Astronomy 21 Midterm Exam, 2012 Winter
Galaxies and Cosmology

3 Feb, 2012 E. S. Phinney
Due in class **2:30pm** Weds 8 Feb, 2012

Do not download or open the exam until you are ready to take it.
Please write the exam in a **Blue Book** (available in the bookstore), and make sure your name and return mail-code is clearly written on the front of each blue book you use. You get 1 point for doing this. Remember to also hand in your optional essay outline and references, if you plan to exercise this option (see online syllabus).

There are 7 questions: 5 essay-type of 5 points each and 2 calculational of 12 points each, for a total of 50 points.

The honor code is in effect. Please follow all of the following instructions regarding this exam. If you feel unclear about any of these instructions, you are required by the honor code to ask for clarification.

- You may not communicate with any other person (except Prof. Phinney) about the contents of this exam, until both you and the other person (if taking Ay 21) have submitted your exams.
- The exam must be completed in a single sitting.
- **The time limit is 3 hours.**
- A non-programmed calculator is permitted, and recommended. Computers and related programmable devices are **not permitted**.
- During this exam, you may refer to your own class notes (written by your own hand), the course homeworks from this year and their official solution sets. You **may not** refer to the textbook (Carroll & Ostlie) or any other documents, paper or electronic.
- The midterm exam score will account for 20% of your grade.

Your completed exam should be handed *in person* to Sterl in class Weds Feb 8.

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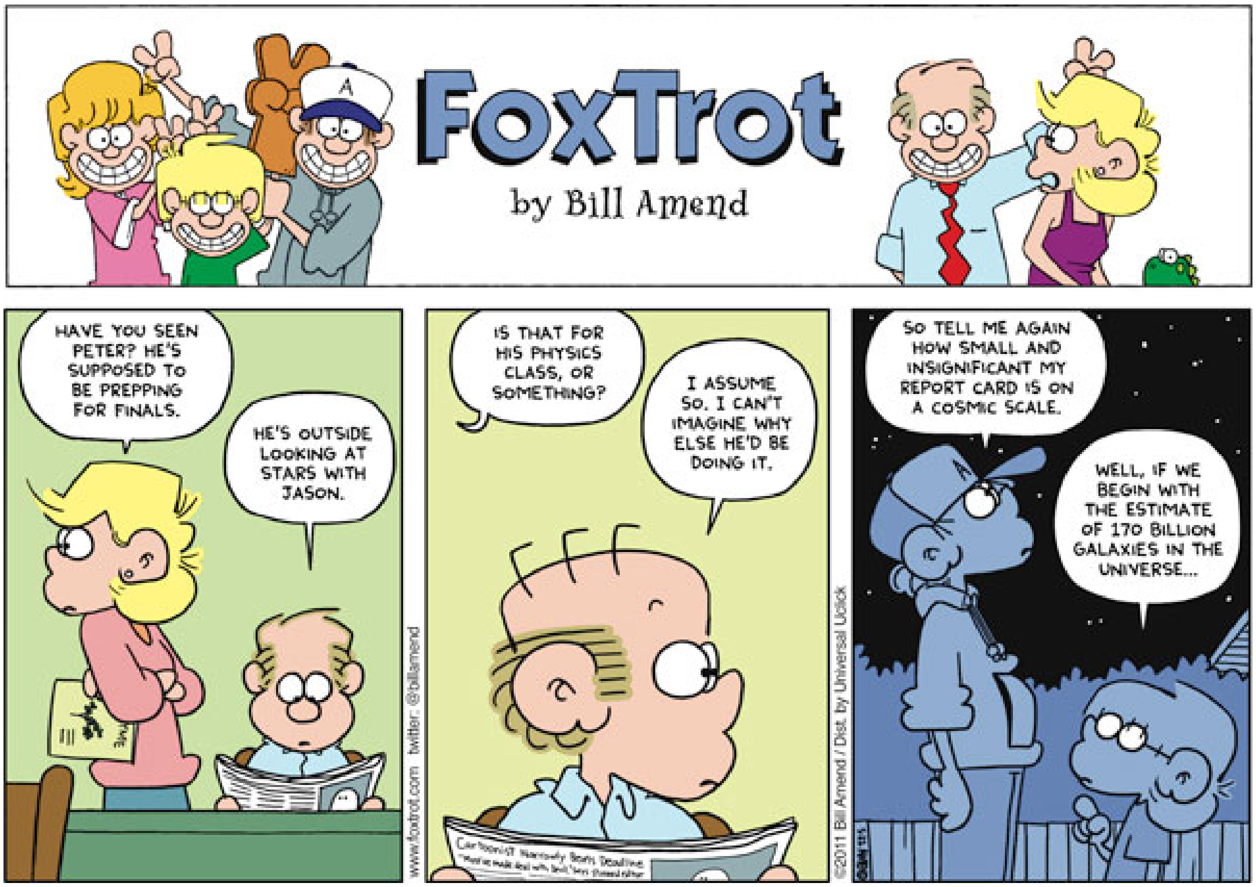
FoxTrot
by Bill Amend
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IS THAT FOR HIS PHYSICS CLASS, OR SOMETHING?
I ASSUME SO. I CAN'T IMAGINE WHY ELSE HE'D BE DOING IT.
©2011 Bill Amend / Dist. by Universal Uclick
SO TELL ME AGAIN HOW SMALL AND INSIGNIFICANT MY REPORT CARD IS ON A COSMIC SCALE.
WELL, IF WE BEGIN WITH THE ESTIMATE OF 170 BILLION GALAXIES IN THE UNIVERSE...

The exam starts on the next page.

Five essay problems:

1. (5pt) Describe the two main morphological classes (E, S) of galaxies, including some discussion of subtypes of each, and the observable properties that correlate with each class.

2. (5pt) Is most of the hydrogen in the Milky Way bound up in stars, or elsewhere? What about in clusters of galaxies? Describe the observational evidence for dark matter in galaxies and in clusters of galaxies.

3. (5pt) The Andromeda Galaxy M31 is located 0.78Mpc from Caltech, giving a Hubble recession velocity relative to Caltech of 55km s^{-1}. Give at least three reasons the actual measured recession speed of M31 on 8 Feb 2012 could differ from this value, and estimate (roughly) the values these contributions could have.

4. (5pt) Explain how Hubble's law is consistent with homogeneity and isotropy of the universe. On what scales is the universe homogeneous and isotropic?

5. (5pt) Describe some of the problems which led to the abandonment of the steady-state model of the universe, and the evidence that the universe began with a hot big bang.

   See the next page for the two calculation problems.

6. (12pt) Suppose there were a component Y of the universe besides matter, radiation and dark energy, and this component Y had the property that its pressure p_Y was related to its mass-energy density ρ_Y by $p_Y = \rho_Y c^2$, where c is the speed of light (this is the most extreme type of matter allowed by special relativity, since such matter has a sound speed equal to the speed of light). Suppose component Y does not interact with other forms of matter, and today has $\Omega_{Y0} = 10^{-7}$, so the Y-matter *today* is utterly unimportant for the dynamics of the universe.

   a) $\rho_Y \propto a^{-s}$, where a is the scale factor of the universe. Find the numerical value of s.

   b) Above what redshift would Y-matter dominate the dynamics of the universe? Would it dominate during hydrogen recombination?

   c) At redshifts where Y-matter dominates the dynamics, $a \propto t^{\mu}$. Find the numerical value of μ.

   d) At redshifts where Y-matter dominates the dynamics, $\rho_Y = A/Gt^2$, where t is time since the Big Bang. Find the numerical value of A.

7. (12pt) At the time of the Big Bang, a photon left galaxy 1 headed towards galaxy 2. If the photon reached galaxy 2 when the universe had age t,

   a) show that the distance *today* between galaxy 1 and galaxy 2 is

$$L(t) = a_0 \int_0^t \frac{c dt'}{a(t')} \,. \tag{1}$$

   b) Throughout all but its most recent history, the universe was dominated by matter and radiation (curvature and dark energy being negligible). Using the Friedmann equation and the expression for $H(\tilde{a}) = H_0 E(\tilde{a})$ (where $\tilde{a} = a/a_0 = (1+z)^{-1}$), show that for t during those times

$$L(t) = \frac{c}{H_0} \frac{1}{\sqrt{\Omega_{m0}}} \int_0^{\tilde{a}(t)} \frac{d\tilde{a}'}{\sqrt{\tilde{a}' + \tilde{a}_{eq}}} = \frac{2c}{H_0} \frac{1}{\sqrt{\Omega_{m0}}} (\sqrt{\tilde{a}(t) + \tilde{a}_{eq}} - \sqrt{\tilde{a}_{eq}}) \tag{2}$$

   where $a_{eq} \equiv \Omega_{r0}/\Omega_{m0} = 3.07 \times 10^{-4}$. Assume that the universe is flat ($k = 0$).

   c) Evaluate $L(t_{ls})$ at the time t_{ls} of the last photon scattering of cosmic microwave background photons, when $1/\tilde{a} = 1 + z_{ls} = 1088$. Express your answer in Megaparsecs.

   d) Show that in a flat universe with cosmological constant neglected, the angle subtended at earth by a comoving length $L(t_{ls})$ at t_{ls} is $\theta_{ls} = L(t_{ls})/[L(t_0) - L(t_{ls})]$, and evaluate θ_{ls} in degrees (t_0 is the present time, and $L(t)$ is given by equation 2). Discuss the implications of the fact that if the past of the universe was always dominated by matter and radiation alone, cosmic microwave background photons arriving at earth from angles more than θ_{ls} came from elements of matter which could never have communicated with each other before the photons were emitted.

The end.