Topics: Starting cosmology: galaxies, distances and redshifts, the Hubble Law

Reading:

- Read sections 4 and 5 of of Ch. 20 in Ryden and Peterson (pp. 482 - 487). You'll want to carefully follow my notes about this material – especially galaxy *distances* in section 4 – below.
- Read the beginning of sec. 3 of Ch. 22 in Ryden and Peterson (pp. 520 - middle of 523). Here too, you'll want to read my notes, below, carefully, to help you understand material from the middle of a chapter you haven't otherwise read.

Summary of work to submit:

- To prepare for Tuesday's class, answer the problem embedded in this assignment and bring your solution to class. Be prepared to discuss it, but you won't have to hand it in.

Overview:

We are switching gears, from planetary systems – which are on a relatively small scale, by astronomical standards – to cosmology, which is on the largest scale. So we'll first start by getting oriented to this scale. We'll remind ourselves about "lookback time" – when we see light from far away objects, we are seeing them as they were in the past (think Physics 5 and special relativity, but this is generically true even if nothing is moving close to the speed of light). We'll see that galaxies are the most sensible unit to think about when we think about matter and light in the universe as a whole. I'm not having you read much in the textbook about galaxies, so pay special attention to my notes below, and also use those notes as a guide for the textbook reading for this class. Cosmology is the study of the universe as a whole, its history, its contents and global properties, and its possible future. The key fact of Cosmology is that the universe is not infinitely old, but rather came into existence in an event called the Big Bang about 14 billion years ago, and it came into existence in a hot, dense, uniform state and has been expanding, cooling, and becoming less uniform over time. This week, we'll see how we know these things and how to think about them. (The thermal history – hot Big Bang, cooling since – is something we may not get to until next week; we'll start with the scale, contents, and expansion first.)

Commentary on the reading, viewing, and other preparation:

Let's start with *scale* – size and spatial distribution – before going on to thinking about what galaxies actually are.

Problem 1

We've encountered the length unit, *parsec*, before. It is defined – along with other astronomical length units – in Tab. A.2 in the appendix. It is equal to 3.26 light years. When we talk about distances to distant galaxies, we use the unit *megaparsec*, which is a million parsecs (3.26 million light years). Be that as it may... a parsec is the typical distance between stars. The nearest star to the Solar System, Proxima Centauri, is 1.3 parsecs (4 light years) away.

So, in the Solar System, we have the solar radius as a characteristic length scale and the AU as another characteristic (and larger) length scale.

Problem 1 continued on next page. . .

(a) How many solar radii away is the nearest star (Proxima Centauri)? How many AU away is it? (Both answers should be to two significant figures only!)

The Milky Way is about 100,000 light years in diameter (30 kiloparsecs).

(b) How many megaparsecs away is the edge of the observable universe (ignoring the expansion of the universe)? Assume that the age of the universe is 14 billion years and that the *observable universe* is defined as a spherical volume of the universe, centered on you, and with a radius equal to the distance light can travel in the age of the universe. Express your answer also in terms of Milky Way radii.

So, is the observable universe big or small, in your opinion?

(c) If the density of matter in the universe is equal to 14 hydrogen atoms per cubic meter, and the Milky Way weighs 10^{11} Solar masses, how many galaxies do we expect to find in the observable universe if the average galaxy weighs the same as the Milky Way? And what, then, would be the expected distance to the nearest galaxy?

When we deep into space with optical telescopes, looking between and beyond the stars, we see fuzzy patches of light that are swarms of billions of stars, gravitationally bound into *galaxies*. Here is an especially empty part of space:

Fig. 1 The Hubble Extreme Deep Field – https://apod.nasa.gov/apod/ap121014.html – nearly everything you see here is a distance galaxy, with billions of stars in each one (plus some gas, dust, dark matter...).

Here's a single galaxy, not too different from the Milky Way:

Fig. 2 The spiral galaxy M81– https://apod.nasa.gov/apod/ap171005.html

If you were to zoom in on many of the blobs of light in the Hubble Extreme Deep Field they'd look like this. Others would look more blobby and unstructured.

If we want to map out matter in the universe on the largest scale, then galaxies are what we should think of as the fundamental units, or building blocks of the universe (not stars, because stars are always found clustered in galaxies). The image of the Hubble Extreme Deep field makes the galaxy distribution look pretty random, but they do tend to cluster together in many cases. You should go to Astronomy Picture of the Day and search for images of galaxy clusters – they are beautiful. The Milky Way is not in a cluster, by the way. Clusters themselves group into superclusters, but beyond some large, maximum scale, there are no larger structures in the universe. The basic large-scale structure of the universe is shown in Fig. 22.7 and 22.8 in the chapter 22 reading. Study the second of those figures and try to understand what the actual physical scale is (you'll want to read about the Hubble Law first, in Ch. 20). We are at the center of that figure and each dot represents a galaxy. Try to convince yourself that the bubbles (voids) between the more filamentary structures define the largest coherent structures in the universe. Beyond that scale, the universe is relatively uniform.

It is a basic assumption of cosmology (to be discussed more on Thursday) that the universe is *homogeneous* – uniform. But of course that can only be true beyond some critical size scale. A related assumption is *isotropy* – the universe looks the same in every direction.

OK, to map out the distribution of galaxies and to understand their motions (which reveal that the universe is expanding) we'll have to understand a few basic things about galaxies and how to measure their properties.

At the beginning of §20.4, three methods of distance determination are listed. You know about the radar method and about parallax. They are accurate, not too dependent on the properties of the object being studied, and easy to understand. But they are limited to relatively small distances. Galaxies are far away, and in fact, it wasn't until telescopes were good enough (1910s and 20s) to see individual stars in them that their great distances were understood.

So, you can't measure their distances with parallax. Instead, you have to use the inverse square law of light (review it if you can't write it down from memory/first principles and define the three variables in it!). This method is called the "standard candle" technique, because it only works for an object that emits a known amount of light (i.e. for which you can *assume* its luminosity, L). Equation 20.25 is key. Please don't worry about the concept of "magnitudes" (eqn. 20.26). But do pay attention to the concept of *distance ladder* and think about how a category of pulsating variable stars, with luminosities proportional to their pulsation periods, could be used as standard candles. The Faber-Jackson (Sandy Faber is Swarthmore class of 1966) and Tully-Fisher relations involve tying the luminosity of a galaxy to the velocities of the stars or gas in it, which can be measured via the galaxies' spectral line widths.

In section 5, we learn about the speeds of galaxies, measured via the Doppler shift. Almost all galaxies are moving away from us – the universe is expanding. That's one of the great discoveries of...all time. Note that the Doppler shift of a galaxy is relatively easy to measure. Take a look at the figure below.

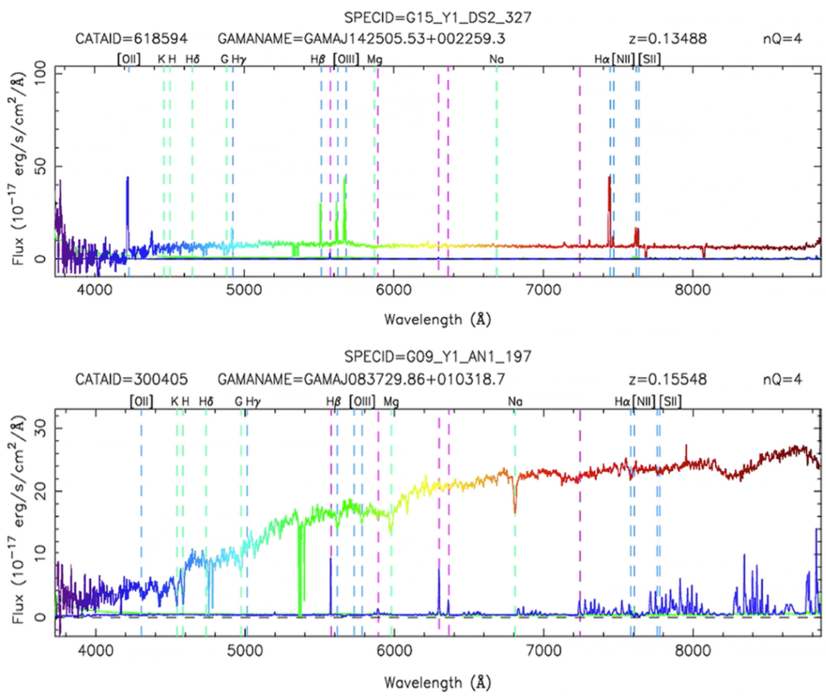

Fig. 3 Spectra of two different galaxies. Note the range on the x-axis – basically the whole optical range and the spectra are conveniently color coded. The top spectrum is from a galaxy with a lot of star formation (and so a lot of hot gas) and is dominated by emission lines while the bottom one is dominated by the light of its brightest stars and so has an absorption line spectrum. Either way, the Doppler shift can be measured. See if you can find the hydrogen Balmer alpha line (3 to 2 transition) in each spectrum. It is labeled, but in neither case is it at its rest wavelength of 6563 Å. Note that the redshift of each galaxy (labeled z) is stated above each plot.

Measuring the speed and distance to a bunch of galaxies enables us to find the expansion rate of the universe – the Hubble constant. Make sure you understand its units.

And make sure you understand (p. 486) how it implies an *age* for the universe (time since the Big Bang).

Come to class with questions!