Astronomy 350 Fall 2011
Homework #7
Due in class: Friday, Oct. 21

1. [**5 points**]. *Black Holes and Time Dilation.* A giant clock is illuminated far from a black hole (i.e., $r \to \infty$). As the image of the ticking clock approaches the hole, brave observers hovering in rockets will see the tick duration change from $(\Delta t)_{\rm emit} = 1$ sec. What will the observed tick duration be at $r = 2R_{\rm Sch}$? at $r = 1.001R_{\rm Sch}$? at $r = R_{\rm Sch}$? Comment on your result. Be sure to also comment on the tick rates that astronauts see when looking at their own wristwatches.

2. [**5 points**]. *The Bullet Cluster and Dark Matter.* In class we discussed the recent but already famous results concerning the "Bullet Cluster" of galaxies. Briefly explain what the bullet cluster is, what the data show, and how the data give evidence in favor of dark matter and against modifications to gravity theory. In your opinion, how much (if at all) does this strengthen the case for dark matter?

3. *The Digital Universe Online.* The Sloan Digital Sky Survey (SDSS) is an ongoing project to map a large fraction of the sky with digital images and spectra. The Sloan survey contains a tremendous amount of cosmological data, most of it publicly available online. The SDSS website and some key pages within it are accessible from the ASTR350 `links` page. Gathering a bit of data, you can quickly arrive at some interesting cosmological conclusions. (*Note*: recall that while you should consult discussions on the website, the wording of your answers must of course be your own! To help avoid even accidental problems, I strongly suggest you close your browser while writing your responses.)

   (a) [**4 points**]. Go to the SDSS main page. Briefly summarize some of the goals and/or main results of the survey?

   (b) [**4 points**]. Briefly summarize the essentials of the survey telescope. Where is the survey telescope located? How large is the telescope, and what kind of telescope is it? How are the images taken? How are the spectra taken in later follow-up observations?

   (c) [**4 points**]. Follow the *navigate* link to go to the SDSS `Navigate Tool`, which will start you on a nearby (and thus large and bright) spiral galaxy; this will be the starting point of your journey. Note that you can use the tool to wander around the sky. As you do this, you can click on objects and an automated code will give information, including a (usually but not always correct) classification of the object as a star in our own Galaxy, or an external galaxy. Estimate the fraction or percentage of the SDSS objects that are stars, and the fraction that are galaxies. A rough estimate is fine, though you are welcome to do something more detailed; in any case, explain how you made your estimate. On the basis of appearance, how are these distinguished?

   (d) [**4 points**]. Now go to a random location in the survey, and from the Explore window launch the `Finding Chart` window. From the help window, see how to label all galaxies in the field of view (to do this, type the letter G into the text box below "Use query to mark objects"; typing S instead gives stars). Using this

feature, and drawing a grid, estimate the number of galaxies in SDSS per square arc minute (one arc minute is denoted 1 arcmin = $1'$, while one arc second is 1 arcsec = $1'' = \frac{1}{60}$ arcmin). You will want to zoom to get a field of view that contains enough galaxies to give a good estimate, but not so many you can't count them.

(e) [**4 points**]. Assuming isotropy, use your estimate from (d) to calculate the total number $N_{\rm gal,SDSS}$ of galaxies the SDSS survey would find over the entire sky. Note that in the whole sky the angular "area" (technically, "solid angle") is 4π steradians $= 1.5 \times 10^8$ arcmin^2. Explain why your result is an *underestimate* of the number of galaxies in the observable universe. Also, compare your result to the population of the United States, now almost exactly 300 million $= 3 \times 10^8$ people.

(f) [**5 points**]. Much more information is available for the SDSS galaxies with measured spectra. Not all SDSS galaxies have spectra, but using the `SpecObjs` option you can identify those that do. Find at least 5 such galaxies randomly (be sure they are galaxies and not stars!). For each, click on the galaxy in the image, then click the `Explore` button to find data and a spectrum for the galaxy. For each of these galaxies, record the redshift z (the number between `fiberid` and `zErr`, and *not* the last number in the `ugriz` list; the correct value is alo written at the bottom of the image of the spectrum). Use the redshift and the Doppler relation $v = cz$ to compute the speed of each of your galaxies.

If you would find it easier to use a spreadsheet to do these and the remaining calculations, that is fine; please attach (or paste in) a copy of the spreadsheet in your response.

(g) [**5 points**]. Use your results from part (f), and Hubble's Law, to compute the distance to each galaxy; express your answer in Mpc. Take the average of these, and use this as an estimate of the average distance $d_{\rm sdss}$ to an SDSS galaxy. This is sometimes also called the "depth" of the survey. Show that your result obeys $d_{\rm sdss} < d_{\rm H}$, where $d_{\rm H} = c/H_0 = 4200$ Mpc is the Hubble length, i.e., the size of the observable universe.

(h) [**5 points**]. Using your value for $d_{\rm sdss}$, compute the volve $V_{\rm sdss}$ of the sphere around us that is accessible to the survey. Then combine your result with that of part (e) to compute the number of galaxies per volume (in galaxies/Mpc^3) in the local universe today. How should this result compare to the results measured by cosmologists in other distant galaxies today?

(i) [**5 points**]. Finally, use your result from part (h) to compute the number of galaxies within the "Hubble volume" today. That is, find the number of galaxies witin the a spherical volume of radius $d_{\rm H}$.

Congratulations! You have now calculated–on the basis of real modern data–the number of galaxies in the observable universe today. Bravo! Compare your result with the current US population and with the global population of about 6.6 billion people.

(j) [**5 bonus points**]. It turns out that the galaxies you used in this exercise were not randomly chosen from all SDSS galaxies and thus are not a "fair sample" of

the SDSS sky. This is because you used galaxies with accurate redshifts. But to measure a galaxy's redshift requires we measure its *spectrum*, and in the SDSS, spectra are only available for bright galaxies. Because you used galaxies chosen for their brightness, sample you drew from was *biased*.

For bonus points: first, explain why it might be that spectra are only available for bright (high-flux) galaxies, and not for dim galaxies.

Then for the rest of the bonus points: go on to explain how this bias might affect your final result? Have you made an overestimate or an underestimate of the total number of galaxies in the universe?