Astro 500

Techniques of Modern *Observational* Astrophysics

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From last time:

Take a look at the texts on reserve:
Start the reading
Evaluate and purchase

What're you going to get?

Required:
o McLean, "Electronic Imaging in Astronomy," Wiley

Recommended:
o Walker, "Astronomical Observations"
o Schroeder, "Astronomical Optics"

Other Useful References:
o Kitchin, "Astrophysical Techiques"
o Bevington & Robinson, "Data Reduction and Error Analysis for the Physical Sciences"
o Gray, "The Observation and Analysis of Stellar Photospheres"
o Cox, "Allen's Astrophysical Quantities"
o Press et al., "Numerical Recipes"

Lecture Outline

- Luminosity & flux
- The *neper*: photons
- Magnitudes & magnitude errors
- Astronomical magnitude systems
- Zeropoint issues
  - ➢ Absolute calibration
  - ➢ Response functions & system transformations
- Surface-brightness
- Interesting astronomical values

Credits: Kron & Spinrad (1992)

Luminosity and Flux

$$dE = L(t)dt$$

$$dE = L_\upsilon(t)d\upsilon\, dt$$

$$dE = L_\lambda(t)d\lambda\, dt$$

$L_\lambda, L_\nu =$ specific luminosity

$$dE_A = f_\upsilon\, dA\, d\upsilon\, dt$$

$$dE = f_\upsilon(4\pi R^2)\, d\upsilon\, dt = L_\upsilon\, d\upsilon\, dt$$

$$\therefore \quad f_\upsilon = \frac{L_\upsilon}{(4\pi R^2)}$$

and similarly for L_λ and f_λ.

- Flux is energy incident on some area dA of the Earth's surface.
- Flux is not conserved and falls off as R^{-2} for a point source.
- All of the above are in units of energy flow per unit time, but there are equivalent expressions for photon flow rate.
- Note: Surface brightness is independent of distance (ignoring cosmological effects)

Flux Units

- Flux (f_ν): measured in Janskys
  - 1 Jy = 10^{-26} W m^{-2} Hz^{-1}= 10^{-23} erg sec^{-1} cm^{-2} Hz^{-1}
- Flux (f_λ): measured in ergs s^{-1} cm^{-2} A^{-1} (cgs units)
- Photon flux (f_γ) is useful for calculating signal-to-noise (counting statistics):
  - Define *neper* = $\Delta\lambda/\lambda = \Delta\nu/\nu = \Delta\ln \nu$
  - The photon flux is:
    - o photons sec^{-1} cm^{-2} $neper^{-1}$ = f_ν/h
    - o where h=6.6256 x 10^{-27} erg sec
  - Useful identify:

1 microJy = μJy = 15.1 photons sec^{-1} m^{-2} $neper^{-1}$

Apparent magnitudes

$$m_1 - m_2 = -2.5\log_{10}\left(\frac{f_1}{f_2}\right) = -a\ln\left(\frac{f_1}{f_2}\right)$$

f_n: the apparent flux of object n.

$$a = 2.5\log_{10} e = 1.08574$$

Pogson's ratio (MNRAS, 1856, 17, 12)

$$m = -2.5\log_{10}\left(\frac{f_1}{f_0}\right) + m_0$$

Will drop "10" here on out.

m_0 : zeropoint of the magnitude system

$f = f_0$ dexp[-0.4(m-m_0)] ← how to get your money back

Absolute Magnitudes

$$m_\lambda - M_\lambda = 5\log_{10} d - 5 + A_\lambda$$

(and similarly for m_v etc.)

$$\therefore \quad \frac{f_1}{f_2} = \left(\frac{d_2}{d_1}\right)^2$$

for the same M

- Absolute magnitude is the apparent magnitude that would be observed if the object were at a distance, d, of 10 pc.
- A_λ is the total extinction due to interstellar dust, in magnitudes, typically take to be only the Galactic foreground screen (Burstein & Heiles 1982, AJ, 87, 1165; Schlegel et al. 1998, ApJ, 500, 525):

HI

IRAS

  - $f = f_0 \exp(-\tau_\lambda)$,
  - $A_\lambda = 1.086\ \tau_\lambda = -2.5 \log(f/f_0)$

See nedwww.ipac.caltech.edu/help/extinction_law_calc.html

Absolute Magnitudes

- For extragalactic observers: *d* in Mpc, plus the so-called k-correction, κ, which accounts for effects of the cosmological expansion
  1) effects of redshifting the rest-frame spectrum in the observed band-pass; and
  2) photon dilution.

$$\boxed{m_\lambda - M_\lambda = 5\log_{10} d + 25 + A_\lambda + \kappa_\lambda}$$

See, e.g.: Schneider, Gunn & Hoessel (1983, ApJ, 264, 337)

Magnitude Errors: S/N ⇔ δmag

$$m \pm \delta(m) = m_o - 2.5\log(S \pm N)$$

$$= m_o - 2.5\log\left[S\left(1 \pm \tfrac{N}{S}\right)\right]$$

$$= \underbrace{m_o - 2.5\log(S)}_{\mathrm{m}} - \underbrace{2.5\log(1 \pm \tfrac{N}{S})}_{\delta\mathrm{m}}$$

What happens when S/N<1 ?

$$\delta(m) \approx 2.5\log(1 + \tfrac{1}{S/N})$$

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

$$\approx 1.086(\tfrac{N}{S})$$

Fractional error

Note: in log +/- not symmetric

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

An alternate magnitude scheme

- **The inverse hyperbolic sine**: Lupton et al. (1999, AJ, 118, 1406)
- Replace log with asinh (i.e., $\sinh^{-1}$)
- Invented to handle errors at low S/N

Definition of asinh mag (μ):

$$m = m_0 - 2.5 \log f \,,$$

$$x \equiv f/f_0,$$

$$\mu(x) \equiv -a\left[\sinh^{-1}\left(\frac{x}{2b}\right) + \ln b\right] .$$

$$\mu = (m_0 - 2.5 \log b') - a \sinh^{-1}(f/2b')$$
$$\equiv \mu(0) - a \sinh^{-1}(f/2b') \,,$$
$$\mathrm{Var}(\mu) = \frac{a^2 \sigma'^2}{4b'^2 + f^2} \approx \frac{a^2 \sigma'^2}{4b'^2} \,,$$

Limiting behaviour:

$$\lim_{x \to \infty} \mu(x) = -a \ln x = m \,, \quad \lim_{x \to 0} \mu(x) = -a\left(\frac{x}{2b} + \ln b\right) .$$

- $a = 2.5 \log e$
- b is a softening parameter that depends on data noise properties -- *this is the boon and the problem*.

Asinh magnitudes: Noise Properties

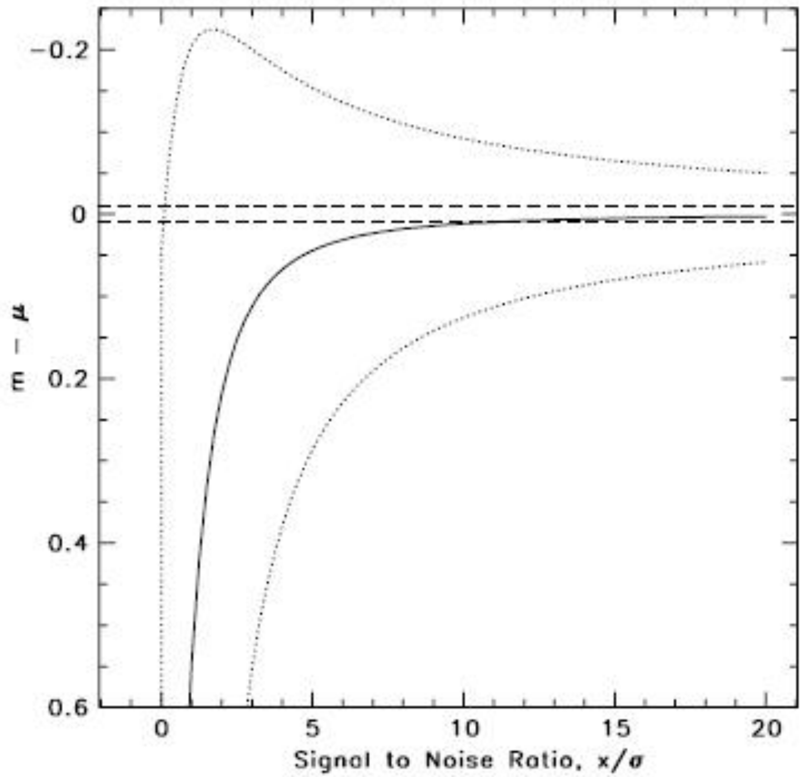


FIG. 1.—Behavior of $m - \mu$ as a function of signal-to-noise ratio x/σ. The solid line is the value of $m - \mu$ and the region between the dotted lines corresponds to the $\pm 1\ \sigma$ error region for m. The dashed lines are drawn at ± 0.01.

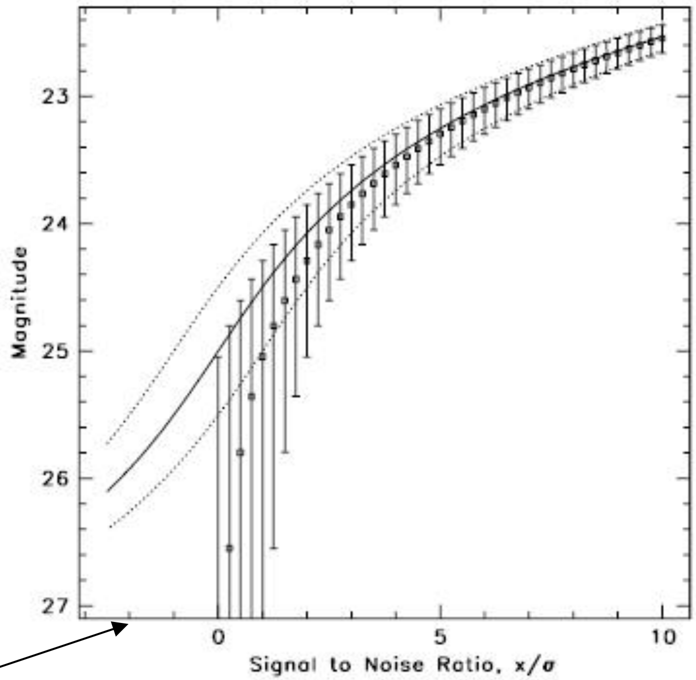


FIG. 2.—Behavior of m and μ and their respective errors as a function of signal-to-noise ratio x/σ. The solid line is the value of μ, and the region between the dotted lines its $\pm 1\ \sigma$ error region; the points with error bars are the classical magnitudes m. We have arbitrarily chosen a zero point of $\mu = 25.0$ for an object with no flux. One other feature of our modified magnitudes is apparent from this figure, namely, that the error band on μ is nearly symmetrical, while the errors in m are strongly skewed at faint magnitudes. For signal-to-noise ratios of less than about 2, $m - \mu$ exceeds the value 0.52 $[\mathrm{Var}(m)]^{1/2}$ quoted in the main body of the paper; this is because of the breakdown of the linear approximation used to calculate m's variance.

Note: negative fluxes “allowed” for asinh

Astronomical Magnitude Systems - 1:3

- Three primary systems for setting the reference flux
  - *Don't confuse magnitude systems and filter systems*
  - Any filter can be used in any magnitude system
  - Any magnitude system can be used for any filter

- **System-1**: Vega or Johnson system

- Vega = α Lyr (A0 V of Pop I abundance) has $V = 0.03$ mag and all colors zero. V is a specific filter + detector response function.
  - Johnson & Morgan (1953, ApJ, 117, 313); Johnson (1965, ApJ, 141, 923)
  - Typical filters: U,B,V,R,I
  - R and I sometimes refered to as Kron-Cousins (R_c,I_c)
  - Near-infrared extension: J,H,K

$$\boxed{\text{Any filter can be used in any system}}$$

Astronomical Magnitude Systems - 2:3

- **System-2**: *griz* or Gunn-Oke system

- BD +17°4708 (F6 subdwarf with B-V=0.43 in the Vega/Johnson system) is defined to have zero colors and g=0 mag.
  - Thuan & Gunn (1976, PASP, 88,543); Wade et al. (1979, PASP, 91, 35); Schneider, Gunn & Hoessel (1983, ApJ, 264, 337); Schild (1984, ApJ, 286, 450)
  - Typical filters: g,r,i,z
- Advantages over Vega system: (i) easier to find faint F subdwarfs to establish tertiary calibrators; (ii) spectral energy distribution (SED) more uniform from 0.5-1 μ.

Any filter can be used in any system

Astronomical Magnitude Systems - 3:3

- **System-3**: *AB*
- $m_{AB} = AB_\nu = -2.5 \log f_\nu - 48.60,$
- f_ν measured in erg sec^{-1} cm^{-2} Hz^{-1} or Jy:
  - f_ν(Jy) = 3631 dex($-0.4 AB_\nu$)
- Constant (48.60) chosen so $m_{AB} = V$ for a flat-spectrum source, i.e., $f_{\nu,0}$ is for α *Lyr* near middle of the *V* band (548 nm).
  - Oke & Gunn (1983, ApJ, 266, 713); Fukugita et al. (1996, AJ, 111, 1748)
  - Sloan Digital Sky Survey (SDSS) uses *AB* system for u',g',r',i',z'
- Advantages: good for comparing fluxes over a large dynamic range in ν (e.g., X-ray to radio) or to theory (*physical* units).
- Disadvantages: no *physical* intuition in the optical-NIR where spectral energy distributions are dominated by stars.

monochromatic magnitude

Still fundamentally tied to α *Lyr* for zeropoint

Any filter can be used in any system

Astronomical Magnitude Systems

TABLE 8. Magnitudes of α Lyr in the AB_{95} and the conventional schemes.

	u'	g'	r'	i'	z'	U	B	V	R_c	I_c
AB_{95}	0.981	−0.093	0.166	0.397	0.572	0.719	−0.120	0.019	0.212	0.453
conv.						0.02	0.03	0.03	0.03	0.024

Fukugita et al. (1996)

Definition of *broad-band* AB magnitude: (S_ν is system response)

$$m = -2.5 \log \frac{\int d(\log \nu) f_\nu S_\nu}{\int d(\log \nu) S_\nu} - 48.60,$$

Note: m_{AB} is typically fainter than $m_{\alpha Lyr}$: sounds better than it "really" is.

Any filter can be used in any system

Astronomical Magnitude Systems

Table 2.1: Fluxes for m = 0

How are these determined?

Band	λ_c (μ)	$\Delta\lambda/\lambda$	Jy	Reference
U	0.36	0.15	1810	Bessell (1979)
B	0.44	0.22	4260	"
V	0.55	0.16	3640	"
R	0.64	0.23	3080	"
I	0.79	0.19	2550	"
J	1.26	0.16	1600	Campins, Rieke & Lebofsky (1985)
H	1.60	0.23	1080	"
K	2.22	0.23	670	"
g	0.52	0.14	3730	Schneider, Gunn & Hoessel (1983)
r	0.67	0.14	4490	"
i	0.79	0.16	4760	"
z	0.91	0.13	4810	"
u'	0.35	0.18		Fukugita et al. (1996)
g'	0.48	0.29		"
r'	0.63	0.22	?	"
i'	0.77	0.29		"
z'	0.91	0.16		"

Johnson

griz

SDSS AB_{95}

nepers

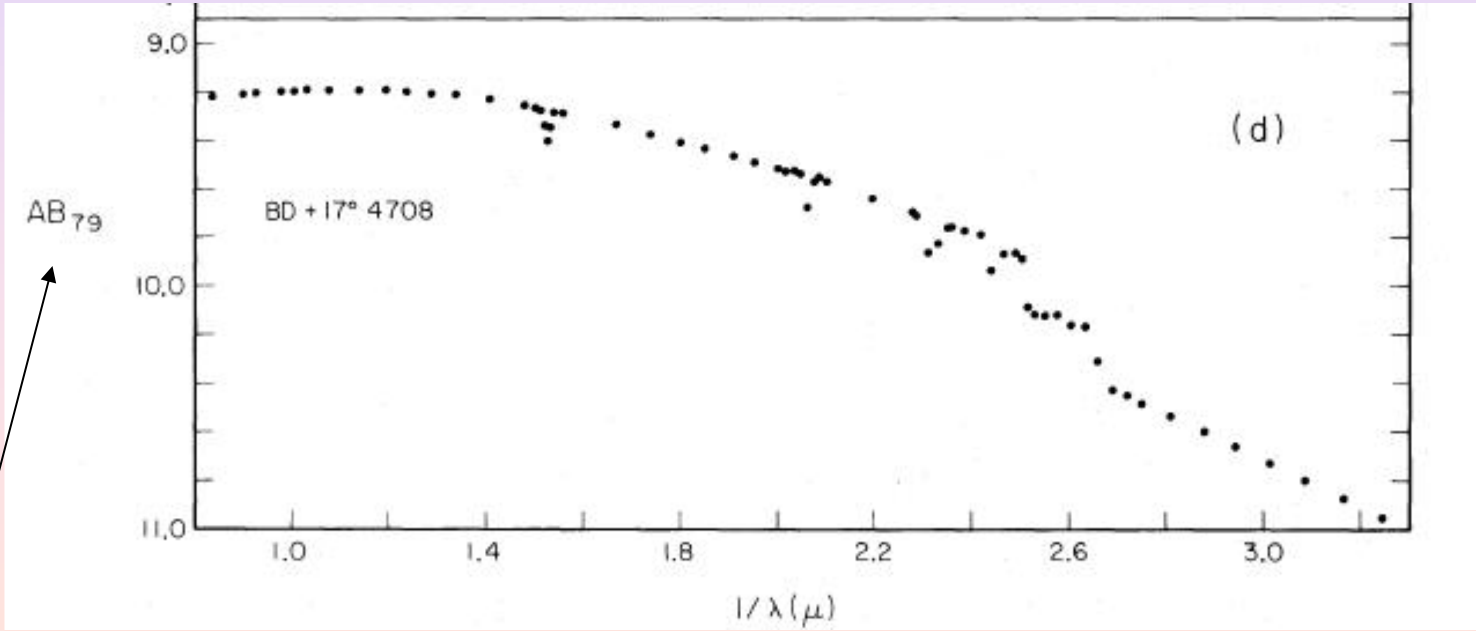
Note uniformity in $\Delta\lambda/\lambda$

Absolute Calibration

- Somehow the apparent flux of star, as counted by some instrument has to be transformed to absolute units of erg sec^{-1} cm^{-2} Hz^{-1}.
- This requires comparison of the stellar flux to a terrestrial black-body source calibrated in a laboratory, but positioned to be observed at nearly the same time as the star through the same telescope and instrument. *Good luck*.
- This sometimes involves cutting holes in telescope enclosures and other *wild* experiments (e.g., see Tug et al. 1977).
- This is highly non-trivial and is a mammoth effort to do it right.
- *How good is right?*
  - Anything worse than few% accuracy isn't worth the effort.
  - This is **hard**. But might be a lot of fun.

Absolute calibration

- *griz* (Gunn) system: BD +17^{o}4708
  - Oke & Gunn (1983, ApJ, 266, 713)
  - Absolute spectro-photometry -- good to 2%.
  - This star was chosen as a standard because of its relatively smooth SED.



NB: AB_{95} (Fukugita et al.'06) uses revised αLyr zeropoint (Hayes'85).

Absolute calibration

- Vega (α Lyr) / Johnson system
  - Hayes & Latham (1975, ApJ, 197, 593): $f_\nu(\lambda$=555.6nm) = 3500 Jy
  - Tug, White & Lockwood (1977, A&A, 61, 679): $f_\nu(\lambda$= 555.6nm) = 3570 Jy
  - Hayes (1985): $f_\nu(\lambda$=555.6nm) = 3590 Jy, quotes 1.5% accuracy
  - Variance (2.5% full range) gives some indication of *external* errors.

Note stars not calibrated in region longward of Balmer limit

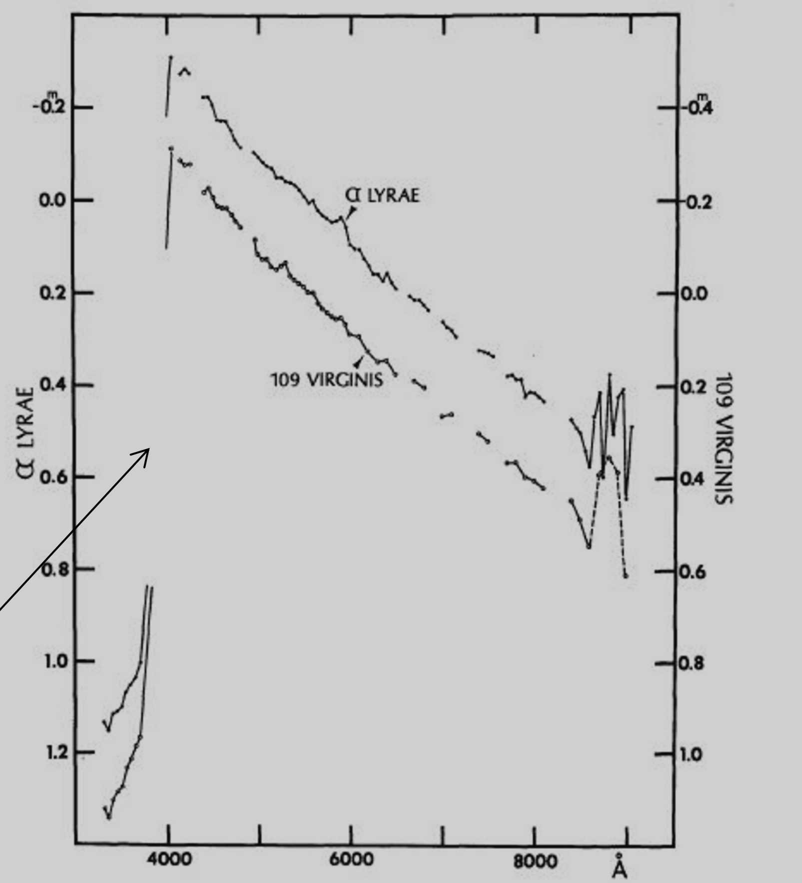


Fig. 2. Final absolute calibration of α Lyr (*upper curve; left ordinate scale*) and 109 Vir (*lower curve, right ordinate scale*) in magnitude units ($M_{1/\lambda}$), normalized to 0.0 mag at 5556 Å

Absolute calibration issues

"We note parenthetically that it is of great importance to attempt to measure the ratio of the flux of BD +17^{o}4708 to that of α Lyr with a truly linear system at a variety of wavelengths as soon as possible."

Fukugita et al. 1996

AB_{95} zeropoint estimated to be good to about 3%

Absolute calibration issues

- Incomplete spectral coverage
  - ➢ UV and IR
- Broad-band flux calibration and λ_c depends on assumed spectral energy distribution (Matthews & Sandage 1963)
- True system response function must be well-characterized
  - ➢ Detector non-linearity (a)
  - ➢ Filter red-leak (b)
  - ➢ Filter + CCD response non-uniformity: calibrator vs. other sytems (c)

(a)

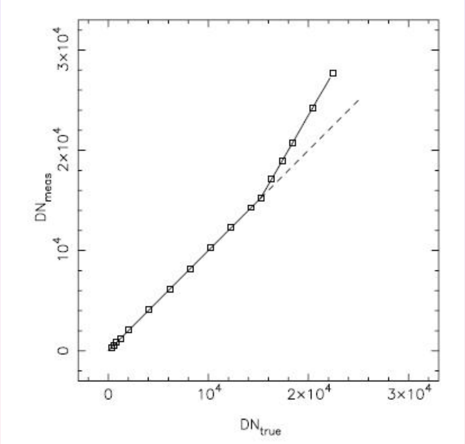
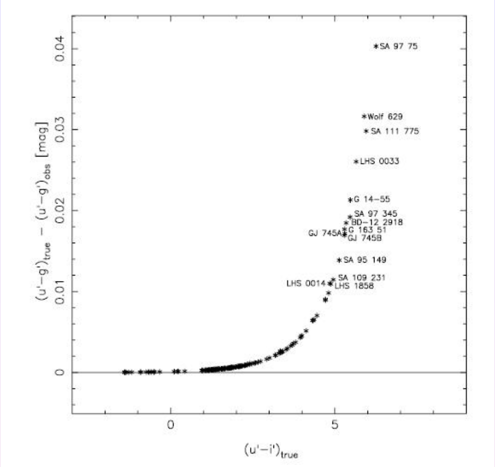


FIG. 1.—Linearity curve for the TK1024 CCD used on the USNO 1.0 m telescope for this program (*solid line*). DN_{meas} is the raw, bias-subtracted value of the signal; DN_{true} is the value that would have been measured if the CCD were completely linear. Note the "knee" at DN ≈ 15,200 ADU. The dashed line acts as a reference for what a fully linear relation would look like.

(b)



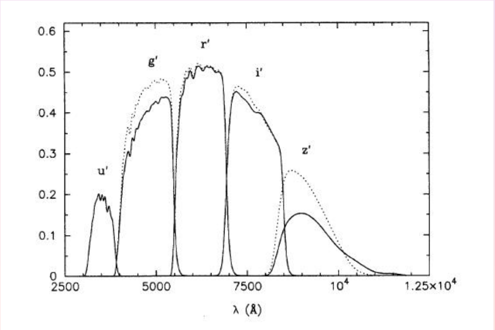


FIG. 7. Response function of the SDSS survey camera (solid curves), as compared with that of the Monitor Telescope (dashed curves), which defines the SDSS photometric system. The two curves are nominally identical for the u' band.

(c)

Defining Response Functions S_λ, S_ν

- Band-pass depends on more than filter transmission
  - Atmospheric transmission (depends on airmass)
  - Detector response
  - *What else?*

z' defined by CCD Si cut-off

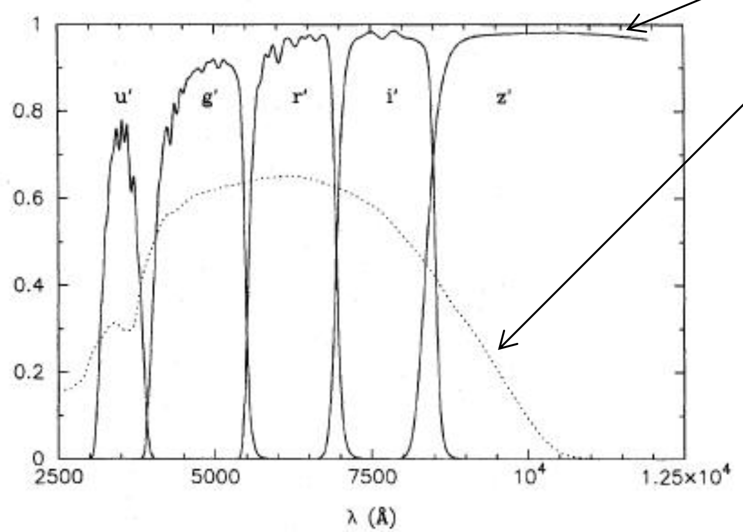


FIG. 1. Transmission of the $u'g'r'i'z'$ filters. Redleaks shortward of 11 000 Å are not shown. The dotted curve is the quantum efficiency of a thinned, UV-coated SITe CCD; this is the detector that is used in the definition of the SDSS system.

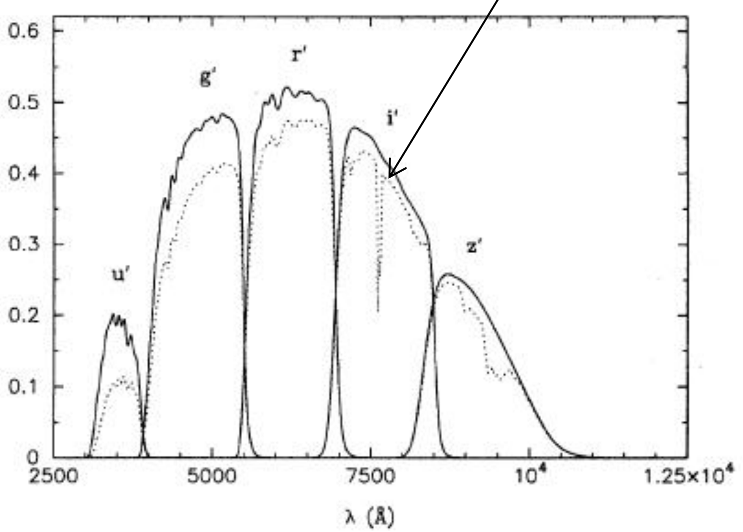


FIG. 2. Response function of the SDSS photometric system, using a UV-coated thinned CCD. Dashed curves indicate the response function including atmospheric transmission at 1.2 airmasses at the altitude of Apache Point Observatory.

Characterizing Response Functions

- Just as band-pass depends on more than filter transmission…
- Effective *wavelength* and *width* of response function also depends on source flux
- … and definition!

Intuitive but: $\lambda_{eff} \neq c/\nu_{eff}$

$$\lambda_{\text{eff}} \equiv \frac{\int \lambda S_\lambda f_\lambda \, d\lambda}{\int S_\lambda f_\lambda \, d\lambda},$$

Kron (1980, ApJS, 43, 305)

well defined: $\lambda_{eff} = c/\nu_{eff}$

$$\lambda_{\text{eff}} = \exp\left[\frac{\int d(\ln \nu) S_\nu \ln \lambda}{\int d(\ln \nu) S_\nu}\right],$$

neper

$$\sigma = \left[\frac{\int d(\ln \nu) S_\nu [\ln(\lambda/\lambda_{\text{eff}})]^2}{\int d(\ln \nu) S_\nu}\right]^{1/2},$$

width

$$\sigma_{eff} = 2\sqrt{\ln 2}\,\sigma\lambda_{eff}$$

effective width

$$Q = \int d(\ln \nu) S_\nu .$$

effective power

Fukugita et al. 1996, based on Schneider et al. 1983 for a specific choice of f_ν

Characterizing Response Functions

- An example:

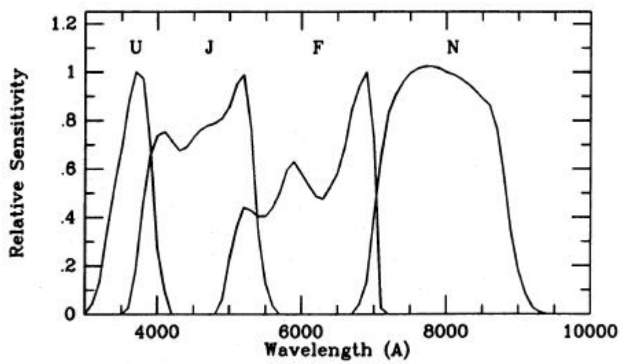


FIG. 1.—Response functions for bandpasses U, J, F, and N. See § III for a description of the derivation of the U and N bands. See Kron (1980a) for the J and F bands.

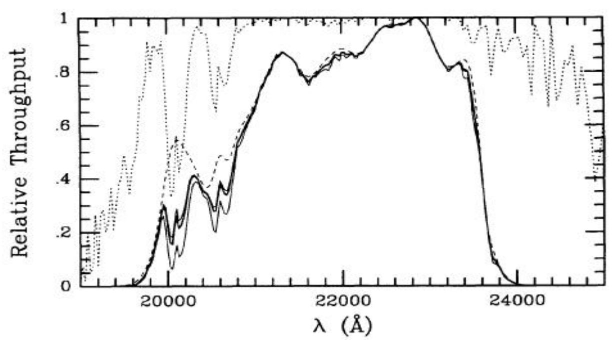


FIG. 10. K band response function for the KPNO IRIM as constructed in this work (see text), and atmospheric extinction (Manduca & Bell 1979) are plotted vs wavelength. The heavy solid line is the adopted curve using 1.15 airmasses of atmospheric extinction. Light solid lines represent models using 1 and 2 airmasses; the dashed line is the product of the filter transmission alone; and the dotted line is the model atmospheric transmission at 1 airmass for KPNO in the summer.

$$\lambda_{\rm eff} \equiv \frac{\int \lambda S_\lambda f_\lambda \, d\lambda}{\int S_\lambda f_\lambda \, d\lambda},$$

TABLE 1

OPTICAL AND NEAR-IR BAND-PASS CHARACTERISTICS

	A0V, $z = 0$				S1, $z = 0.3$			
Band	λ_c	λ_{50}	FW_{50}	FW_{90}	λ_c	λ_{50}	FW_{50}	FW_{90}
U	3721	3775	325	700	3647	3675	325	725
B_J	4526	4500	775	1425	4618	4700	875	1500
R_F	5983	5950	1075	1875	6108	6175	950	1825
I_N	7837	7800	875	1700	7944	7950	950	1675
K	21882	21925	1550	3200	...	...	...	...

NOTE.—λ_c is the first moment of the tranmission function × spectrum product, i.e. the flux-weighted mean filter wavelength. λ_{50} is the wavelength at which 50% of the energy is enclosed, i.e. the median. FW_{50} is the full-width at the 50% power-point. FW_{90} is the full-width at the 90% power-point. All measures are in Å. Columns 2-5 are calculated for an A0V star at rest ($z = 0$) from the stellar atlas compiled by Bruzual & Charlot (1993). Columns 6-9 are calculated for the extreme starburst composite galaxy spectrum designated 'S1' from Kinney *et al.* (1996), which does not extend beyond 1μm; this spectrum is shifted to $z = 0.3$, typical of the redshifts if the program objects. (A redshifted A0V spectrum has nearly identical values for K.) Filter transmission curves are from Kron (1980; B_J, R_F), Koo (1986; U, I_N), and Bershady *et al.* (1994; K band)

Alternatively, a nice little theorem:

- If

$$\lambda_{\rm eff} = \exp\left[\frac{\int d(\ln \nu) S_\nu \ln \lambda}{\int d(\ln \nu) S_\nu}\right],$$

and

$$\sigma = \left[\frac{\int d(\ln \nu) S_\nu [\ln(\lambda/\lambda_{\rm eff})]^2}{\int d(\ln \nu) S_\nu}\right]^{1/2},$$

- then

$$\boxed{\frac{d\lambda_{eff}}{d\alpha} = \lambda_{eff}\,\sigma}$$

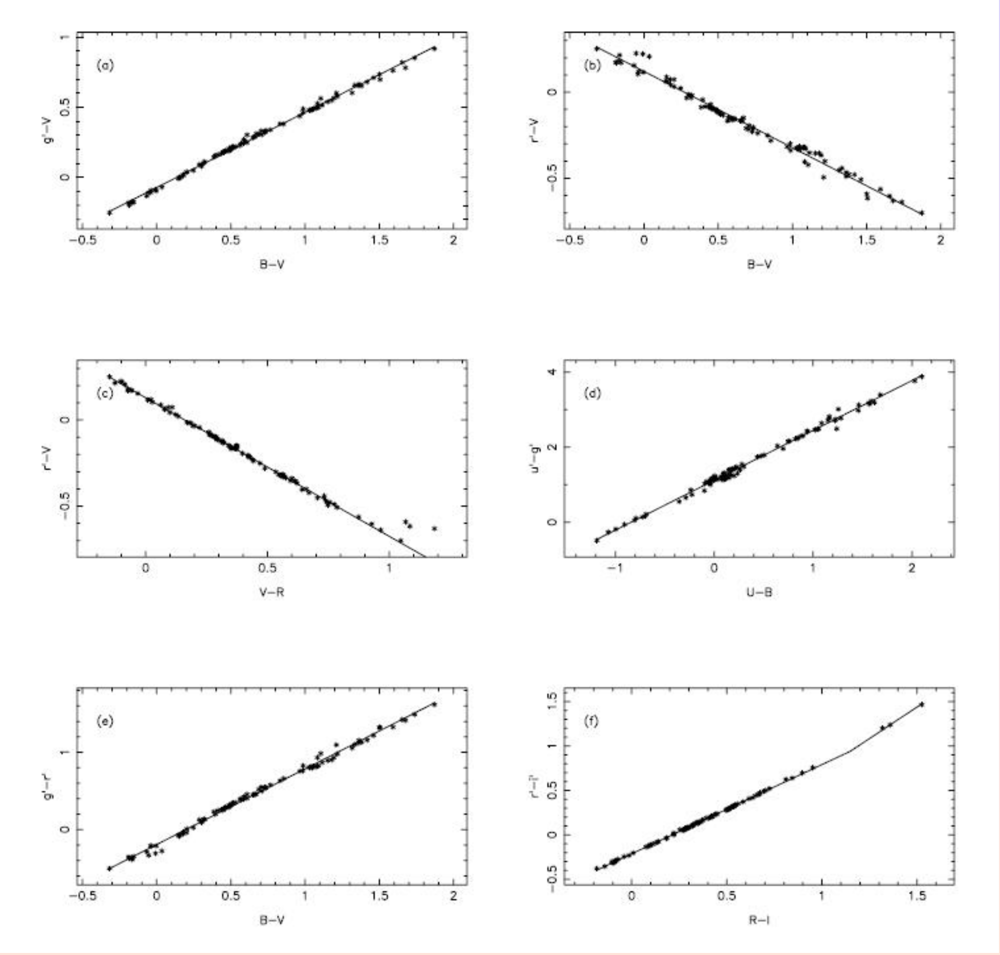
where $f_\nu \propto \nu^\alpha$, i.e., a power-law of index α

What is assumed for f_ν and why is this an interesting choice? Astrophysical or esthetic?

System Transformations

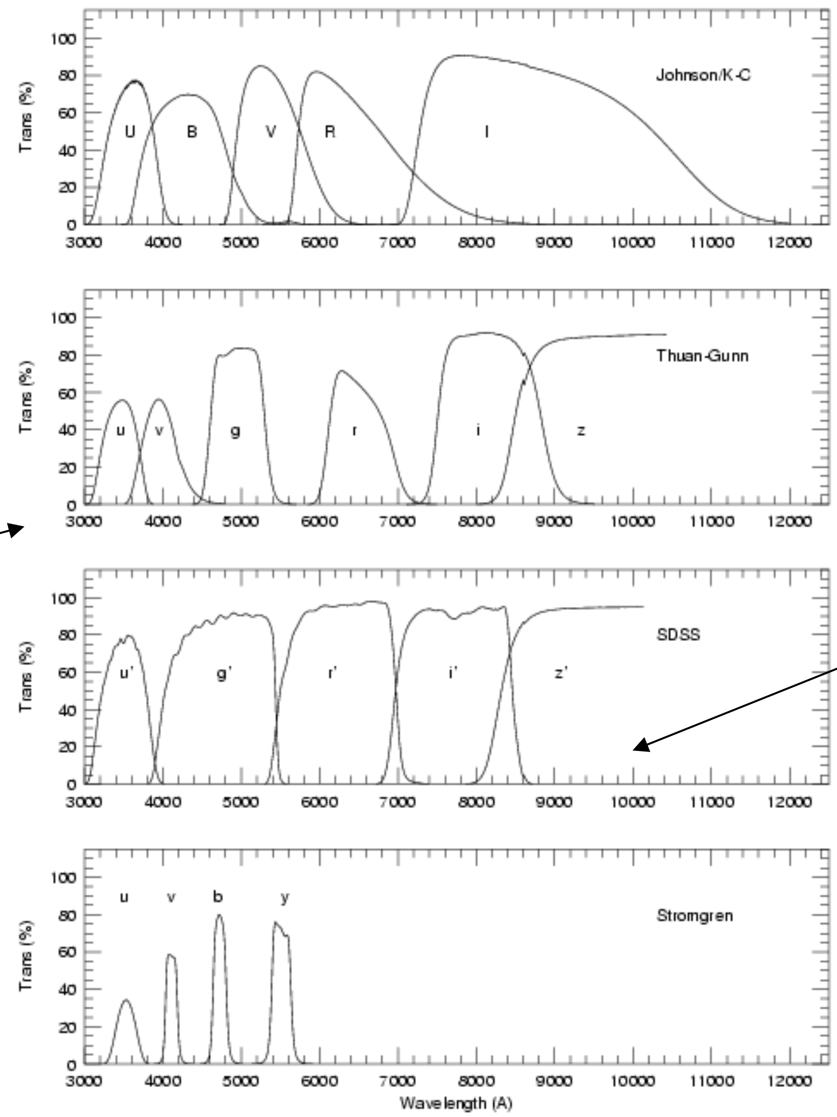
- Transformations specific to filter/response systems *and* spectra.
- Equations for z=0 stars
- Errors significant if
  - Extreme colors
  - Spectral breaks
  - Line-dominated

$$
\begin{aligned}
g' &= V + 0.56(B-V) - 0.12, \\
r' &= V - 0.49(B-V) + 0.11, \\
r' &= V - 0.84(V-R_c) + 0.13, \\
u' - g' &= 1.38(U-B) + 1.14, \\
g' - r' &= 1.05(B-V) - 0.23, \\
r' - i' &= 0.98(R_c - I_c) - 0.23 \qquad (R_c - I_c < +1.15) \\
&= 1.40(R_c - I_c) - 0.72 \qquad (R_c - I_c \geqslant +1.15), \\
r' - z' &= 1.59(R_c - I_c) - 0.40 \qquad (R_c - I_c < +1.65) \\
&= 2.64(R_c - I_c) - 2.16 \qquad (R_c - I_c \geqslant +1.65),
\end{aligned}
$$



Common

Filter curves



3100Å is the UV atmospheric cutoff

1μ silicon bandgap

SDSS vs Johnson *Response* Curves

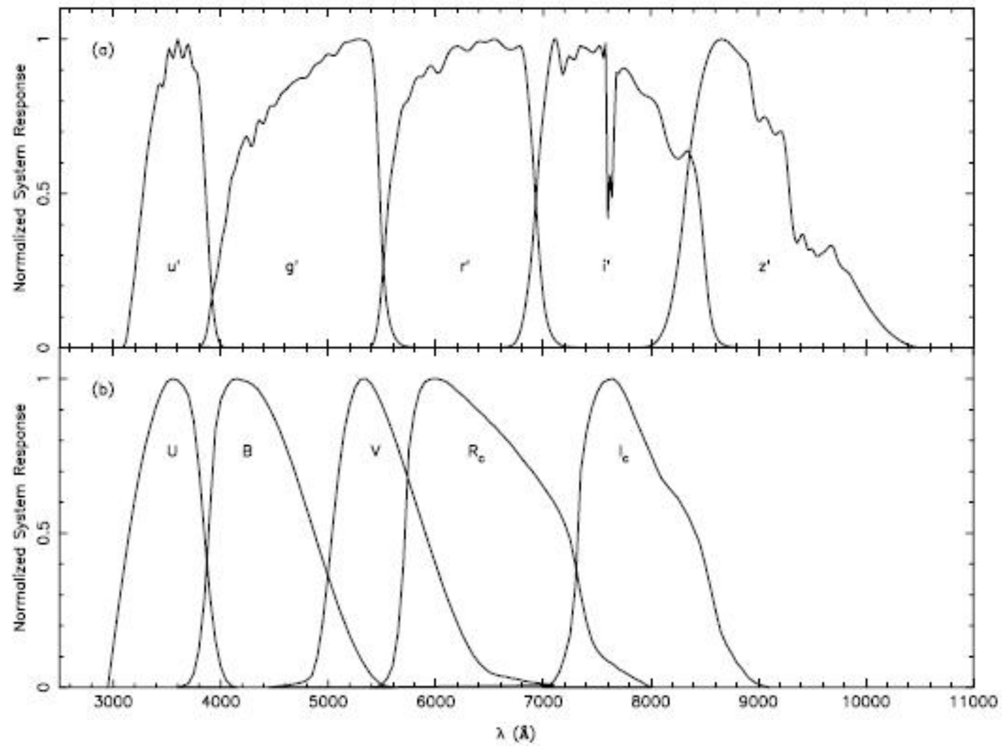


FIG. 3.—The (normalized) responses of the $u'g'r'i'z'$ system bandpasses (at 1.2 air masses of extinction) compared with those of the Johnson-Morgan-Cousins ($UBVR_CI_C$) system. (Filter curves for the Johnson-Morgan UBV filters and for the Cousins R_CI_C filters were obtained from the General Catalogue of Photometric Data, at http://obswww.unige.ch/gcpd/gcpd.html; Mermilliod, Mermilliod, & Hauck 1997.)

Some useful references

Magnitues systems (Pogson and asinh luptitudes for SDSS):

- http://skyserver.sdss.org/dr7/en/help/docs/algorithm.asp?key=photometry

Zeropoints and transformations: (SDSS-II DR7) – note references therein

- http://classic.sdss.org/dr7/algorithms/fluxcal.html
- http://classic.sdss.org/dr7/algorithms/sdssUBVRITransform.html

Same, but for SDSS-III DR8:

- https://www.sdss3.org/dr8/algorithms/fluxcal.php
- https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php
- https://www.sdss3.org/dr8/algorithms/ugrizVegaSun.php

A very interesting read on establishing photometric systems:

- http://classic.sdss.org/dr3/algorithms/sdssphot.ps

Some more recent papers on transformations:

- Bilir+2008 MNRAS
- Chonis & Gaskell 2008, AJ, 135, 264

Surface Intensity

- Finite size source (subtends a real angle)
- Specific intensity per unit angle
- Also called *surface brightness* ←
- Units:
  - (Jy sr^{-1}) - f_ν
  - (W m^{-2} Hz^{-1}sr $^{-1}$) - f_ν
  - (erg arcsec^{-2} cm^{-2} Hz $^{-1}$) - f_ν
  - (erg arcsec^{-2} cm^{-2} A^{-1}) - f_λ
  - (mag arcsec^{-2}) - either
- What happens when the source is not resolved?

Surface Intensity

$$dE_\nu = I_\upsilon(\Omega,\upsilon,t,p)\ \ d\upsilon\ \ dt\ \ dA\ d\Omega$$

and similarly for $I_\lambda\, d\lambda$, where I will depend on:

- Ω, measured in RA and Dec,
  i.e., location where you are receiving the light.
- ν = frequency (or equivalent wavelength)
- t = Integration time
- p = polarization

Observation

$$E = \int [I_\nu(\Omega,t,p) + S_\nu(\Omega,t,p)]R_\nu(\Omega,\upsilon,p)d\Omega\, d\upsilon\, dt\, dA$$

$$E = A\Omega t \int (\bar{I}_\nu + \bar{S}_\nu)\bar{R}_\nu\, d\upsilon$$

- E = total energy received during measurement
- I_ν, S_ν = energy from object and sky, respectively
- R_ν = system response function including atmosphere, telescope, instruments optics (including filters), and detector quantum efficiency.
- $\bar{I}_\nu$, $\bar{S}_\nu$, $\bar{R}_\nu$ = time-angle-area averaged quantities

When is this important?

Measures of Surface Brightness

- S_{10} definition: units equivalent # of m=10 mag A0 stars deg^{-2}.
  - Can convert to Jy sr^{-1} using Table 2.1.
- Monochromatic solar luminosity: to convert between $L_{\odot}pc^{-2}$ and mag $arcsec^{-2}$
  - use monochromatic solar luminosity (Table 2.2).

Table 2.2

λ	L_{ν}
μm	10^{18} erg sec^{-1} Hz^{-1}
0.36	1.24
0.44	3.31
0.55	5.30
0.64	6.28
0.79	6.86
1.26	6.55
1.60	6.01
2.22	3.63

Interesting V-band magnitudes (Vega)

- Sun: $V = -26.7$
- Full moon: $V = -12.6$
- Sirius: $V = -1.5$
- Naked eye limit: $V = 6$
- Brightest stars in Andromeda: $V = 19$
- Present day detection limit: $V \sim 29\text{-}31$

- Night sky: $V = 21.5$ (best sites, dark time)
- Night sky: $V = 18$ (bright time)

What's different about these last two?

Take away:

- The notes contain a suitable reference for almost all of your future needs with optical-NIR photometry.

- Band-passes and calibration requires detailed information about filters, detector, telescope (optics), and atmosphere.

- Well-calibrated photometry is difficult to achieve.
  - 10%? You're not trying hard enough.
  - 5%? Ok.
  - 3%? Good. You are pressing the limit of the absolute calibration.
  - 1%? Don't fool yourself; you're limited by the absolute calibration.

Which brings up the topic of precision vs accuracy…

Random vs systematic error

- Same as the difference between precision vs accuracy
  - Precision: How well can you measure a quantity (what's the variance of repeat measurements)?
  - Accuracy: How well do your measurements (in the mean) reflect the value you are trying to measure?
  - *Know the difference – fundamental.*
- We're lucky when an astronomical result includes a quote of random error. Systematic errors in astronomy are rarely addressed, but this is changing; it has long been common-place in Physics.
- In error handling and reporting, be a physicist in rigor with the intuition of an astronomer.