Addenda for Observational Cosmology Readings Chapter 5

SerjeantNotes4Chapter5. Dave, 11/22/19 – 12/10/19.

The front cover picture of our book is the starburst galaxy **M82** which has a cigar shape due to being seen edge on (the light-bluish color-left to right down diagonal). Galactic wind (L to R upwards diagonal) was seen by Chandra in x-rays. Messier 82 is referred to in Figure 5.3 on page 163 and also on page 179. It is next to one of the prettiest spiral galaxies we know, M81, in Ursa Major (see photo at http://astropixels.com/galaxies/M81M82-A01.html). The "star bursting" in M82 is believed to be due to a history of changing gravitational interactions with its companion galaxy, M81.

Chapter 5 The distant multi-wavelength Universe (this is not an easy chapter).

Light Power Names:

The various terms and units for cosmic flux radiance and intensity can get involved and challenging -- as in this chapter. We have to try to use the proper words and definitions to avoid confusions. Astrophysics looks at the entire electromagnetic spectrum rather than just what the human eye sees (so we don't talk very much about luminous flux in SI lumens but rather just power in general in watts).

The y-axis EGB of **Figure 5.1** is labeled "strangely" as: νI_ν /[nW · m^2 · sr] with background in the numerator of "B" $\propto$ Equation B shown below. This y-axis is ~ a spectral radiance. Chapter Five begins with trying to get a handle on this initially difficult conceptual problem.

Definitions:

Radiant flux or luminosity, L, is radiant power, P=dE/dt in watts [unit W=joule/second]. Recall that page 11 had "energy flux" S as luminosity/area. "Irradiance" is also used for watts per square meter.

"**Spectral** flux" or "spectral luminosity" is power per unit frequency, $B=L_\nu=dP/d\nu$ W/Hz (but we can also encounter dP/dλ's for spectra by wavelengths).

Intensity in photometry and radiometry (e.g., Ex.5.1) includes solid angles, Ω, in "steradians" =area/r^2, or $I = dP/d\Omega$. So, **spectral intensity** is in W/[sr Hz] {$dP/d\Omega d\nu$}. There are 4π sr's over the whole sky above Earth. {But sometimes the term "intensity" is also used for units of watts per square meter too.}

Radiance includes the surface area (W/meters squared) of a reference or detector.

Spectral radiance is in W/[m^{2}srHz] (as in **Exercise 5.1** on page 160 and also called spectral intensity per unit area). For radio frequencies, the jansky (Jy) has units of W/m^{2}Hz as a radio spectral irradiance or flux density. Whew!

There is also a general consideration of measures of electromagnetic power that is placed in various containers: Visual astronomy for faint distant objects gathers a statistical number of discrete photons per unit time and places them in a bucket (such as the opening aperture of a telescope in square meters). Then a portion of that bucket goes into the eye (aperture 4-8 mm) for a count onto the retina (the eye bucket). The range of vision is 400-750 nanometer wavelengths or frequency from 4.0 – 7.5×10^{14} Hz or 0.40 - 0.75 peta-hertz (PHz) – a frequency bucket of width $\Delta\nu$ = 0.35 PHz.

If we plot frequency on a **log scale**, this bucket range is 14.60 to 14.875, or $\Delta\log\nu = 0.275$. If we partition the log ν scale into uniformly repeating units like this one, the next bucket up will be from 14.875 to 15.15 or 0.75 to 1.413 PHz. Notice that this bucket has a frequency width of $\Delta\nu = 0.66$ PHz which is greater than the previous interval; the frequency bucket sizes change! How can we account for gathering units of incoming power into these changing bucket sizes? That is the purpose of Ex. 5.1. {Another consideration is that the photon energy also changes in each bucket, $E = h\nu$ with each new mid-frequency . And, to avoid this, we restrict our interests to only how much "power" goes into a bucket, $\Delta P = \Delta E$/second}.

Exercise 5.1 uses B= "background intensity per decade of frequency" on a log-log scale that astrophysicists like. I don't think the solution write-up is very clear. If we just have a simple function, y = f(x) we can easily plot it on log-log scales. But the meaning of y for spectral luminosity is $dP/d\nu$ referring to how much power, ΔP, we place into a bucket of frequency range, $\Delta\nu$, with a linear range that changes in size along a log frequency axis.

The following noe might be better: Let an element of background intensity be "b" such that $I_\nu = db/d\nu$ "spectral flux". A decade (power of ten) of frequency is a change of one unit of $\log_{10}\nu$, and the rule of changing base of logs is that $\log_{10}\nu = \ell n(\nu)/\ell n10 \sim \ell n\,\nu/2.3$. We also know from calculus that $d\ln(\nu) = d\nu/\nu$. Then,

$$Eqn. B: \quad B = \frac{db}{dlog_{10}\nu} = 2.3\frac{db}{dln\nu} = 2.3\nu\frac{db}{d\nu} = 2.3\nu I_\nu$$

The x-axis of **Figure 5.1** is a log scale of wavelength; so frequency = c/λ is also a log scale (in an opposite direction). And the y-axis is a log scale in units of $B \propto \nu I_\nu$. The text labels the y-axis as a log spectral radiance.

Figure 5.2: On page 12 we had $dN/dS \propto S^{-5/2} = S^{-2.5}$. So, "normalizing" counts dN/dS may be accomplished by multiplying by $S^{+2.5}$ to get a "horizontal line" (page 160).

[Bottom of page 161] The "rest frame" of a source is labeled "cm" or "e" for the emitting center of mass (from previous page 34). Invariant light speed c is $\nu\lambda$, so $\nu = c/\lambda$. "o" here means "observed" by us – so $\lambda_o = (1+z)\lambda_{cm}$ implies $\nu_o = \nu_{cm}/(1+z)$, and $\nu_{cm} = \nu_o(1+z)$ is used in **Eqn. 5.3**.

Radiant energy can go out in all directions. For observers, it can come in from all directions covering all 4π square radians of a unit sphere (the CMB for example). So, "per sr" means reducing that incoming energy to $1/4\pi$ sr $\simeq 8\%$. Now the energy density $E_\nu(\nu,z)$ on page 161 is over a volume of a cubic mega parsec, Mpc^3; but we will only see that over a facing area of a square Mpc. We care about the energy rays through that face that come towards us, and they travel at the speed of light, c. So, to get watts (joules per second) of power per square radian in **eqn. 5.4**, we multiply eqn. 5.3 by $c/4\pi$.

The math for K-corrections (page 162) is hard and involved, and it applies to **sub-millimeter** wavelengths (SM sometimes means $\lambda \sim 0.3$ to 1.0 mm). "FIR," far infra-red, means from a low of about $\lambda \sim 15$ µm up to 1 mm; so **Figure 5.3** is for IR on the left and FIR on the right (a lot of bandwidth-names have some degree of overlapping of domains). Notice that the various spectral profiles for z=1-6 bunch up at λ = 1 mm, so SM flux density is somewhat independent of z.

Last time, we referred to astronomical color filter labels as "BVRIzJHK" imaging from B=blue to "z" near 1 μm and up to a K filter near λ = 2.2 μm. There exist additional IR filters LMNQ covering 3.5 μm to 21 μm – but that only gets us to the middle of figure 5.3.

The "colors" in **Figure 5.4** go all the way up to 21 mm wavelengths; and 1 to 300 mm is called **microwave**. Figure **5.5** shows λ =0.85 mm (sub-millimeter-galaxies, "SMGs").

The Atacama Large Millimeter Array in the high desert of Chile covers λ = 0.32 to 8.6 mm and became operational after our book was published (> 2010). **ALMA** (p.165) has 50 antennas of 12 m diameter and some later added on along with huge super-computers for interferometry processing and analysis. For more on "ALMA and its observational Achievements" see (for example): https://www.fujitsu.com/global/documents/about/resources/publications/fstj/archives/vol53-3/paper02.pdf

"In astrophysics, a BzK galaxy is a galaxy that has been selected as star- forming or passive based on its photometry in the B, z, and K photometric bands." Both BzK and EROs are mentioned on **page 166** and 146.

"**Rayleigh-Jeans tail"** Page 168 (and page 100) refers to the RJ tail of the black body (BB) distribution but doesn't give its formula. It is simply the BB equation evaluated at very low frequency. To do this, we can expand an exponential in a power series of a variable x. And, for small values of x, we only look at the first terms: $e^x = \Sigma_o^\infty x^n/n! \simeq 1+x$, where $x^o = 0! = 1$. So the term $(e^x - 1) \simeq x$. Using this low frequency limit, the BB equation (eqn 2.2 pg 43) reduces to:

$$I_{BB}(\nu,T) = 2\pi h\nu^3/[c^2(\exp(h\nu\backslash kT)-1)] \rightarrow I_{RJ}(\nu,T) = \mathbf{2\pi\nu^2 kT/c^2},$$

where x was = $(h\nu/kT)$.

This says that the left corner of the BB profile curve is a parabola, $I \propto \nu^2$. Planck's constant, h, is gone! – so the tail is classical rather than quantum.

Figure 2.1 on page 41 shows the straight-line RJ tail on the left side: notice that an order of magnitude change on the x-axis gives 2 orders of change on the y axis—as expected for a parabola $I \propto \nu^2$.

If we {wrongly} continued this parabolic profile upwards to high frequencies, we get what was called the **Ultraviolet Catastrophe!** (an infinite contribution of high frequencies). Planck's quantum of action h introduced in 1900, solved this previously major dilemma.

The various forms of the equations for Black Body radiation in texts and journals show the "radiance versus intensity" problems mentioned above: $I(\nu, T)$ is emitted power integrated over all solid angles and called "energy flux density" on pg 161. There are also equation forms for BB "B(T)" for "spectral radiance (p168)," and a form u(ν,T) as energy density per unit volume (the formulas have different coefficients and units). It can get confusing.

DUST "Most cosmic dust particles are between a few molecules to 0.1 μm in size." Dust is a big topic, and there are many different kinds of dust – see https://en.wikipedia.org/wiki/Cosmic_dust The top line of page 170 says that "dust in galaxies is roughly about λ ~70-130 μm" as shown in the 2nd peak from the right on Fig**ure 5.1** – EGB versus CMB. Dust clouds are transparent to radio wavelengths (λ ~ 1 meter). Radio luminosities correlate well with dusty FIR luminosity (**Fig 5.13**). The radio wavelength chosen for that figure is near 0.2 meters.

Exercise 5.4: Using **SI** (~MKS – a scale for humans) at the atomic scale is kind of nuts with its references so many orders of magnitude away (like 10^{-34} Js or 10^{-23} J/K). Since we are given a wavelength in microns [212.5 μm] lets stay there and also use a more appropriate energy in electron volts instead of joules. A really useful constant is **hc = 1.24 eV · μm** (write it down). And Boltzmann constant k = 8.616×10^{-5} eV/Kelvin.

Then the ratio (hν /kT) → (hc)/λkT = 1.24/[212.5 · 8.616 $\times 10^{-5}$ · 20 kelvins] = 3.386 – the numbers no longer look ridiculous. SI **is** generally encouraged for physics, but CGS never went away (astrophysicists were measuring supernova explosions in ergs!), high energy physics often uses "natural" units with c = $\hbar$ = 1 – which could make everything into units of eVs or cm's, and some people use Planck Units or set G = 1 or k_B=1 for other "natural" units).

The galactic and stellar evolutions described in this chapter seem very tentative as if there is a lot more to be learned. And articles in astrophysics (like in ArXiV.org) show a lot of activity in this arena. There is a lot of uncertainty and many surprises
Stellar Feedback explains why star formation is so inefficient. "Although supernova explosions and stellar winds happen at very small scales, they affect the interstellar medium (ISM) at galactic scales and regulate the formation of a whole galaxy." Numerical modeling is helping to understand feedback mechanisms, but there is a lot that is still unknown.