Photometry

Lecture 4 at 1st ISGL

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Contents of this Lecture

- Effects of the atmosphere
- Magnitude Systems
- Filter Systems
- Photometric Calibration
- Howto Measure Colors of Objects

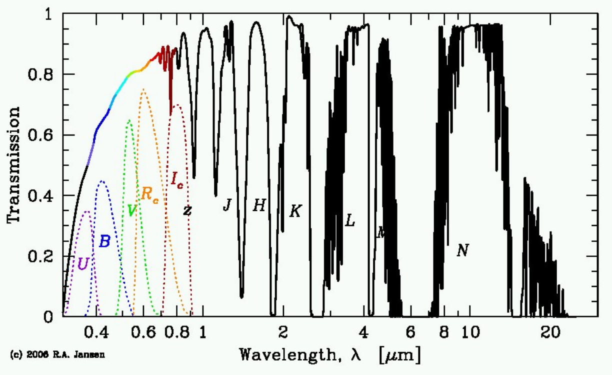
Atmospheric Effects

When the Sun rises or sets it looks redder than when it is high in the sky. The same is true for stars, but there are a number of other important effects as well.

We will look at

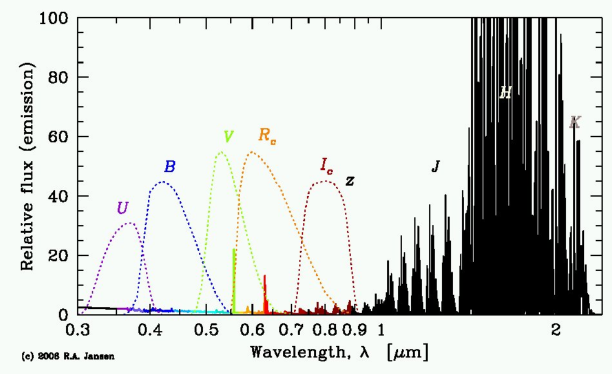
- Atmospheric transmission and emission
- Scattering
- Refraction
- Dispersion
- Seeing
- Scintillation

Atmospheric Transmission



Atmospheric transmission from UV to mid-IR. Absorbing molecules are mostly O_3 (near-UV and visible) and O_2, H_2O, CO_2, and N_2O in the IR. Strongly depends on precipitable water vapour.

Atmospheric Emission



The visible sky is relatively free from emission, except the Oi lines at 5577Å, 6300Å, and 6363Å. Beyond ∼ 7500Åthe spectrum is dominated by series of OH lines. Their strength varies from night to night (or even faster).

Sky Brightness as Function of Moon Phase

Lunar Age	U	B	V	R	I
0	22.0	22.7	21.8	20.9	19.9
3	21.5	22.4	21.7	20.8	19.9
7	19.9	21.6	21.4	20.6	19.7
10	18.5	20.7	20.7	20.3	19.5
14	17.0	19.5	20.0	19.9	19.2

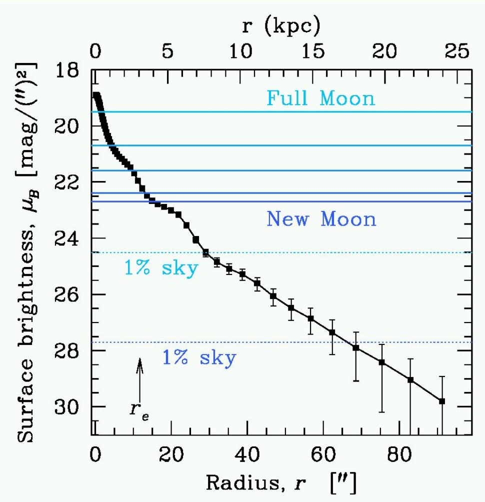
At CTIO according to Alistair Walker, NOAO Newsletter #10, measured in mag/arcsec^2.

Note that 5 mag difference is a factor 100 in flux!

Also depends on angular distance to the moon.

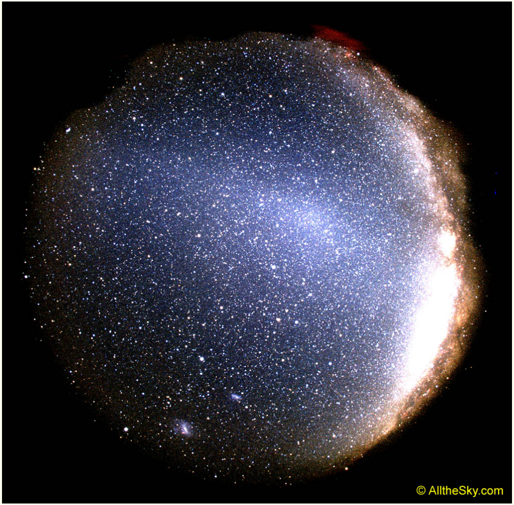
Consequence for Extended Objects

Surface brightness profile of a near-by spiral galaxy.



Jansen et al. 2000, ApJSS 126, 271

Zodiacal Light and Gegenschein

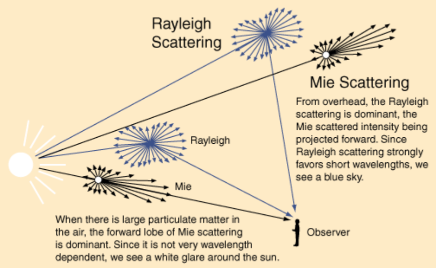


Sun light reflected by dust in the Solar System.
Non-atmospheric variation of sky brightness.

Scattering in the Atmosphere

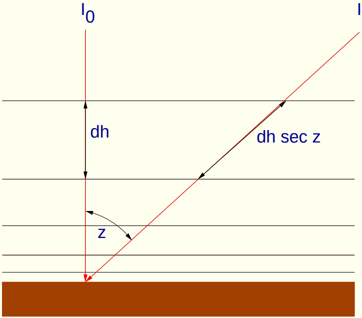
Two types of scattering are important in the atmosphere

1. Rayleigh scattering – If the scattering particles are much smaller than the wavelength. $I \propto \frac{1}{\lambda^4}$, radial dependence $\propto (1 + \cos\theta)$.
2. Mie scattering – If the scattering particles are comparable in size to the wavelength. Strong forward scattering, almost wavelength independent.



Extinction = absorption + scattering

Extinction and Airmass



$$\mathrm{d}I = -I\kappa \mathrm{d}h$$

$$\ln I = \int_0^\infty \kappa(h)\mathrm{d}h + \mathrm{const}$$

We denote the extinction coefficient for one airmass by K.
With a zenith distance z we then have

$$\frac{I}{I_0} = e^{-K \sec z} \quad \text{with} \quad \sec z = \frac{1}{\cos z}$$

$$m - m_0 = -2.5 \log(I/I_0) = -2.5 \log(e^{-K \sec z}) \approx 1.086\, K \sec z$$

Refraction and Dispersion

Atmosphere is curved, not plane parallel as assumed before.

Light path is curved due to refraction in the atmosphere.

For very precise photometry it may be necessary to replace z with a function $M(z)$, $M(0) = 1$. $M(z)$ is tabulated, but often only for standard pressure at sea level.

Refraction also changes the zenith distance of an object. The observed zenith angle is always smaller than the true one.

Refraction is also wavelength dependent, this is called atmospheric dispersion. The refraction index is higher for shorter wavelength.

This leads to a color dependent change of zenith distance.

Dispersion

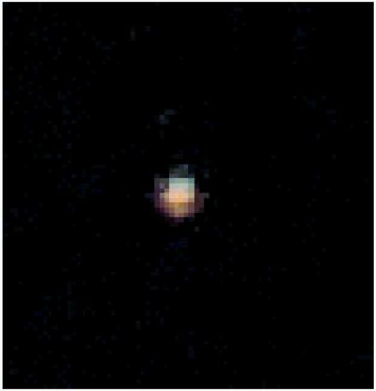


Figure 5: Example of the effects of atmospheric dispersion. The stellar image above was observed in a quick succession of BVR exposures at the 6.5 m Magellan '*Baade*' telescope with the IMACS instrument in Dec 2003 (R. Jansen & R. Windhorst) — before the atmospheric dispersion corrector was commissioned. The air mass was 1.33 (i.e., $z \simeq 41°$) and the seeing $0''.75$ (3.38 pixels) FWHM. Atmospheric dispersion caused a noticeable differential shift of the centroids of the B and R images on the CCD of $\sim 1''.0$.

R.A. Jansen

Seeing and Scintillation

Along its path through the atmosphere the light encounters turbulence. In turbulence the density and with it the refractive index changes. Turbulence leads to two separate effects:

1. Seeing
2. Scintillation

Seeing is caused by the atmosphere up to several tens of meters above the telescope and is a broadening of the PSF.

Scintillation is caused by turbulence at several kilometers altitude. It is a change of intensity, seen as the twinkling of stars.

Magnitude Systems

Magnitudes are defined as a relative unit:

$$m_1 - m_2 = -2.5 \log\left(\frac{f_1}{f_2}\right) = -2.5 \log f_1 + 2.5 \log f_2$$

How can we tie this to a physical flux scale?

The historical reference is Vega (αLyr), which by definition has $m_{\rm Vega} = 0$ in all passbands.

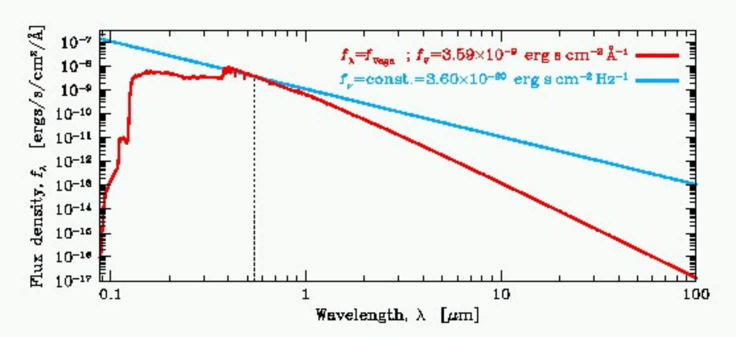
Then

$$m = -2.5 \log f_\lambda + 2.5 \log f_{\lambda,\rm Vega}$$

The last term is called the "zero point" in the Vega magnitude system.

Note that above definition also means that Vega has a color of 0 in any two filter pairs.

The Vega Spectrum



R.A. Jansen

The Vega spectrum is very different from a constant flux density. Consequently, $m = 0$ corresponds to very different physical fluxes in different passbands.

Magnitude Systems

To avoid the changing flux densities in the Vega system and exceedingly small fluxes outside the UV and near-IR, the AB magnitude system was devised by Oke & Gunn in 1983.

In the AB magnitude system the reference spectrum is flat in $f_\nu = \text{const}\,[\text{ergs}\,\text{s}^{-1}\,\text{cm}^{-2}\,\text{Hz}^{-1}$.

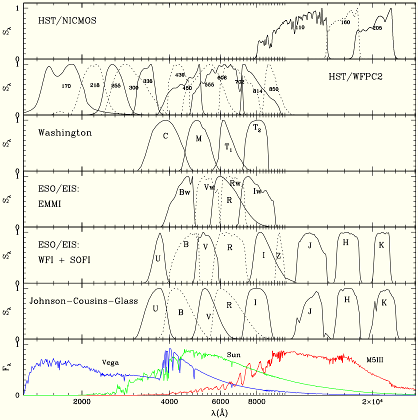
The constant is chosen such that $m_\text{V}^\text{Vega} = m_\text{V}^\text{AB} = 0$, or $f_\nu \mathrm{d}\nu = f_\lambda \mathrm{d}\lambda$ averaged over the V filter.

However, most magnitudes are still given in the Vega system. The AB system is often preferred for extragalactic and near-IR observations.

If nothing specified, assume Vega.

Filter Systems

A number of filter systems has been developed since the original Johnson UBV system. Some are expansions of the Johnson system, like Johnson UBVRIJKL, others are completely new. Some examples from Girardi et al. (2002):



Filter Systems

Just a few examples:

- Johnson – U, B, V, R, I, expanded to near-IR by J, K, L. Blue cut-off determined by atmosphere, not by filter.
- Kron-Cousins/Cousins – R_c, I_c are better behaved at the red end; better positioned with respect other filters.
- Strömgren – u, b, v, and y. Medium band filters, designed for stellar astrophysics. u and b straddle the Balmer and Ca H+K break at 4000 Å.
- Washington system – C, M, T_1, T_2 designed for metallicity studies in old stars.
- 2MASS filters J, H, K_s ("K-short") – shifts K to an effective wavelength of 2.15 μm, avoiding the strong OH bands at the red end of Johnson K.

Filter Systems

More examples:

- Gunn – u, g, r, i, z have steeper cut-offs. Precursor of HST and Sloan filters.
- Sloan filters – u', g', r', i', z' with square filter transmission curves and minimal overlap and minimal gaps between filters. Optimal broad-band filter for photometric redshifts.

Plus a few more broad-band systems, medium-band filter, and a whole bunch of narrow-band filters for different emission lines, both at rest and redshifted.

In addition, it is very difficult (impossible) to recreate filter transmission curves exactly matching the original transmission curves. This leads to the concept of instrumental magnitudes, that need to be converted to standard system magnitudes.

Photometric Calibration

We cannot always observe Vega to calibrate our data (especially from the Southern hemisphere).

Several dozen of secondary standards were measured by Johnson during WWii in his UBV system. A number of inconsistencies in magnitudes and colors was discovered later. To minimize inconsistencies $m_{\mathrm{V}}(\mathrm{Vega})$ was adjusted to $+0.035 \pm 0.012$.

In 1992 Arlo Landolt published $UBVR_cI_c$ photometry for a number of standard fields containing several stars each close to the celestial equator. Landolts system is again slightly different from the original Johnson system.

In 2000 Peter Stetson published a catalog of many more standard stars on the Landolt 'Selected Areas', but without U-band magnitudes. Stetson photometry is reduced onto the Landolt system.

Excerpt from Landolt's Catalog

TABLE 1. *UBVRI* photometry of Baldwin–Stone secondary spectrophotometric standard stars.

	1985.0										Mean Errors of the Mean					
Star	α	δ	V	B-V	U-B	V-R	R-I	V-I	n	m	V	B-V	U-B	V-R	R-I	V-I
	h m s	° ′ ″														
LTT 377	00 41 02.9	−33 44 06	11.219	+0.477	-0.083	+0.292	+0.296	+0.588	16	9	0.0010	0.0015	0.0028	0.0008	0.0015	0.0018
LTT 1020	01 54 08.6	−27 32 53	11.510	+0.551	-0.222	+0.357	+0.368	+0.725	14	9	0.0016	0.0024	0.0029	0.0013	0.0027	0.0024
EG 21	03 10 22.1	−68 39 28	11.366	+0.033	-0.708	-0.088	-0.077	-0.164	14	9	0.0016	0.0008	0.0035	0.0013	0.0024	0.0024
LTT 1788	03 47 49.8	−39 11 19	13.145	+0.466	-0.283	+0.314	+0.330	+0.648	15	11	0.0023	0.0034	0.0059	0.0018	0.0036	0.0028
LTT 2415	05 55 48.7	−27 51 31	12.201	+0.399	-0.228	+0.269	+0.293	+0.565	15	9	0.0018	0.0026	0.0041	0.0031	0.0028	0.0044
LTT 2511	06 16 01.6	−59 12 02	13.917	-0.058	-0.933	-0.014	-0.009	-0.023	27	14	0.0058	0.0037	0.0052	0.0029	0.0064	0.0075
L745-46A	07 39 39.2	−17 22 35	13.041	+0.254	-0.634	+0.158	+0.161	+0.320	15	9	0.0041	0.0085	0.0062	0.0031	0.0057	0.0077
LTT 3218	08 40 57.4	−32 53 40	11.846	+0.225	-0.575	+0.093	+0.110	+0.203	14	7	0.0016	0.0029	0.0024	0.0013	0.0029	0.0035
LTT 3864	10 31 33.1	−35 33 03	12.167	+0.484	-0.199	+0.324	+0.337	+0.662	11	6	0.0018	0.0033	0.0036	0.0018	0.0033	0.0036
LTT 4364	11 44 53.2	−64 45 24	11.497	+0.194	-0.677	+0.168	+0.141	+0.310	11	6	0.0033	0.0021	0.0024	0.0018	0.0021	0.0033
LTT 4816	12 38 00.6	−49 43 02	13.782	+0.175	-0.697	+0.007	+0.029	+0.034	10	6	0.0041	0.0044	0.0060	0.0035	0.0108	0.0136
CD -32° 9927	14 10 53.1	−32 59 02	10.440	+0.342	+0.116	+0.173	+0.160	+0.333	10	5	0.0025	0.0022	0.0076	0.0022	0.0016	0.0035
LTT 6248	15 38 04.8	−28 32 40	11.798	+0.490	-0.233	+0.326	+0.353	+0.679	13	7	0.0017	0.0019	0.0044	0.0019	0.0025	0.0025
EG 274	16 22 32.7	−39 11 45	11.008	-0.127	-0.998	-0.127	-0.137	-0.266	10	5	0.0022	0.0019	0.0019	0.0013	0.0013	0.0025
LTT 7379	18 35 20.7	−44 19 24	10.219	+0.607	-0.045	+0.359	+0.355	+0.715	12	6	0.0012	0.0017	0.0040	0.0023	0.0014	0.0017
LTT 7987	20 10 01.1	−30 15 45	12.206	+0.063	-0.693	-0.083	-0.064	-0.149	11	6	0.0021	0.0042	0.0060	0.0024	0.0066	0.0069
LTT 9239	22 51 52.6	−20 40 15	12.065	+0.608	-0.148	+0.382	+0.386	+0.769	14	8	0.0029	0.0027	0.0045	0.0019	0.0029	0.0035
LTT 9491	23 18 48.0	−17 10 24	14.100	+0.026	-0.862	+0.046	+0.024	+0.071	19	10	0.0037	0.0034	0.0046	0.0048	0.0076	0.0119

Photometric Calibration

Instrumental and standard star magnitudes are related in the following way:

$$m_{\mathrm{standard}} - m_{\mathrm{inst}} = ZP + K \sec z + CT \cdot \mathrm{color}$$

We need to determine three quantities to photometrically calibrate our images to a standard systems:

1. The zeropoint ZP determines the flux level relative to which the magnitudes are defined;
2. The extinction coefficient K describes how the extinction changes with varying airmass
3. The color term CT describes the color transformation from the instrumental system to the standard system.

Color is the color of a standard star in the standard system, e.g.,

$$R - r = ZP + K \sec z + CT \cdot (V - R)$$

Color Terms

The equation

$$m_{\mathrm{standard}} - m_{\mathrm{inst}} = ZP + K \sec z + CT \cdot \text{color}$$

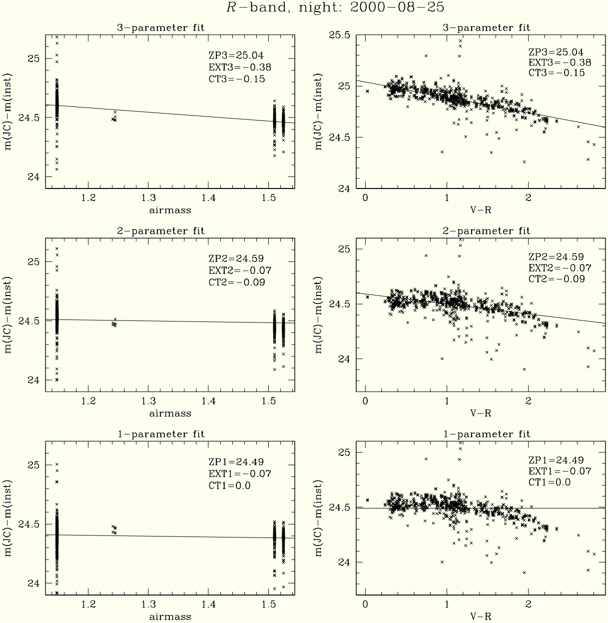
assumes that a linear relation exists between instrumental colors and standard colors. This is the case only when the filters transmission curces are close to the standard ones.

For example, the WFI U and B filters are too far from Johnson filters to be transformed to standard magnitudes.

To transform instrumental magnitudes to standard magnitudes you need to observe your objects in at least two filters.

For many purposes, especially, in extragalactic astronomy you can do everything in the instrumental system, if you know the filter transmission curves.

Calibration Plots in THELI



How to Measure Magnitudes

For precise photometry you need to measure the flux of your standard stars as closely as possible to the method used for determing the standard star magnitudes.

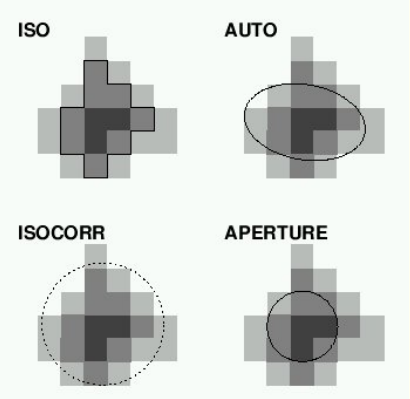
Landolt measured flux in a $14''$ aperture. Some objects are contaminated by neighboring objects in the aperture.

Stetson fitted a function to the stellar PSF and integrated over this function.

Generally, many people choose too small apertures for stellar photometry. Remember that only 84% of the light is in the Airy disk! The Moffat profile is even flatter.

How to Measure Magnitudes

For extended sources PSF fitting is not an alternative anymore. Various magnitudes can be defined



Apertures defines by isophotes, elliptical fits to object, correction for flux outside isophote, or fixed size aperture.

Measuring Color

Defining a color for an extended object can be difficult. The object may have a different size in different colors, e.g., red bulge/blue disk of spiral galaxies.

To measure colors reliably the same aperture must be used on in all passbands.

Elliptical apertures automatically matched to the object in one passband or isophotal magnitudes are used.

It is important that images in different passbands are on the same pixel grid. SWarp can do this.

Correction for different PSF (seeing) in different passbands must also be made (convolve all images to the one with the worst seeing).

This is a very complex process, beyond what we can do in this course.

That’s it. Thanks for listening!