Announcements

- **Midterm exam in two weeks.** Your midterm exam in Astronomy 660 will take place in two weeks, on Tuesday, March 19 (this was the date tentatively announced in the Course Syllabus, as well). It will include all of the material that we have covered up until that time, and will likely consist of a combination of multiple choice, short answer, long (problem) answer, and essay types of questions. More details on its nature and content will be discussed next week (in particular, on Thursday, March 14!). The exam is worth 25% of the course grade.

- **Next homework collection on Thursday, March 14.** The next collection of homework will occur at the start of class on Thursday, March 14 (two days later than previously announced). Note that solutions will be posted immediately after the due date, so that you may have them to study from for the midterm exam.

Reading Guide

This week, we temporarily dip back into the study of galaxies to (briefly) consider what we know about galaxy evolution, as gleaned (mainly) from studies of galaxies at different redshifts (and, thus, different points in cosmic time). Then, we continue onwards with cosmology, to fully develop our understanding of the “simple”, matter-only universe. Text sections are given in the rough order of coverage in class.

1. **Text – Chapter 26 (partial): Galactic Evolution.**
   As we discussed in class, we are only taking a brief, mostly qualitative, study of the evolution of galaxies. To this end, the required reading from this chapter is minimal, and covers mainly what was discussed in class (note that class went a tad further in some areas than the reading, and vice versa). This includes the following subsections: Evidence of Interactions (on pages 999 – 1001); Mergers in Elliptical and cD Galaxies (on pages 1013 – 1015); The Hierarchical Merger Model (on pages 1023 – 1025); Metallicity Gradients, The Formation of Elliptical Galaxies, and Galaxy Formation in the Early Universe (on pages 1028 – 1032). You are encouraged to thumb through the parts of the chapter not covered by these assigned readings, but you are not specifically responsible for anything in there.

2. **Text – Chapter 29, selected sections.** The main subsections that we are covering this week include the following:
   - §29.1: p. 1156 – 1158 – The Age of the Pressureless “Dust” Universe. This was formally derived in class last week for the flat universe; note the expressions given for the open and closed universes by the text, and be sure you understand how they behave.
   - §29.1: p. 1158 – 1159 – The Lookback Time. This was formally derived in class last week.
   - §29.4: p. 1201 – 1203 – Distances to the Most Remote Objects in the Universe. This follows fairly closely the derivation and descriptions given in class for measuring the proper distance to points in space. Note the interesting discussion on the peculiar nature of distances in a closed universe to end the section.
   - §29.4: p. 1203 – 1204 – The Particle Horizon and the Horizon Distance. Read just the first few paragraphs of this section, down to equation 29.156 on page 1204. Note that the book discusses “the radiation era” – an early time in the universe’s history when the mass-energy was dominated by photons – that we have not yet discussed. Focus for now just on the matter-only result (i.e., equation 29.155).
   - §29.4: p. 1206 – 1207 – The Arrival of Photons. This section follows very closely our class discussion on this topic.
   - §29.1: p. 1162 – The Deceleration Parameter. Here the book simply “introduces” $q_0$, the deceleration parameter that we shall formally derive together in class.
Homework Questions: Due *Thursday, March 14*

The following questions represent the next part of the next homework set, which you will turn in at the start of class on Thursday, March 14 (note slight change from earlier date announced).

Please answer the following questions as completely as possible. In the case of numerical problems, please indicate your final answer by circling it. Partial credit for incorrect answers will only be given if work is clearly shown. All problem numbers refer to the end of chapter questions from the text.

36. (10 points) A particularly simple universe is one that is completely empty of any mass-energy — no matter, no radiation, no contribution to energy density of any sort. Such a universe is sometimes referred to as a “Milne” universe. Demonstrate that a Milne universe permits only two of the following three dynamical possibilities: (1) An empty, static, spatially flat universe; (2) an expanding positively curved (“closed”) universe in which $R(t) \propto t$; (3) an expanding or contracting negatively curved (“open”) universe in which $R(t) \propto t$ for the expanding case.

37. (15 points total). For a matter-only, expanding universe of pressureless dust:

(a) (5 points) Make a plot that shows how $H/H_0$ varies with redshift for $0 \leq z \leq 5$, and $\Omega_0 = 0, 0.5, 1.0, \text{ and } 2.0$. Put all four of the curves on the same plot, and clearly label them.

(b) (10 points) Describe in words and equations as clearly as you can how the value of $H/H_0$ for the $\Omega_0 = 0$ (“empty”, or “Milne” Universe) “makes sense” at the time in the Universe’s evolution corresponding to redshift $z = 1$. The more complete and convincing your answer, the better!

38. (5 points) For a universe consisting only of pressureless dust, show that

\[
\frac{1}{\Omega} - 1 = \left( \frac{1}{\Omega_0} - 1 \right) (1 + z)^{-1}.
\]

To derive this equation, you may use any of the equations given to you in Section 29.1 of the text as starting points (i.e., you do not have to derive the text equations, just use them to derive the equation above). Discuss the behavior of $\Omega$ as $z \rightarrow \infty$.

39. (15 points total) In this problem, you are going to consider the details of the path taken by a photon that was released at $t \rightarrow 0$ that is just now arriving at Earth (i.e., this is a photon that is just now arriving from the particle horizon), in a flat, pressureless matter-only universe with $h = 0.71$.

In class, you learned that, in terms of proper distance from Earth, this photon was actually traveling away from us for a time, before it began to make progress towards us. Here, after a few preliminaries, you will calculate the amount of time the photon spent in both parts of its journey, and then the maximum proper distance away from us that the photon achieved while in flight. You may use any equation found in Chapters 27 or 29 of your text as starting points for any question (i.e., you do not need to rederive them here), so long as you explicitly state which equations they are — i.e., you must label them.

(a) (2 points) What is the Hubble Time, $t_h$, for this universe? Give your answer in Gyr.

(b) (2 points) What is the present age of this universe, $t_0$? Give your answer in Gyr.

(c) (2 points) What is the present horizon distance, $d_{h,0}$, of this universe? Give your answer in Gly.

(d) (5 points) In terms of its proper distance from us, for how many years (give your answers in Gyr) was this photon traveling away from our location, $t_{\text{away}}$? For how many years was it traveling towards us, $t_{\text{towards}}$? Be sure to label both answers clearly!

(e) (4 points) What was the maximum proper distance from us, $d_{p,\text{max}}$, achieved by the photon during its flight? Express your answer in Gly.