Brightness Units in Astronomy

Bolometric Brightness

The simplest measure of how much radiation we receive from some astronomical object is its "bolometric brightness" – i.e. the total amount of energy (in the form of electromagnetic energy) reaching the Earth, per unit collecting area. Units would be watts per metre squared: W m^{-2}. The name comes from an instrument called a "bolometer" which is basically something that heats up when radiation falls on it – by measuring how much it heats up, you can work out how much radiation landed on it.

Unfortunately, it is rarely possible to measure a bolometric brightness. Virtually all detectors and telescopes are sensitive to only a particular range of frequencies or wavelengths. To compute the bolometric brightness you'd need to combine non-bolometric data from many wavebands. The only exception would be when a given astronomical source emits all its radiation in a particular emission line.

Flux per unit wavelength or frequency

So in practice, when we measure how much radiation we receive from some object, we usually mean the energy *at some particular frequency*, not the integral of the energy over all frequencies (which would be the bolometric brightness). To be precise, we measure the energy ΔE received over a particular frequency range $\Delta\nu$, or a particular wavelength range $\Delta\lambda$ (ν is frequency and λ is wavelength). We typically take the limit as ΔE tends to zero:

$$f_\nu = \frac{dE}{d\nu} \text{ or } f_\lambda = \frac{dE}{d\lambda}$$

where f_ν is the flux per unit frequency (W m^{-2} Hz^{-1}), or f_λ is the flux per unit wavelength (W m^{-2} m^{-1}).

Traditionally radio astronomers use f_ν while optical astronomers use f_λ. We wouldn't want to make things too easy, after all. f_ν and f_λ are related by:

$$\lambda f_\lambda = \nu f_\nu$$

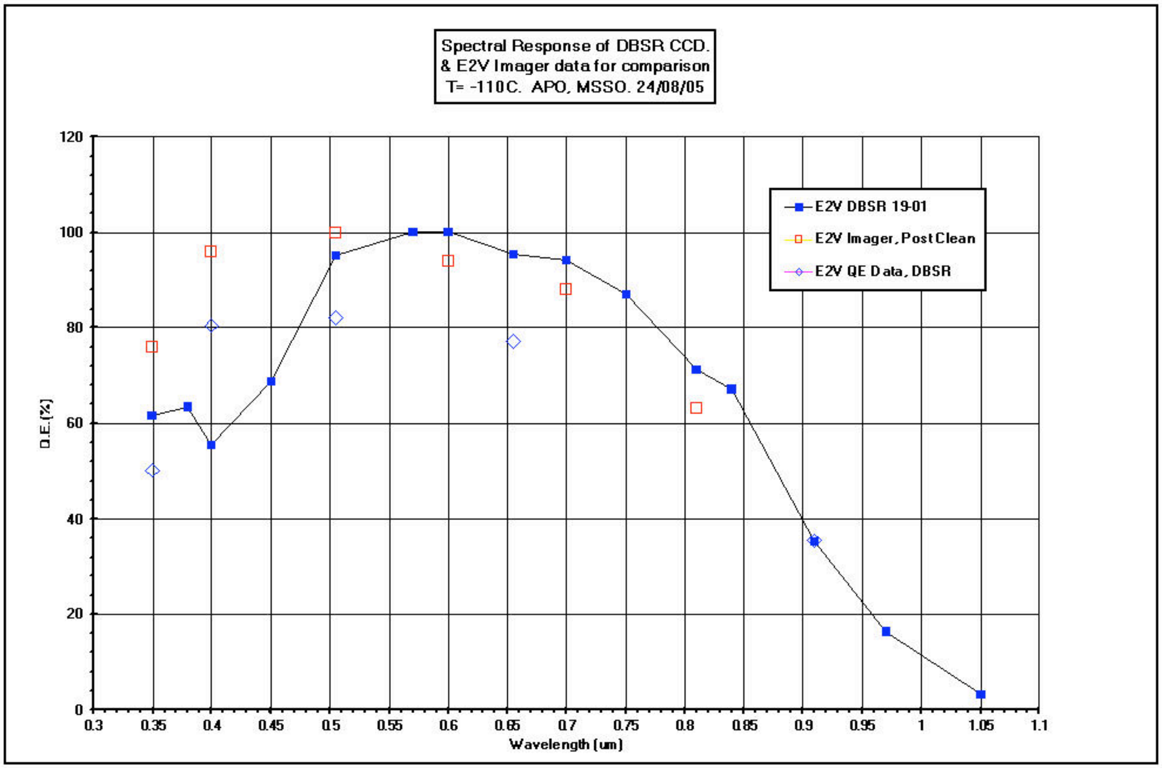
Radio astronomers have a special unit for f_ν: the Jansky. One Jansky = 10^{-26} W m^{-2} Hz^{-1}.

Broad-band observations

Most spectroscopic data, once reduced, will give results in flux per unit wavelength or per unit frequency. Radio astronomy tends to do the same thing, even for broad-band observations. But imaging data at UV, optical and IR wavelengths often uses a different approach: broad-band imaging.

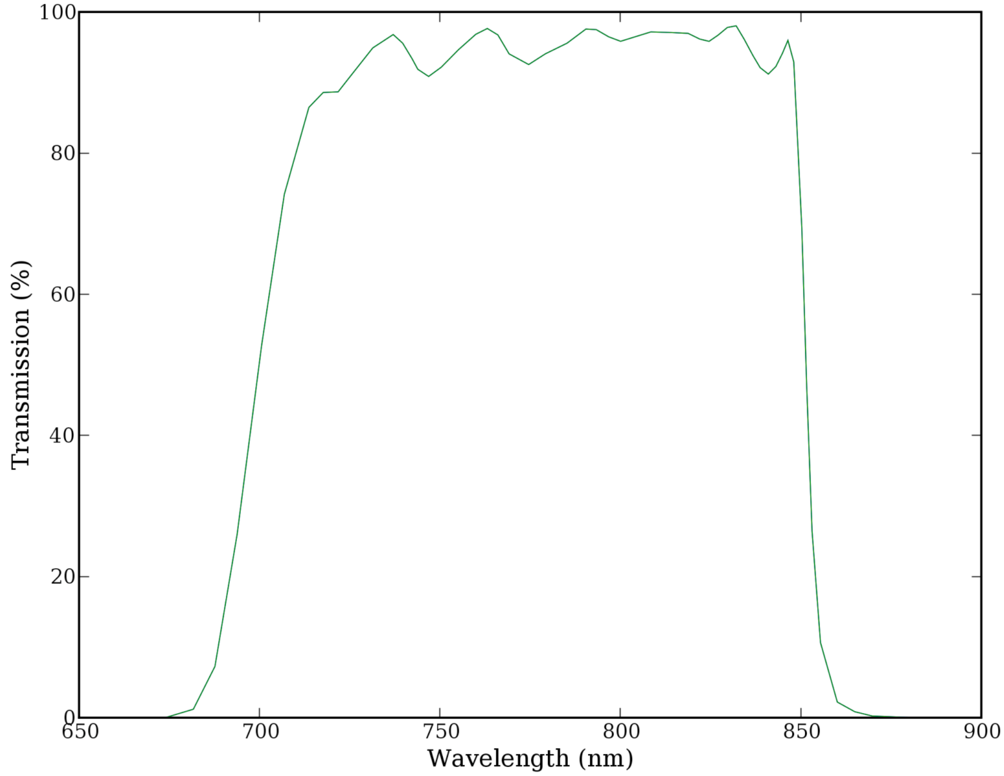
The idea is to increase the sensitivity of your observation by using a detector that is sensitive to a wide range of wavelengths. This gives you many more photons to detect, at the expense of you not knowing precisely what wavelength they have.

Typically you have a detector, perhaps a CCD. The sensitivity of any detector is a strong function of wavelength, as we'll discuss later in the course. Here, for example, is a plot of the sensitivity of the CCD detector used in the blue arm of the 2.3m Double Beam Spectrograph:



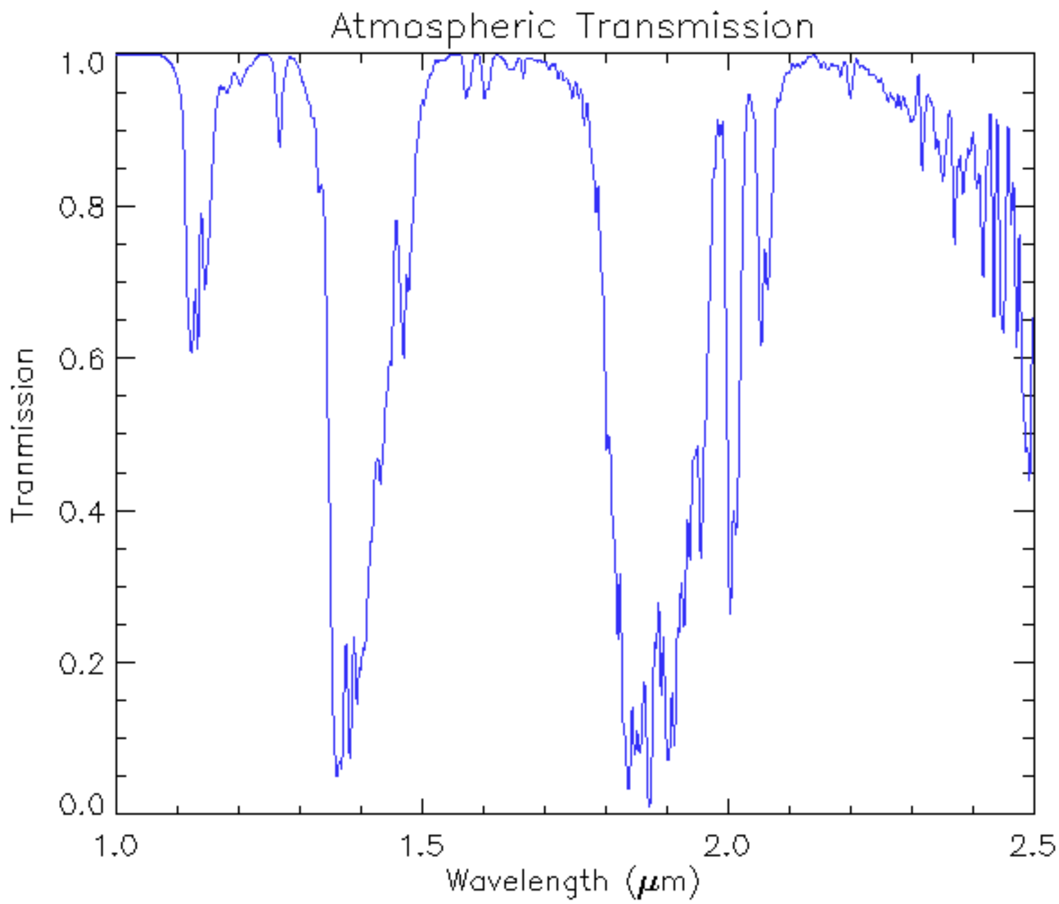
(the units are detector quantum efficiency, which is the fraction of photons hitting the detector which are actually recorded).

Observations are sometimes made using an unfiltered detector (primarily by solar system researchers looking for moving objects, and not caring what their colours are). But normally, a filter is put in front of the detector, to further narrow-down the range of wavelengths observed. Each filter is described by a curve showing the fraction of light it passes as a function of wavelength. Here, for example, is the transmission curve for the SDSS r filter on the Wide Field Imager (WFI) on the AAT:



The next complication is the telescope and instrument. Most telescope mirrors and lenses let certain wavelengths of light through better than others. This isn't usually a huge effect, except at UV wavelengths.

Then there is the atmosphere. At certain wavelengths, the atmosphere is pretty opaque. Here, for example, is a plot showing the fraction of light that penetrates the atmosphere in the near-IR:



(from http://mtham.ucolick.org/techdocs/instruments/LIRC/LIRCfltrs/atmtrans.html). This curve is not constant, but varies with the amount of water vapour and dust in the atmosphere. Generally the atmosphere isn't too bad in the optical and cm-wave radio, but is nasty in the mm and sub-mm radio and in the IR. At UV wavelengths, ozone makes the atmosphere almost completely opaque.

If you multiply all these curves together, you will get a plot of your sensitivity as a function of wavelength. And it's usually horrible…

Getting Physics out of a Broad-Band Flux

So let's say you've measured how many photons you detect per second from a given source, as observed through some particular filter. How the hell do you turn this into something physically meaningful, given all the complexities described above?

The most straightforward way is modelling. Take a model of the spectrum of your target. Multiply by the filter bandpass, CCD curve and atmospheric transmission (if you know them). Integrate the remainder to predict what you see.

Usually, however, more simple and approximate techniques are used:

Magnitudes

Broad-band fluxes at optical and near-IR wavelengths are typically expressed in the ancient unit: magnitudes. These were invented by Hipparchos of Alexandria in the 2nd century BC. In his catalogue, the brightest stars were called "1st magnitude", ones that seems "twice as faint" were called "2nd magnitude" and so on, down to 5th magnitude.

The magnitude of a source (apparent magnitude) tells you the ratio of how bright it appears to be, compared to the star Vega. Both must be observed with the same filter and detector. A source will have, in general, a different magnitude for each different filter/detector combination, unless its spectrum is identical to that of Vega.

Magnitudes are a logarithmic scale. A 5 magnitude difference is nowadays defined as a factor of 100 in brightness. The scale goes backwards, so a star of magnitude 5 is 100 times fainter than a star of magnitude 0. One magnitude thus corresponds to a change in brightness of $100^{(1/5)} = 2.5118864\ldots$.

Now consider two objects. With a given observational setup, you detect fluxes of f_1 and f_2 from two objects. The difference in magnitude between (m_1-m_2) them is given by:

$$2.5118864^{(m_1 - m_2)} = \frac{f_2}{f_1}$$

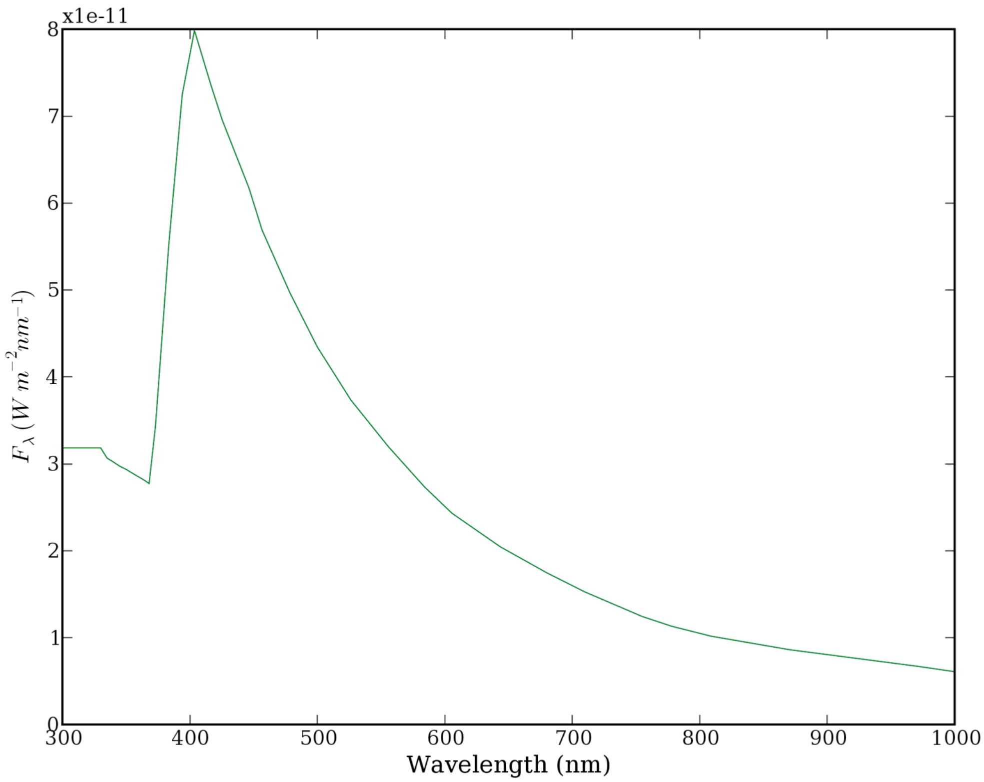
Taking logs, we find that

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

To convert a magnitude into an approximate flux, you need to know how bright Vega is as observed in that filter with that instrument. For the most common filters, there are some fairly standard values for Vega's flux (the flux of a 0 magnitude object). Mike Bessell is the world authority on this: the following values are extracted from various papers of his:

Filter	Central Wavelength	Bandpass width	Flux of zero magnitude star
	(nm)	(nm)	($W\ m^{-2}\ nm^{-1}$)
U	365	70	4.175×10^{-11}
B	440	100	6.32×10^{-11}
V	550	90	3.631×10^{-11}
R	700	220	2.177×10^{-11}
I	880	240	1.126×10^{-11}
J	1300	240	3.147×10^{-12}
H	1600	240	1.138×10^{-12}
K	2100	350	3.961×10^{-13}

Here is a plot of Vega's optical spectrum, which can be used to estimate fluxes for other filters (note y-axis scale listed top-left):



To accurately predict a magnitude, you should integrate this spectrum over your observing bandpass, do the same for a model of your target, and ratio the two.

A "colour" is the ratio of how bright a given object is, as observed by two different filters. As magnitudes are logarithmic, you simply subtract the magnitudes, eg: B-V is a measure of the ratio of fluxes in the B and V filters. Larger values of B-V indicate a source that is relatively stronger at longer (V) wavelengths.

Recently, a number of astronomers, fed up with this "Vega-based" magnitude system, have started using so-called "AB-magnitudes". Instead of being the ratio of the brightness of your target to that of Vega, they are the ratio of the brightness of your target to a hypothetical object having the same brightness as Vega at 550nm, but with a spectrum that is constant (in f_ν). The AB magnitude of a source with a given flux is given by: $m_{AB} = -2.5 \times \log_{10}(f_\nu) - 56.1$ where f_ν is measured in W m^{-2} Hz^{-1} (Oke & Gunn 1983, ApJ 266, 713)

Crude Magnitudes

In practice, it is not possible to observe Vega and most targets with the same observational set-up. Vega is too bright for this. Instead, there are many published sets of secondary standards, with known fluxes in various standard filter sets (eg. Graham 1982, PASP 94, 265, and several papers by Landolt).

The simplest way to measure a magnitude is to observe one or more of these secondary stars, then your target, then some secondary stars again. Take the ratio of the fluxes measured from your target to those measured from the standard stars, and hence calculate the magnitude.

This method is typically accurate to ~5%, if the observations are made on a cloudless (photometric) night. This is fine for many applications, but if you need to do better, you'll have to worry about a couple of extra effects:

1: Are you using exactly the same filters and detector as was used to measure the magnitudes of the secondary standard stars you are using? There are, for example, many different definitions of the "B" "V" and "R" filters (eg Johnson-Cousins, Bessell, Mould). And even if you are using the same filters, your detector may well have a different wavelength sensitivity curve.

This difference would not be a problem if you could observe Vega and your target with your observing set-up. But unfortunately, you have to rely on secondary standards. And these have different spectra both to Vega and (most likely) to your targets. This means that the integral over your bandpasses will be somewhat different.

The best way to correct for this is full integrations over model spectra, but there are standard "color term" corrections which allow you to do a fairly good job of correcting between the most widely used filter sets.

2: Did you observe the standard stars and your target at the same elevation? If not, the atmosphere will effect them differently, and you will need to apply an "extinction correction". Once again there are standard corrections (assuming average dust properties in the atmosphere) but to get higher precision you'll need to measure how much the atmosphere is absorbing on your night, by observing stars at a range of elevation angles.

It is beyond the scope of this course to describe these techniques in detail: I just want you to know that they exist, so you can find them if you need them. Mike Bessell is our local expert.