Topics: More on the Hubble Law, cosmological principle, contents of the universe, scale factor to describe expansion, Olbers' paradox

Reading:

- Read the beginning of Ch. 23 in Ryden and Peterson (pp. 526 - 531). Read up to the beginning of the discussion of the CMB. You can read about the CMB, all the way to the end of sec. 1 on p. 533.
- Review the material from Tuesday – reread the end of §20.5 from the middle of p. 485 (isotropy and homogeneity); review the slides from Tuesday's class (on the website); study Fig. 22.8 and think about the smallest size (in redshift, z) on which the universe looks homogeneous – and read the last paragraph on p. 522.

Summary of work to submit:

- Nothing to hand in for Thursday's class.

Overview:

Are you willing to approximate the matter in the universe as a smooth fluid (or gas), multicomponent (baryons, neutrinos, photons, dark matter) but well-mixed – at least on very large scales?

Are you comfortable with the observed velocity $\propto$ distance of distant galaxies being interpreted as a uniform expansion?

If the expansion proceeds at a constant rate (given by the Hubble constant), then we can ask, how long ago were things that are a distance, d, away today, a distance $d = 0$ from each other? That time is the age of the universe (if the expansion rate is always the same). The *dynamics* of the universe seem to be an impulsive expansion at $t = 0$ (the Big Bang) that may slow with time (due to attractive forces of things in the universe) or speed up with time (due to repulsive forces). An empty universe should expand at a constant rate...but we know our universe isn't empty.

We need to categorize "stuff" (particles) in the universe. Their mass-energy has gravity that should slow the expansion. And the mass-energy density of the different components of the cosmic fluid changes differently as the universe expands depending on various properties.

Commentary on the reading, viewing, and other preparation:

Particles are categorized into only a few types by cosmologists. Baryons are atomic nuclei (protons and neutrons) – regular matter. Electrons are actually leptons, not baryons, but they travel around with baryons and don't weigh very much, so in terms of a mass census of stuff in the universe, we just lump the light weight electrons in with the baryons – regular matter.

Photons are particles too. They don't have mass but they do have energy. That means that they have gravity (yes, really!). But baryons (because they're heavy) are slow whereas photons are fast (as you know). Photons lose energy as space expands because they are subject to redshifting (longer wavelength light means lower energy photons), whereas baryonic matter keeps its mass per particle as the universe expands. (This will be important later – think about it, no matter how much matter dominates over photons now, when the universe was very small, in the past, photons had more energy than matter – early in the universe's history, photons dominated the dynamics of the expansion.)

Neutrinos are like photons in that they are (nearly) massless and travel (close to the) speed of light. But they are *not* like photons in that they don't interact with matter via the electromagnetic force. Photons are the way the electromagnetic force is transmitted and protons and electrons have charge and interact through the electromagnetic force (with themselves, each other, and photons). Neutrinos don't. They pass right through regular matter without interacting (hardly) at all. Neutrinos are all over the place, they are produced in the nuclear reactions inside stars, they are common but ghostly.

Dark matter... we don't know what it is, but there's very good evidence that it is a massive particle that we haven't found in particle accelerators (yet). Maybe because it's so massive (it takes more energy to produce massive particles). We know that dark matter interacts with regular matter (and photons) via gravity but we can see (ha-ha!) that it does *not* interact via the electromagnetic force. They pass through regular matter (and other dark matter) without interacting (no collisions, no friction, no absorption or emission of photons) – except via gravity. We'll talk soon about evidence for dark matter and how we know its properties.

Among other things, we'd like to know what the average density of each of these kinds of particles is in the universe (average over that largest-scales – those that gives us a homogeneous universe).

Note that particle masses (e.g. in Tab. 23.1) are usually described by the equivalent (rest mass) energy, from $E = mc^2$. A relatively heavy particle like a proton ($m_{\mathrm{p}} = 1.67 \times 10^{-27}$ kg) has a rest energy of almost a billion electron volts (a GeV)! Note also (though not discussed in this part of the reading) that particles (except for the photon) have anti-particles that have identical masses but opposite charges. When a particle and antiparticle meet, they turn into two photons.

Olbers' paradox is important in that it provides independent evidence (independent from the Hubble law – the expansion of the universe) that the universe is not infinitely old. (As a thought experiment many centuries ago, stars were considered, but the same argument applies to galaxies.) Go through the math on pp. 528-30 carefully. Note that a *solid angle* is a two-dimensional angle. We've talked about the angular size of an object (like the Sun); we can also talk about its angular area, or solid angle, in square degrees or square radians. Square radians are called *steradians*. If the angular radius of the Sun in 0.25 degrees (0.004 radians) then its solid angle is $\pi 0.25^2$ degrees^2 or $\pi 0.004^2 = 6 \times 10^{-5}$ steradians. In the discussion of Olbers' paradox, the solid angle of a star is given by eq. 23.2 and the surface brightness, Σ_*, of an object like a star is its flux per solid angle (W m^{-2} ster^{-1}). Both flux and solid angle decrease as the square of the distance so the surface brightnesses of a star is independent of distance.

And if we consider concentric shells centered on the Earth and full of stars, the number of stars should go up as the volume of each shell (if stars are uniformly distributed) and the volume of a thin spherical shell goes up (not as r^3 but) as $4\pi r^2 dr \propto r^2$. Again, this is cancelled by the r^{-2} decrease of solid angle with distance so the fraction of each shell's area that's covered by stars is also independent of distance. And thus we can compute the covering fraction of the sky by stars (eq. 23.6 and 23.7) and eventually relate that to an average surface brightness of the sky (eq. 23.9) which we then can compare with an observed sky-averaged surface brightness (p. 530). As an aside, I'll point out that stars covering other stars and blocking our view of them is not considered.

Read the second paragraph of p. 530 carefully to see the importance of Olbers' paradox.

Think carefully about the scale factor, $a(t)$ – we'll be using it a lot! You can think of it as a "characteristic" length scale of the universe - but it's unitless so it only has relevance in terms of how it changes in time. If the universe grew by 20 percent over a billion years (that is, the distances between any two galaxies increased by 20 percent), then a went from 1 to 1.2. Note that volumes scale like a^3.

And note further that the Hubble constant (or, more properly, parameter) is a function of time and is defined formally to be the time rate of change of the scale factor divided by the scale factor itself (both are functions of time). Makes sense, $H_{\rm o} = v/d$. The dot above a variable denotes a time derivative – a notation invented by Newton, by the way.

Note that the redshifting of light is stated on p. 531 as a secondary resolution of Olbers' paradox. When you start to read about the CMB, think about how in fact, we do see photons coming from every direction in the sky (because we see back to a time when the universe was dense, uniform, and hot) but they have been redshifted. A lot. And so they are in the millimeter wavelength part of the radio spectrum. If our eyes were sensitive to long-wavelength radio waves, no one ever would have posed Olbers' paradox – the sky would look very bright indeed.