Making SEDs (2020) – L.M. Rebull

We have brightness measurements of many sources in many bands. We would like to make spectral energy distributions (SEDs) of the optical through FIR bands. We need to convert all the brightnesses into energy densities because an SED is, well, an *energy* distribution. The unit conversions are the hairy part, and in order to really understand all the steps, I've broken it into something uncharacteristically (for me) cookbook-like. Watch your units. You *will* get this wrong the first time you do it, and it will be a units issue, and it will not be off by just a little but by factors of many orders of magnitude, like 10^{10}.

The goal here: prove to yourself that you can make at least 5 SEDs. Note that I'm not expecting you to make all the SEDs we will ever need … I have code that does it really fast. Focus on learning how to do this rather than making a tool that will enable you to do this on an industrial scale. (I gotchu for the industrial scale.)

Magnitude = brightness, no explicit units (other than "magnitudes").
Flux = energy per area per unit of time (energy/area/time).
Analogy: Watching cars under an overpass; flux is like how many cars per lane per second.
Luminosity = energy per unit of time (energy/time).
Analogy: Luminosity is like the total number of cars per sec.
Flux Density = energy per unit of time per area per photon (energy/time/Hz or energy/time/m, where the "per Hz" or "per m" is "per photon frequency" or "per photon wavelength."
Analogy: Flux Density is like how many red cars there are per sec per lane.

Wavelength is represented by λ, and frequency is represented by ν. (Also, $\lambda\nu = c$, where c is the speed of light. Watch your units; if your wavelength is in microns, the speed of light should not be in km/s.)

Concept	Task	Space for your notes
What do you have?	1. **We have measurements of the brightness for many bands for many objects.** For one object (probably the first one in the spreadsheet, but your choice), look at its line in the spreadsheet. Find the columns with magnitudes. Not all magnitudes will be present for each object. Identify which magnitudes you have. The column headers for the brightness in magnitudes will look like "umag" with different characters in the "u" position to	

	indicate the bandpass, and "mag" to indicate magnitude. If the column header includes "merr", that number is the error in the magnitude. A "-9" means no data (not a really bright measurement). Columns measuring brightness in flux density units have headings that include "flux" and are already in Jy (or some variant thereof, like microJanskys μJy); "ferr" is error in flux density.	
What do you need?	2. **We want energy densities for each object for each band so that we can make an SED for each object**. You need to manipulate each magnitude measurement to calculate the energy density at each wavelength (also called band or bandpass). The columns with brightness measures that are already in Jy need some manipulation as well, but not nearly as much. To do this, I suggest you insert additional columns right by the magnitude column to calculate each step. *Use as many columns as you need, and place them wherever you want, in order to get the job done.* The first calculation will likely take several columns. After you get the hang of it (and debug your calculations), I bet you can do it in just one additional column per band.	
Convert all mags to flux densities, F_ν	3. **Convert magnitudes to flux densities**. Use the equation $F=F_{Vega}/10^{\wedge}(magnitude/2.5)$. F_{Vega} is the zero point flux density for each wavelength. The units of F_{Vega} should be the same as you want to get out – if you want Jy, then F_{Vega} should be in Jy (or if you want μJy, then F_{Vega} should be in μJy). Because the brightness (flux density) of Vega (F_{Vega}) is different for each band, this number is different for each waveband. **HOWEVER**, watch for AB magnitudes (as we have for PanSTARRS)... there, the zeropoint is **not** F_{Vega}, but 3631 Jy. Check the Excel file wavelengths.xlsx for information customized for our project, or the wiki page "Central wavelengths and zero points" to get these numbers for in more generic cases:	

	http://coolwiki.ipac.caltech.edu/index.php/Central_wavelengths_and_zero_points Extra credit: do the unWISE brightnesses too. They come in nanoMaggys (nMgy). Vega mags = 22.5 - 2.5 * $\log_{10}$(flux in nMgy) Convert these to Vega mags and then to Jy.	
Change units of F_ν to cgs units	4. **Convert flux density to cgs units**. You have some columns where you've calculated the flux densities from the magnitudes, but you have other columns that started in flux densities. You need to convert all of these numbers that are in Jy (Janskys) or some varietal thereof (mJy, μJy) to ergs/sec/cm^2/Hz. **Caution**: some of these numbers might be in μJy or mJy, not Jy. 1 Jansky = 10^{-23} ergs/s/cm^2/Hz. You can figure out how to convert this to Watts/m^2/Hz (e.g., mks units rather than cgs) if you want, but be consistent throughout otherwise the units won't work. My examples here are all in cgs units (because UChicago taught me this way; I have no better excuse).	
Change F_ν into F_λ	5. Another conversion is needed because the units aren't quite right yet. We have F_ν ("per frequency" meaning "per Hz") and we need F_λ ("per wavelength" meaning "per cm"). To convert F_ν into F_λ, multiply by c over lambda squared: $F_\lambda = F_\nu\ (c/\lambda^2)$ (To derive this, to show why it's not just c over lambda, you need calculus. $\lambda\nu = c$ but $\nu = c/\lambda$ and you need to get it into differentials to get "per frequency" or "per Hz", but d/dx(1/x) is $1/x^2$ so it's c/λ^2.) The speed of light, c, is 3×10^{10} cm/sec. λ also needs to be in cm for the units to work out. This number is the central wavelength, sometimes called the effective wavelength, e.g., the effective center of the filter. See the wiki page "Central wavelengths and zero points" to get these numbers. If you have this number in microns, you have to convert this number to cm. (Recall that 1 μm = 10^{-4} cm).	

Calculate λF_λ	6. What we actually need to plot is **energy density**. What we have right now is still **flux density** (just in different units, now F_λ, compared to when we started). Energy density is λF_λ. To go from ergs/sec/cm^2/cm (where that last "per cm" is "per photon's wavelength"), we need to multiply by the photon's wavelength to get ergs/sec/cm^2. This number will, of course, be different for each band – it will be the filter's central wavelength. (Note for completeness: If you think in frequency, as some radio astronomers do, you could also have skipped the prior step and calculated and plotted νF_ν. However, I don't know the frequencies of the various bandpasses off the top of my head… but I do know their wavelengths. That's why we're going with λF_λ.)	
Take the log	7. Now you have the energy density of this particular wavelength (λF_λ). We want to plot the log of this number, so take the log of it (log λF_λ). This is what we will put on the y-axis for the SEDs.	
Identify the wavelength	8. The x-axis for the SEDs is the log of the wavelength for the magnitude you just worked above. Identify the wavelength **in microns** and take the log of it to get ready for plotting. (Others in the past have made another tab in the spreadsheet just for wavelengths in order to force Excel to plot, but do what you need to in order to get the job done.) (Note for completeness: (1) You might ask why not plot λ in cm since we've been working in cm so far. You can of course do this. But I remember the wavelengths of the bandpasses in microns, and in order to read a wavelength off the plot, one already has to think in log space, so that's why we're plotting wavelength in microns – it just makes reading the plot a little easier IMHO. Do whatever you want to get the job done. (2) You could also plot log νF_ν against log ν, but see above re: thinking in wavelength not frequency. Also, the shape of the blackbody function against	

	λ is what we've been playing with thus far; plotting against ν flips around the shape of the blackbody function unless you plot with ν increasing to the left … Again, do what you want to get the job done, but I suspect you will want to plot λF_λ against λ, especially if you want your plot to closely match mine or your neighbor's.)	
Do it again!	9. **Get λF_λ for every band for that object!** Repeat steps 3 through 8 for each magnitude that you have. Repeat steps 5 through 8 for each flux density that you have.	
Make the plot!	10. Fight with Excel to get it to plot log λF_λ on the y-axis and log λ on the x-axis. I will be of very little help here because I don't plot very often in Excel. You will need something it calls "scatter plots" (as opposed to, say, pie charts or histograms). You may wish to hide un-necessary columns, leaving only the log λF_λ column for the y-axis.	
Repeat for another object	11. **Make SEDs for the other objects!** "Fill down" to complete the calculations for additional objects. Plots don't come so automatically, unfortunately. Watch for "no data" errors – if there are no data at that band, you can't put it in the SED.	

The first SED you make takes a long time, but then more or less the rest come along for free. It gets easier to plot if you work in a programming language in which, honestly, you can make plots more easily than in Excel. I program in IDL (if you want to learn a language, pick Python, not IDL) and I can make SEDs for >4000 objects in less than 2 minutes. But my first one took a long time.