

Physci 120, Winter 2009

Lab 2

Galaxy environments, clusters of galaxies, and dark matter

Introduction

Although the distribution of galaxies on large scales is quite uniform, on smaller scales, comparable to the mean separation between bright galaxies (about one million parsecs), galaxy distribution is far from being homogeneous. Galaxies are arranged in a variety of large *structures* from *groups* of a few galaxies (the nearest example is *the Local Group* formed by our Milky Way, Andromeda Galaxy (M31) and a few dozen faint satellite galaxies, including the Magellan Clouds) and *clusters of galaxies* containing dozens and hundreds of bright galaxies, to galaxy superclusters and filaments which span tens of millions of parsecs in size.

Although these structures can be clearly seen in the diagrams showing three-dimensional distribution of galaxies, in most cases they are not as obvious in the distribution of galaxies in the sky. This is because on the sky we see galaxies at different distances projected onto the same area, which tends to “wash out” the structures. Nevertheless, the basic tendency of galaxies to cluster can be estimated by counting numbers of galaxy pairs separated by a certain angle on the sky and comparing it to the number of pairs expected for a uniform distribution. Such statistic, called *galaxy correlation function*, has historically been a very powerful tool of studying clustering of galaxies and is still actively used in astronomy.

In the first part of the lab, you will perform a simple counts exercise to see the tendency of galaxies to cluster for yourself. You will then explore environments of typical galaxies in random fields (called *field galaxies*) and galaxies in groups and clusters. The key lesson of this exercise will be that galaxies in clusters are systematically different than galaxies in random fields: namely, clusters contain unusual concentrations of bright galaxies and a most galaxies in a cluster have similar colors and are redder than typical galaxies in the field . You will see that this fact can be used to search for clusters on the sky using galaxy colors and you will carry out such search based on what you learn in the first half of the lab.

In the final part of the lab you will estimate total gravitational mass of a cluster using the virial theorem and compare it to the total mass associated with its galaxies. You will see that the two masses are vastly different, thereby recovering one of the oldest and strongest observational evidence for the existence of *dark matter* in the universe, which was originally obtained by US astrophysicists Fritz Zwicky and Sinclair Smith in the mid-1930s using very similar method to what you will use.

Galaxy clustering

As noted above, galaxies tend to *cluster* on the scales of the order of mean separation between galaxies. We can quantify this tendency by comparing the number of galaxies within a certain angular radius of another galaxy and compare it to the number expected if galaxies were distributed uniformly on the sky.

For this exercise we can use the random fields used in the Hubble lab to perform galaxy counts reuse your previous counts or you can choose a random field within the sky area covered by the SDSS survey yourself. Load the SDSS Galaxy Query kml plugin from the directory showed to you by TA and activate the SDSS Galaxy Photometric Layer by checking the box next to it, make sure the SDSS Galaxy Spectroscopic Layer is turned off (by unchecking it). Zoom in on a random field of 5 arcminutes across (the size is indicated in the lower right corner of the Sky window).

Count galaxies within the fields identified by the photometric plugin (galaxies with circles). To estimate the mean separation between galaxies on the sky, we need to estimate their mean density: $\bar{n} = N/A$, where N is the number of galaxies in the area and A is the area, which we will compute in arcminutes squared (arcmin^2). To measure the area of the viewing window, use the ruler icon in the icon bar at the top of the Sky window. Once you click on the ruler icon, a window and a target box will pop up. Bring cursor to one edge of the viewing area and click, then bring the cursor to the opposite edge (you will see the line stretching after the cursor, make sure the line is horizontal or vertical, depending on which side of the viewing rectangle you are measuring) then click when the cursor reaches the edge. The ruler window will report the angular distance between the two points (i.e., the length of the stretched line) in degrees (recall that 1 degree is equal to 60 arcminutes). Compute the area of the viewing window rectangle in arcminutes squared using your measurements and the mean density of galaxies in your area. You can reuse the counts from the previous lab for other fields to estimate the mean number of galaxies better.

Lab tasks.

- *Estimate the mean density of galaxies with SDSS photometry, \bar{n} , (identified by circles by the photometric plugin). Report the number and the details of calculations used to obtain it.*
- *Estimate the mean angular distance between galaxies used in the counts by taking an inverse cube root of the mean density: $\bar{d} = \bar{n}^{-1/3}$. Report this number as well.*
- *Choose one of the galaxies used in estimating of \bar{d} and zoom-in on it to the zoom level (number in right bottom corner) equal to $2\bar{d}$ (be careful to estimate the number in the same units, the scale in the corner is given in arcminutes and arcseconds). Count the number of the circled galaxies within the regions. Then zoom-out to the original view, choose another galaxy and repeat. Perform such counts for a dozen galaxies or so.*
- *How many galaxies do you usually find when you zoom-in to $2\bar{d}$? Is this consistent with what you expect for a uniform distribution?*

Galaxy luminosities and colors in different environments

We will first explore galaxies in the typical random field (called “field galaxies”). Make sure the **SDSS Galaxy Query plugin** used in the previous part is still activated and it identifies galaxies with circles, and activate the **Color-Magnitude plugin**, which plots the r -band apparent magnitude (x -axis) and colors (difference in apparent magnitude in g and r filters, in the y -axis) of galaxies in the field in the graph in the top left corner of the field of view. This plot is called *the color-magnitude diagram* (CMD). You can use one of the random fields used before, or choose your own. Zoom on the field to the scale of about 15 arcminutes or so (number in the lower right corner).

Lab tasks.

- *Describe how galaxies in the random fields are distributed in the CMD.*
- *Load **Groups** location file and examine CMD around galaxy groups (small groupings of galaxies). Describe any difference you notice from the CMD distribution of galaxies in the random fields.*
- *Load **Clusters** location file and describe the distribution of galaxies in the CMDs and the differences from random and group locations.*
- *Zoom-in onto the region around the brightest cluster galaxies (say central 5 arcminutes) and examine the CMD of galaxies in this region. Now zoom-out, center on a region in the outskirts of the cluster (say 20-30 arcminutes away from the BCG), zoom-in to 5 arcminute level again and examine CMD. How does the distribution of galaxies changes when you move to the outskirts of clusters?*
- *Examine clusters at different redshifts (you can get the redshift by clicking on the brightest galaxy near the center of each cluster). How does the distribution of galaxies change in the CMD for clusters at higher redshifts?*
- *Discuss and interpret your results in terms of what you learned about properties of galaxies in nearby clusters and what you know about spectra of red elliptical galaxies.*

Hunting for clusters

In the previous section you should have learned that cluster fields contain unusual concentration of bright galaxies which look more yellow (“redder”) than most field galaxies. Galaxies in clusters form a horizontal “ridge” or “sequence” in the color-magnitude diagram. In this portion of the lab you will use this fact to carry out a “blind” search for galaxy clusters in the sky. This method of searching for clusters, done in an automated and systematic way using a computer analysis of images, was pioneered just ten years ago by the University of Chicago Prof. Michael Gladders (among others) and is the most efficient way of finding new clusters using the optical images and multi-band photometry (measurements of apparent magnitudes of galaxies through different filters).

To perform the search, go to a random field on the sky (you can go to one of the random fields used above or choose a random area on the sky yourself, just make sure you are well within the SDSS coverage). Zoom-in (or zoom-out depending on the initial zoom of your view) to the level at which the marker in the lower right hand corner of the Sky view window shows approximately 15 arcminutes (i.e., $0^{\circ}15'$...).

Once you choose the zoom level, keep it the same throughout the exercise (you can play with it once you find a cluster). Now turn off (uncheck) the **imagery layer** in the bottom list on the panel on the left hand side of the Sky window. This should get rid of the SDSS image of the sky, leaving a gray uniform background with the CMD diagram remaining. Now scan the sky making $\approx 15'$ steps. You can do this, for example, by clicking on the left most edge of the field of view and dragging it all the way to the right (or, similarly, from the bottom to top). The order or direction of your steps is not very important, but it may make sense to do them in one direction once you chose it. Please count the number of steps you take (thereby roughly estimating the area you scan to find a cluster).

If you stumble onto an area which may credibly look like it contains a cluster, you can try to make smaller shifts about the center of the field of view to see if it makes cluster signature in the CMD more pronounced. If you believe you may have found a cluster, turn the **imagery layer** back on and scan the field of view visually. If it looks like there is a cluster in particular area, zoom on it and examine to make sure (hint: look for large, bright elliptical galaxies in the field of view similar to the brightest cluster galaxies you've examined in the Hubble lab; these are candidates for cluster centers which you can examine by zooming in on their locations). If you are not sure there is a cluster after visual inspection, consult with the TA, or simply continue searching for a more obvious case. Once you find the cluster, you are ready for

Lab tasks.

- *Estimate the rough area you surveyed to find a cluster. How many such clusters per square degree of the sky would you then expect? How rare are clusters based on your measurements (how many would there be in the entire sky; the entire sky has the area of approximately 41253 square degrees)?*
- *Turn on the SDSS Galaxy Query layer (uncheck the Photometric Layer, make sure the Spectroscopic layer is turned on. Find galaxies with SDSS spectra, look for the spectra of the brightest galaxies in the cluster area. Find the approximate redshift of the cluster.*
- *Examine galaxies with SDSS spectra in the area. Do all of them have similar redshifts. If not all, why not?*
- *Turn off the CMD layer, zoom-out to view larger than $15'$ across. Examine redshifts of galaxies with SDSS at larger distances from the brightest cluster galaxies. Try to find the most distant galaxy from the BCG which still has redshift similar to that of the BCG. Measure the angular distance between BCG and the most distant galaxy using the ruler icon. Quote the number — this will be your rough estimate of the cluster extent.*

- Identify several (the more, the better but not more than 10) galaxies within extent of the cluster with redshifts close to that of the BCG. Record their redshifts and calculate the mean redshift of the cluster using their individual redshifts.
- Using the angular extent measured above and the estimated redshift of the cluster, compute the actual physical extent of the cluster in Mpc corresponding to the angular extent assuming the Hubble constant value of $H_0 = 70 \text{ km/s/Mpc}$.

Measuring cluster mass using Virial Theorem

If, in the previous section of the lab, you found a nearby cluster ($z \sim 0.05 - 0.15$) with at least five member galaxies that had spectra and similar redshifts to that of the BCG, you can use the cluster you found to measure its mass using the virial theorem in this section. If the cluster you found is at higher redshift and/or does not have enough galaxies with measured spectra, you can use one of the systems in the `Clusters` list used above to examine cluster environments. In the latter case, you have to redo the exercise of estimating cluster extent on the sky and converting it into physical extent in megaparsecs.

Once the cluster is chosen, center the field of view on the BCG and adjust zoom so that the field of view encompasses the entire extent of the cluster. Identify cluster members (i.e., galaxies with SDSS spectra and measured redshifts similar to that of the BCG) among galaxies identified with a circle with the SDSS Galaxy Spectroscopic plugin. Record the redshifts of the member galaxies and calculate the mean redshift of the cluster.

To estimate cluster mass, you will use the so-called *virial theorem*. This theorem relates the kinetic, K , and potential, W , energies of the system and applies to any self-gravitating system in equilibrium (e.g. it also applies to the Sun, Earth, stellar clusters, etc.):

$$W = -2K. \quad (1)$$

The kinetic energy of a cluster is

$$K \approx \frac{1}{2} M_{\text{tot}} \langle v_{\text{gal}}^2 \rangle, \quad (2)$$

where M_{tot} is the *total* gravitating mass of a cluster (which we aim to measure) and $\langle v_{\text{gal}}^2 \rangle$ is characteristic velocity dispersion of cluster material. We will estimate the latter by using dispersion of velocities of the cluster member galaxies about the mean cluster velocity, which can be calculated as

$$\langle v_{\text{gal}}^2 \rangle \equiv 3 \frac{\sum_{i=1}^{N_{\text{gal}}} (cz_i - c\bar{z})^2}{N - 1} = 3c^2 \times \frac{\sum_{i=1}^{N_{\text{gal}}} (z_i)^2 - N_{\text{gal}} \bar{z}^2}{N_{\text{gal}} - 1}. \quad (3)$$

The factor of 3 in front is to account for the fact that redshifts measure only velocity along the line of sight, while virial theorem applies to velocities along all three dimensions of space; \bar{z} is the mean redshift of the cluster you measured using the N_{gal} galaxies with spectroscopic redshifts z_i , which you have recorded in the previous step.

The potential energy of the self-gravitating system of mass M_{tot} is negative by definition and is given by

$$W = -\alpha \frac{GM_{\text{tot}}^2}{R}, \quad (4)$$

where α is a numeric factor of order unity which depends on how mass is distributed within the system, R is the physical extent of the system, and $G = 6.6726 \times 10^{-8} \text{ cm}^3 \text{ s}^{-2} \text{ g}^{-1}$ (in cgs units) is the universal gravitational constant. For the mass distribution expected in clusters $\alpha \approx 0.5$ (good assumption for the accuracy of your measurement which will be to a factor of two or so), and we will use this number to compute the mass.

Combining equations 1, 2, and 4 we get:

$$M_{\text{tot}} = \frac{R \langle v_{\text{gal}}^2 \rangle}{\alpha G}. \quad (5)$$

Lab tasks:

- Using your tabulated redshifts z_i of galaxy members calculate the mean redshift \bar{z} and $\langle v_{\text{gal}}^2 \rangle$ in km/s.
- Use equation 5 to estimate total mass of the cluster within the extent you measured. R is half the cluster diameter that you measured and take $\alpha = 0.5$. Be careful with units and give the result in solar masses M_{\odot} (where $M_{\odot} = 1.989 \times 10^{33} \text{ g}$).
- Count the number of red bright galaxies around the cluster within R (with or without spectra) to get a rough number of cluster galaxies. Each of such bright galaxies has total mass in stars of about $10^{11} M_{\odot}$ (give or take a factor of 2-3). This number is determined from luminosities of these galaxies and average luminosity and mass of old stars which these galaxies consist of. Estimate roughly the total mass in stars within R using the number of galaxies you counted and the average stellar mass of $10^{11} M_{\odot}$. How does this mass compare to the total mass M_{tot} you calculated using the virial theorem? How big is the difference?

The difference between mass in stars and total mass is one of the pieces of observational evidence we have for existence of large amounts of dark gravitating matter in the universe on large scales. Actually, in clusters there are large amounts of hot plasma mostly consisting of hydrogen and helium nuclei and electrons, but the mass of this plasma measured from its X-ray emission still falls far short of explaining the measurements of total cluster masses.