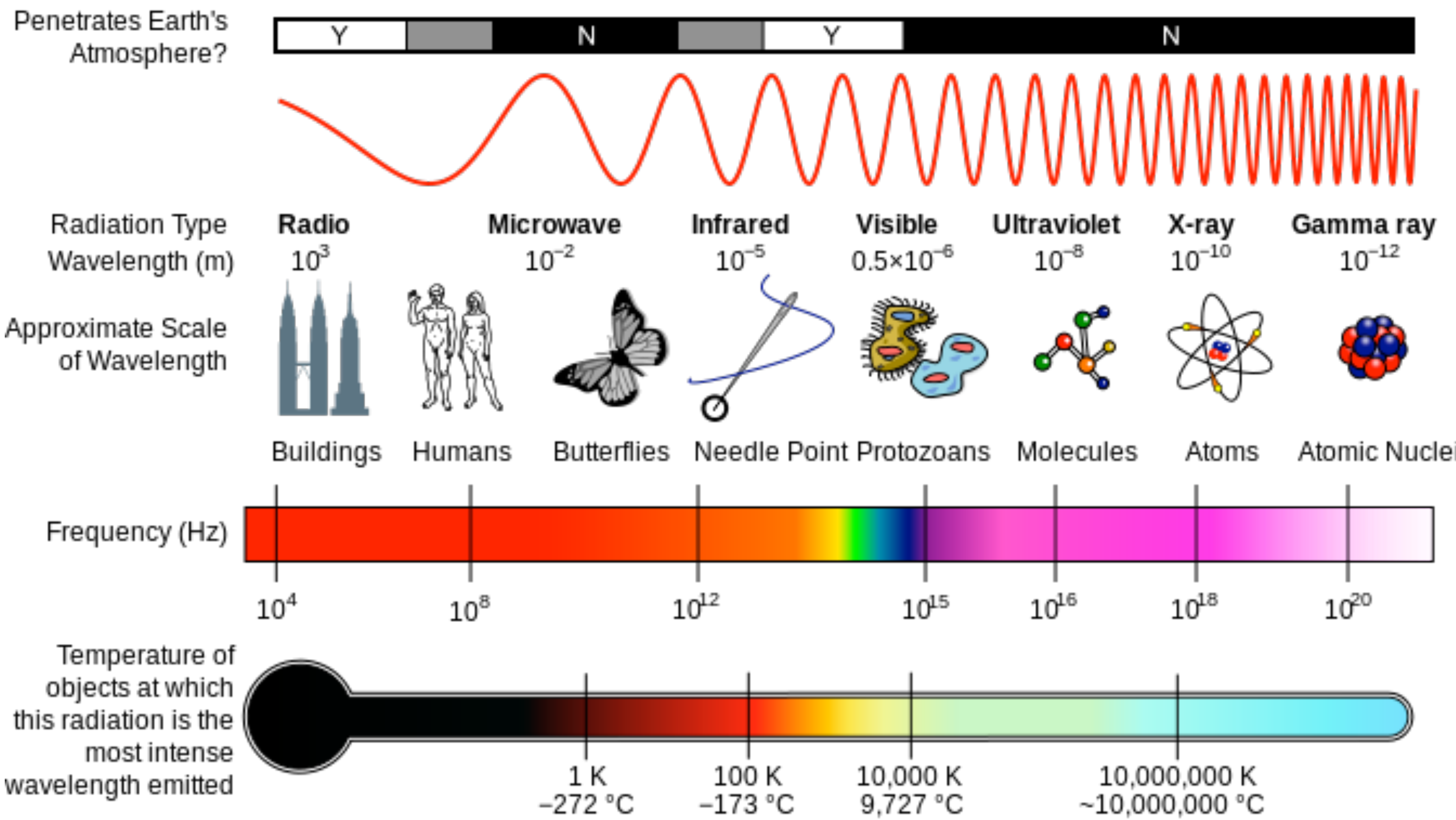
Light and magnitudes

Ast 401/Phy 580
Fall 2015

Electromagnetic Spectrum



Optical

Optical observations are limited to about 3200Å–10000Å. The latter is 1 micron (μm)

(About the units: 1A = 10^{-10} m. It's about the size of an atom; i.e., the Bohr radius is about 1/2 Å. It's not unusual to express optical wavelengths in nanometers (10^{-9} m), so we could also say optical is 320nm–1000nm, or 320nm–1μm.)

"Visible" wavelenths (what your eye can see) is about 4,500Å to 6500Å.

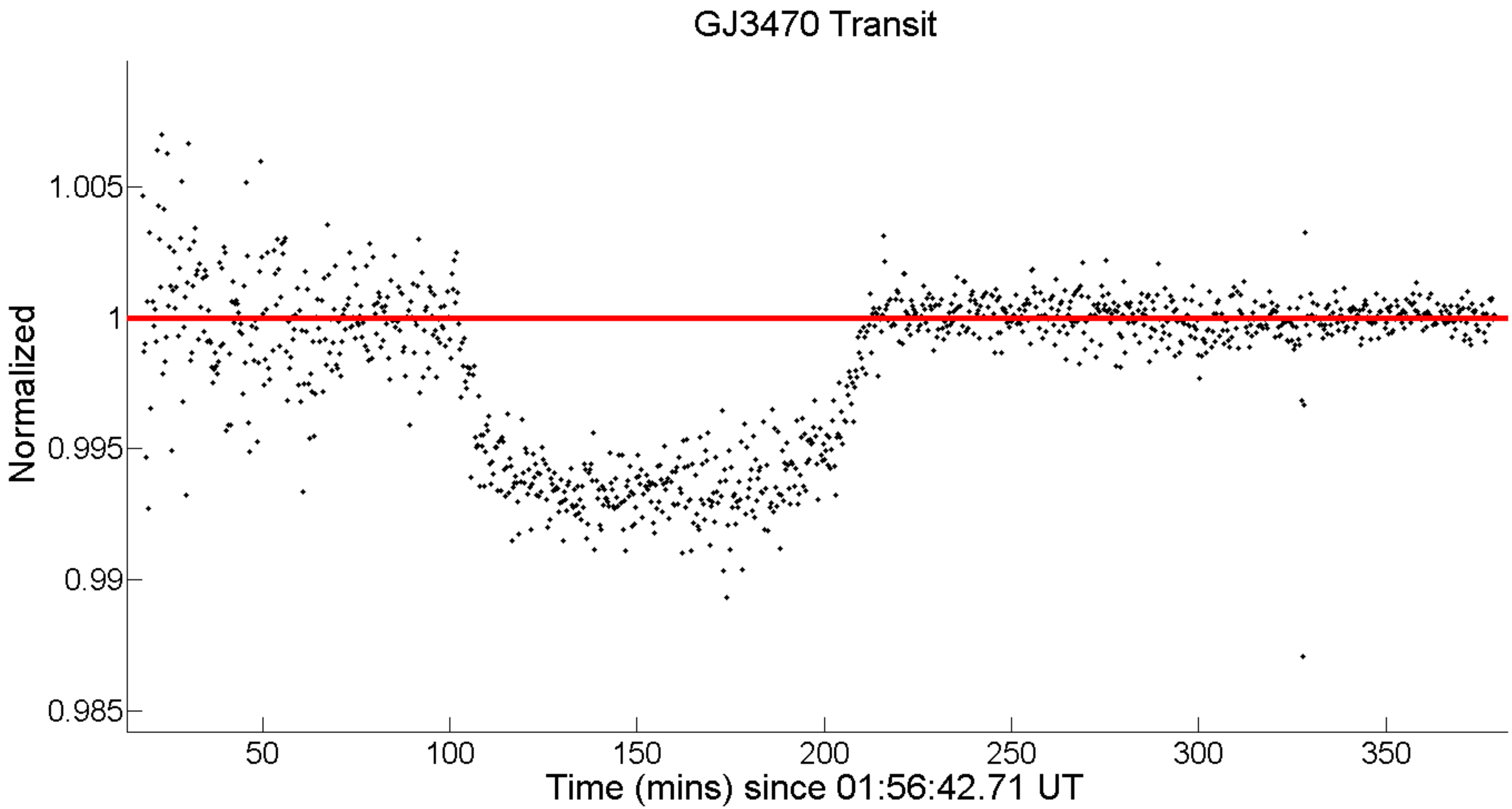
Flux

Photometry is the science (art?) of measuring the amount of light coming from an astronomical object, the flux in some bandpass.

Photometry vs Spectrophotometry

With broad- or narrow-band photometry you are measuring the flux integrated over some filter bandpass. Poor wavelength resolution generally, but can be very accurate: 1% is typical "goal" for all sky-photometry; differential photometry can be as good as 0.1% or better.

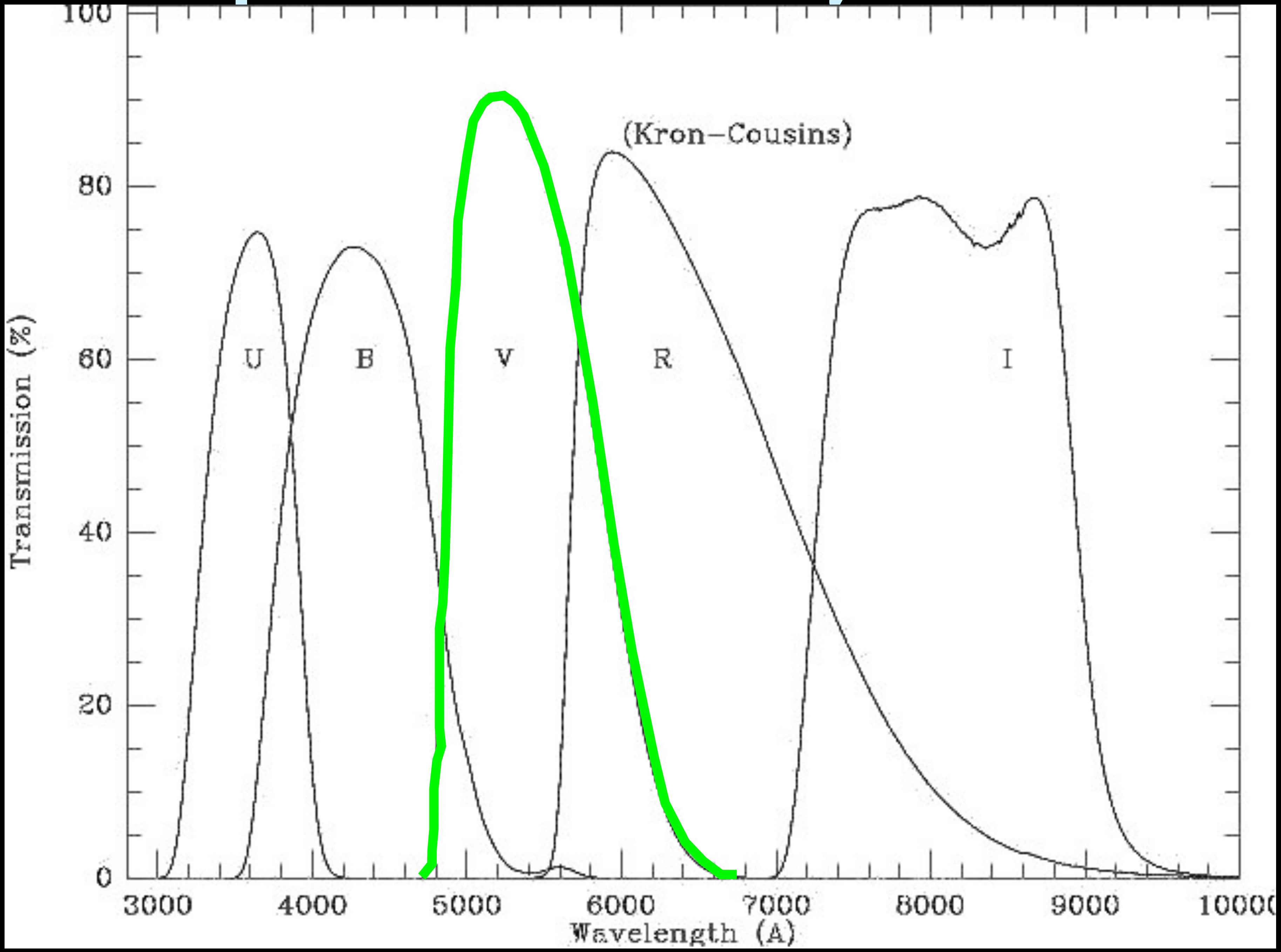
Light Curve for exoplanet transit



Light Curve Observed and created by Webber, Barman, Taylor, Levine, Strosahl

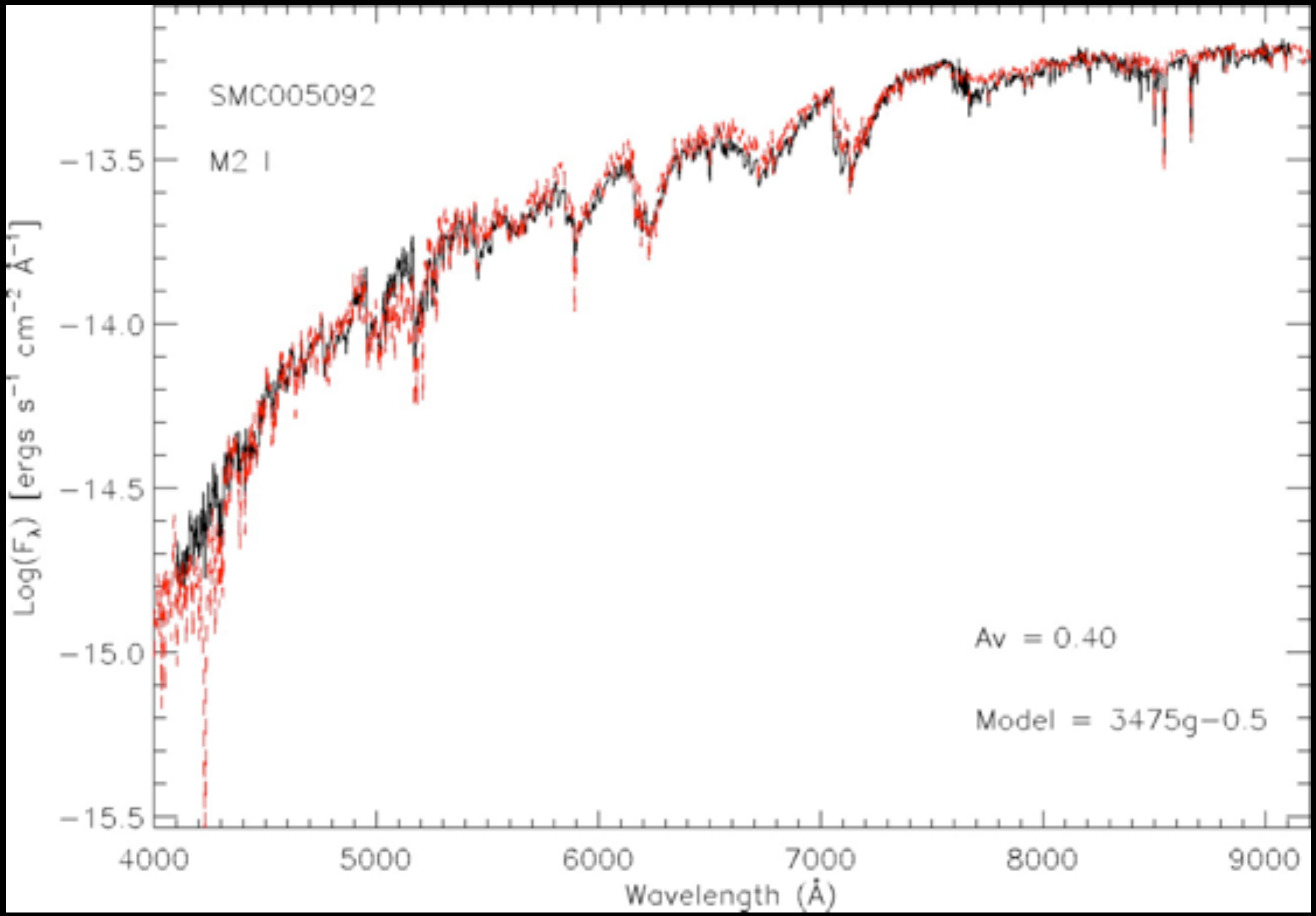
Photometry vs Spectrophotometry

Poor spectral resolution though: typical broad-band filter is about 500A wide!



Photometry vs Spectrophotometry

By contrast, spectrophotometry typically has a resolution of about Å, but precision is limited to 1-2%.



Photometry vs Spectrophotometry

So why not always do spectrophotometry?

Conventional photometry has the advantage that you can go much fainter, and more accurate.

Spectrophotometry has the advantage of good wavelength resolution.

Fluxes

Units of flux are usually:

$[f_\lambda]$= ergs s^{-1} cm^{-2} $Å^{-1}$ or $[f_\nu]$=ergs cm^{-2} Hz^{-1}

and when we do spectrophotmetery, that's what we measure.

But when we do filter photometry, we are actually measuring a flux averaged over a bandpass:

It's the flux weighted by the sensitivity function:

$$F = \int f_\lambda \times S_\lambda \, d\lambda \;/\; \int S_\lambda \, d\lambda$$

Magnitudes

Often what we want to know is the RATIO of fluxes: a star is so much brighter at THIS wavelength than at THAT wavelength, or THIS star is so much brigher than THAT star at the same wavelengths. Magnitudes provide a short-hand way of doing so.

Magnitudes

Consider two stars with fluxes F_1 and F_2. Then the magnitude difference between them are:

$m_1 - m_2 = -2.5 \log (F_1/F_2)$

e.g., if $F_1/F_2 = 100$, then $m_1 - m_2 = -5.0$ magnitudes.

Historically, “magnitudes” came about because the Greeks (Hipparchus or maybe Ptolemy) assigned numbers to the brightness of stars. Really bright stars were 0 or 1, while the faintest you could see was about 6th. Your eye turns out to be logarithmic (surprise!) and 1-->6 was close to 100x.

Magnitudes

Mathematical convenience: what if we wanted to know the flux of a star to 1%? How much is that in magnitudes? Consider two stars, one of which has a flux that is 99% of the other. Then, the difference in magnitudes between them is

$$m_1 - m_2 = -2.5 \log (f_1) + 2.5 \log (f_2), \text{ with } f_2 = 0.99 f_1$$

$$m1 - m2 = -2.5 \log (f_1) + 2.5 \log (0.99 f_1) =$$

$$-2.5 \log (f_1) + 2.5 \log (f_1) + 2.5 \log (0.99) = 0.0109 \text{ mags.}$$

In other words, 1% is about 0.01 mag.

Magnitudes

This trick works well at 10%:

2.5 log (0.90) = 0.11 mag

At 30% it's failing a bit:

2.5 log (0.70) = 0.39, not exactly 0.30.

But at <10% it's a good approximation!

Magnitudes

Vega has a magnitude of 0. It was decided to simply DEFINE the magnitude scale at each wavelength relative to Vega. (Well, more or less...)

So, when we say a star has a magnitude of 13.25 in the "B" band we are really saying that the star is $10^{-(13.25)/2.5}$ x as bright as Vega is in the B band. Whatever that is.

Magnitudes

Or to put it another way, if a star has a flux that is 0.01 x that of Vega, then it has a magnitude of 5.0.

Magnitudes

Object	Magnitude
Sun	-26.7
Full Moon	-12
Sirius	-1.4
Vega	+0.0
Betelgeuse	+0.4
Polaris	+2.0
Naked Eye Limit	+6
Visual limit 6-inch	+13.0
CCD 5min 6-inch	+16.0
Hubble Deep Field	+30.0

Quiz

An image from the Hubble Space Telescope reveals two equally bight stars, each with V=14.00, separated by just 0.1". If you observe these from the ground, where their light will be combined, how bright will the (composite) star appear to be?

Answer

Let f_1 and f_2 be the flux from each of the two stars. (Note f_1=f_2.)

V1=-2.5log(f_1) + C = 14.00 --> $f_1=f_2=10^{-(14-C)/2.5}$

f1+f2 = $2 \times 10^{-(14-C)/2.5}$

Vcombined = -2.5log(f_1+f_2) + C =

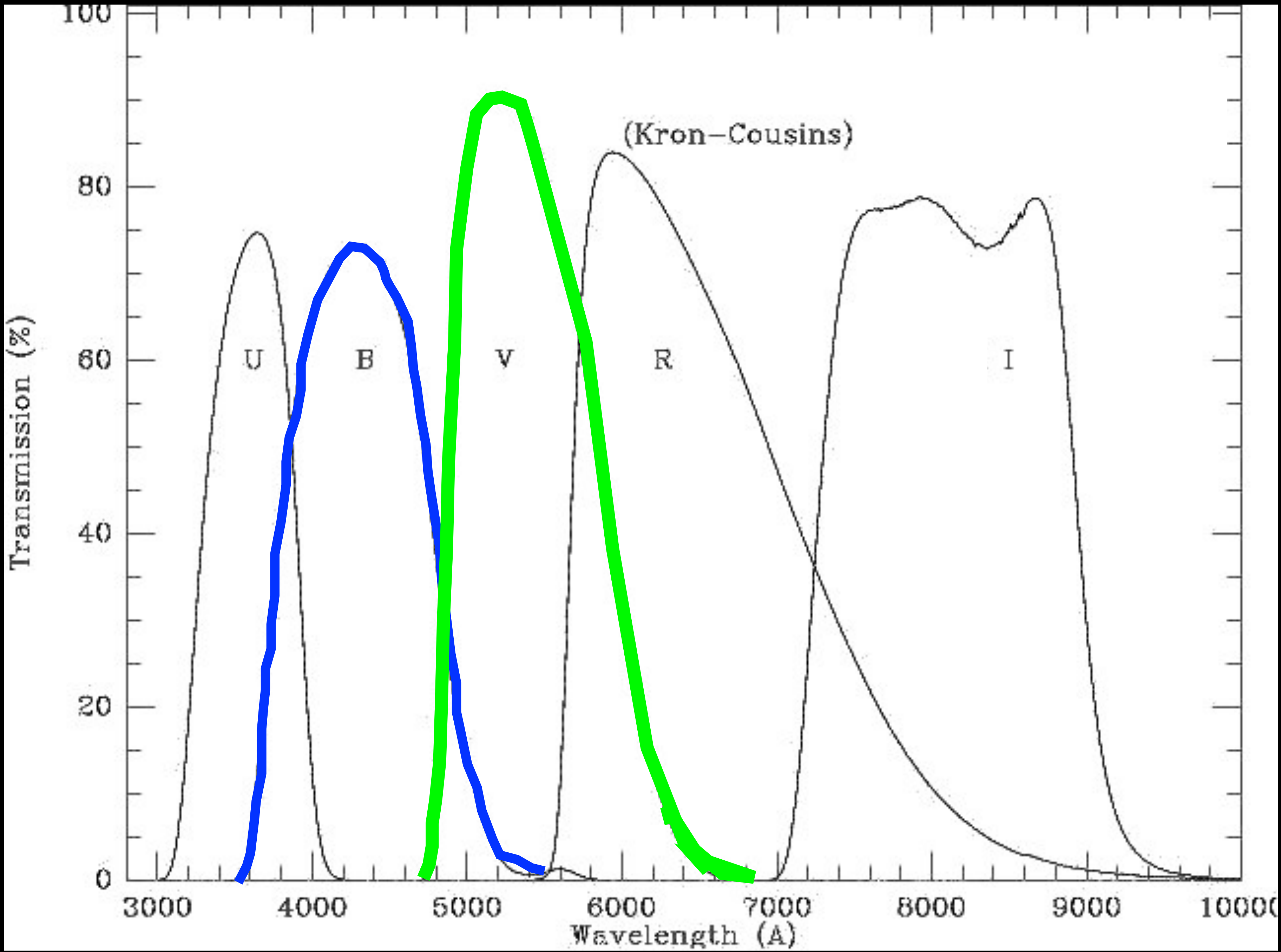
$-2.5\log(2x^{10-(14-C)/2.5}) + C=$

=-2.5log(2)+-2.5x((14-C)/2.5) + C

=-2.5log(2)+14 + C - C = 13.25

Colors

We use filters to limit the wavelength range when we do photometry. Most common is UBVRI in the optical, and JHK in the near-infrared.



Colors

$$B-V = -2.5 \log (F_B/F_V) + \text{Const}$$

What's with this "+ Const"? Recall that the magnitude system is set up relative to Vega, essentially a 10,000° K black-body. What we really have in terms of fluxes then is

$B-V = -2.5 \log (F_B/F_{B,Vega} \;/\; F_V/F_{V,Vega})$. But $F_{B,Vega} \neq F_{V,Vega}$! So, we just have to remember that a black-body with a temperature of 10,000° K is defined to have zero colors in the UBVRI system.

Colors

Because bigger magnitudes mean fainter, a star with a B-V = -0.3 is very, very blue. One with a B-V = +2.0 is very, very red. All normal stars are between these extremes.

Other fun colors: U-B, B-V, V-R, R-I, and including near infra-red colors, J-K and a wonderful combination, V-K. Stars have different ranges among these.

How do we measure a magnitude?

When we observe at the telescope, we actually obtain the number of ADUs per second for a star. This is the INSTRUMENTAL magnitude. We get the magnitude then by comparing this to a standard star. There are some complications, and we'll be talking a lot about that in the next few weeks.

Doing photometry...

Imagine I observe a star with the BLT and measure a count rate of 100 ADUs/sec in V, and 200 ADUs/sec in B. The star is:

a) Red

b) Blue

c) Don't know

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a) Red

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c) Don't know

Doing photometry...

Okay, now imagine you observe a standard star at the same airmass of the previous star, that has a B-V of 0.0 and a V magnitude of 12.0. It has a count rate of 1000 ADUs/sec through the V filter and 2000 ADUs/sec through the B filter. What is the brightness at V of the aforementioned star (V: 100 ADUs/sec and B: 200 ADUs/sec):

a) 14.5

c) 17.0

b) 12.0

d) 9.5

e) Still can't tell

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a) 0.75 (-2.5 log (2))

b) 0.00

c) -0.75

d) Can't tell

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Quick Summary

* Astronomers like to use magnitudes to characterize fluxes because magnitudes are logarithmic in nature, and we usually are only interested in the RELATIVE brightness of things.

* $m_\lambda = -2.5 \log (f_\lambda)+C_\lambda$

* If star A is 10x brighter than star B at a particular wavelength, its magnitude is 2.5 magnitudes smaller:

$$m_{\lambda A} = -2.5 \log (f_{\lambda A}) + C_\lambda$$

$$m_{\lambda B} = -2.5 \log (f_{\lambda B}) + C_\lambda$$

$$\rightarrow m_{\lambda A} - m_{\lambda B} = -2.5 \log (f_{\lambda A}) + C_\lambda - [-2.5 \log (f_{\lambda B}) + C_\lambda]$$

$$= -2.5 \log (f_{\lambda A}/f_{\lambda B})$$

$$= -2.5 \log(10.) = -2.5$$

Absolute magnitudes

What we've been talking about so far have all been APPARENT magnitudes---how bright objects appear to us on Earth in a particular band-pass.

For comparing objects, what we really need to know is the ABSOLUTE magnitude---what magnitude the object would have if it were at some standard distance, 10 parsecs.

Absolute magnitudes

Since flux varies by r^{-2} we can expect

$f_{observed}/f_{absolute} = 100/r^2$.

Let M_V = absolute magnitude, and m_V be apparent magnitude, both at V. Then:

$m_V - M_V = -2.5 \log (f_{observed}/f_{absolute}) = -2.5 \log (100/r^2) = 5 \log r - 5$

"$m_V - M_V$" is called the DISTANCE MODULUS.

Absolute magnitudes

Thus $M_V = m_V - 5 \log (r) + 5$

where r is the distance to the object in parsecs (pc).

Let's try it and see. m_V for the sun is –26.7, and it's at a distance of 1 AU. There are 206265 AUs in a parcsec, so r = 1/206265 pc = 4.84×10^{-6} pc. So $M_V(\text{sun}) = -26.74 - 5 \times \log (4.84 \times 10^{-6}) + 5 = 4.83$.

If the sun were at a distance of 10 parsec, it would be visible, but only faintly!

Absolute magnitudes

In contrast, consider the star Deneb. It has m_V=1.3 and is located a distance of 490 pc. What's its absolute magnitude?

$1.3 - M_V = 5 \log (490) - 5$

M_V=-7.2. If Deneb was this close, it would be 10x brighter than Venus at its brightest (V=-4.8).

Compare this to +4.8 for the sun! Deneb is intrinsically 12 mags more luminous (at V), or about 70,000x.

Absolute magnitudes

Two stars are intrinsically identical (same size, some effective temperature). One has an apparent magnitude of 10, and the other one had an apparent magnitude of 15. How much further away is the fainter one?

a) 10x

b) 100x

c) 1000x

d) Huh?

Absolute magnitudes

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b) 100x

c) 1000x

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Bolometric Magnitudes

Often an observer wants to know the total flux integrated all wavelengths in order to compare to theoretical models. This total flux is sometimes given as the bolometric magnitude, M_{bol}.

$M_{bol}=M_V+B.C.$, where the B.C. is the "bolometric correction", computed from model atmospheres as a function of effective temperature or B-V. The B. C. is not 0 for Vega or for the sun, but is somewhat arbitrarily defined so that the B.C. is never greater than 0.

Bolometric Magnitudes

Here are some bolometric corrections for main-sequence stars according to Kurucz model atmospheres:

Teff	B-V	B.C.
3500	1.9	-2
4000	1.7	-1.1
5000	0.9	-0.4
6000	0.6	-0.2
7000	0.4	-0.1
8000	0.2	-0.1
10000	0	-0.4
25000	-0.2	-2.6
50000	-0.3	-4.5

Bolometric Magnitudes

M_{bol} for the sun is 4.75. So, if we want the total flux relative to the sun, we have:

$$M_{bol} - 4.75 = -2.5 \log L/L_{sun}$$

$$M_{bol} = -2.5 \log L/L_{sun} + 4.75$$

If a star is 100x more (bolometrically) luminous than the sun, what is its bolometric magnitude?

a) $4.75 - 5 = -0.25$

b) $4.75 + 5 = 9.75$

c) Where did 5 come from?

If a star is 100x more (bolometrically) luminous than the sun, what is its bolometric magnitude?

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Special flashback reminder!

Stefan-Boltzmann law:

$$L = 4\pi\sigma R^2 T^4_{eff}$$

"Special" (apparent) magnitude

An astronomer named Don Hayes and collaborators rationalized this in the 1970s. Using a black-body light source they borrowed from the National Bureau of Standards, they used the same telescope and instrument to measure it as Vega. They mounted the black-body on the catwalk of the 4-meter and observed it from across the mountain with the 2.1-meter telescope! What they found was:

$m_\nu = -2.5 \log f_\nu - 48.60$ if f_ν is in ergs cm^{-2} Hz^{-1}

Magnitudes

Those magnitudes are sometimes referred to as "AB" magnitudes or "spectrophotometric magnitudes." They agree with V magnitudes (more or less) but differ at other wavelengths as 0.00 mag corresponds to constant m_ν

Homework_4 Due 9/29

1) You measure a magnitude of a star as +10.0. But it turns out this star is a binary star, consisting of two stars, one of which is 2x brighter than the other. What would the individual magnitudes of the two components be if you could measure them? Hint: m_{total} is not equal to m_1+m_2. Instead, it's the fluxes that add.

2) This binary star is in a cluster you know is 1000 pc distant. What is the absolute visual magnitude of the two components?