Astronomical Imaging and Photometry: Introduction

General Outline of the Series of Lectures

1. Introduction—magnitudes, fluxes and flux densities, AB scale, S/N, dynamic range, etc.

2. Detectors—a little history, CCDs and how they work and are made, CMOS and IR detectors, Double-correlated sampling and kTC noise, future prospects.

3. An overview of optics for astronomy---First- and third-order optics, aberrations, simple physical optics and diffraction. Telescopes.

4. The atmosphere---Seeing, absorption, and backgrounds

General Outline, Continued

5. Doing photometry.---Processing the Images, measuring astronomical objects on images, calibrating the measurements. The devil in the details. Pitfalls.

6. Spectroscopy and Spectrophotometry---Dispersive elements, a little history, resolving power, detectors, spectrograph optics, slits and fibers, FRD, techniques toward IFUs. Pitfalls.

7. A tour of a spectrograph design---designing the PFS for Subaru.

The Magnitude Scale

Originally, the classical Greeks divided the stars into six magnitude bins according to brightness, from 1 (brightest) to 6 (faintest which can be seen with the naked eye). It was conceived as a logarithmic scale and the ratio was thought to be 2.

*In 1856, Pogson proposed that the system be formalized. It was known then that a typical first magnitude star was *about* 100 times as bright as a typical sixth magnitude star, so Pogson saddled all of posterity with the POGSON ratio = $100^{1/5} = 10^{0.4}$ =2.512...*
He could just as easily have proposed e = 2.718.., which would have made magnitudes the same as natural logarithms and which would have fit the situation as it was known then just as well, and made our lives subsequently infinitely easier, but he was an Englishman, and Napier was a Scot, and....
well, you know.

So the FLUX F from an astronomical object is related to its (apparent) magnitude m by

$$F = Const * 10^{-0.4*m}$$

or

$$m = - 2.5 \log_{10} F + C \quad \text{(hereinafter } \log = \log_{10}\text{)}$$

We can also, of course, use magnitudes to measure LUMINOSITY, by referring to a standard DISTANCE, usually taken to be 10 pc; thus the ABSOLUTE MAGNITUDE M of a source is related to its apparent magnitude by

$$m = M + 5 \log (d/10) = M + 5 \log d - 5.$$

If we are to build instruments to detect astronomical objects and understand and analyze the measurements we must know something about C, and exactly what we mean by m and F.

Fluxes and Flux Densities

The FLUX is what we measure with some detector, which is sensitive to the total power, total energy, or (more typically) total number of photons detected in some wavelength region, in some region of the focal plane of a telescope, normally averaged or added over some known time. But we NEVER measure the total flux.

Detector systems have some efficiency function $S(\lambda)$ which is a product of several factors:

- ***$T(\lambda)$ the transmission of the telescope***
- ***$A(\lambda)$ the transmission of the atmosphere***
- ***$f(\lambda)$ the transmission of any on-purpose filter in the system***
- ***$q(\lambda)$ the efficiency of the detector itself***

For modern visible and near-IR detectors, $q(\lambda)$ is usually a QUANTUM EFFICIENCY, the probability of detection of a photon at λ..

So we never measure the TOTAL (bolometric) flux, both because of the fact that no real detector is sensitive to all wavelengths, the fact that the atmosphere is not transparent to all wavelengths, (more later) the fact that we almost never WANT the bolometric flux, because we want some information about the spectral energy distribution of the astronomical object, AND that for the detectors we will be talking about, number of photons, not energy, is the detected quantity. This is a very important point, which we need always to remember.

So what we MEASURE is a signal s which is, if we can count photons,

$$s = At \int F_\nu(\lambda)\, S(\lambda)\, d\nu/(h\nu)$$

F_ν	*Flux *density*-- power per unit frequency per unit area*
$S(\lambda)$	*Efficiency as above*
A	*Collecting area of Telescope*
t	*total integration time*

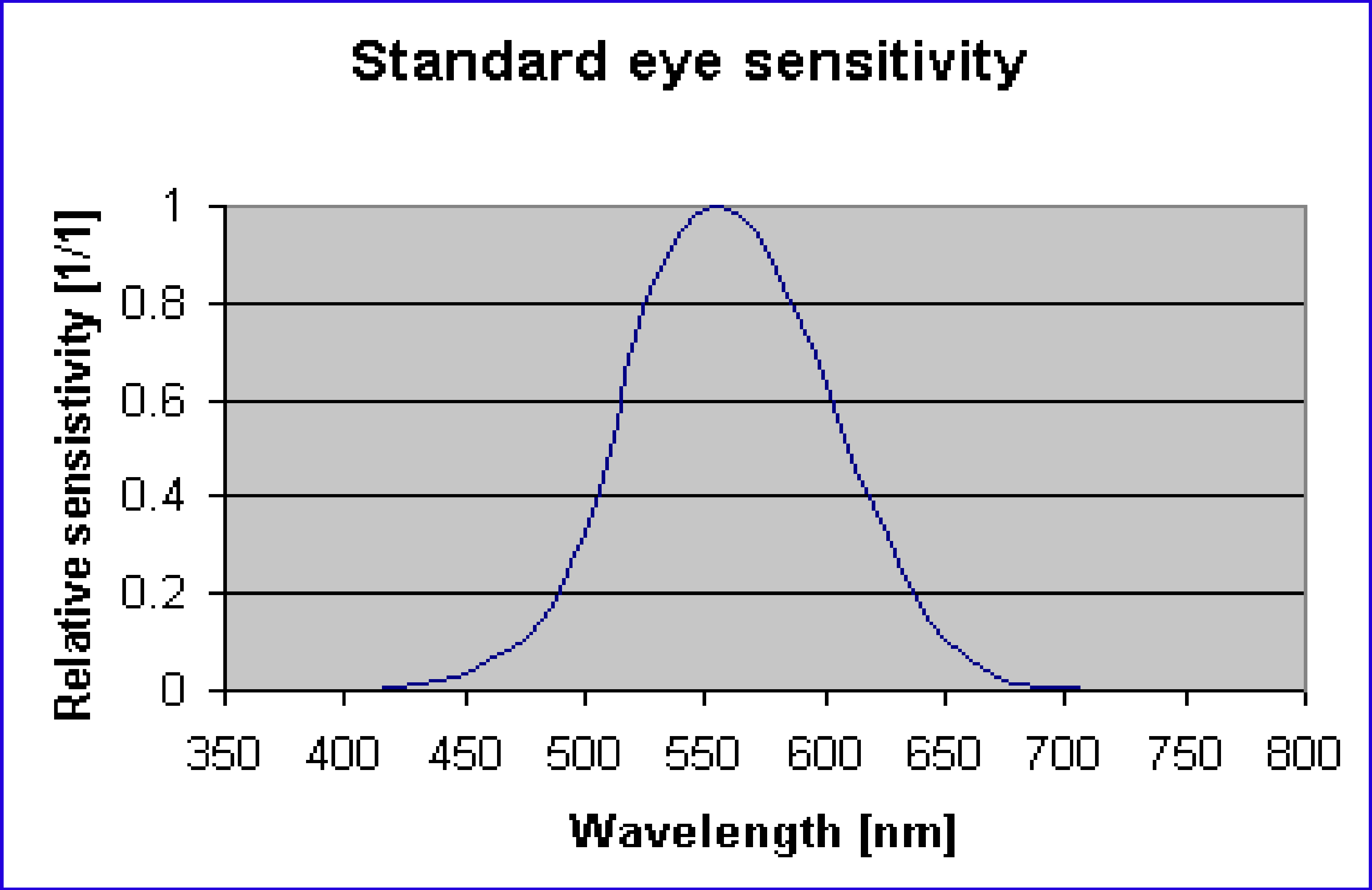
NOTE that $F_\nu(\lambda)\, d\nu/(h\nu)$ is the number of photons incident on the atmosphere of the earth per unit area per unit time in the frequency interval $d\nu$.

Now there are a number of PHOTOMETRIC SYSTEMS defined at the hardware level by various combinations of detectors and (usually) sets of filters used to isolate (usually fairly broad) wavelength regions. Let's look at some response curves for a few of these systems.

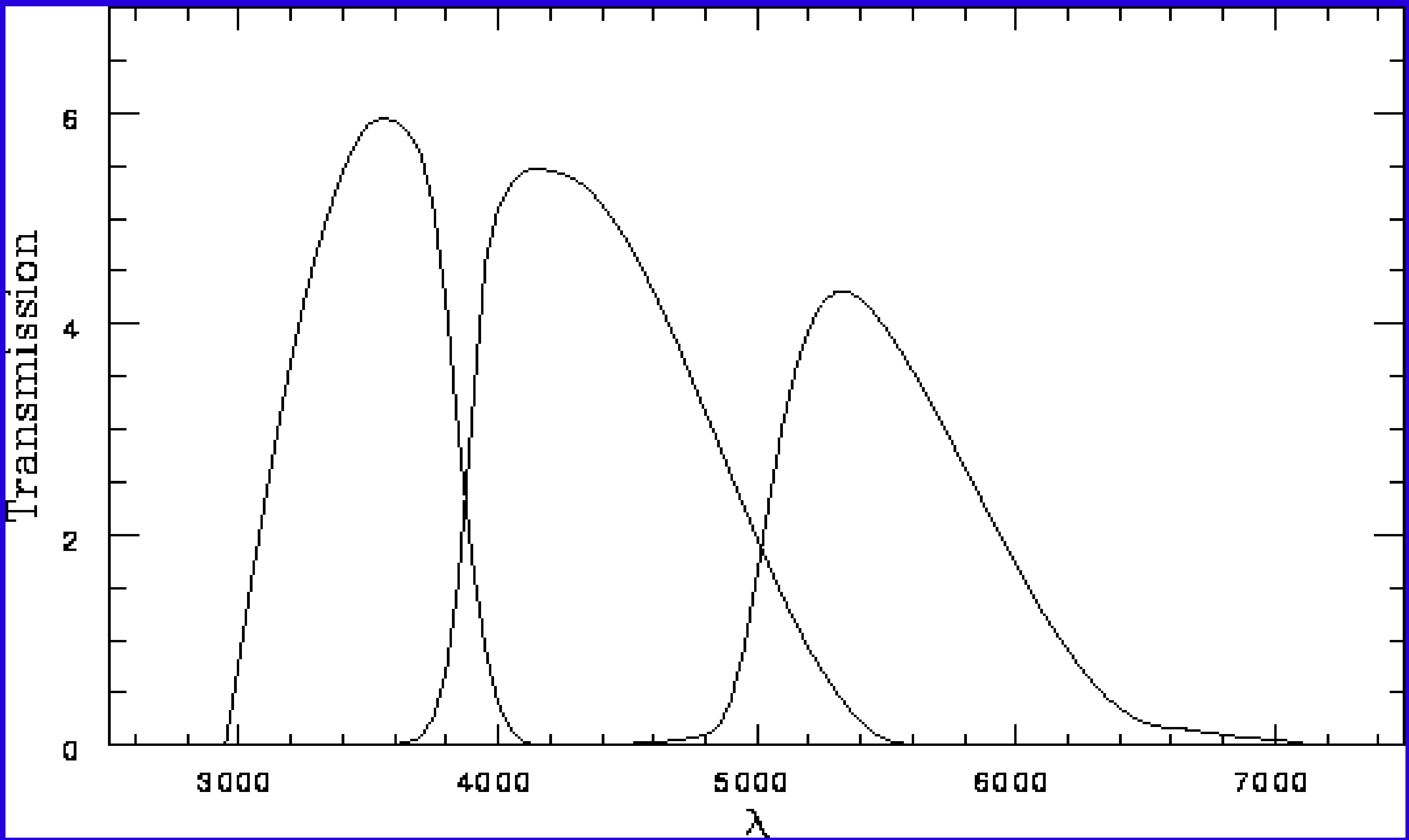
These are the BROADBAND PHOTOMETRIC SYSTEMS, with $\delta\lambda/\lambda \sim \delta\nu/\nu$ typically 0.1 or so.

First, the archetype of them all, the `photoptic' response of the human eye, some approximation of which typically defines a VISUAL band, then the very common but quite old Johnson UBV (V=visual) system, and the newer SDSS five-color system, and the Subaru HSC system

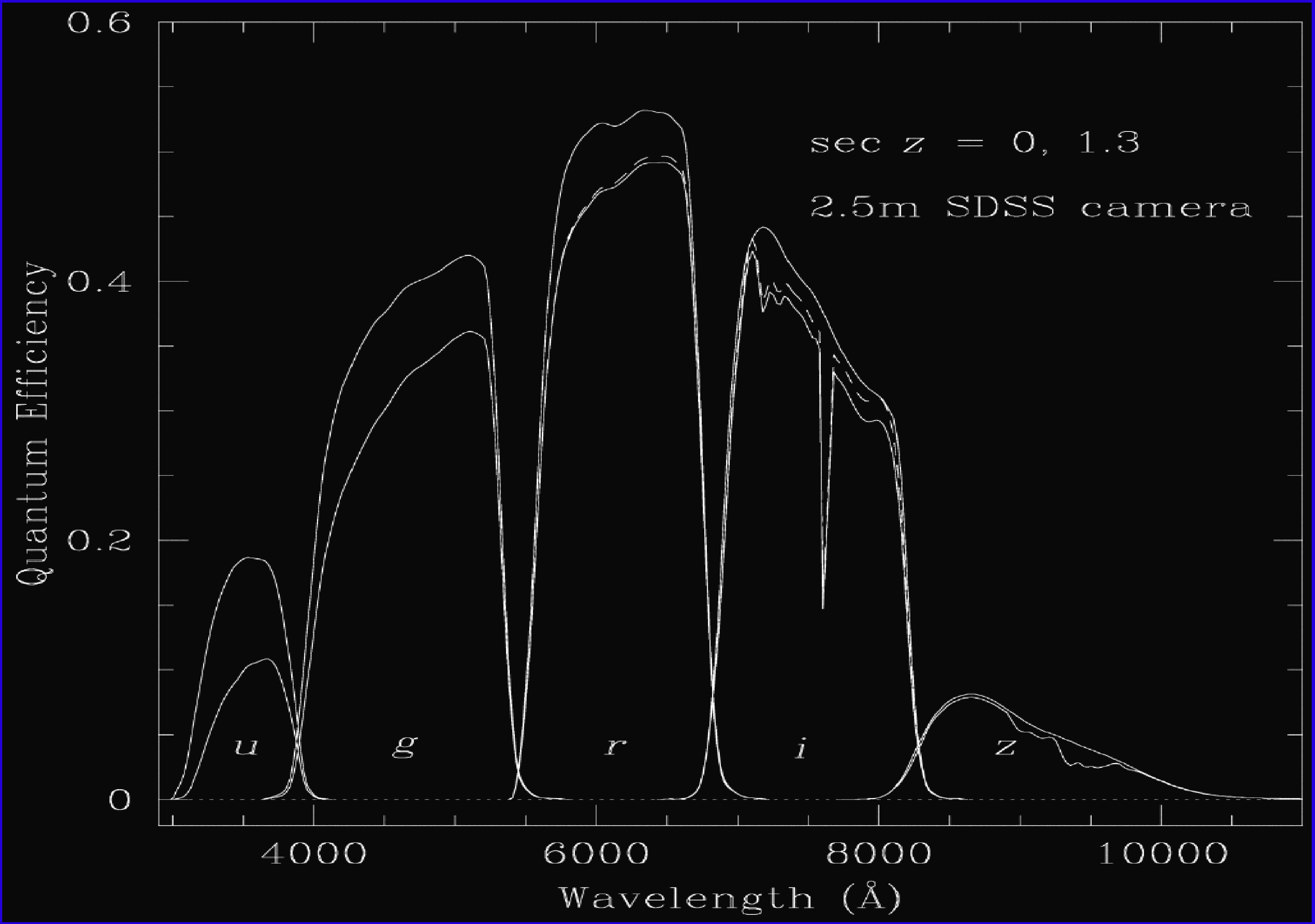
The Human Eye



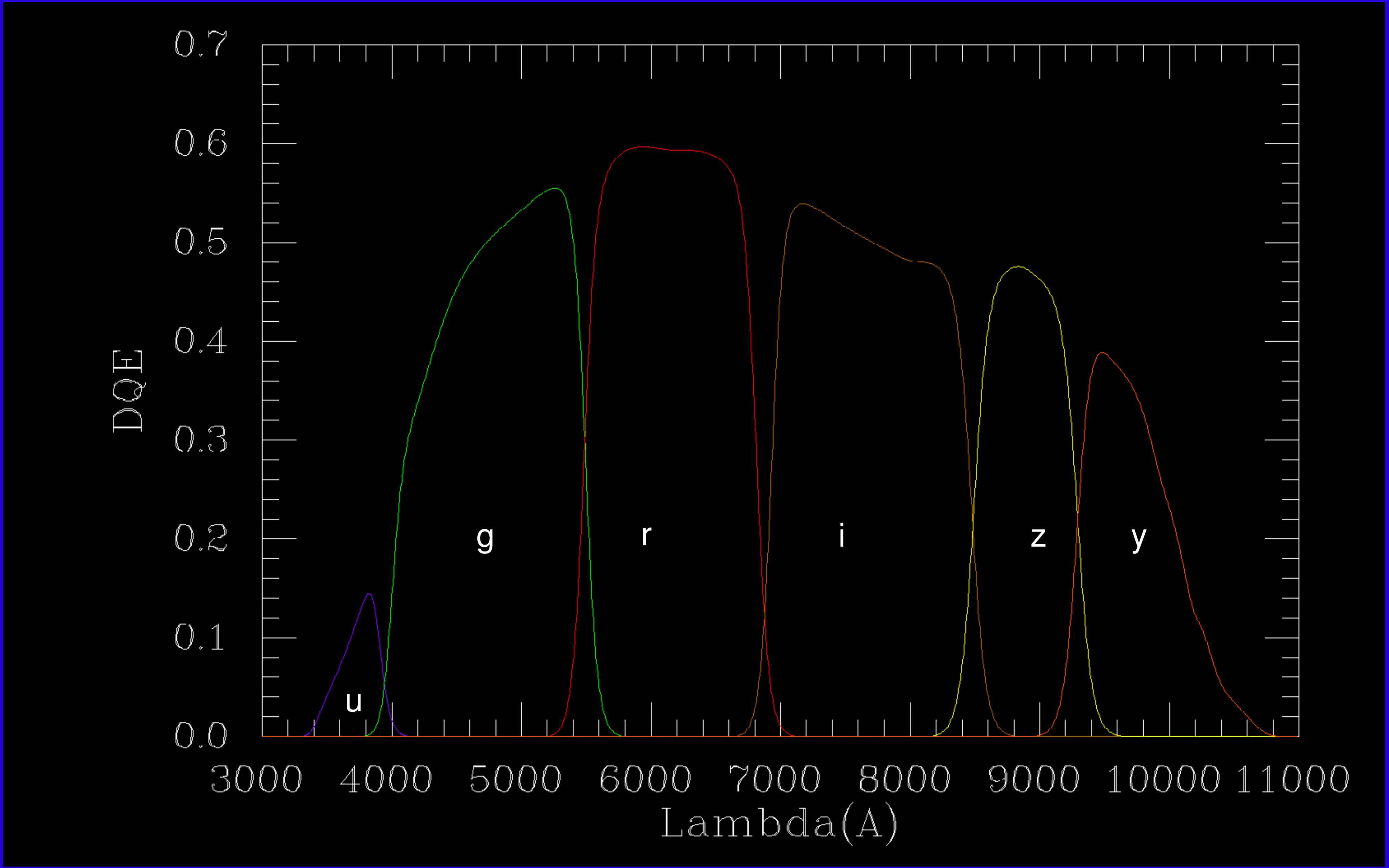
The Johnson UBV system



The SDSS System



The Subaru HSC System



Flux Densities and the AB system

For a given filter/detector combination, say "f", the magnitude associated is

$$m_f = -2.5 \log \int F_\nu(\lambda)\, S_1(\lambda)\, d\lambda/\lambda \quad + \; C$$

Where S_1 is the normalized response (h is gone, $d\nu/\nu = d\lambda/\lambda$), a constant multiple of the physical response function $S(\lambda)$ such that

$$\int S_1(\lambda)\, d\lambda/\lambda \; = 1$$

Now F and S_1 are both nonnegative, so the integral is the flux density at some wavelength in the support of S_1, and, in fact, near the peak of S_1 if F is reasonably smooth and S_1 not too wide.

At V=0, the V flux defined above is 3.63E-20 erg cm^{-2} sec^{-1} Hz^{-1} for a source with F_ν = constant

Oke in 1969 defined monochromatic magnitudes, the so-called AB scale:

$$AB_\nu = -2.5 \log (F_\nu (cgs)(\lambda) / 3.63e\text{-}20) = -2.5 \log F_\nu - 48.60$$

and magnitudes defined with this zero-point constant are called AB magnitudes, ie, for cgs flux density

$$AB_f = -2.5 \log \int F_\nu(cgs)(\lambda)\, S_1(\lambda)\, d\lambda/\lambda - 48.60$$

AB magnitudes have the advantage that they are directly related to the flux density at a wavelength near the mean wavelength of the filter; they have the disadvantage that they lure one into believing one can calculate the real flux density. The physical flux density scale is known only to a few percent over the visible wavelength range.

Photons – How many ???

Each photon carries energy $h\nu = 1.98e\text{-}12/\lambda(\text{microns})$ erg.

The number of photons is, as before,

$$s = At \int F_\nu(\lambda)\, S(\lambda)\, d\nu/(h\nu) \sim (At/h)\, F_\nu(<\lambda>) \int S(\lambda)\, d\lambda/(\lambda)$$

$$\sim (Atq/h)\, F_\nu(<\lambda>)$$

q is the SYSTEM EFFICIENCY and is the integral in the line above; it is clearly approximately the total quantum efficiency at the mean wavelength of the filter times the logarithmic width of the filter; $q \sim <S>\Delta\lambda/\lambda$, so the total number of photons in an observation is approximately

$$s \sim (At/h)<S>\Delta\lambda/\lambda\ F_\nu(<\lambda>) = 1.51e7\ F_\nu(<\lambda>)(\text{Jy})\ A(\text{m}^2)\ t(\text{sec})\ <S>\Delta\lambda/\lambda$$

$$\sim 550\ A(\text{m}^2)\ t(\text{sec})\ <S>\Delta\lambda/\lambda \quad \text{at AB=20; } <S>\Delta\lambda/\lambda \sim 0.1\text{, so } \sim 50$$

Photons – The Eye

The fully opened iris in most humans is about 6mm in diameter, A ~ 3e-5 m^2. A 7th magnitude star is about 5Jy, and the eye integrates for ~0.05 sec, so the total number of photons *received* for this detection is about 7 !!! Pretty good.

The Sky

The sky in the daytime is not dark. Why?

The sun is an absolute magnitude 4.83 G2IV-V star; at 1 au = 4.84e-6 pc;
Its apparent visual magnitude is thus -26.8.

The atmosphere scatters about 10 percent of the light incident on it, more-or-less isotropically. We will discuss this in much more detail later. 10 percent is 2.5 magnitudes, so the whole sky has an apparent magnitude of ~ -24.3. There are 20,000 square degrees in a hemisphere, 10.75 magnitudes, so the visual brightness of the daytime sky is about

-13.5 per square degree
-4.7 per square arcminute
+4.2 per square arcsec

The resolution of a very good eye is about 1 arcminute, so the sky is too bright to see any but the brightest stars against it.

The Moonlit Sky

The full moon is about 450,000 times fainter than the sun, 14.1 mag, so is about V ~ -12.7. The corresponding numbers for the sky brightness are

+0.8 per square degree
+9.4 per square arcminute
+18.3 per square arcsec,

so at a typical ground-based resolution of ~ 1 arcsecond, the moonlit sky dominates the signal for pointlike objects fainter than about 18th magnitude. The moon's brightness (and the brightness of the moonlit sk) falls off rapidly with phase:

0	0.00 m
40	1.06 m
80	2.24 m
120	3.93 m

The Dark Sky

Is not dark; we will discuss the origins of the light later, but for now we note that its V brightness is, in good sites, about 21.7 magnitude per square arcsecond, about a factor 25 fainter than the full moonlit sky, and roughly equal to the moonlight contribution at phase ~110 degrees. The moon's phase angle must be considerably larger for the moon to be negligible. The situation is worse in the blue, where the scattering is worse, and much better in the red, where both the scattering is smaller AND the sky brightness from natural emissions much, much larger.....but this just means that the moon is less bad—the sky is very bright.

Back to Photons: Signal-to-Noise

Go back to our photon rate equation:

$s \sim 1.51e7\ F_\nu(<\lambda>)(Jy)\ A(m^2)\ t(sec)\ <S>\Delta\lambda/\lambda$

$\sim 5.48e10\ \ F_\nu(<\lambda>)(Maggies)\ A(m^2)\ t(sec)\ <S>\Delta\lambda/\lambda$

$\sim 5.48e10\ \ 10\hat{}(-0.4\ AB_\nu)\ A(m^2)\ t(sec)\ <S>\Delta\lambda/\lambda$

1 maggie is the flux from an AB= 0 star, 3630 Jy

Sky is 21.7 at best; a 3.5-meter telescope with
50% efficiency in a 20% filter has $A<S>\Delta\lambda/\lambda \sim 1$,
so we get ~115 photons/sec from a 1 arcsec^2 patch on the sky.
In 1 arcsec seeing, so the FWHM of the image is 1 arcsec, the
image occupies ~ 4 arcsec^2 effectively.

We thus have both signal and background, each of which carries its own noise signature. How accurately can we measure the brightness of an object?

If we receive s photons from the object and b photons from the sky UNDER the object, and we presume that we can measure the sky OUTSIDE the object infinitely precisely, the noise in the measurement is $(s + b)^{1/2}$ *, since photon arrival is random and the noise is therefore Poisson.*

Thus the signal-to-noise ratio, the inverse of the statistical precision of the measurement, is

$$S/N = s/(s + b)^{1/2}$$

There are two regimes, one in which $s > b$*; i.e. objects brighter than the sky under them, and the converse,* $s << b$*, objects much fainter than the sky under them.*

S/N ALWAYS is proportional to $t^{1/2}$ under constant conditions.

In the bright limit, $S/N = s^{1/2}$, and is independent of the sky background and the image size (seeing), so long as one remains in the bright limit.

In the faint limit, S/N is proportional to s, since the noise is all from the sky, and is inversely proportional to the square root of the sky background and inversely to the image size.

Therefore, at FIXED S/N, the time required to acquire a measurement is inversely proportional to the source brightness in the bright limit and inversely proportional to the SQUARE of the source brightness in the faint limit. To go a magnitude fainter requires $2.5^2 \sim 6$ times as long for faint objects.

$t \sim b\, d^2 / s^2$ in the faint limit, where d is the seeing diameter.

To cover some range in wavelength requires a number of filters which is inversely proportional to $\Delta\lambda/\lambda$. Since the number of photons in a given exposure time is proportional to $\Delta\lambda/\lambda$ for both the star and the sky, the time to reach a given S/N in a single filter is inversely proportional to $\Delta\lambda/\lambda$, and since it requires a number of filters to cover the range which is also inversely proportional to $\Delta\lambda/\lambda$, the time required goes inversely as the SQUARE of $\Delta\lambda/\lambda$ The ability to measure at different wavelengths simultaneously by means of a dispersive element like a grating or dichroic filters (gaining a MULTIPLEX advantage) is therefore highly desirable for high-wavelength-resolution studies of the spectral energy distributions of astronomical sources.

Typical calculation.

Reach 25^{th} magnitude with our 3.5-meter telescope with S/N = 5 (a typical definition of "detection") with our good dark sky.

25^{th} magnitude -> 1.0e-10 maggies, so

s ~ 5.5 photons/sec

4 pixels of sky at 21.7 mag/sec2 is magnitude 20.2, 450 photons/sec

so

$S/N = (5.5t)/(450t)^{1/2} \sim 0.25t^{1/2} = 5$ at t= 400 sec, an easy exposure.

But many questions remain.

What makes the star ~ an arcsecond across?

How do I need to sample the star image to get the accuracy I need?

How well can I determine the center of the star image, ie to measure the position of the star? What limits the accuracy of this measurement ?

What wavelength region should (can) I work in? That is,

- *Where do good detectors work?*
- *Where is the sky transparent?*
- *Where is the sky reasonably dark?*
- *What do I do if I need to work in a wavelength region in which there are problems with one or more of the above?*

What if I am interested in extended objects?

What happens if the field is so crowded that I cannot treat the object I am interested in, or any object, as isolated?

How do I choose filters to maximize my observing efficiency given the science I wish to do?

How do I actually REDUCE my data so as to get a true measurement as free as possible from instrumental/atmospheric/optical artifacts? What limits my accuracy in making this measurement?

*What are the *systematic* errors in absolute photometry and spectrophotometry? (How well do we know the AB_ν scale? can it be improved? How?)*

We will address some of these questions here. To address them all is a whole course, and there is not enough time. You should know that not all of them have very satisfactory answers... :-(