Ay 122 - Fall 2012

Imaging and Photometry
Part I

(Many slides today c/o Mike Bolte, UCSC)

Imaging and Photometry

- Now essentially always done with imaging arrays (e.g., CCDs); it used to be with single-channel instruments
- Two basic purposes:

1. **Flux measurements** (photometry)
    - Aperture photometry or S/N-like weighting
    - For unresolved sources: PSF fitting
    - Could be time-resolved (e.g., for variability)
    - Could involve polarimetry
    - Panoramic imaging especially useful if the surface density of sources is high
2. **Morphology and structures**
    - Surface photometry or other parametrizations

What Properties of Electromagnetic Radiation Can We Measure?

- Specific flux = Intensity (in ergs or photons) per unit area (or solid angle), time, wavelength (or frequency), e.g., $f_\lambda = 10^{-15}$ erg/cm^2/s/Å - a good spectroscopic unit
- It is usually integrated over some finite bandpass (as in photometry) or a spectral resolution element or a line
- It can be distributed on the sky (surface photometry, e.g., galaxies), or changing in time (variable sources)
- You can also measure the polarization parameters (photometry ➙ polarimetry, spectroscopy ➙ spectro-polarimetry); common in radio astronomy

Measuring Flux = Energy/(unit time)/(unit area)

Real detectors are sensitive over a finite range of λ (or ν). Fluxes are always measured over some finite bandpass.

Total energy flux:

$$F = \int F_\nu(\nu) d\nu$$

Integral of f_ν over all frequencies

Units: erg s^{-1} cm^{-2} Hz^{-1}

A standard unit for specific flux (initially in radio, but now more common):

$$1 \text{ Jansky (Jy)} = 10^{-23} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$$

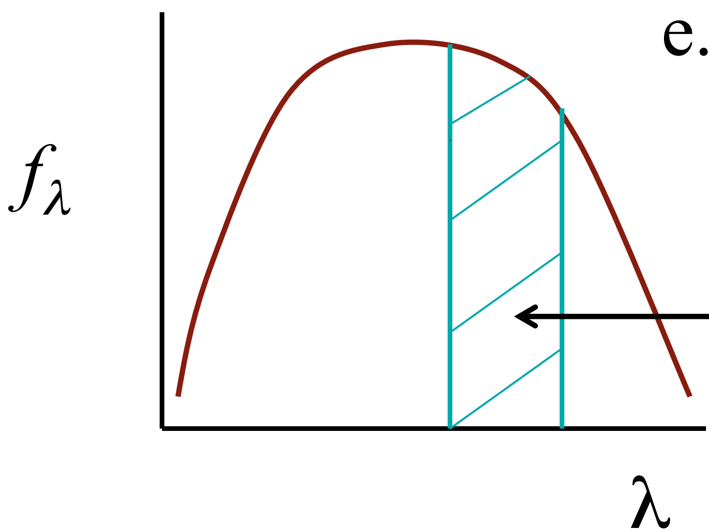
f_ν is often called the ***flux density*** - to get the ***power,*** one integrates it over the bandwith, and multiplies by the area

Fluxes and Magnitudes

For historical reasons, fluxes in the optical and IR are measured in magnitudes: $m = -2.5\log_{10} F + \text{constant}$

If F is the total flux, then m is the bolometric magnitude. Usually instead consider a finite bandpass, e.g., V band.

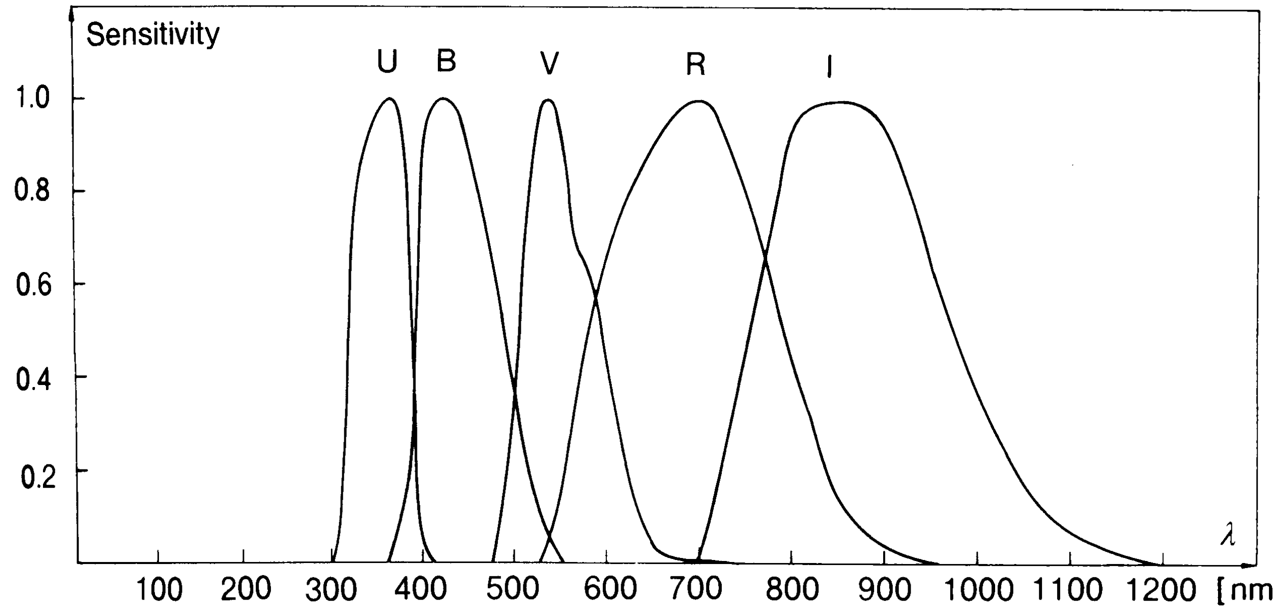
e.g. in the V band ($\lambda \sim$ 550 nm):



$$m_V = -2.5\log_{10} F + \text{constant}$$

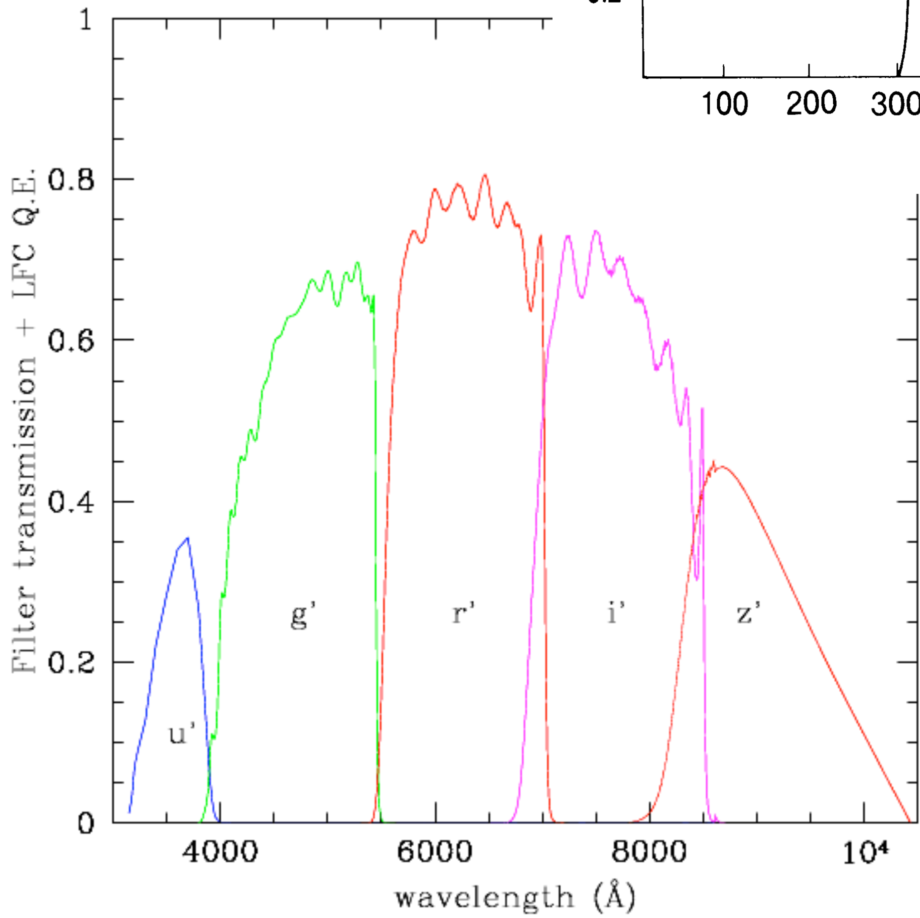
flux integrated over the range of wavelengths for this band

Johnson →



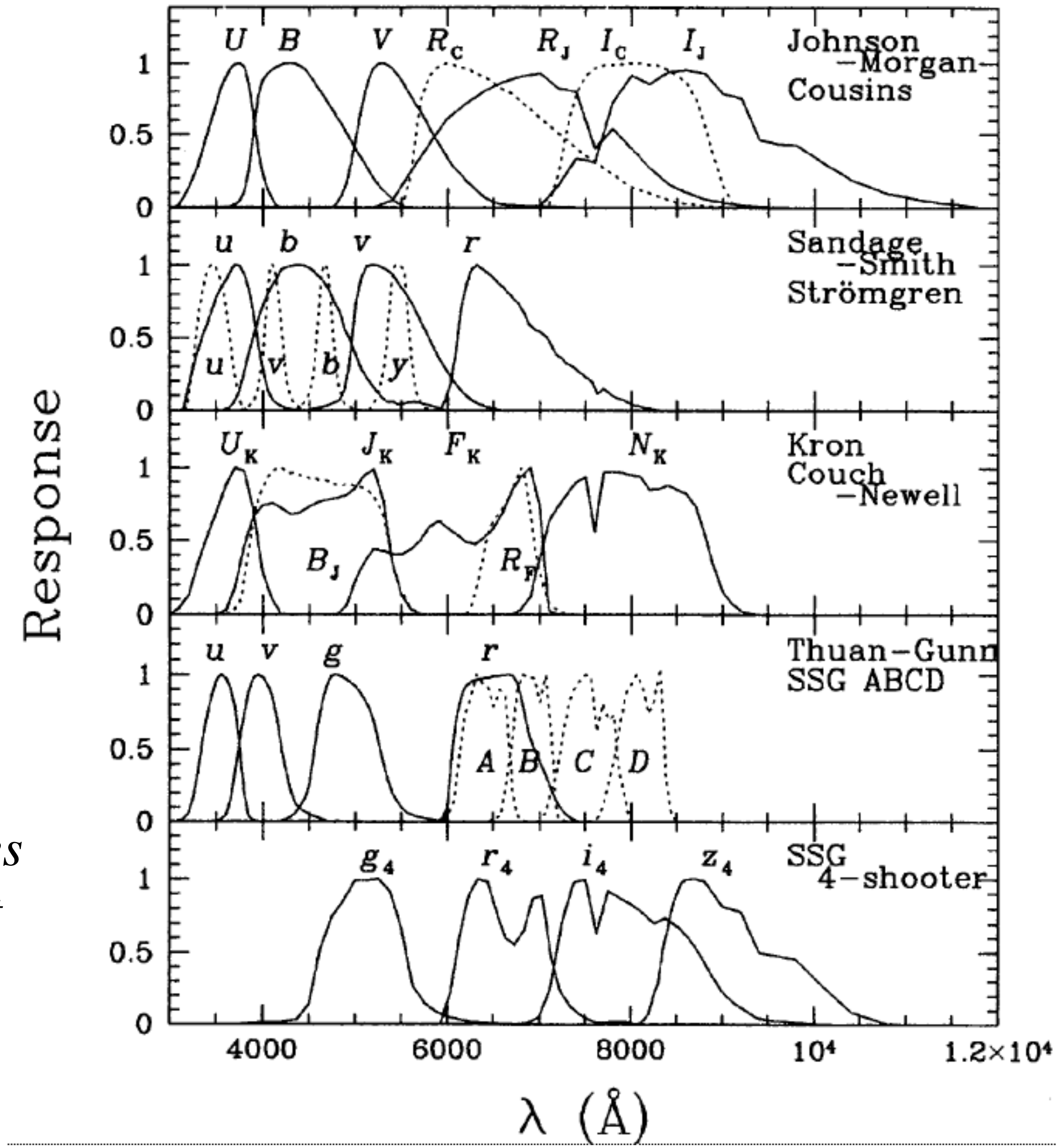
Gunn/SDSS

↓



Some Common Photometric Systems (in the visible)

There are way, way too many photometric systems out there …

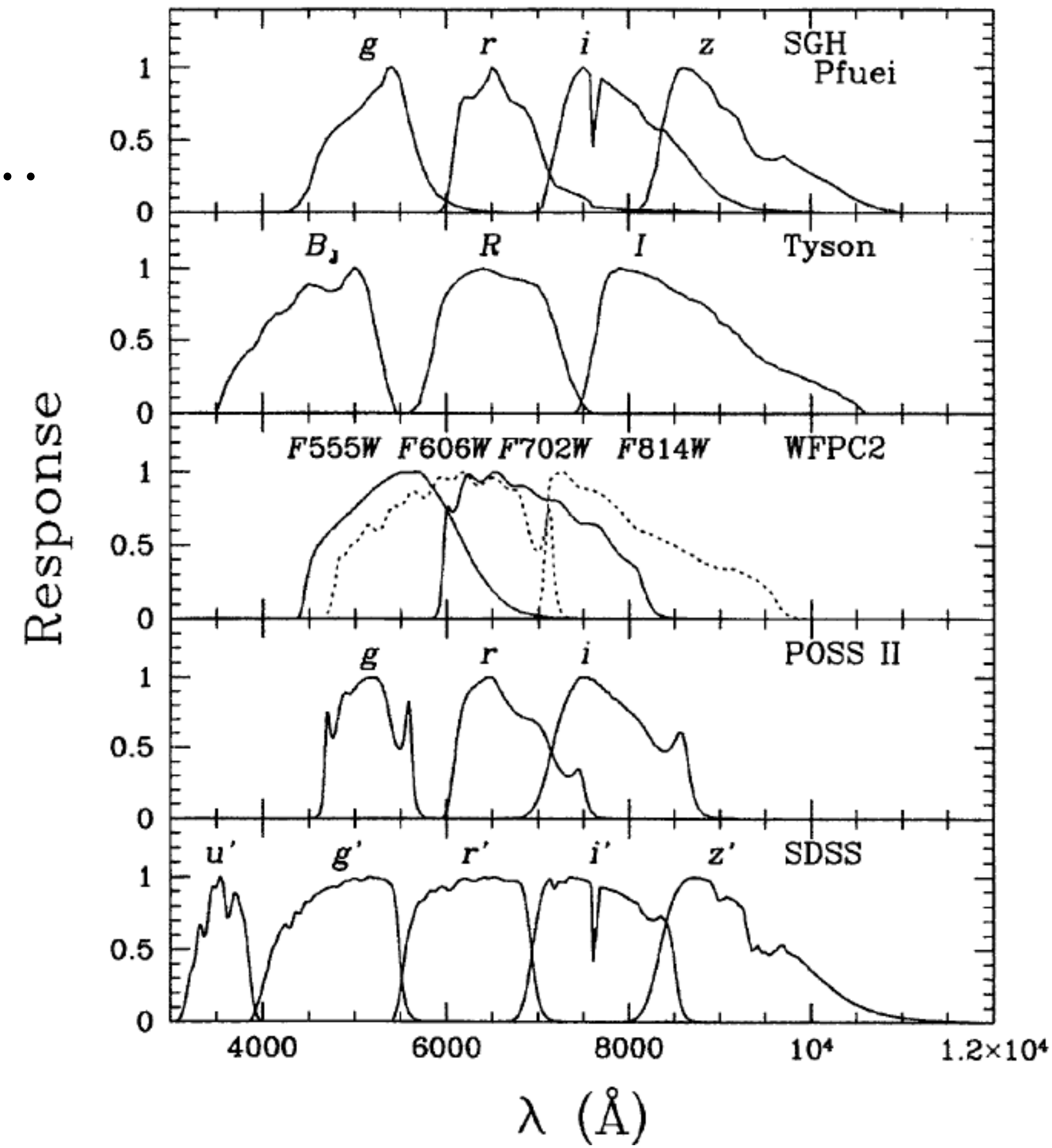


(Bandpass curves from Fukugita et al. 1995, PASP, 107, 945)

… and more …

… and more …

… and more …



Using Magnitudes

Consider two stars, one of which is a hundred times fainter than the other in some waveband (say *V*).

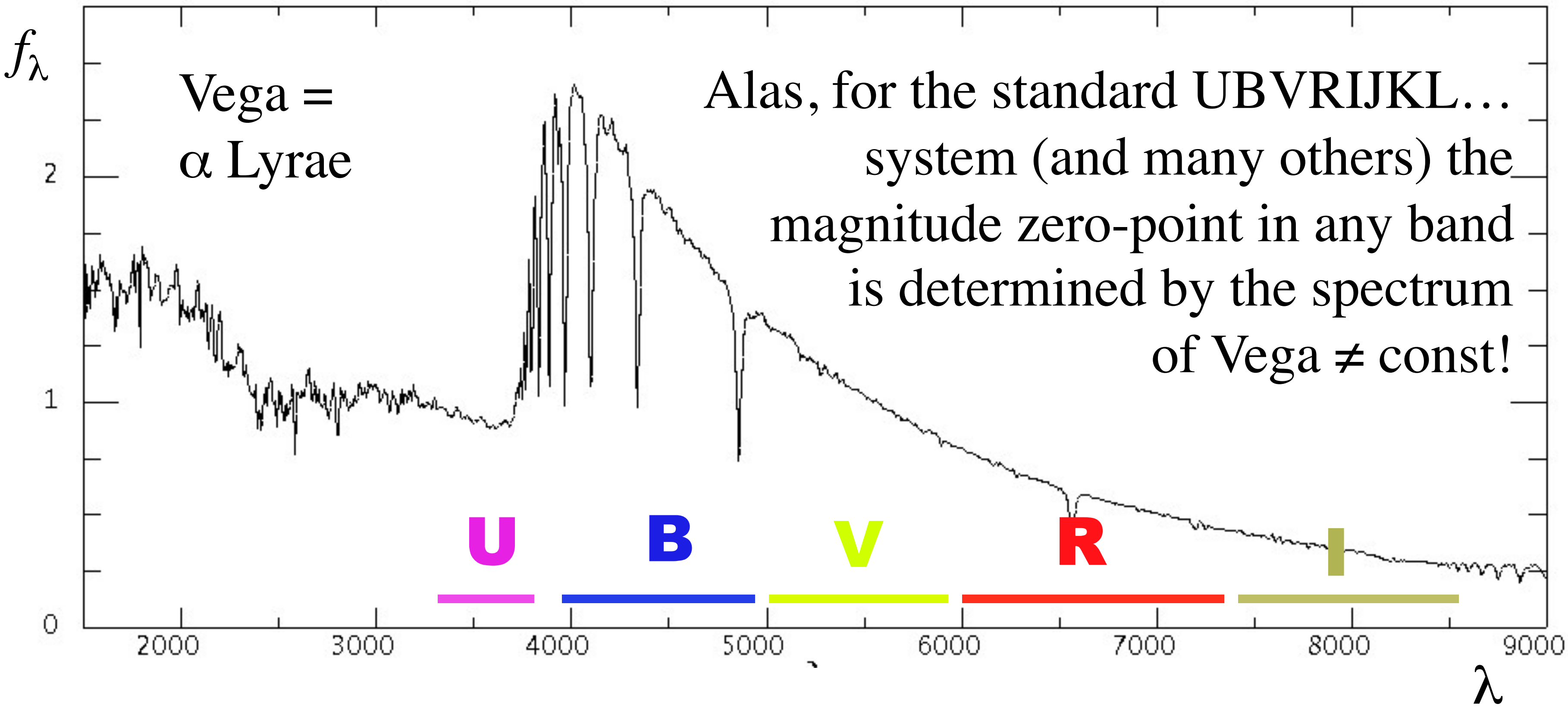
$$m_1 = -2.5\log F_1 + \text{constant}$$

$$\begin{aligned} m_2 &= -2.5\log(0.01F_1) + \text{constant} \\ &= -2.5\log(0.01) - 2.5\log F_1 + \text{constant} \\ &= 5 - 2.5\log F_1 + \text{constant} \\ &= 5 + m_1 \end{aligned}$$

Source that is 100 times **fainter** in flux is five magnitudes fainter (**larger** number).

Faintest objects detectable with *HST* have magnitudes of ~ 28 in R/I bands. The sun has m_V = -26.75 mag

Magnitude Zero Points



Vega calibration ($m = 0$): at $\lambda = 5556$:

$f_\lambda = 3.39 \times 10^{-9}$ erg/cm²/s/Å

$f_\nu = 3.50 \times 10^{-20}$ erg/cm²/s/Hz

$N_\lambda = 948$ photons/cm²/s/Å

A more logical system is AB_ν magnitudes:

$$AB_\nu = -2.5 \log f_\nu \text{ [cgs]} - 48.60$$

Photometric Zero-Points (Visible)

bandpass system	band	ref[a)]	$\lambda_{\rm eff}$ (Å)	FWHM (Å)	$\lambda_{\rm eff}^{\rm Vega}$ (Å)	$f_{\lambda,\rm eff}^{\rm Vega}$ ($\times 10^{-9}$cgs/Å)	$c(\nu_{\rm eff}^{\rm Vega})^{-1}$ (Å)	$f_{\nu,\rm eff}^{\rm Vega}$ ($\times 10^{-20}$cgs/Hz)
Johnson-Morgan	U_3	Buser 78	3652	526	3709	4.28	3617	1.89
	B_2	AS69	4448	1008	4393	6.19	4363	4.02
	V	AS69	5505	827	5439	3.60	5437	3.59
Cousins	R_C	Bessell 90	6588	1568	6410	2.15	6415	3.02
	I_C	Bessell 90	8060	1542	7977	1.11	7980	2.38
Johnson	R_J		6930	2096	6688	1.87	6693	2.89
	I_J		8785	1706	8571	0.912	8545	2.28
SDSS	u'		3585	556	3594	3.67	3530	1.54
	g'		4858	1297	4765	5.11	4748	3.93
	r'		6290	1358	6205	2.40	6210	3.12
	i'		7706	1547	7617	1.28	7623	2.51
	z'		9222	1530	9123	0.783	9098	2.19
Thuan-Gunn	u		3536	412	3542	3.33	3519	1.38
	v		3992	469	4013	6.62	3967	3.50
	g		4927	709	4888	4.84	4885	3.89
	r		6538	893	6496	2.09	6498	2.96

(From Fukugita et al. 1995)

Magnitudes, A Formal Definition

$$m = -2.5\left[\log \int d\lambda R(\lambda) f_\lambda - \log \int d\lambda R(\lambda) f_\lambda(\alpha \text{ Lyr})\right]$$

Because Vega (= α Lyrae) is declared to be the zero-point! (at least for the UBV… system)

e.g.,

$$U = -2.5 \log \int d\lambda R_U(\lambda) f_\lambda - 14.08 + c_U ,$$

$$B = -2.5 \log \int d\lambda R_B(\lambda) f_\lambda - 13.00 + c_B ,$$

$$V = -2.5 \log \int d\lambda R_V(\lambda) f_\lambda - 13.76 + c_V ,$$

where the peak of the response function is normalized to unity, and c represents the magnitude of α Lyr; $c_U = 0.02$, $c_B = c_V = 0.03$ (Johnson and Morgan 1953).

Defining effective wavelengths (and the corresponding bandpass averaged fluxes)

$$\lambda_{\rm eff} = \frac{\int d\lambda \, \lambda R(\lambda)}{\int d\lambda R(\lambda)},$$

$$f_\lambda^{\rm eff}(\alpha \text{ Lyr}) = \frac{\int d\lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)}{\int d\lambda R(\lambda)},$$

$$\lambda_{\rm eff}(\alpha \text{ Lyr}) = \frac{\int d\lambda \, \lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)}{\int d\lambda f_\lambda(\alpha \text{ Lyr}) R(\lambda)},$$

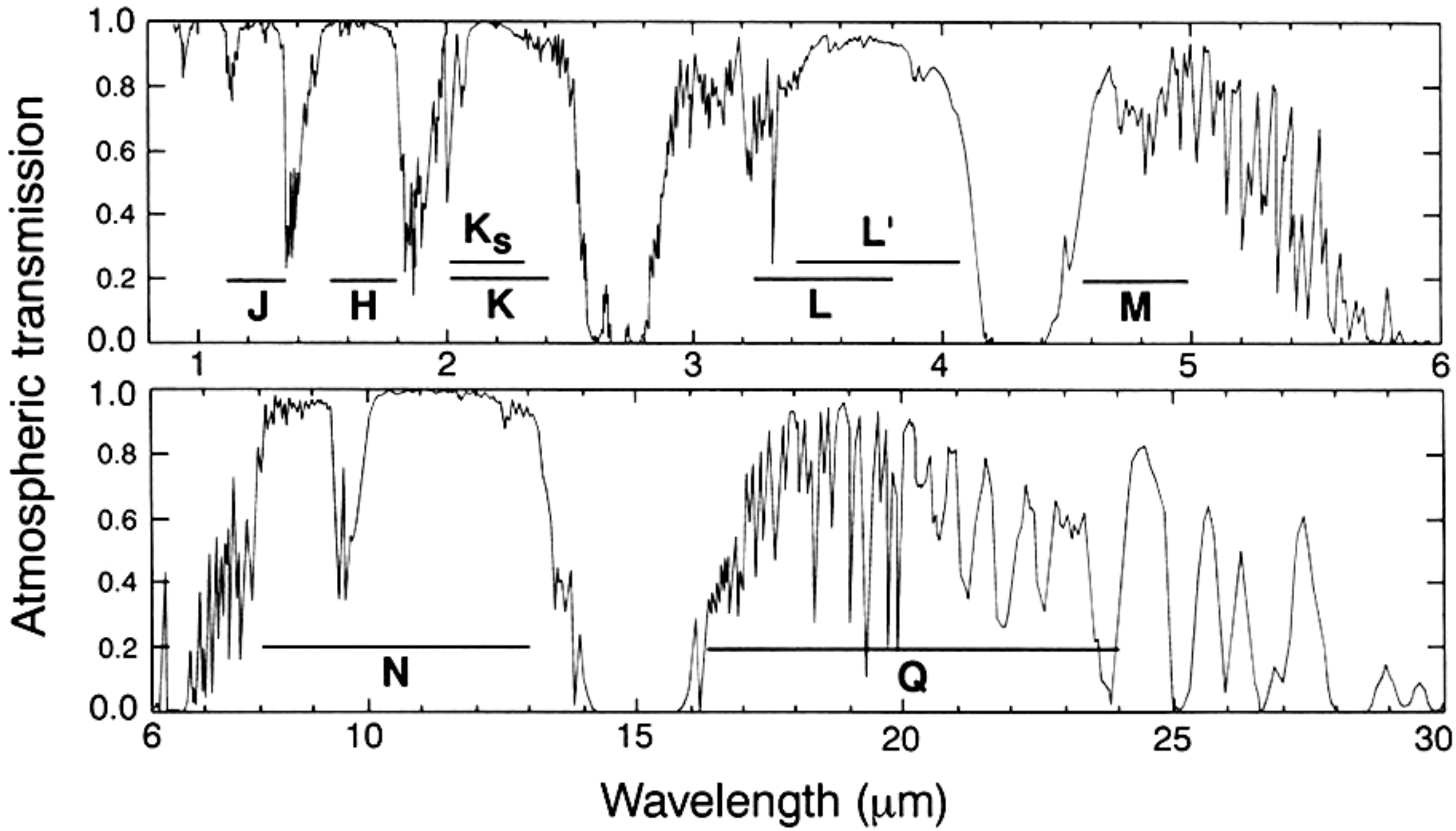
$$f_\nu^{\rm eff}(\alpha \text{ Lyr}) = \frac{\int d\nu f_\nu(\alpha \text{ Lyr}) R(\nu)}{\int d\nu R(\nu)},$$

$$\nu_{\rm eff}(\alpha \text{ Lyr}) = \frac{\int d\nu \, \nu f_\nu(\alpha \text{ Lyr}) R(\nu)}{\int d\nu f_\nu(\alpha \text{Lyr}) R(\nu)}$$

where $f_\nu = \lambda^2 f_\lambda / c$ and $R_\nu = R_\lambda$.

The Infrared Photometric Bands

… where the atmospheric transmission windows are



Infrared Bandpasses

Table 7.5. *Filter wavelengths, bandwidths, and flux densities for Vega.*[a]

Filter name	λ_{iso}[b] (μm)	$\Delta\lambda$[c] (μm)	F_λ (W m^{-2} μm^{-1})	F_ν (Jy)	N_ϕ (photons s^{-1} m^{-2} μm^{-1})
V	0.5556[d]	...	3.44×10^{-8}	3 540	9.60×10^{10}
J	1.215	0.26	3.31×10^{-9}	1 630	2.02×10^{10}
H	1.654	0.29	1.15×10^{-9}	1 050	9.56×10^{9}
K_s	2.157	0.32	4.30×10^{-10}	667	4.66×10^{9}
K	2.179	0.41	4.14×10^{-10}	655	4.53×10^{9}
L	3.547	0.57	6.59×10^{-11}	276	1.17×10^{9}
L'	3.761	0.65	5.26×10^{-11}	248	9.94×10^{8}
M	4.769	0.45	2.11×10^{-11}	160	5.06×10^{8}
8.7	8.756	1.2	1.96×10^{-12}	50.0	8.62×10^{7}
N	10.472	5.19	9.63×10^{-13}	35.2	5.07×10^{7}
11.7	11.653	1.2	6.31×10^{-13}	28.6	3.69×10^{7}
Q	20.130	7.8	7.18×10^{-14}	9.70	7.26×10^{6}

Infrared Bandpasses

Effective Wavelengths[1], Zeropoint Fluxes[2] and Magnitudes [3]

	V	J	H	K	L	L'	M	(M)
λeff	0.545	1.22	1.63	2.19	3.45	3.80	4.75	4.80
ZP	0.000	0.90	1.37	1.88	2.77	2.97	3.42	3.44
F_λ	3590	312	114	39.4	6.99	4.83	2.04	1.97
F_ν	3600	1570	1020	636	281	235	154	152

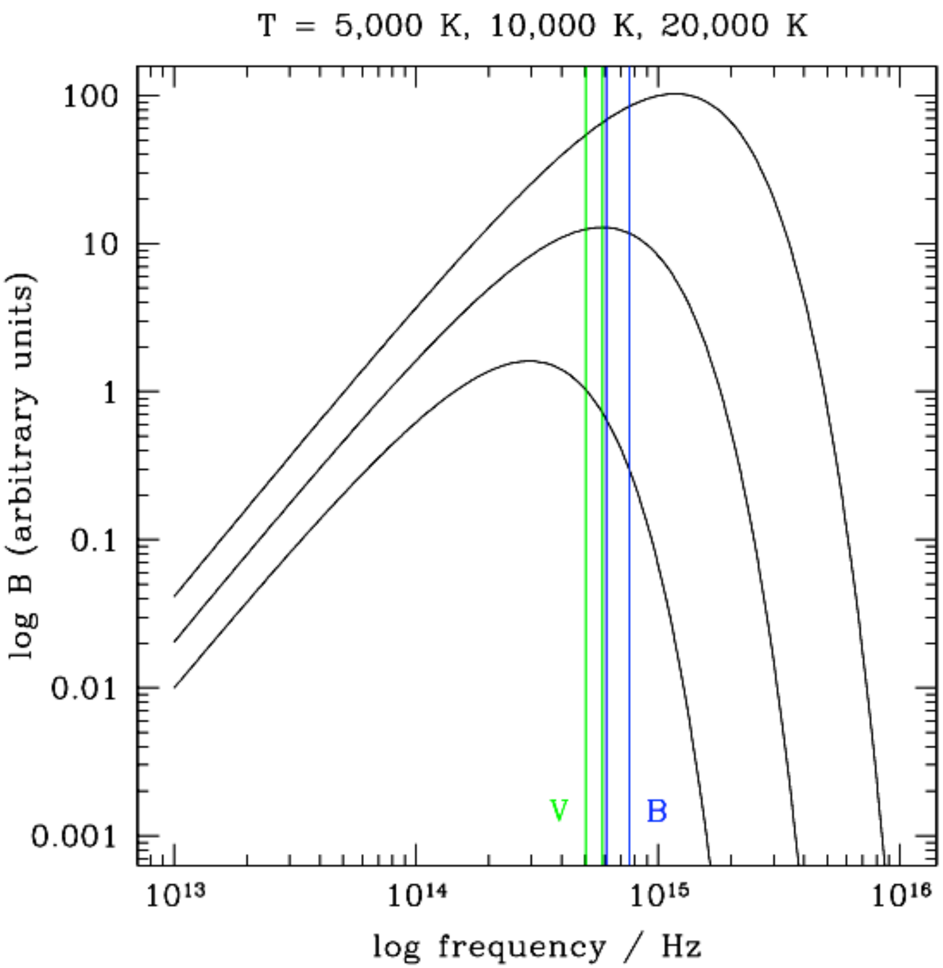
1 In μm

2 $F_\lambda(10^{-15}$ W cm^{-2} μm$^{-1})$, $F_\upsilon(10^{-30}$ W cm^{-2} hz$^{-1})$ for a 0.03 magnitude star from Dreiling and Bell, and Bell Vega models for adopted passbands.

3 $\text{Mag} = -2.5 \log\langle F_\upsilon \rangle - 66.08 - \text{ZP}$

Colors From Magnitudes

The color of an object is defined as the difference in the magnitude in each of two bandpasses: e.g. the *(B-V)* color is: $B\text{-}V = m_B\text{-}m_V$



Stars radiate roughly as blackbodies, so the color reflects surface temperature.

Vega has T = 9500 K, by definition color is zero.

Apparent vs. Absolute Magnitudes

The absolute magnitude is defined as the apparent mag. a source would have if it were at a distance of 10 pc:

$$M = m + 5 - 5 \log d/\text{pc}$$

It is a measure of the **luminosity** in some waveband.

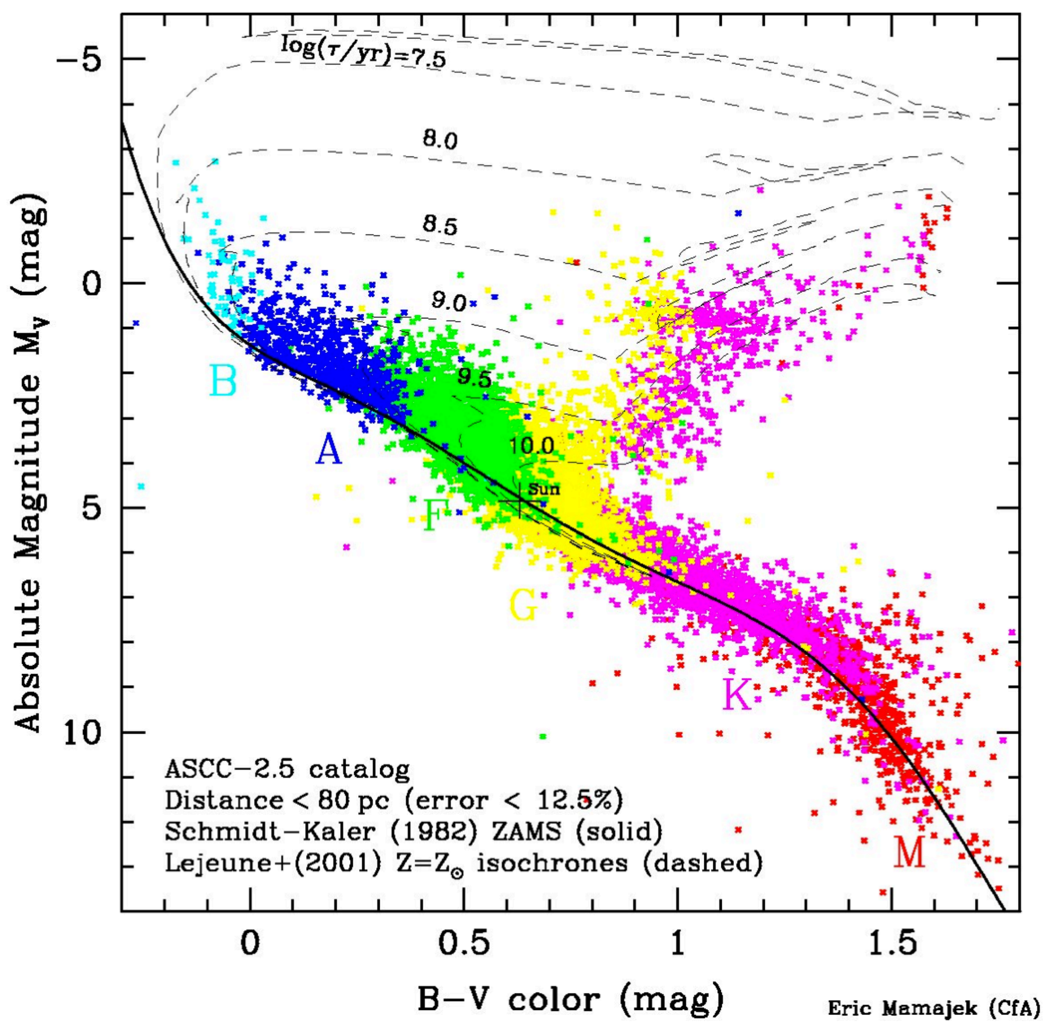
For Sun: $M_{\odot B} = 5.47$, $M_{\odot V} = 4.82$, $M_{\odot bol} = 4.74$

Difference between the apparent magnitude m and the absolute magnitude M (any band) is a ***measure of the distance*** to the source

$$\underbrace{m - M}_{\textbf{Distance modulus}} = 5 \log_{10}\left(\frac{d}{10 \text{ pc}}\right)$$

Why Do We Need This Mess?

Relative measurements are generally easier and more robust than the absolute ones; and often that is enough.



An example: the Color-Magnitude Diagram

The quantitative operational framework for studies of stellar physics, evolution, populations, distances …

Photometric Calibration

- The photometric standard systems have tended to be zero-pointed arbitrarily. Vega is the most widely used and was original defined with V= 0 and all colors = 0.
- Hayes & Latham (1975, ApJ, 197, 587) put the Vega scale on an absolute scale.
- The AB scale (Oke, 1974, ApJS, 27, 21) is a physical-unit-based scale with:

$$m(AB) = -2.5\log(f) - 48.60$$

where f is monochromatic flux is in units of erg/sec/cm^2/Hz. Objects with constant flux/unit frequency interval have zero color on this scale

Photometric calibration

1. Instrumental magnitudes

Counts/sec

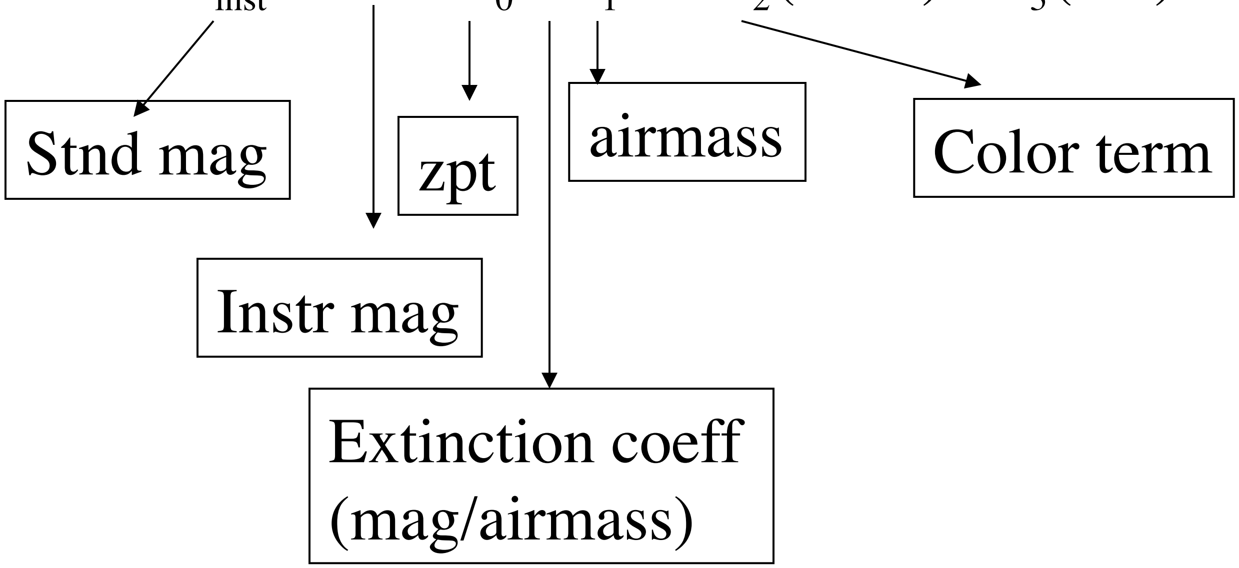
$$m = c_0 - 2.5\log(I \bullet t)$$
$$= c_0 - 2.5\log(I) - 2.5\log(t)$$

$m_{instrumental}$

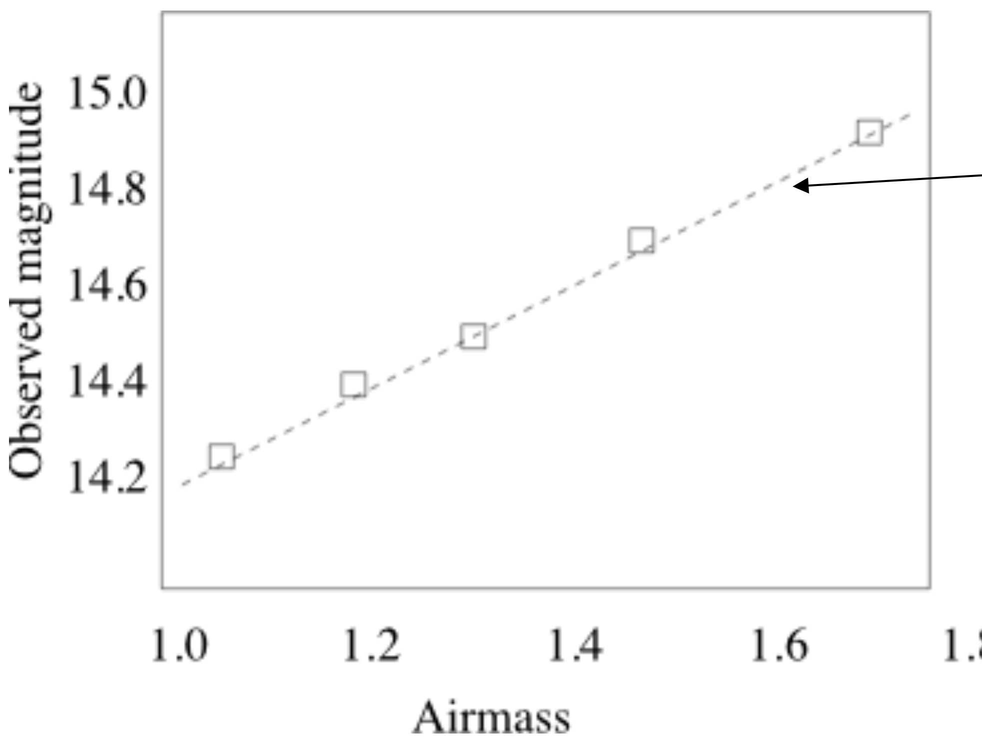
Photometric Calibration

- To convert to a *standard* magnitude you need to observe some standard stars and solve for the constants in an equation like:

$$m_{inst} = M + c_0 + c_1 X + c_2(\mathrm{color}) + c_3(\mathrm{UT}) + c_4(\mathrm{color})^2 + \ldots$$



- Extinction coefficients:
  - Increase with decreasing wavelength
  - Can vary by 50% over time and by some amount during a night
  - Are measured by observing standards at a range of airmass during the night

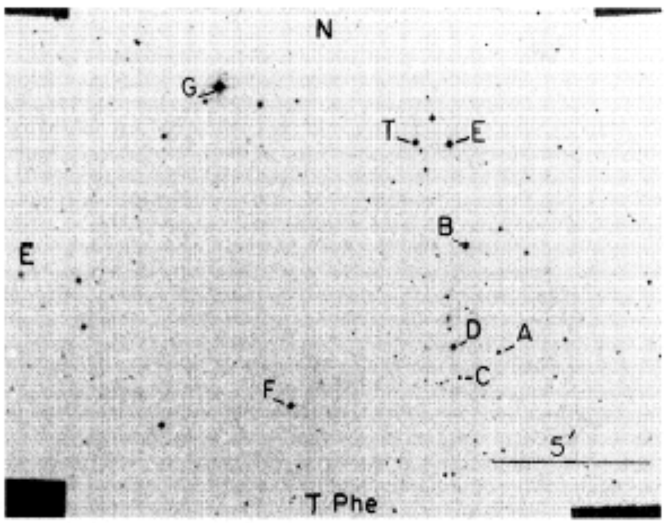


Slope of this line is c_1

Photometric Standards

- Landolt (1992, AJ, 104, 336; and 2009, AJ, 137, 4186)
- Stetson (2000, PASP, 112, 995)
- Gunn/SDSS (Smith et al. 2002, AJ, 123, 2121)
- Fields containing several well measured stars of similar brightness and a big range in color. The blue stars are the hard ones to find and several fields are center on PG sources.
- Measure the fields over at least the the airmass range of your program objects and intersperse standard field observations throughout the night.

Photometric Calibration: Standard Stars



Magnitudes of Vega (or other systems primary flux standards) are transferred to many other, secondary standards. They are observed along with your main science targets, and processed in the same way.

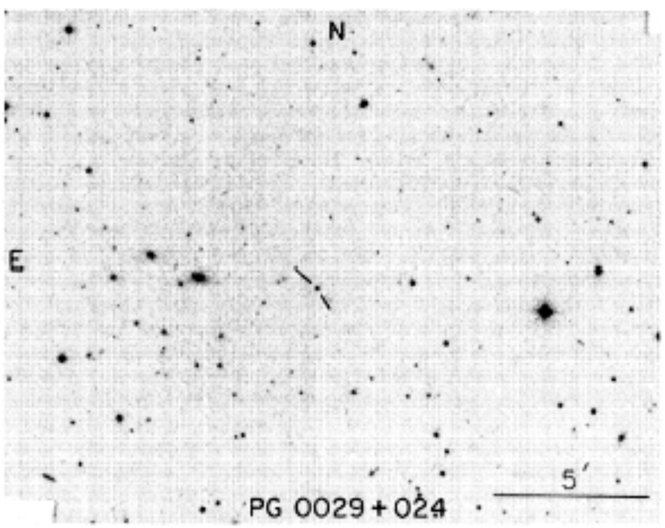
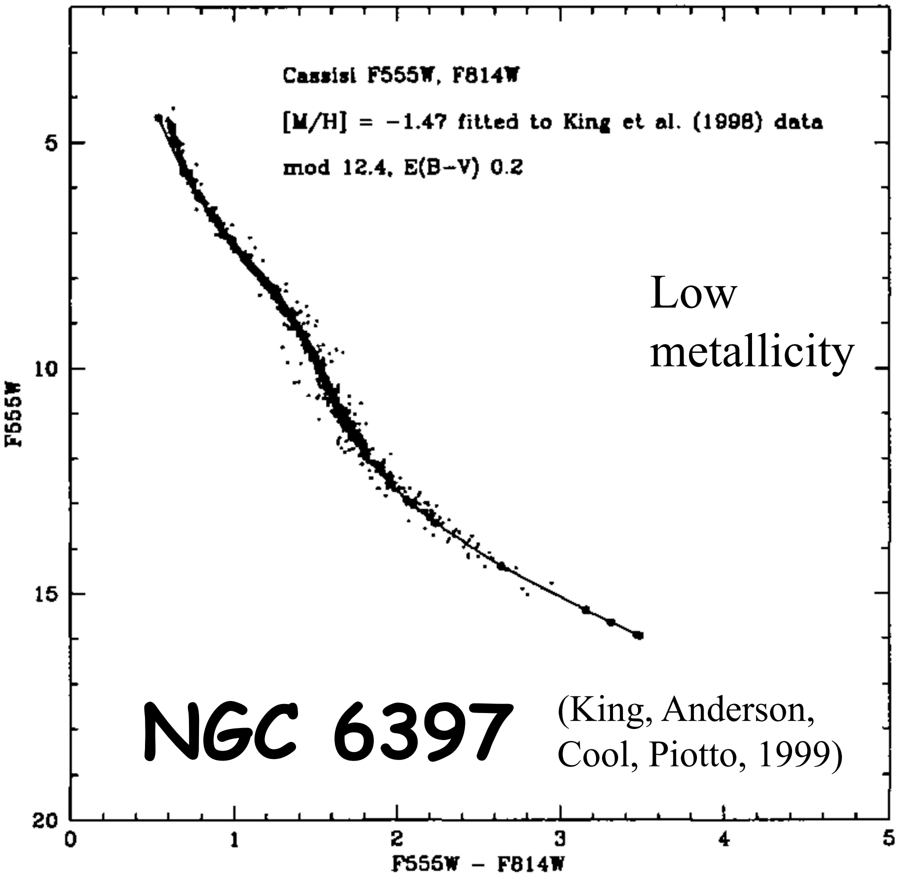
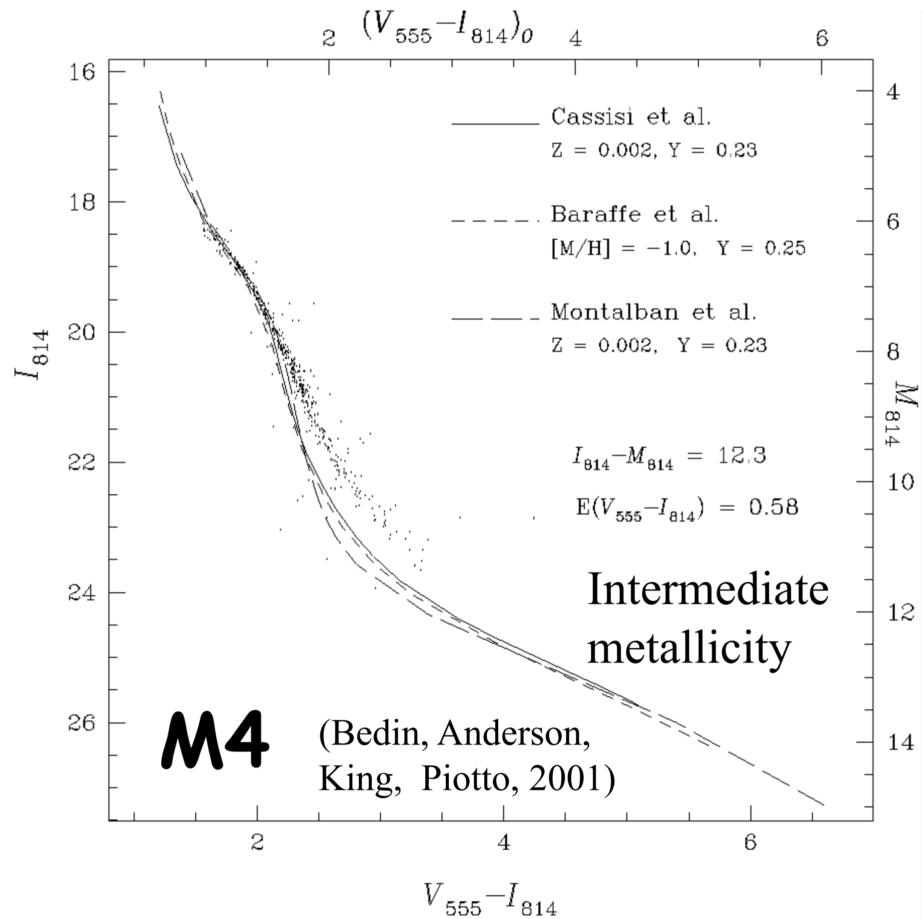


PLATE 21. (a) The field for the T Phe sequence. Star B is the eclipsing binary RW Phe. (b) The field of the star PG0029+024.

Star	α(2000)	δ(2000)	V	B-V	U-B	V-R	R-I	V-I	n	m	V
TPHE A	00:30:09	-46 31 22	14.651	0.793	0.380	0.435	0.405	0.841	29	12	0.0028
TPHE B	00:30:16	-46 27 55	12.334	0.405	0.156	0.262	0.271	0.535	29	17	0.0115
TPHE C	00:30:17	-46 32 34	14.376	-0.298	-1.217	-0.148	-0.211	-0.360	39	23	0.0022
TPHE D	00:30:18	-46 31 11	13.118	1.551	1.871	0.849	0.810	1.663	37	23	0.0033
TPHE E	00:30:19	-46 24 36	11.630	0.443	-0.103	0.276	0.283	0.564	34	8	0.0017
TPHE F	00:30:50	-46 33 33	12.474	0.855	0.532	0.492	0.435	0.926	5	3	0.0004
TPHE G	00:31:05	-46 22 43	10.442	1.546	1.915	0.934	1.085	2.025	5	3	0.0004
PG0029+024	00:31:50	+02 38 26	15.268	0.362	-0.184	0.251	0.337	0.593	5	2	0.0094
PG0039+049	00:42:05	+05 09 44	12.877	-0.019	-0.871	0.067	0.097	0.164	4	3	0.0020
92 309	00:53:14	+00 46 02	13.842	0.513	-0.024	0.326	0.326	0.652	2	1	0.0035
92 235	00:53:16	+00 36 18	10.595	1.638	1.984	0.894	0.911	1.806	5	2	0.0058
92 322	00:53:47	+00 47 33	12.676	0.528	-0.002	0.302	0.306	0.608	2	1	0.0007
92 245	00:54:16	+00 39 51	13.818	1.418	1.189	0.929	0.907	1.836	21	8	0.0028
92 248	00:54:31	+00 40 15	15.346	1.128	1.289	0.690	0.553	1.245	4	2	0.0255

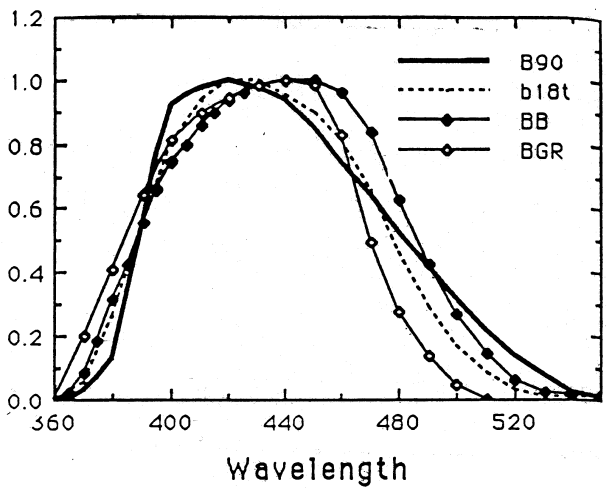
We often need to compare observations with models, on the ***same photometric system***

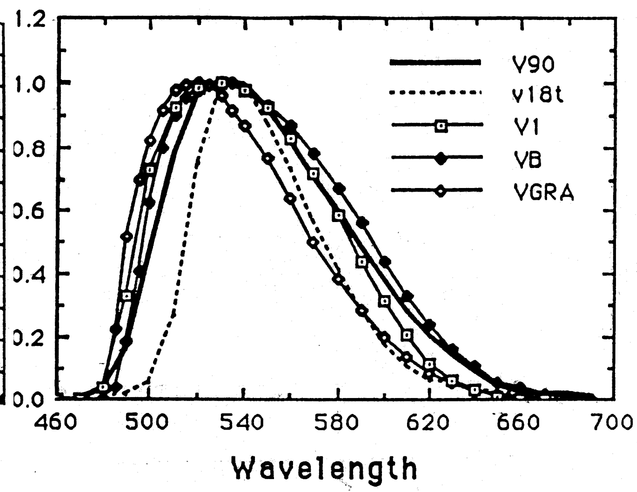


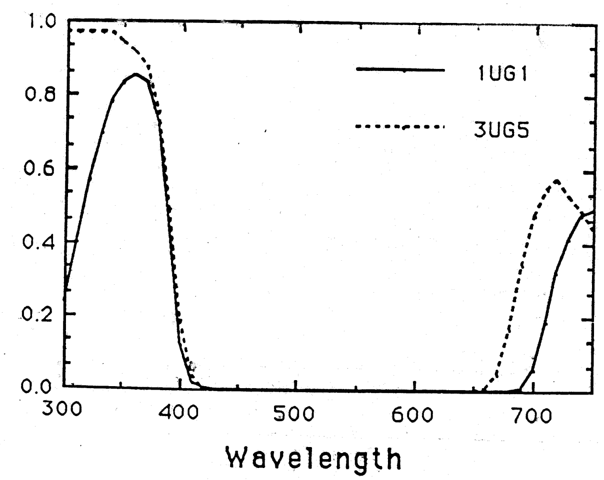


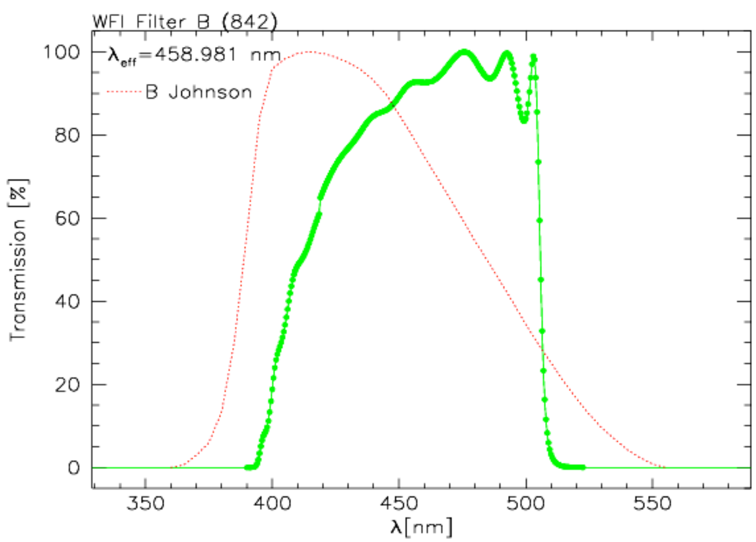
Always, always transform models to observational system, e.g., by integrating model spectra through your bandpasses

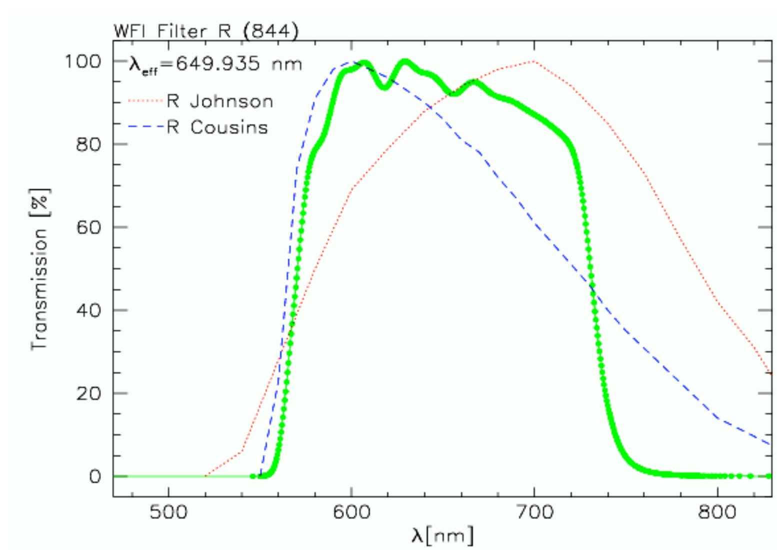
Alas, Even The “Same” Photometric Systems Are Seldom Really The Same …





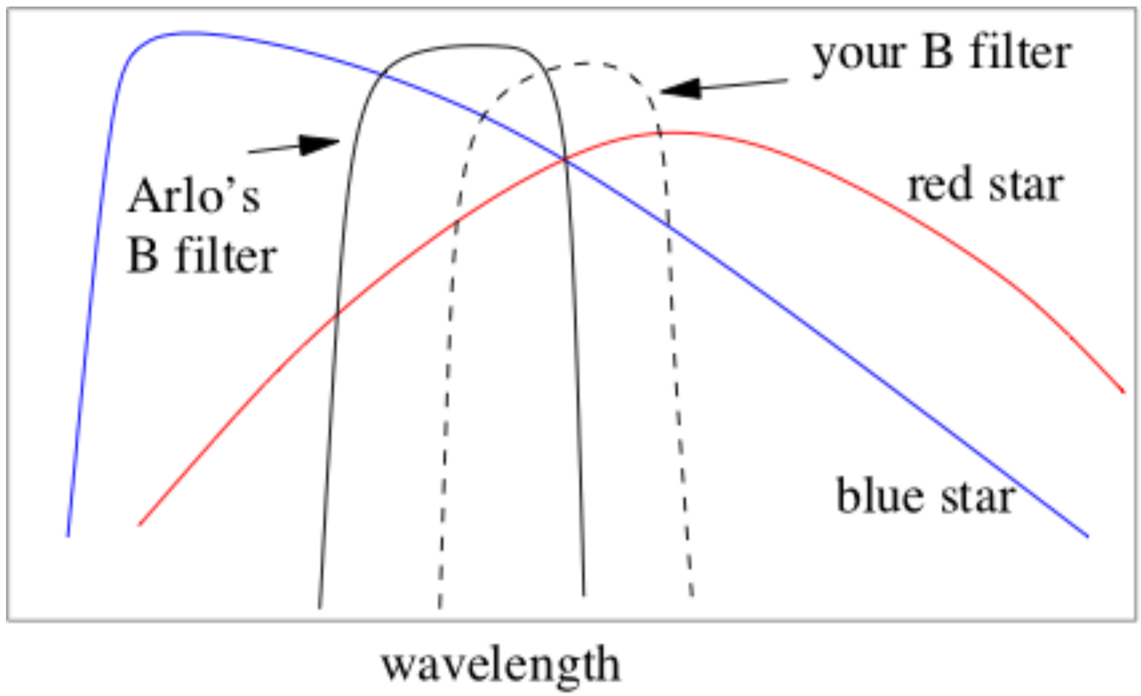






This Generates Color Terms …

… From mismatches between the effective bandpasses of your filter system and those of the standard system. Objects with different spectral shapes have different offsets:



A photometric system is thus effectively (operationally) ***defined by a set of standard stars*** - since the actual bandpasses may not be well known.

Interstellar Extinction

- Strongly dependent on the bandpass, but also on the direction (types of dust)
- The easiest approach: look it up in Schegel, Finkbeiner & Davis (1998, ApJ, 500, 525)
- Useful links at http://irsa.ipac.caltech.edu/applications/DUST/docs/background.html

INTERSTELLAR EXTINCTION LAW

λ	$E(\lambda - V)/E(B-V)$	A_λ/A_V
U	1.64[a]	1.531
B	1.00[b]	1.324
V	0.0[b]	1.000
R	−0.78[b]	0.748
I	−1.60[b]	0.482
J	-2.22 ± 0.02	0.282
H	-2.55 ± 0.03	0.175
K	-2.744 ± 0.024	0.112
L	-2.91 ± 0.03	0.058
M	-3.02 ± 0.03	0.023
N	−2.93	0.052
8.0 μm	−3.03	0.020 ± 0.003
8.5	−2.96	0.043 ± 0.006
9.0	−2.87	0.074 ± 0.011
9.5	−2.83	0.087 ± 0.013
10.0	−2.86	0.083 ± 0.012
10.5	−2.87	0.074 ± 0.011
11.0	−2.91	0.060 ± 0.009
11.5	−2.95	0.047 ± 0.007
12.0	−2.98	0.037 ± 0.006
12.5	−3.00	0.030 ± 0.005
13.0	−3.01	0.027 ± 0.004

[a] From Nandy *et al.* 1976.
[b] From Schultz and Wiemer 1975.

The Concept of Signal-to-Noise (S/N)

or: How good is that measurement really?

- **S/N = signal/error** (If the noise is Gaussian, we speak of 3-σ, 5- σ, … detections. This translates into a probability that the detection is spurious.)
- For a counting process (e.g., photons), error = $\sqrt{n}$, and thus S/N = $n / \sqrt{n} = \sqrt{n}$ ("Poissonian noise"). This is the *minimum possible error;* there may be other sources of error (e.g., from the detector itself)
- If a source is seen against some back(fore)ground, then

$$\sigma^2_{\text{total}} = \sigma^2_{\text{signal}} + \sigma^2_{\text{background}} + \sigma^2_{\text{other}}$$

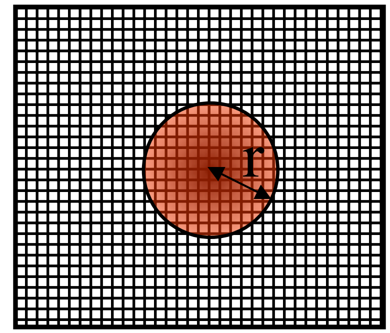
Signal-to-Noise (S/N)

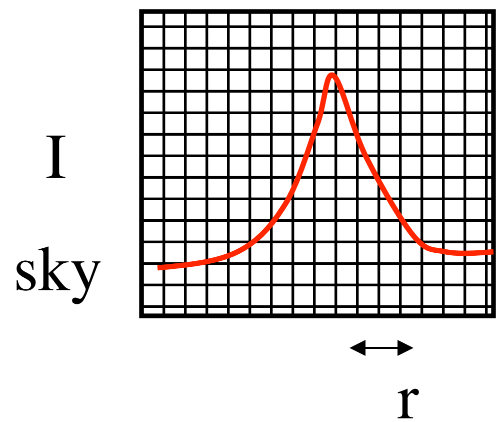
- Signal=$R_* \bullet t$

time

detected rate in e-/second

- Consider the case where we count all the detected e- in a circular aperture with radius r.





- Noise Sources:

$\sqrt{R_* \cdot t}$ $\Rightarrow$ shot noise from source

$\sqrt{R_{sky} \cdot t \cdot \pi r^2}$ $\Rightarrow$ shot noise from sky in aperture

$\sqrt{RN^2 \cdot \pi r^2}$ $\Rightarrow$ readout noise in aperture

$\sqrt{\left[RN^2 + (0.5 \times \text{gain})^2\right]} \cdot \sqrt{\pi r^2}$ $\Rightarrow$ more general RN

$\sqrt{\text{Dark} \cdot t \cdot \pi r^2}$ $\Rightarrow$ shot noise in dark current in aperture

$R_* = \text{e}^-/\text{sec}$ from the source

$R_{sky} = \text{e}^-/\text{sec/pixel}$ from the sky

$RN =$ read noise (as if RN^2 e^- had been detected)

Dark = e^- /second/pixel

S/N for object measured in aperture with radius r: n_{pix}=# of pixels in the aperture= πr^2

Noise from the dark current in aperture

$$\frac{\text{Signal} \quad R_* t}{\text{Noise} \quad \left[R_* \cdot t + R_{sky} \cdot t \cdot n_{pix} + \left(RN + \frac{\text{gain}}{2} \right)^2 \cdot n_{pix} + \text{Dark} \cdot t \cdot n_{pix} \right]^{\frac{1}{2}}}$$

Readnoise in aperture

$$\sqrt{(R_* \cdot t)^2}$$

Noise from sky *e*- in aperture

All the noise terms added in quadrature
Note: always calculate in *e*-

Side Issue: S/N ⇔ δmag

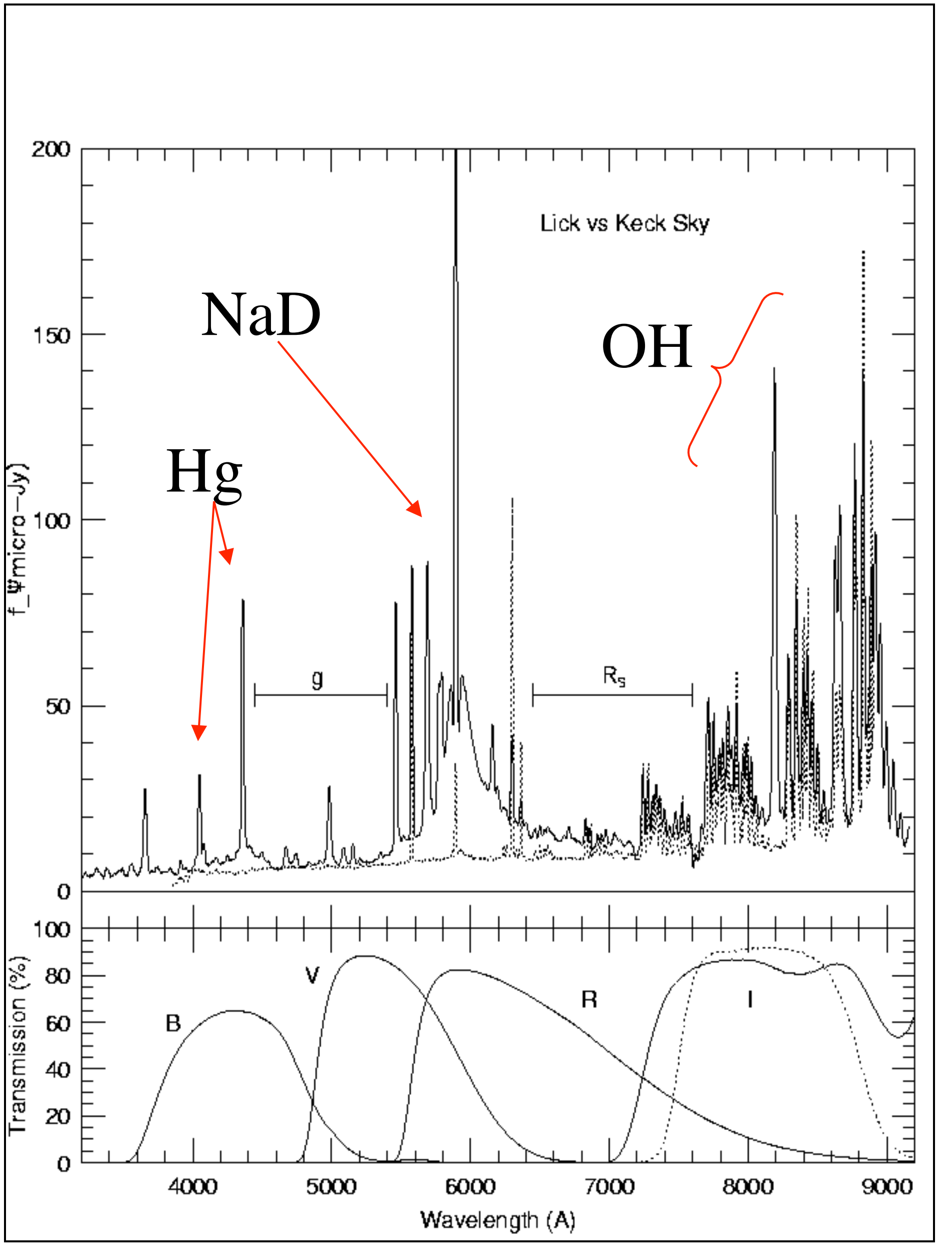
$$m \pm \delta(m) = c_o - 2.5\log(S \pm N)$$
$$= c_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right]$$
$$= c_o \underbrace{- 2.5\log(S)}_{m} \underbrace{- 2.5\log(1 \pm \tfrac{N}{S})}_{\delta m}$$

$$\delta(m) \approx 2.5\log(1 + \tfrac{1}{S/N})$$
$$= \frac{2.5}{2.3}\left[\tfrac{N}{S} - \tfrac{1}{2}(\tfrac{N}{S})^2 + \tfrac{1}{3}(\tfrac{N}{S})^3 - \ldots\right]$$
$$\approx 1.087(\tfrac{N}{S})$$

Note:in log +/- not symetric

Fractional error

This is the basis of people referring to +/- 0.02mag error as "2%"



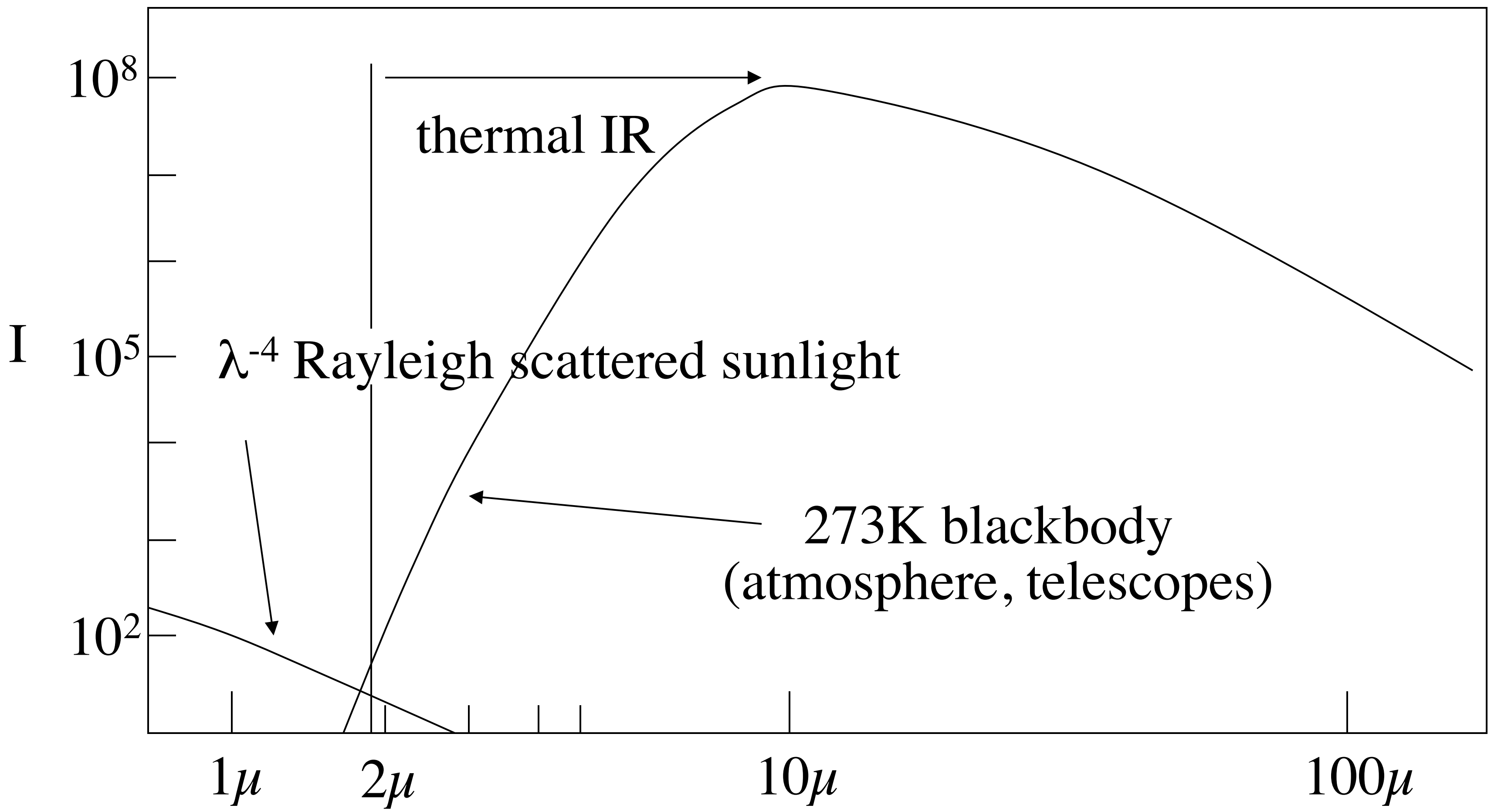
Sky Background

Signal from the sky background is present in every pixel of the aperture. Because each instrument generally has a different pixel scale, the sky brightness is usually tabulated for a site in units of mag/arcsecond^2.

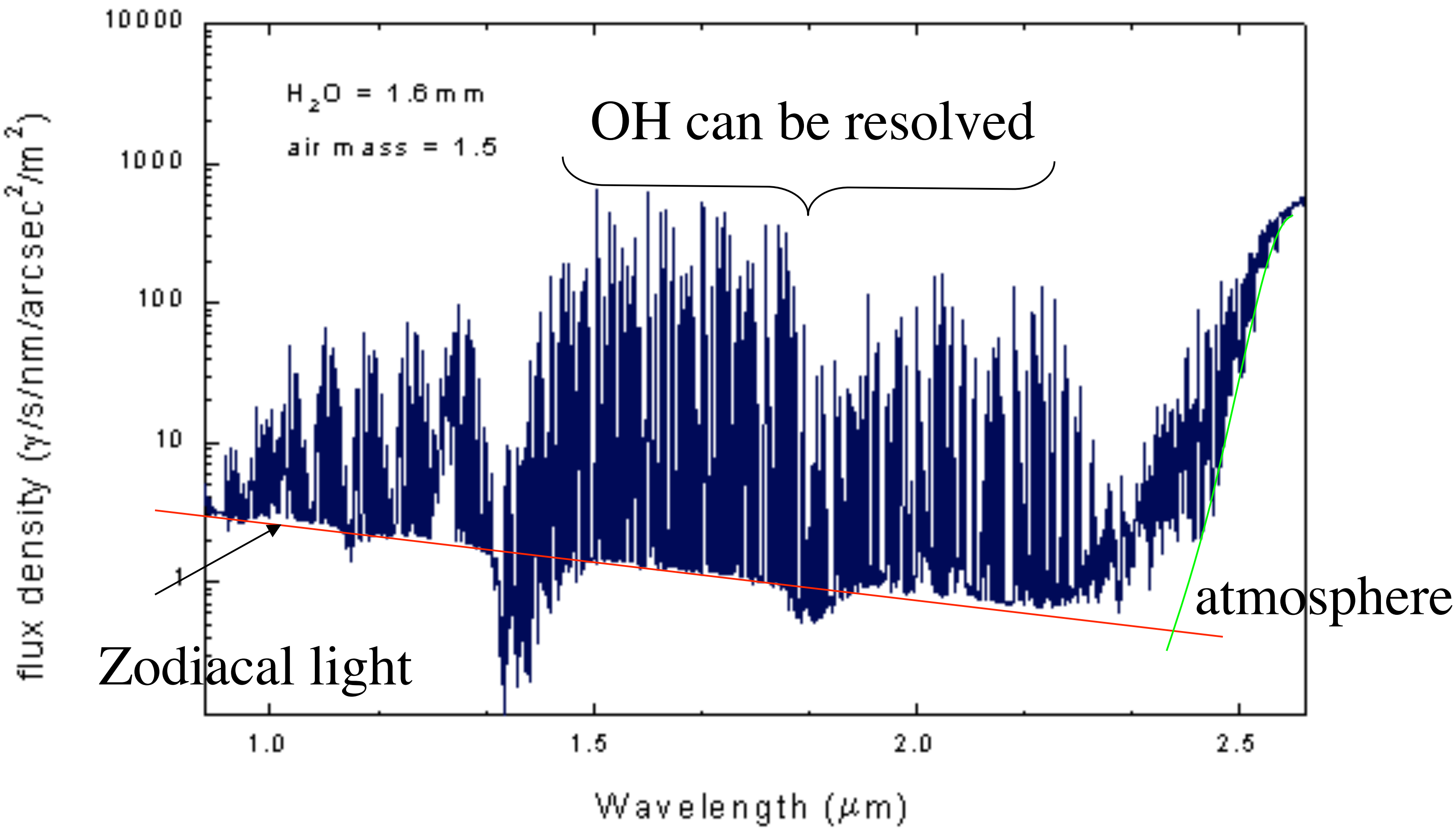
(mag/□″)

Lunar age (days)	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

IR Sky Backgrounds



IR Sky Backgrounds



Scale ⇒"/pix (LRIS - R : 0.218"/pix)

Area of 1 pixel = (Scale)^2 (LRIS – R : 0.0475"^{2}

this is the ratio of flux/pix to flux/"

In magnitudes:

$$I_{pix} = I_{''} Scale^2$$

$I \Rightarrow$ Intensity (e^-/sec)

$$-2.5\log(I_{pix}) = -2.5[\log(I_{''}) + \log(Scale^2)]$$

$$m_{pix} = m_{''} - 2.5\log(Scale^2)$$

(for LRIS - R: add 3.303mag)

and

$$R_{sky}(m_{pix}) = R(m = 20) \times 10^{(0.4 - m_{pix})}$$

Example, LRIS in the R - band:

$$R_{sky} = 1890 \times 10^{0.4(20-24.21)} = 39.1\ e^- /pix/sec$$

$$\sqrt{R}_{sky} = 6.35e^- /pix/sec \approx \text{RN in just 1 second}$$

S/N - some limiting cases. Let's assume CCD with Dark=0, well sampled read noise.

$$\frac{R_* t}{\left[R_* \cdot t + R_{\text{sky}} \cdot t \cdot n_{\text{pix}} + (RN)^2 \cdot n_{pix}\right]^{\frac{1}{2}}}$$

Bright Sources: $(R_* t)^{1/2}$ dominates noise term

$$S/N \approx \frac{R_* t}{\sqrt{R_* t}} = \sqrt{R_* t} \propto t^{\frac{1}{2}}$$

Sky Limited $(\sqrt{R_{sky} t} > 3 \times RN)$: $S/N \propto \dfrac{R_* t}{\sqrt{n_{pix} R_{sky} t}} \propto \sqrt{t}$

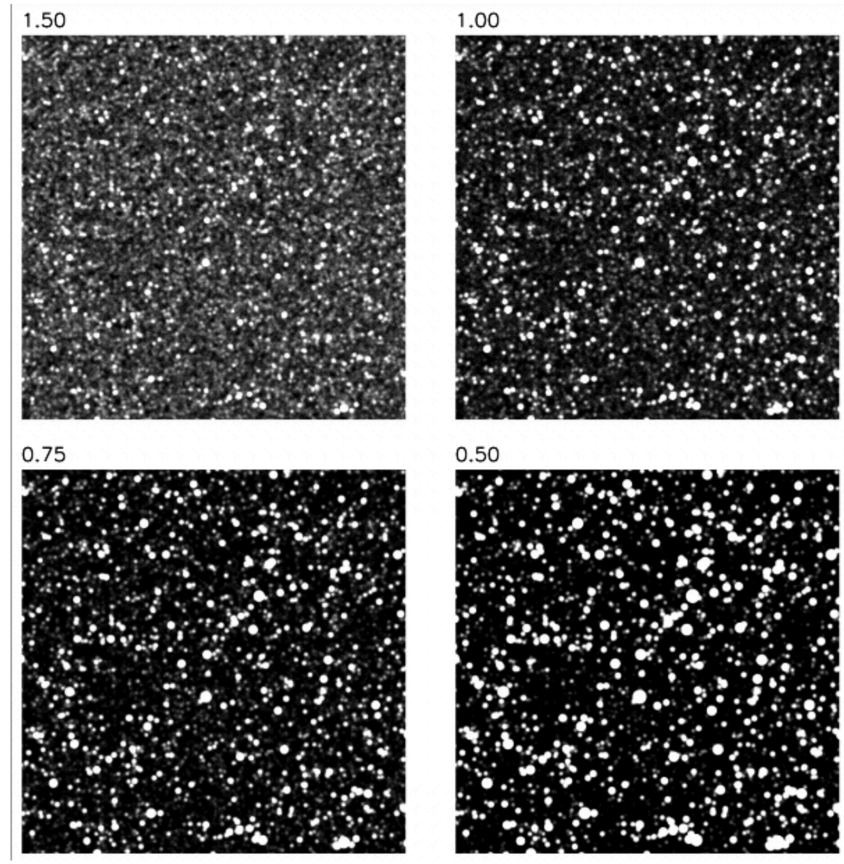
Note: seeing comes in with n_{pix} term

What is ignored in this S/N eqn?

- Bias level/structure correction
- Flat-fielding errors
- Charge Transfer Efficiency (CTE) 0.99999/ pixel transfer
- Non-linearity when approaching full well
- Scale changes in focal plane
- A zillion other potential problems

Confusion Limit

- Flux error due to the fluctuations of the number of faint sources in a beam (PSF)
  - Also, astrometric errors
- Rule of thumb: confusion becomes important at ~ 30 sources/beam
  - The deeper you go, and the larger the beam, the worse it becomes
  - Cut at s/b ~ 30 may be too optimistic
- Typically considered in radio or sub-mm, but relevant in every wavelength regime
- Depends on the slope of the faint source counts, $d\ log\ N / d\ log\ S = -\beta$



Simulated sky images for different values of β (from Hogg (2007, AJ, 121, 1207)

Summary of the Key Points

- Photometry = flux measurement over a finite bandpass, could be integral (the entire object) or resolved (surface photometry)
- The arcana of the magnitudes and many different photometric systems …
- Absolute calibration hinges on the spectrum of Vega, and a few primary spectrophotometric standards
- The S/N computation - many sources of noise, different ones dominate in different regimes
- Issues in the photometry with an imaging array: object finding and centering, sky determination, aperture photometry, PSF fitting, calibrations …