Topics: Cosmic Microwave Background (CMB), and the Newtonian Friedmann equation

Reading:

- Read the rest of section 1 and all of section 2 of Ch. 23 (pp. 531-535).
- Supplement the CMB reading with the set of slides I've posted on the website.
- We will read sec. 3 of Ch. 23 for Thursday, so you're encouraged to read ahead into that section.

Summary of work to submit:

- Nothing to hand in for Tuesday's class.

Overview:

Both the observed expansion of the universe (the Hubble law) and Olbers' paradox imply that the universe has a finite age. We know that gas cools as it expands – the expectation is that the early universe was hot and dense. If so, we should see the radiation from that earlier epoch when we look at the distant universe. And indeed we do – but it is highly redshifted and so this cosmic background radiation is in the microwave part of the radio spectrum. It is uniform over the sky (to one part in 10^5) indicating that the early universe was not just hot and dense, but quite uniform. The expansion of the universe has caused the thermal radiation from this early epoch to redshift and cool. So the expansion history of the universe is intimately tied to the CMB's properties. We need a way of describing, quantitatively and physically, the expansion of the universe. The Freidmann equation does that for us. At the end of §23.1 we begin to derive the Friedmann equation by simply considering the dynamics of an expanding sphere of self-gravitating gas (Fig. 23.3) and we see the scale factor, $a(t)$, is used to describe the radius of that sphere. Interesting results emerge just from the beginning of this simple analysis in section 1: the fate of the expanding universe is determined by the density of matter in the universe and the Hubble constant. This is analogous to the fate of a projectile launched from the Earth: an initial impulse followed by the steady slowing due to gravity (see the middle of p. 534).

Commentary on the reading, viewing, and other preparation:

Read the slides – images and text – about the CMB carefully. Think about the analogy of the sky on an overcast day. You see the lit up underside of the clouds. The photons you see fight their way through the opaque ("optically thick") cloud layer and then stream directly from there into your eyes. The early universe was opaque due both to its high density and also to the fact that it was hot and hydrogen was ionized. Free electrons (those not bound to atoms) are efficient at interacting with photons of all wavelengths. Once hydrogen is cool and neutral (the electrons are all attached to protons – hydrogen nuclei) photons can only be absorbed if they have very specific energies (those corresponding to energy level differences in the hydrogen atom). So once the universe cools enough for hydrogen to be neutral, the gas in the universe is suddenly transparent.

Keep in mind that the conditions are the same everywhere in the universe at any given time. We see the "surface of last scattering" and the blackbody photons emitted from it only because of the lookback time phenomenon. If we look far enough away, we're seeing the universe at a time when it was just transitioning from opaque to transparent. We have to look 14 billion minus about 300,000 light years away to see that. Note that tomorrow, that surface of last scattering will be one more light-day further away from you...

OK! The spectrum of that light from 300,000 after the big bang is a blackbody with a temperature of 2.7 K. That's the 3000 K expected for hydrogen that's transitioning from ionized to neutral, redshifted by a factor of $z \sim 1100$ accounting for the subsequent expansion of the universe.

But what about the spatial distribution of the CMB radiation? That's addressed by the latter two-thirds of the slides. It is – after removing various "foregrounds" – amazingly uniform, indicating that the early universe was very uniform (same density and temperature everywhere – at leas to one part in 10^5). Note that all the structure we see today (planets, stars, galaxies, galaxy clusters) grew from these initial very small, but non-zero, inhomogeneities in the early universe. (The inhomogeneities – hot and cool spots – in the CMB maps shown in the last couple slides are due to slight differences in the density of the gas in the early universe; the denser regions had slightly more gravity and they grew into today's galaxy clusters whereas the lower density regions evolved into the voids we see in the large scale structure maps.)

This CMB stuff can be a little hard to think about. Come to class with questions.

At a basic physics level, let me point out: the intensity (I or sometimes J) that is in the definition of the Planck function (e.g. eq. 23.16) has units of flux per solid angle (same as surface brightness, that was introduced in the discussion of Olber's paradox). As I've previously noted, this intensity is proportional to surface flux. Indeed, for a uniform surface emitting light the intensity is equal to the surface flux divided by π. As you follow the derivations and concepts on pp. 531-32, think about how surface flux for a blackbody is $F = \sigma T^4$ and how energy density, u, is plausibly related to the flux divided by the speed of the things carrying the flux. At the very least, divide the units of flux by the units of velocity and verify that you get units of energy density.

Recognize the first law of thermodynamics (eq. 23.21)? Please ask about it in class if you're not familiar with it. Pretty interesting how we can just treat the CMB photons like they're a gas and apply the first law to them. Note that the final result (mid-page 533) that the blackbody temperature scales inversely with the scale factor – here derived from thermodynamic considerations – is consistent with the concept of the peak wavelength of a blackbody and the idea that those wavelengths would get redshifted in proportion to the scale factor as the universe expands.

Section 2 presents and equation of motion of the universe (talk about grandiose!). It's super simple...because we're treating the material in the universe as a homogeneous (uniform) fluid that's described simply by its density. A sample volume expands or contracts based on its initial velocity (from the Big Bang) and the constant effects of gravity (from the mass inside the volume). That's all there is to it!

Will the volume expand forever? Depends on the gravity (via the density) and the inertia (via the Hubble constant). The related concept of the critical density (eq. 23.33) is very important.