDO (David Dunlap Observatory) system has been mainly restricted to relatively bright stars.

Thuan–Gunn system

The uvgr system of Trinh Xuan Thuan and James E Gunn was devised in the mid-1970s from the UBVR system for use with an S20 photocathode detector and in order to avoid the strong mercury emission lines from city lights and [O I] lines in the night sky. The g and r bands are of similar width to the V and R bands whereas the u and v bands are about half the width of the U and B bands. The $g - r$ color has a longer baseline than $V - R$ but transforms well.

Photographic systems

Originally photographic emulsions were only sensitive to light blueward of 490 nm. These were the O emulsions. Different chemical sensitizing shifted the red sensitivity cutoff to longer wavelengths: G 580 nm, D 650 nm, F 700 nm and N 880 nm, 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. Attempts were made to convert the photographic colors onto the photoelectric UBVR system but these were not often very accurate because of limitations in iris photometry and poor matches of the bandpasses. In recent years, astronomical photography has undergone a renaissance caused, first, by the development of new fine-grain emulsions (Kodak IIIaJ, IIIaF and more recently TechPan) and the utilization of methods of greatly increasing the sensitivities of the J, F and TechPan emulsions (using hydrogen gas) and of the N emulsions (using silver nitrate solution) and, second, by the use of new scanning microdensitometers and better methods of intensity calibration. Averages of several wide-field Schmidt camera plates or higher scale prime-focus plates can now produce photometry to a few per cent to very faint limits. 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–Gunn g systems using IIIaJ plates, to Cousins R or Thuan–Gunn r using IIIaF plates, and to 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.

CCD photometric systems

The high quantum efficiency of CCDs and their inherent linearity have made them the detectors of choice in recent years for most areas of photometry. Unfortunately, the advantages of the CCDs were initially not fully attained because some users paid insufficient care to define their passbands and to standardizing their photometry. This resulted in internally precise results but an inability to relate these results with much confidence to the standard system data or to theoretically derived magnitudes and colors. Astronomers now realize the importance of matching their CCD passbands to standard passbands or deriving accurate passbands for their natural systems to enable them to be calibrated using synthetic photometry.

The standard BVRI system can easily be realized with thinned CCDs and colored glass filters but the U system is more problematical owing to the lower UV response of many CCDs. The Z band, between I and J, is also now often added to CCD UBVRI-based systems.

The HST WFPC2 photometric system

The Wide Field Planetary Camera (WFPC2) on the HUBBLE SPACE TELESCOPE has a suite of interference filters that cover both the space UV and the optical spectrum. Although not identical to the well-established UBVRI and uvby systems, there are passbands that are quite similar. A lot of attention has been given to calibrating the WFPC2 system both from actual ground-based observations where possible and from synthetic photometry so that excellent transformations are possible to the older standard systems and reliable temperature calibrations can be made from model atmosphere fluxes. Figure 2 shows some of the WFPC2 bandpasses. Table 3 lists effective wavelengths

Table 3. Effective wavelengths (nm) and FWHM bandpasses (nm) for CCD-based systems.

	λ_{eff}	λ_{eff}	$\Delta\lambda$		λ_{eff}	λ_{eff}	$\Delta\lambda$		λ_{eff}	λ_{eff}	$\Delta\lambda$
HST 336	334	339	47	HIP B_T	421	439	70	SDSS u′	356	360	64
439	430	443	71	V_T	526	542	100	g′	475	500	135
450	451	477	107	H_P	517	595	230	r′	620	632	137
555	532	559	147					i′	761	772	154
675	667	675	127	UBV B	436	464	94	z′	907	907	147
814	788	805	147	V	545	558	85	EROS BE1	485	506	109
				R	641	666	160	RE1	657	679	191
MACHO B	519	543	144	I	791	799	143	BE2	539	575	190
R	682	700	178	Z	909	906	96	RE2	767	796	260

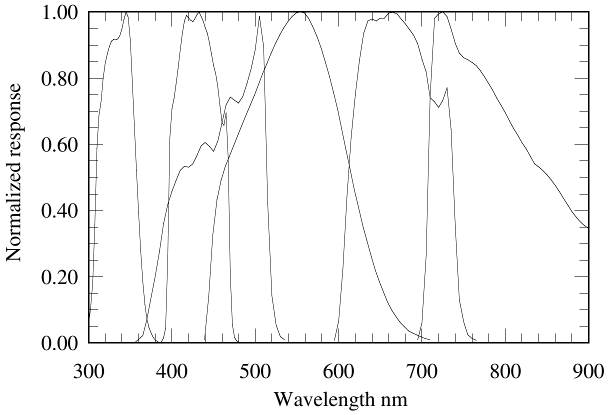

Figure 2. Some of the passbands of the HST photometric system.

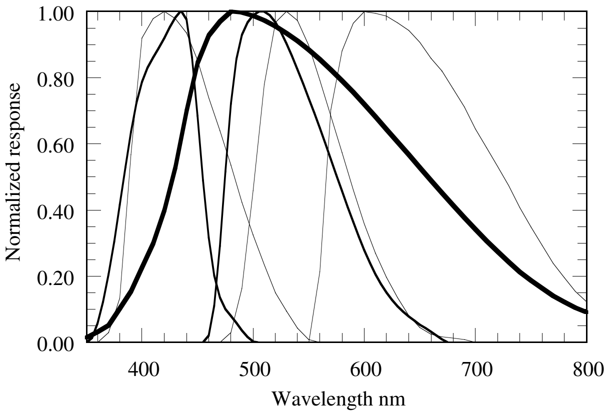

Figure 3. The Hipparcos passbands in comparison with the standard BVR passbands. H_P is shown by the thickest line, B_T and V_T are shown by the medium thick lines and BVR are shown by the thin lines.

(for an A0 and M0 star) and FWHM of some of the HST passbands and those of the other CCD systems discussed below.

The Hipparcos and Tycho photometric systems

The ESA Astrometric Satellite, Hipparcos, used three independent photometric detectors. The main Hipparcos passband (H_p) corresponded primarily to the spectral response of the S20 photocathode of the image dissector scanner combined with the transmission of the optics. The Tycho photometric data were derived from the star trackers and measured magnitudes in B_T and V_T, with passbands somewhat similar to standard B and V. Figure 3 shows the Hipparcos and Tycho passbands in relation to the standard BVR passbands. The large width of the H_p passband results in significant systematic differences between the H_p magnitudes and standard V magnitudes, depending on reddening, metallicity and luminosity. Nevertheless, the extremely high precision H_p magnitudes ($\sim$0.0015) and the lower but still good precision ($\sim$0.012) for the Tycho V_T magnitudes combined with the whole-sky coverage make these catalogs an invaluable resource, not only for measurements of individual stars, but for enabling intercomparisons to be made between and within ground-based photometric systems.

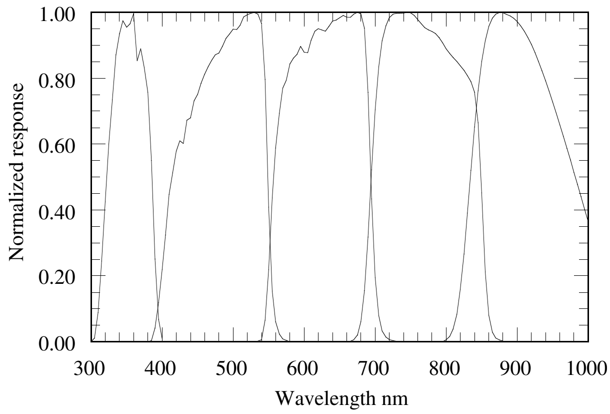

Figure 4. The Sloan Digital Sky Survey passbands.

The Sloan Digital Sky Survey photometric system

This photometric system comprises five color bands (u′, g′, r′, i′ and z′) that divide the entire CCD sensitivity range between the atmospheric UV cutoff near 300 nm and the CCD cutoff near 1100 nm. The passbands, related to those of the Thuan–Gunn system, and shown in figure 4, are essentially nonoverlapping and most are wider than those of the UBVRI system, ensuring high efficiency for faint object detection. For ease of transformation into other systems or duplication of the system by others, it would have been better were the bands to have overlapped more with a less rectangular profile but the system itself will be very well defined by observations made with a duplicate detector and filters on a separate telescope. Unlike most other photometric systems, the zero points of the SDSS system have been placed on the spectrophotometric AB magnitude system defined by the absolute fluxes of four F subdwarfs. The passbands are essentially filter defined and in general have blue edges defined by a colored glass and red edges by a short-pass interference coating (see FILTERS).

Gravitational lensing projects

The MACHO photometric system

The MACHO project for monitoring gravitational microlensing events utilizes simultaneous CCD imaging in two passbands by sharing the light between two cameras using a dichroic beam splitter. The blue and red bands are further limited using an interference filter on the red side and the sensitivity cutoff of the thick CCDs on the blue side. The blue band approximates a broad blue-shifted V band while the red band approximates the R band. Good transformations are possible to the VR system and reliable calibrations are possible using synthetic photometry. As well as detecting many microlensing events, the MACHO project has provided unique and invaluable data on variable stars in the Magellanic Clouds and the Galactic Bulge.

The EROS photometric system

The EROS1 observations were taken consecutively through two broadband filters B_{E} and R_{E} that produced respectively passbands midway between B and V and R and I. Two different sets of filters were used during the course of the observations and the $B_{\mathrm{E}} - R_{\mathrm{E}}$ colors were transformed into V–I. EROS2, like MACHO, has two cameras and the light is divided using a dichroic beamsplitter. The division is made at a redder wavelength (~650 nm) than for the EROS1 system and the EROS2 blue band more resembles the Hipparcos passband.

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