Astronomy 406, Fall 2013
Problem Set #8

Due in class: Friday, Nov. 1;   Total Points: 60 + 5 bonus

1. *The Digital Universe Online: Galaxy Redshifts, Distances, and Densities.* 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 ASTR406 `links` page. Gathering a bit of data, you can quickly arrive at some interesting cosmological conclusions.

   (a) [5 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?

   (b) [5 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.

   (c) [5 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.

   (d) [5 points] Your first task as a cosmologist is to compute the redshifts of a handful of real galaxies. To do this, you will need galaxy 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. Using rest wavelengths from the SDSS line list (also linked from the course page), compute redshifts for two lines for each galaxy, and show that these agree with each other, and with the value computed by the automated software.

Also for each galaxy, make note of its r magnitude, the middle value in the $ugriz$ entries.

You will use these redshifts and other data to compute more properties of the galaxies; you may find it convenient to use a spreadsheet or simple computer program to do this.

(e) [5 points] Use your results from part (1d), 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.

(f) [10 points] The flux from each galaxy (in different wavelength bands–i.e., colors) are given as the values of $ugriz$, which are expressed as apparent magnitudes. For each of your five SDSS galaxies, the r-band magnitude m_r, you recorded measures the flux centered at 625 nm and thus "red." Using your distance to each galaxy, also calculate the absolute magnitude M_r for each galaxy.

Together with the absolute r-band magnitude of the Sun $M_{\odot,r} = 4.4$ mag, compute each galaxy's r-band luminosity in units of $L_{\odot,r}$. Compare your galaxies' luminosities to the Milky Way luminosity, $L_{{\rm MW},r} \sim 2 \times 10^{10} L_{\odot}$, and comment.

(g) [5 points]. Using your value for $d_{\rm sdss}$, compute the volume $V_{\rm sdss}$ of the sphere around us that is accessible to the survey. Then combine your result with that of part (1c) to compute the number density $n_{\rm gal}$, i.e., the number of galaxies per volume, in the local universe today. Express your answer in galaxies/Mpc^3. Use the galaxy number density to estimate the typical spacing between galaxies in the universe today. Compare your result to the size of the Milky Way, and the distance to M31, $d_{\rm M31} = 0.7$ Mpc.

(h) [5 points]. Compute the average luminosity $\langle L \rangle$ of your galaxies, expressed in units of $L_{\odot}$. Use this and the number density to estimate the galaxy luminosity density $\mathcal{L}$ in units of $L_{\odot}$ Mpc^{-3}. (This is not a hard problem!)

(i) [5 points]. Finally, use $\mathcal{L}$ to find the mass density ρ of the universe, in $M_{\odot}$ Mpc^{-3}. Do this assuming that the average mass-to-light ratio is that of

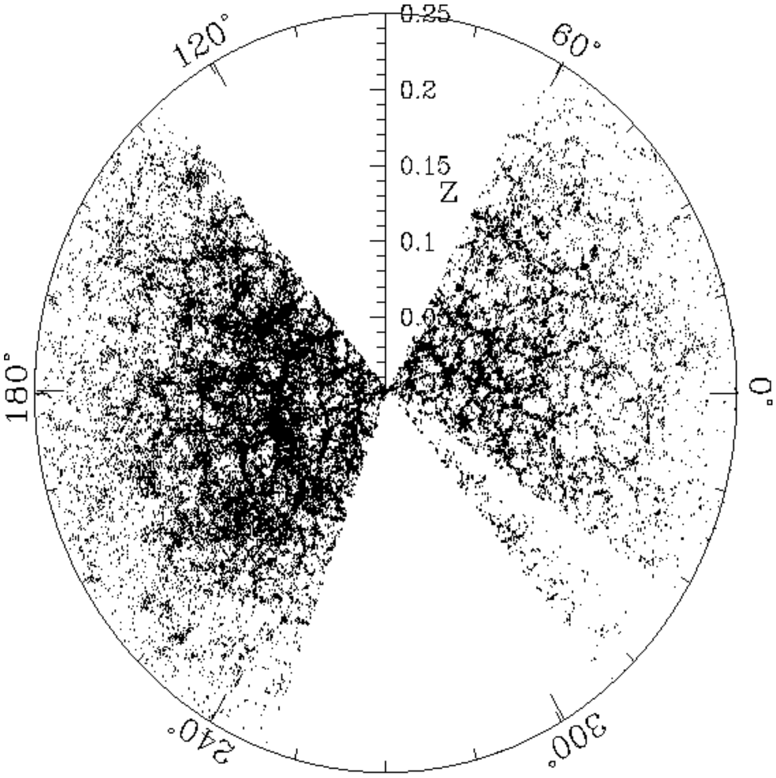
  i. local stars
  ii. galaxy halos
  iii. galaxy clusters

Comment on the impact of the difference in these mass-to-light ratios. Which one do you think is the most appropriate for determining the mass density of the universe?

(j) [5 **bonus** points]. You have made a very rough estimate of the luminosity density of the local universe. In fact, the enormous galaxy harvest in the SDSS survey allows for one to make a very careful and accurate calculation of this quantity.[1]. What are some ways that our simple calculation could be improved and could take advantage of the full SDSS dataset?

[1] Indeed, this has been done: Blanton, M.R. et al. (2003) *The Astrophysical Journal* **592**, 819-838

2. *Redshift Surveys and the Cosmological Principle.* Results from galaxy surveys like SDSS are often presented as "pie slices" in redshift space. Across a long, narrow strip of the sky, each galaxy's angular position is plotted versus its redshift z. The results for slide of the SDSS survey (also from Blanton et al 2003) appear at right; a large image is also available on course links page. Note that the angles outside of the filled-in pie slices (which were along the celestial equator) were not covered by the survey, so the absence of points does not mean a ture lack of galaxies!
We wish to understand this plot and it's connection to your results in Problem 1.



Large−Scale Structure sample10

(a) [5 points] We wish to understand the range of validity of the cosmological principle. In the plot you see that the galaxy distribution has structure–clumps and voids. Imagine "smoothing out" the galaxies on the plot, smearing the distribution out over circles of different size. If the size is very small (say, the typical spacing between galaxies) the resulting smoothed distribution is still lumpy.

i. From the plot, estimate the size (in redshift units) of the largest "blob" (technical term) in the map.

ii. Also estimate the size of the smallest circle needed to smooth the galaxies to the point that the distribution is no longer lumpy. Then use Hubble's law to express this size in Mpc.

iii. Explain why the scale in part (ii) marks the onset of the validity of the cosmological principle.

(b) [5 points] There is a scarcity of points at the highest redshifts on the plot. Is this a violation of the cosmological principle? Explain.