Photometric Systems

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1 Introduction

This lecture aims to give some general information to consider when working with photometric measurements and a description of some particular systems which are in widespread use. The processes of data reduction to determine instrumental fluxes will not be covered, as these are largely instrument, observing mode and telescope specific, as well as taking too much time to cover here.

2 Magnitudes and Colours

In general a magnitude is,

$$m = -2.5\log_{10}(\text{something}) + \text{ZP}$$

where ZP is a constant which sets the zero-point of the magnitude scale. If a measurement of a quantity Q is made in a particular band B in a given photometric system, then by convention the magnitude is,

$$B = -2.5\log_{10}(Q_B) + \text{ZP}_B$$

Often the band B is given a subscript to denote the system it is from when bands of the same letter from multiple systems are being compared (e.g. R_C and R_J for R band magnitudes in Cousins and Johnson systems). The quantity Q is often simply referred to as a 'flux', however this is ambiguous and there are several possibilities that are used in real photometric systems:

1. Energy flux (Wm^{-2}) e.g. for bolometric detectors
2. Photon flux ($\text{s}^{-1}\text{m}^{-2}$) e.g. for photon counting detectors such as CCDs
3. Monochromatic flux density ($\text{Wm}^{-2}\text{Hz}^{-1}$) e.g. for spectrophotometric systems (c.f. AB system)

It is particularly important to note that (1) and (2) are not generally equivalent. Given a number of photons received in some finite bandwidth you cannot trivially say what the total energy of those photons was, and the converse is also true. For narrow bands observing relatively flat-spectrum sources, the variation of $h\nu$ over the band can often be ignored. However for broad bands or any band that is likely to contain sharp lines or jumps, conversion between counts and energies is not possible without detailed knowledge of the spectrum and the system response.

A photometric colour is the difference between magnitudes in two different bands. Within a photometric system one can often measure colours more accurately than individual magnitudes. Indeed it is common to present multi-band photometry as a single magnitude and several colours. It is usually the colours of an object that are of astrophysical interest rather than the observed magnitudes themselves.

3 Performing photometry

A photometric measurement can be summed up as an integral over wavelength,

$$Q = \int_0^\infty f_\lambda R_\lambda d\lambda = c\int_0^\infty \frac{f_\nu}{\lambda^2} R_\lambda d\lambda$$

where Q is the measured quantity and f_λ is the source wavelength flux density (e.g. $\text{Wm}^{-2}\text{Å}^{-1}$), or f_ν is frequency flux density (e.g. $\text{Wm}^{-2}\text{Hz}^{-1}$ or Janskys). R_λ is the total system response as a function of wavelength. For the last part we note that $\frac{d\nu}{d\lambda} = -\frac{c}{\lambda^2}$.

The measured quantity Q above is an energy flux. For photon counting detectors we have to scale f by $1/h\nu \equiv \lambda/hc$ to get the number of photons,

$$Q = \frac{1}{hc}\int_0^\infty (\lambda f_\lambda) R_\lambda d\lambda = \frac{1}{h}\int_0^\infty \left(\frac{f_\nu}{\lambda}\right) R_\lambda d\lambda$$

Of course in a real photometric measurement we do not perform this integral, we just read Q from our detector (or more likely from our reduced data). Hence we can't convert between photon counts and energies. However if we wish to perform photometry in a system based on energy measurements using a photon counting detector we can modify the system response by $h\nu \equiv hc/\lambda$ to compensate,

$$Q = \int_0^\infty (\lambda f_\lambda)\left(\frac{R_\lambda}{\lambda}\right) d\lambda = c\int_0^\infty \left(\frac{f_\nu}{\lambda}\right)\left(\frac{R_\lambda}{\lambda}\right) d\lambda$$

which is the same as the first equation above, but now with a photon counting detector and a modified system response.

3.1 The System Response R_λ

R_λ is effectively the probability that a photon reaching the vicinity of the Earth gets measured by our detector (regardless of whether we are measuring energies or just counting photons). For a space based observatory R_λ is a purely instrumental quantity, however for ground based observations the atmosphere must be accounted for. Hence we split R_λ into an atmospheric and an instrumental component,

$$R_\lambda = A_\lambda S_\lambda$$

3.1.1 Instrumental response, S_λ

Any reflective or transmissive element in the optical path can have a wavelength dependant response. In most photometric observations there are three main parts to consider:

- reflectivity of mirror surfaces (surface material choice, tarnishing)
- filters
- detector response (quantum efficiency)

If transmissive elements such as lenses, beamsplitters and cryostat windows are present then they must be considered too. Obviously the filters are the part which you can choose to define your photometric bands, but for broadband photometry the response of the detector and mirrors are important. Unfortunately many photometric bands in the past have been defined by detector response, which makes duplicating them with different detectors difficult.

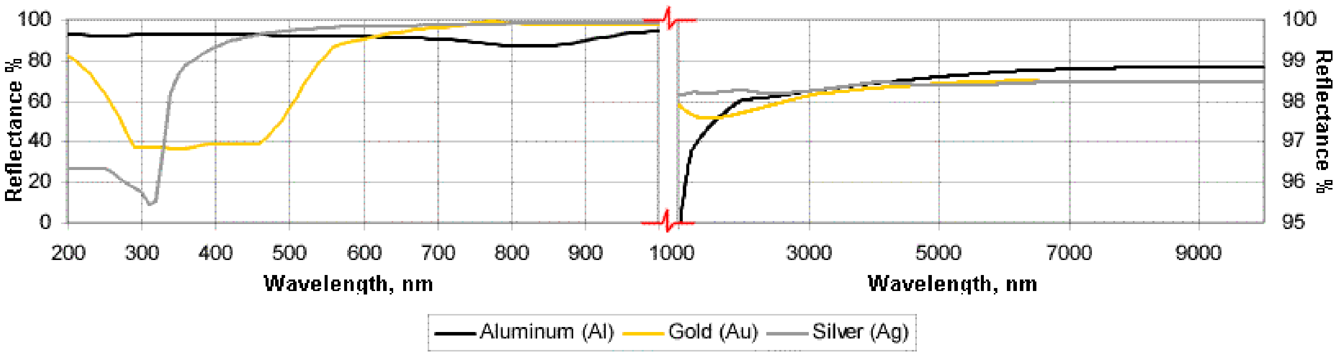


Figure 1: Reflectivity of aluminium, gold and silver at NUV to NIR wavelengths. Note the different scales on the left and right plots. Taken from `http://www.kruschwitz.com/HR's.htm`.

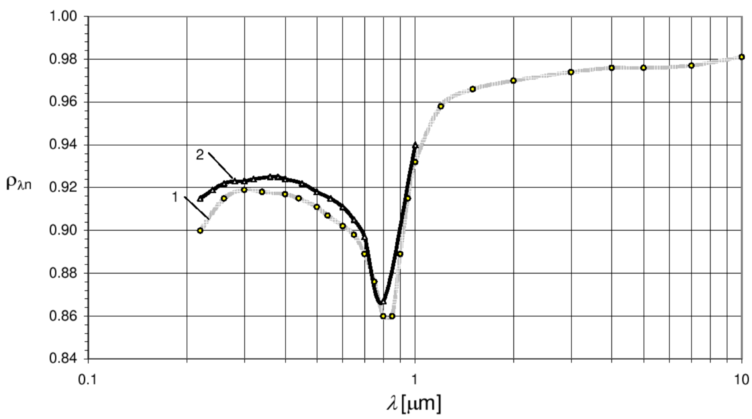


Figure 2: Reflectivity of aluminium at NUV to NIR wavelengths, Taken from Bartl J. & Baranek M, Measurement Science Review, 2004, 4-3, 31.

3.1.2 Atmospheric extinction, A_λ

The atmosphere is by far the biggest limitation and source of frustration for ground based photometry. The visible portion of the spectrum is perhaps the least affected, but atmospheric extinction is still a major consideration. Rayleigh scattering by air molecules has a smooth profile across the visible spectrum, increasing rapidly shortward of about 3000 Å. Extinction from ozone imparts a complicated spectrum on blue observations, and prevents any observations shortward of 3000 Å. Emission/absorption lines in the rest of the visible, whilst a major consideration for spectroscopy, are a relatively minor concern for broadband photometry.

In the near/mid-IR water and carbon dioxide block many wavelength regions, restricting observations to certain bands. The transmission in these bands can very considerably with atmospheric conditions, which limits the accuracy and repeatability of ground-based near/mid-IR photometry. In the far-IR the atmosphere is effectively opaque, although bands at 200 μm and longer (often referred to as the *submillimetre* region) can be used at sites with especially low precipitable water vapour.

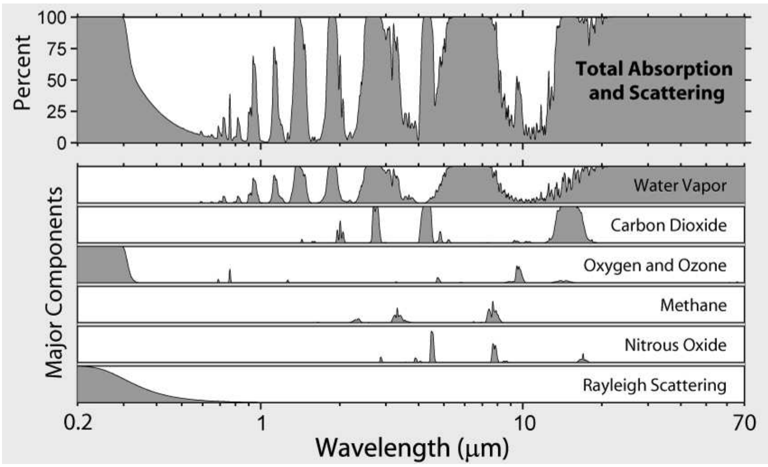
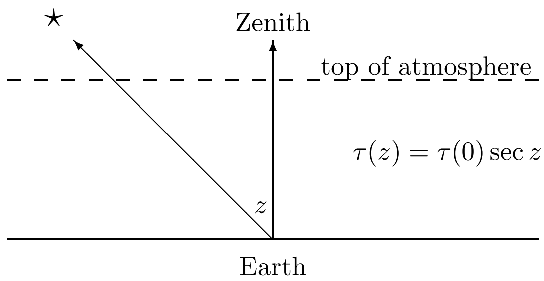


Figure 3: components of extinction from visible to mid/far-IR. Taken from `http://www.globalwarmingart.com`

Atmospheric extinction is a function of *airmass*, $\sec z$. Remembering that transmission $\propto e^{-\tau}$ and that magnitudes are the log of fluxes, we see that we can write an observed magnitude as,

$$m_\lambda(z) = m_{\lambda,0} + e_\lambda \sec z \quad \text{(Bouguer's Law)}$$

where $m_{\lambda,0}$ is the magnitude which would be measured with no atmosphere and e_λ is the wavelength dependant extinction coefficient.



It is possible to determine e_λ by observing standard stars at various airmasses (a minimum of two). If there are standard stars in the field of the target then it is possible to effectively ignore e_λ by including it in the zero-point offset, although this means you have no information about the atmosphere. The advantage of knowing the atmospheric extinction is that the wavelength dependence of the extinction can be used to determine the effect on the photometric bandpass of the atmosphere at the time of observation.

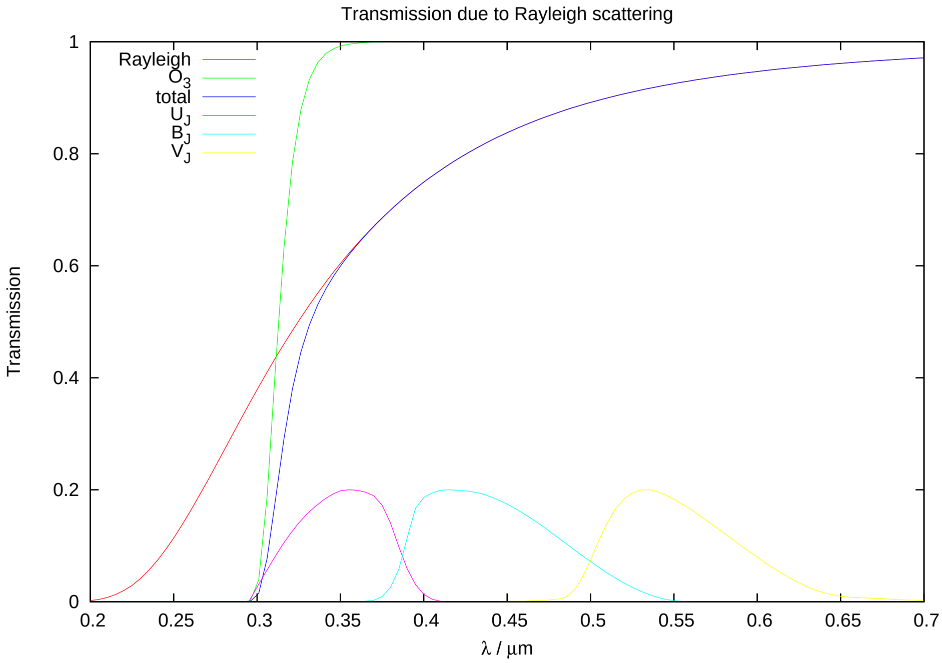


Figure 4: Atmospheric transmission at zenith due to Rayleigh scattering and ozone at NUV and visible wavelengths for a typical atmosphere. Values are plotted for an observer at a pressure of 0.8 atm. Johnson U, B and V bandpasses (arbitrary scale) are shown for comparison. Note that the shape of the blue edge of the U band is determined by the atmospheric transmission. Rayleigh scattering parametrisation from Bucholtz A. 1995, Applied Optics, 34, 2765.

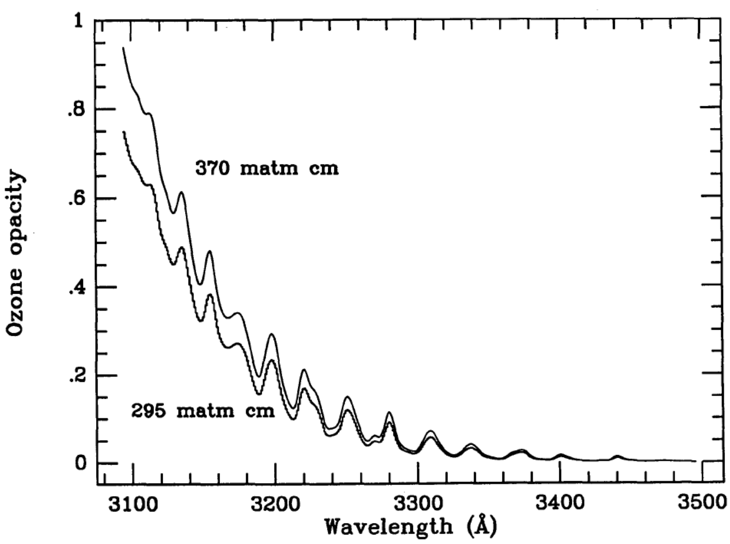


Figure 5: Ozone opacity for maximum and minimum ozone column densities at Kitt Peak observatory (Schachter J. 1991, PASP, 103, 457). Shortward of 3000 Å the atmosphere is effectively opaque.

3.2 Standard stars

To avoid needing highly accurate determinations of R_λ, photometric systems are traditionally defined by the magnitudes of sets of standard stars. These should ideally be well distributed over the sky and cover a wide range of magnitudes, types of object and colours.

Recently determinations of R_λ have become good enough to allow calculation of accurate *synthetic* photometry to be performed using astrophysical models or observed spectrophotometry. This allows defining systems in terms of ideal sources e.g. flat f_ν or f_λ as in AB and STMAG systems (see sections 4.3 and 4.4).

3.3 Transforming between similar photometric systems

When we refer to a photometric system what we mean is a set of system responses (bands) and a definition of the zero point for each band. As the system response includes the telescope and the atmosphere at the observing site which defined the system, it is rarely possible to exactly recreate the system responses of a standard system. If it is desired to make observations in a common photometric system, then what is done is to approximately recreate the system responses of the photometric system and then apply corrections based on knowledge of the type of object being observed. These corrections are usually determined empirically, and are expressed in terms of colours in the photometric system, hence they are referred to as *colour corrections*.

As an example, here is a transformation from Tycho B_T,V_T to Johnson B_J,V_J for unreddened main-sequence stars (taken from "Guide to the Tycho-2 catalogue"):

$$V_J = V_T - 0.090(B_T - V_T)$$
$$(B_J - V_J) = 0.850(B_T - V_T)$$

The transformation between systems is really dependant on the spectrum of each object, and colour corrections are just an approximation to this. However, converting to a standard system in this way is acceptable as long as the colour corrections are small (not much larger than the uncertainties in the measured magnitudes), and are well determined for the type of object being studied. This is particularly useful for small publications of photometry as it allows direct comparison with other measurements. Conversely, for large photometric surveys it is best to use the system in which the observations were made without converting to a standard system (i.e. define a new system), and publish colour corrections to common systems if desired. Within a survey it may still be necessary to determine and apply colour corrections if for instance the instrumental setup changes slightly or multiple observatories are used.

4 Zero Points

4.1 Vega systems

In historical visible photometric systems a common choice of zero point is to set the colours of the Northern A0 V star Vega (α Lyr) to be zero, i.e. it has the same magnitude in all bands. In the Johnson system Vega has a magnitude of 0.03 in all bands. At visible wavelengths Vega is a reasonable choice of standard as it is not variable, it is single, it is bright over the whole visible spectrum, and is relatively unreddened by interstellar dust. Unfortunately Vega is too bright to observe with most modern instrumentation, so it is not possible to directly place observed photometry or spectrophotometry on a Vega system. Other standards must be used, which will have only been calibrated against Vega with older instruments. An A0 V star exhibits quite strong hydrogen absorption lines, which will fall in many photometric bands, making calibration more difficult. At mid-IR and longer there is also strong emission from a debris disk around Vega, making it of much less use as a standard at these wavelengths.

4.2 Gunn systems

Instead of using Vega as a reference these systems adopt F-type subdwarfs (very metal deficient main sequence stars) as standards, in particular the star BD +17 4708. In these systems BD +17 4708 is defined to have all colours equal to zero, with all magnitudes equal to 9.50, which is approximately equal to its Johnson V magnitude.

These stars have very smooth spectra at visible wavelengths and are significantly fainter than A0 stars like Vega, so there are many unreddened examples with suitable magnitudes distributed randomly over the sky. By comparison most A0 stars of similar magnitude are in the galactic plane and more subject to interstellar reddening.

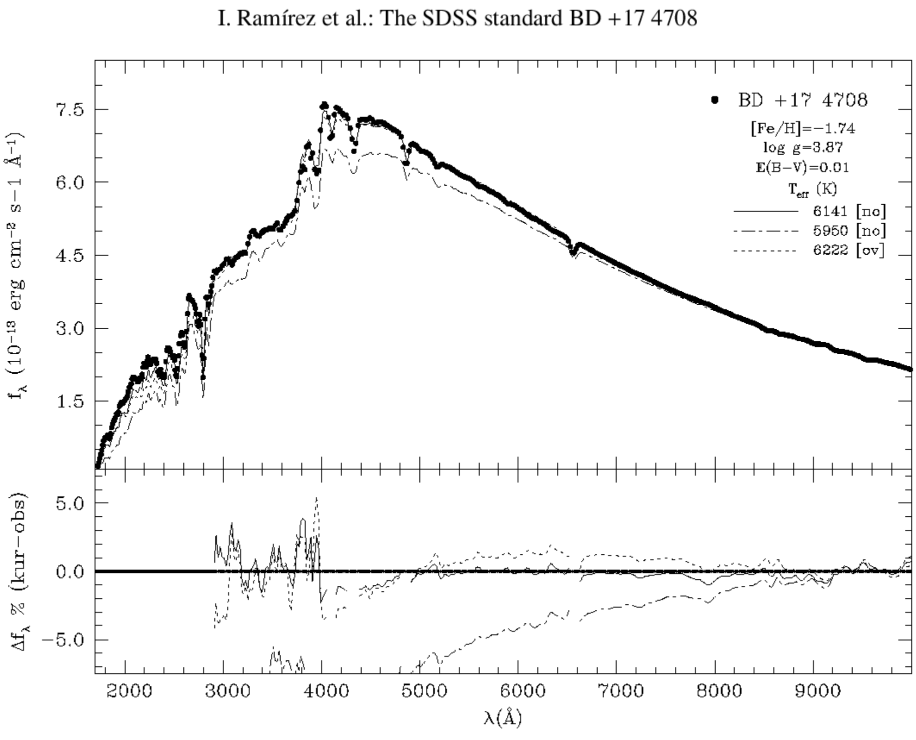


Figure 6: Visible spectrum of BD +17 4708 from Ramìrez I. et al. A&A 2006, 459, 613. Note the lack of strong features longward of 5000 Å.

4.3 AB systems

AB (ABsolute) systems define the colours of a source of constant frequency flux density, f_ν to be zero. Zero magnitude in these systems corresponds to the flux density of Vega at the effective wavelength of the Johnson V band (∼5500 Å).

The main advantage of this system is that it allows spectrophotometry to be presented in magnitudes. The AB magnitude corresponding to a monochromatic flux density f_ν is defined to be,

$$\mathrm{AB}_\nu = -2.5 \log_{10} f_\nu - 48.60$$

4.4 STMAG systems

This is conceptually the same as the AB system, except colours are zero for a source of constant *wavelength* flux density, f_λ. This is the normalisation system used for Hubble Space Telescope photometry. Again zero magnitude in these systems corresponds to the flux density of Vega at the effective wavelength of the Johnson V band ($\sim$5500 Å), leading to,

$$\mathrm{STMAG}_\lambda = -2.5 \log_{10} f_\lambda - 21.1$$

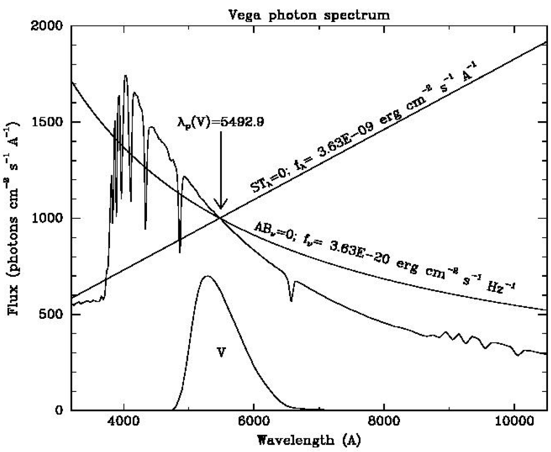


Figure 7: Spectra in units of photon flux for zero points in Vega, AB and STMAG systems.

5 Common photometric systems

Here I will give some information about some specific optical and near-IR systems in current use.

5.1 Visual magnitude

The definition of magnitudes originated from observations made by eye, so the first system was naturally the response of the human eye. V bands in systems since then have usually been designed to be similar to this.

5.2 Photographic magnitudes

Photographic emulsions are most sensitive to blue light, and a typical photographic response defines the photographic magnitude system. A *photovisual* system was constructed by adding a yellow filter to emulate the visual response. Photographic magnitudes are inherently inaccurate due to the nonlinear response of photographic emulsion. Photographic systems are still used from all-sky Schmidt surveys, but for any accurate work follow-up photoelectric photometry is usually needed.

5.3 Johnson & Morgan UBV

B and V bands are intended to match photographic and photovisual bands described above, and a shorter wavelength U band was introduced. The system uses a particular photomultiplier tube (RCA IP21) with a filter for each band (2 for the B band) and assumes aluminium mirrors. Problems with this system are that the blue cutoff of the U band is set by the atmosphere, and the red cutoff of the V band is set by the photomultiplier. As these bands are so widely used it is common to get filters for different detectors that will closely match the UBV bands.

5.4 Johnson extensions

After the Johnson & Morgan system was defined in 1953 it has been extended many times, with bands added at longer wavelengths and intended for different detectors. Johnson did provide R and I bands, but these were not accurately defined. Later two standard sets of R and I bands were constructed by Kron and Cousins, and both systems are still in use. These systems are often written as $UBV(RI)_C$ or $UBV(RI)_K$.

Near-IR bands ($ZJHKLMNQ$) were added, but there is little standardisation and it is almost always necessary to work in the system of a particular observatory rather than transforming to any other system.

5.5 Hipparcos/Tycho

The Hipparcos satellite provided extremely accurate (of order 1 millimag) visible photometry in 3 bands. The Tycho bands, denoted V_T and B_T were intended to be similar to Johnson V and B filters. The band used for astrometric measurements, denoted Hp, is very broad with a peak response between the V and B bands. The zero points of the Hipparcos/Tycho photometry are chosen to match the Johnson system such that,

$$Hp = V_T = V_J \quad \text{for } (B - V) = 0$$

$$B_T = B_J \quad \text{for } (B - V) = 0$$

Hence this is effectively a Vega system, with $Hp(\text{Vega}) = V_T(\text{Vega}) = B_T(\text{Vega}) = 0.03$.

5.6 2MASS $JHKs$

Near-IR bands are in general largely determined by atmospheric windows, so almost all near-IR systems have a J, H and K band. The 2MASS $JHKs$ bands are similar to the Johnson JHK ones, with the main difference being that Ks has a bluer red cutoff to reduce the effects of thermal emission. It is important to note that the J band's red cutoff is determined by the atmosphere and varies with the amount of water vapour from night to night.

2MASS magnitudes are normalised to a Vega system, but with Vega having a magnitude of 0.00 rather than 0.03 as in the Johnson system. Objects brighter than around 4th magnitude in any of the 2MASS bands are saturated, so 2MASS photometry is only accurate for sources fainter than this. Atmospheric transmission uncertainty limits the precision of 2MASS magnitudes to about $\sigma = 0.04\,\text{mag}$.

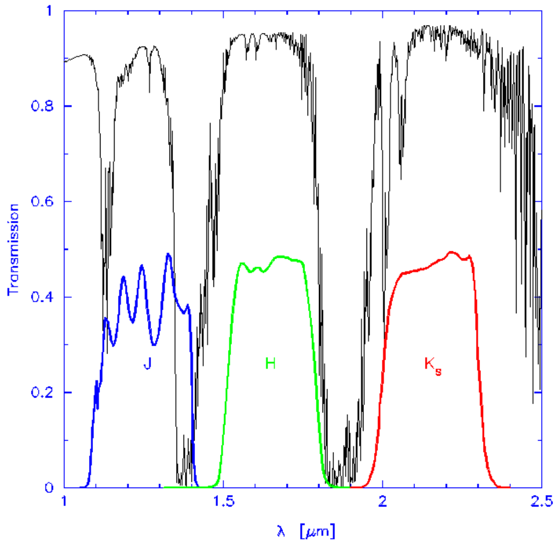


Figure 8: Instrumental and typical atmospheric response (S_λ and A_λ in the notation above) for 2MASS bands.

5.7 SDSS $u'g'r'i'z'$

This is a Gunn system using F-type subdwarfs as primary standards. The bands span the full sensitivity range of CCDs from 3000 to 10000 Å. The band profiles have been chosen to avoid atmospheric absorption/emission lines to improve repeatability, and have been optimised for providing photometric redshifts of galaxies rather than determining properties of stars.

The reason for the primes ($'$) in the band names is that the bands are shifted relative to the designed (unprimed) bands, due to the filters being used in a vacuum.

5.8 Strömgren $uvby\beta$

All the preceding systems have been composed of broad bands, which make them suitable for a wide range of astronomical sources, including faint ones for which a wide bandwidth to gather photons is desirable. The Strömgren system uses narrow bandwidths and is intended for determining parameters of stars, primarily T_{eff} and $\log g$. There are two filters of differing widths centered on the Hβ line.

References

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[3] Kitchin C.R., 2003 book, "Astrophysical Techniques", ISBN: 0-7503-0946-6