

## Photometric reduction - extinction and standard systems

Also see paper by Sung and Bessell 2000 PASA 17, 3.  
Standard stars - CCD photometry, Transformations and Comparisons.

### 1. Atmospheric extinction and absorption.

In the UV- visible - red part of the spectrum light suffers mainly continuous absorption by the air molecules, aerosols and dust particles. There are also absorptions at specific wavelengths from mainly O<sub>2</sub>, CO<sub>2</sub> and H<sub>2</sub>O. Ozone causes the atmospheric cutoff below 290nm.

The continuous absorption is proportional to the path-length traversed while the specific absorptions show a curve of growth effect as for any other line absorption and are often saturated and do not vary directly with path-length. To remove these absorption lines and bands in spectrophotometry one usually measures a pseudo\* line-free star and divides the other stars by this stellar line-free spectrum thus removing the atmospheric or "telluric" lines.

The usual practice in optical photometry is to correct the data to outside the atmosphere (airmass of 0). In the IR one usually corrects to inside the atmosphere at the zenith or an airmass of 1. The difference arises from the fact that one can assume an extrapolation from airmass 1 to 0 in the visible but not in the IR (due to the optical thickness of the H<sub>2</sub>O absorption). Theoretical absorptions of standard atmospheres can be used if one needs to produce outside atmosphere absolute fluxes for comparison with model fluxes.

The differential form of the atmospheric continuous absorption is

$dI = -I\tau dx$  where  $I$  is the intensity,  $\tau$  is the absorption coefficient / unit length.

Integrating this through the whole atmosphere, taking logs and then making mags one gets

$m_0 = m_{obs} - kX$ . It is usual to express the length  $X$  in units of the airmass at the zenith, and the extinction is expressed in magnitudes per airmass. Normally one observes high enough above the horizon that we can treat the atmosphere as a plane parallel slab and use  $\sec Z$  as the length.

$\tan z = \sin(\text{Lat}) \sin(\text{Dec}) + \cos(\text{Lat}) \cos(\text{Dec}) \cos(\text{HA})$        $\sec z = 1/\cos z$

But there are simple polynomial expansions in terms of  $\sec Z$  to account for the curvature. One such expansion is given by Young (1974) as  $X = \sec z (1 - 0.0012 \tan^2 Z)$ .

The continuous extinction of the atmosphere is primarily Rayleigh scattering by gas molecules which is proportional to  $\lambda^{-4}$ , and scattering by larger particles, aerosols and dust which is almost independent of wavelength. (In the IR the absorption is dominated by water, which incidentally is therefore the overwhelming green-house gas.)

The  $\lambda^{-4}$  component therefore shows only a small seasonal variation while the neutral component shows a much larger variation, due to volcanic eruption (H<sub>2</sub>SO<sub>4</sub> ejection), smoke, dust and haze.

That is, the colour terms in extinction should be fairly constant with the main variation in the neutral. Mean extinction coefficients, weekly even monthly or yearly can be used quite successfully for visible photometry although it must be monitored because of the possibility of it changing due to stratospheric and local particulate injections. In the IR especially in the summer the extinction is a big problem and can vary on short time scales, minutes to hours and must be monitored continuously.

Because of the rapid change of extinction with wavelength in the UV and blue, the extinction will vary significantly across the wavelength band of a broad band filter, And because stars of different temperature have fluxes that also vary significantly across a broad band pass, (we say that a red star has a redder effective wavelength than a blue star) the result is that blue stars will undergo greater light loss in the U and B band than does a red star. This effect on the extinction is usually accounted for by introducing a colour term in the extinction coefficient. This can be calculated theoretically from stellar fluxes, filter bandpasses and extinction curves but is often measured by observing pairs of blue and red stars at several airmasses.

That is at two airmasses 1 and 2

for the blue star,  $m_1 - m_2 = k_b (X_1 - X_2)$  and for the red star  $M_1 - M_2 = k_r (X_1 - X_2)$  and  $k_b \neq k_r$ .

So by plotting  $k_b$  &  $k_r$  against the B-V or V-I colours of the stars one fits a linear relation

$k = k' - k''(B-V)$  or  $k = k' - k''(V-I)$ , where  $k'$  is called the primary extinction coefficient and  $k''$  the secondary extinction or colour term. SPIDER permits a colour term for all magnitudes or colours, but in

general people have decided to use a colour term in the B-V but not the U-B extinction. The U-B extinction is double valued with colour because of the discontinuous effective wavelength shift for stars with a large Balmer Jump so Johnson decided to not complicate things with this and adopted no colour term in his original system.

Extinction can be measured by following a star as it moves through different airmasses with time but the best method is to observe groups of standard stars at different airmasses, say a group at 1.75 and other groups at 1.5, 1.3 and 1.0 within a short time of each other. In this way you measure the "instantaneous" extinction and not have to wait many hours on a single star during which time the sky could have changed. Given a choice, never work at airmasses greater than 2.0 and try and avoid exceeding 1.5. Most importantly ensure that your standards cover the airmass range of your program stars. Plan your observations and predict the airmasses that your program stars will be at and at what time.

The UBVRI system has traditionally been reduced using the V magnitude but the U-B, B-V, V-R, V-I, or R-I colours. You should stick with this approach if at all possible. On the other hand it is only by reducing U, B, R, and I individually can you see how closely your passband matches that of the standard system. CCD photometry is invariably reduced in this way as well.

Typical extinction values for UBVRI

V = 0.15 - 0.19 (got to 0.24 during the Pinitubo eruptions)

U-B = 0.28

B-V = 0.12 - 0.02(B-V)

V-R = 0.04

R-I = 0.035

Having solved or adopted extinction values one corrects all the data to outside the atmosphere.

*To reiterate, in general extinction does not vary much night to night or more specifically the colour extinction (the extinction in U-B, B-V, V-R, V-I) does not change from night to night. The neutral can, and this shows up as a variable extinction. in U, B, V, R and I. This means that if one gets the extinction well in one band, say V, extinction in the other bands can be calculated from the normally constant colour extinction values*

### **Getting onto the standard system.**

The next step is to compare the outside atmosphere magnitude and colours for the standard stars with their "standard" values. For this one calculates the differences  $v_{\text{obs}} - V_{\text{true}}$  etc and regresses these differences against a relevant colour. If one's natural system is identical to the standard system then there should be no slope in the regressions. In general this will not be the case. Most programs calculate a linear regression. This can lead to systematic errors so be careful. But people like linear fits because they get two numbers, a zeropoint and a slope which can be compared from night to night, or run to run, whereas the coefficients of a quadratic or cubic fit cannot be so compared. The best photometrists reduce their data to their own natural system or to a linear system and only transform to the "standard" system when their observations are complete. This enables them to use a higher order fit to the standard system but keep the advantages of linear fits from night to night. One can do this by back transforming the standard colours to one's natural system for the transformations. Others do it by applying standard non-linear corrections before doing linear fits. Either ways, it makes the external errors the smallest.

If one finds it necessary to use 2 straight line segments, then make sure that the colour separating the 2 sections are recorded and that the break is always made at the same spot.

Try and understand why there is a colour term of the size that is measured and this will help one decide what colour to regress against. For example it is better to use B-V in the V transformation than V-I. Why? If you use V-I or V-R then you should use 2 different slopes. Colours involving R will always have two slopes because the shape of the R band produces a large excursion in the effective wavelength of R for M stars. Sometimes it is better to use two colour terms in the transformation, for example B-V sometimes has a U-B as well as a B-V term in it. Most programs do not allow this.

*The closer one's passbands are to the standard the smaller the colour terms, the less complicated the corrections and the more likely the astrophysical correctness of the standard colours are measured.*

The choice of standards stars is most important. Best to use the standards of Cousins & Menzies et al. from the SAAO. Landolt equatorial stars are good but there are some subtle differences; in particular the U-B systems are not the same. Bessell (1995) has published corrections to the Landolt system to put those standards onto the Cape-Cousins system. The transformed values can be obtained by anonymous ftp from [mso.anu.edu.au](http://mso.anu.edu.au). Login as anonymous, password your email address, cd /pub/bessell/.

### **Other standard systems.**

There are several photometric systems other than the UBVRI system that are increasingly in use.

See article by Bessell in the new Encyclopedia. Can be downloaded from

<http://www.mso.anu.edu.au/~bessell/>

### **Comment on the use of "smooth" stellar spectra for atmospheric lines and band removal.**

See paper by Bessell on spectrophotometry for details and for lists of standard stars and smooth stars.

PASP 111, 1426, 1999.

\* For low resolution observations, for wavelengths between 400nm and 1000nm the spectrum of an extremely metal-poor K star, ( $[\text{Fe}/\text{H}] < -2.0$ ) such as HD140283, HD122563, HD2796, HD4306 are normally used. Before being used for division, one needs to remove the hydrogen and other strong lines such as Ca I & II, Na I. Most sharp telluric lines are redward of about 589nm. but shallow broad ozone absorption is evident below 330nm. For wavelengths below 400nm it is good practice to use an O star perhaps an O subdwarf with very little Balmer jump and very weak lines, not for atmospheric absorption correction but for first order detector/grating sensitivity correction. See Bessell PASP 111, 1426 1999 for lists of such stars.

\* At high resolution, the metal-poor stars have too many lines to be used successfully to divide through by so it is better to select a very fast rotating star which will only have very broad lines. The sharp telluric lines then stand out very clearly. Choose a fast rotating mid-B star if possible which will have only a few lines. These broad lines should be removed by hand before dividing. The more recent Yale Bright Star Catalog (HR) indicates the rotational velocity of stars so provides a good source list.

\* In the IR, ie beyond 1 micron, at low resolution, an early G dwarf or a halo K giant are good stars to divide through by. At high resolution it is necessary to use a broad line early-type star again.