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Project #4: "Stickman"
Physics 228, Winter 2022

Introduction

The process of forming a star is miraculous on its own, using several branches of physics to fully describe. However, to understand the Universe as a whole requires a larger scale view. We can learn even more by studying how these individual stars group together with gas and dust into galaxies, and ultimately into clusters of these "island universes". To explore how we differentiate between the different flavors of galaxies, I will be conducting an analysis on the light we receive from spiral versus elliptical galaxies. The data in question were taken by the *Sloan Digital Sky Survey* (SDSS) and the Center for Astrophysics (CFA) Redshift Survey, extensive databases full of galaxy observations including positions, integrated colors, redshifts, etc. Choosing a representative set of galaxies from a cluster will allow us to generate color-color diagrams with key insights into the composition and nature of each, which can be compared against classifications. Additionally, I will demonstrate how the integrated color of a galaxy directly correlates with the strength of the Hα emission line, and what this entails for star formation. Finally, I will showcase the distribution of clusters in the Universe by constructing a recessional velocity diagram out of a large sample of galaxies from CFA, revealing a system of filaments and voids.

Analysis

Analysis 1 -- Galaxy Colors

Data/Procedure

A total of 20 galaxies were carefully chosen as a representative group from the galaxy cluster Abell 2255 to construct a color-color diagram; ten of which were spirals, the other 10 were ellipticals. Each selected galaxy had its object ID, position, redshift, and integrated light in several filters (u, g, r, i, z) recorded from SDSS. These values were imported into Microsoft Excel to utilize its plotting tools, from which a single diagram pitting u-g and g-r colors against one another was created (Figure 1). The spiral galaxies were plotted in blue data points, and the ellipticals in orange.

Analysis

Immediately we notice that the galaxies follow a highly linear relationship when plotted against these parameters; as u-g color value increases, so does g-r. A larger color index indicates light which tends to be relatively redder, so it makes sense that a larger u-g color would be followed by a larger g-r color as well. More interesting is how the spiral and elliptical galaxies have distributed themselves—they do not occupy the same regions of color-color space. The elliptical galaxies have grouped close together, tending towards larger color values. In fact, no spiral galaxy from this sample has a color index higher than an elliptical's. In contrast, the spirals tend towards lower indices and cover a far wider range of colors in general. Recalling that a galaxy's integrated light depends on its contents, or stars contained within, producing lower color indices requires hotter stars. So, it appears that spiral galaxies contain more younger, hot stars than elliptical galaxies, an indication that spiral galaxies are hotbeds for new star formation. But why do the spiral galaxies occupy such a large space on the diagram? A possible explanation is that each spiral galaxy is unique, and thus have different rates of star formation. A spiral galaxy with lower color indices (bluer light) would correspond to a high star birth rate, while the redder spirals are more dormant, placing them closer to the elliptical galaxy domain on the diagram. In large datasets, because of this established pattern we would be able to make generally accurate predictions about galaxy types based solely on color-color. This technique can act as either supporting information to previous observations, or a good initial prediction to springboard into other analyses.

Analysis 2 – Galaxy Spectra

Data/Procedure

The SDSS SkyServer database also contains spectral information about its galaxies. For each of the ten spiral galaxies in the previous dataset, optical spectra were analyzed to determine the strength of the Hα emission line. This was done by recording the peak y-value given by the emission line and dividing that by the y-value given by the continuum at the bottom (in order to normalize across spectra). This data is shown in Table 1. Then, a graph was created of each galaxy's Hα line plotted against g-r color (Figure 2).

Analysis

The relationship between the strength of Hα line and g-r color is highly linear—that is, as g-r color increases, Hα line strength decreases. Hα emission lines in spiral galaxies are indicative of HII regions within the interstellar medium, meaning that stronger emission corresponds to higher rates of active star formation. Therefore, the galaxies on our graph with lower g-r color (bluer light) are shown to have higher star formation rates due to stronger Hα emission than the redder spirals. We see this behavior because the g-r color is representative of all the stars in the galaxy, so a lower value means that a galaxy generally has hotter, younger stars within it, a prime sign of active star formation. On the other hand, redder spirals will generally have older, cooler stars to match this color, which are not accompanied by HII regions.

Analysis 3 – Large Scale Structure of the Universe

Data/Procedure

A large set of data containing 1156 total galaxies was selected from CFA in a narrow range of declination, but large range of right ascension as a representative slice of the Universe (essentially fixing the declination). Note that the dataset is magnitude limited, containing galaxies brighter than B=15.5. After each galaxy's RA was converted from hours, minutes, seconds format to a single number, the galaxies were plotted on a graph of recessional velocity versus right ascension (recessional velocity, or redshift, acts as a stand-in for distance). A single outlier galaxy was removed from the data, along with some scaling tweaks to help improve the form of the diagram. Figure 3 shows the results of the plot, a system of filaments and voids.

Analysis

This graph demonstrates that galaxies are not uniformly distributed through space, rather, they clump together into filaments known as superclusters, creating a figure colloquially known as the Stickman. The spherical space seen in between these filaments are void of any observable matter. Why do we see this type of behavior? It is theorized that the Universe, early on in its life, contained small density variations which were exaggerated by expansion over time, causing material to gather in the filament structures we see here. Also, note how the filaments tend to be elongated radially outward in every direction while the voids are circular, making it appear that our position is at the center of the Universe (which we know to be false). A possible explanation for this is the "Fingers of God" effect where random peculiar motions of galaxies, or the deviations from the Hubble flow, cause a doppler shift from the observer's perspective. By using Hubble's law relating redshifts and distances, I was able to calculate a rough size for one of the voids. I first measured the radial difference in redshifts across the indicated void. Then I estimated the center of the void, obtained its radial distance, and used trigonometry to find the diameter of the void along the x-axis of the diagram. With the distances of both axes of the void, I calculated its area based on an ellipse, which gave me a size of 5524.36 Mpc^2. From these measurements for the void size, I was able to find the size of the filaments outlining the void. I did this by approximating the perimeter of the void and dividing it by two, giving me a size of 135.326 Mpc. These filaments, along with the void, have been indicated on the diagram. My work for these calculations can be found attached.

Conclusion

My analyses here demonstrate how astronomers can predict the contents of galaxies based on photometric and spectroscopic observations. I found that galaxy classifications are not only based on the shape of a galaxy, but also on color indices. I discussed the implications of the differences in regions of space occupied by spiral and elliptical galaxies on a color-color diagram, concluding that the contents of the two types are largely explained by whether or not there is active star formation. I also discovered that the galaxy classification for spirals allowed wiggle room based on rates of formation, evident by a large spread in color index. Then, I demonstrated that color index also gives clues into the spectra we should expect from a specific spiral, a result of HII star forming regions being the main source of strength for the Hα emission line. Finally, I took at step back to get a bigger picture of our Universe's structure by constructing a diagram which demonstrated that the density of galaxies is not uniform, but clumped into filamentary structures, a remnant of the distribution of matter at the Universe's origins.

To conclude, it is important to note that galaxies cannot be fully described by only their integrated light or star formation rates. We can learn a lot more about the nature of a particular galaxy through its shape, mass-to-light ratio, rotational rates, etc., and the physical causes of these features (such as spiral density waves/perturbations causing spiral arms to remain intact). It would also be foolish to try to create hard and fast boundaries that separate galaxy types; consider Lenticular galaxies, which have the shape of spirals but star populations that resemble ellipticals. Thus, true, in-depth analyses require observations of several other things than what I have presented here.

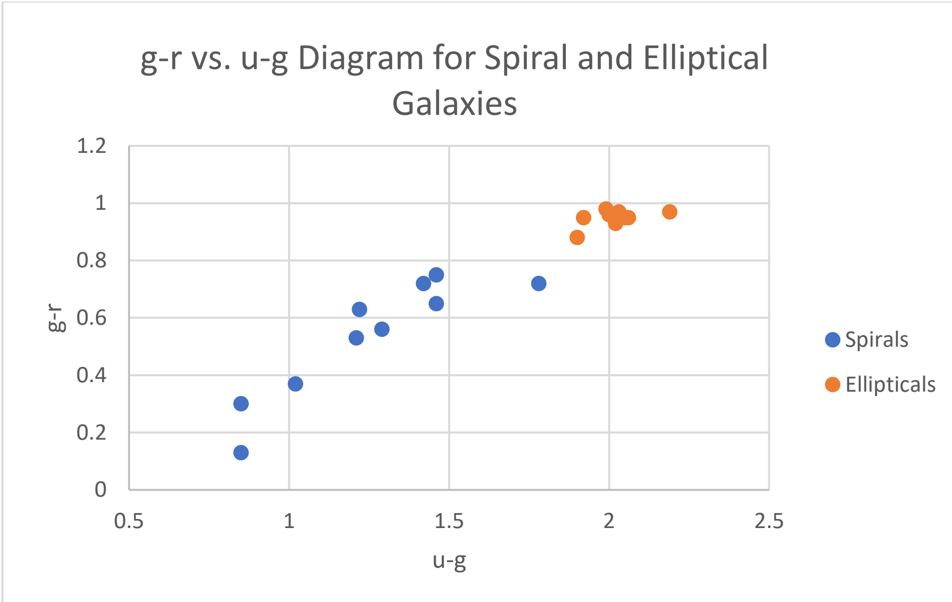


Figure 1: Color-color diagram demonstrating the linear relationship between u-g and g-r color indices. The 10 spiral galaxies are plotted as blue, and the 10 ellipticals as orange.

SDSS objid	g-r	Halpha line
1237671768542478711	0.75	2
1237671768542544154	0.72	3.3333333
1237671768542544196	0.63	4.6875
1237671768542544199	0.56	4.8235294
1237671768542544330	0.37	7.7142857
1237671768542609591	0.53	5.1333333
1237671939804561948	0.3	8.9333333
1237671939804561964	0.13	11
1237671939804561999	0.65	2.3684211
1237671939804627453	0.72	3.1578947

Table 1: Calculated Hα line strengths for each of 10 spiral galaxies.

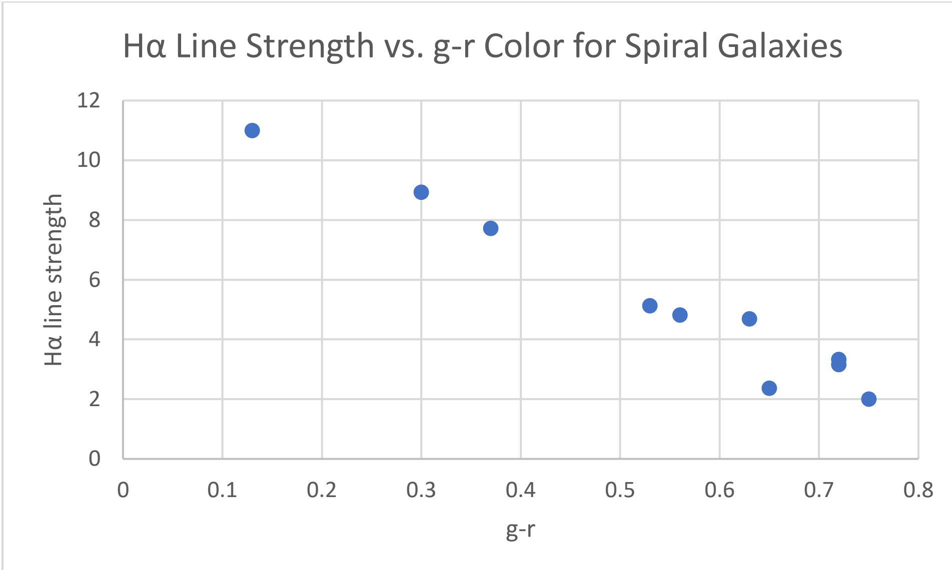


Figure 2: Color vs. emission line strength diagram, demonstrates the inverse relationship between g-r color and Hα line strength.

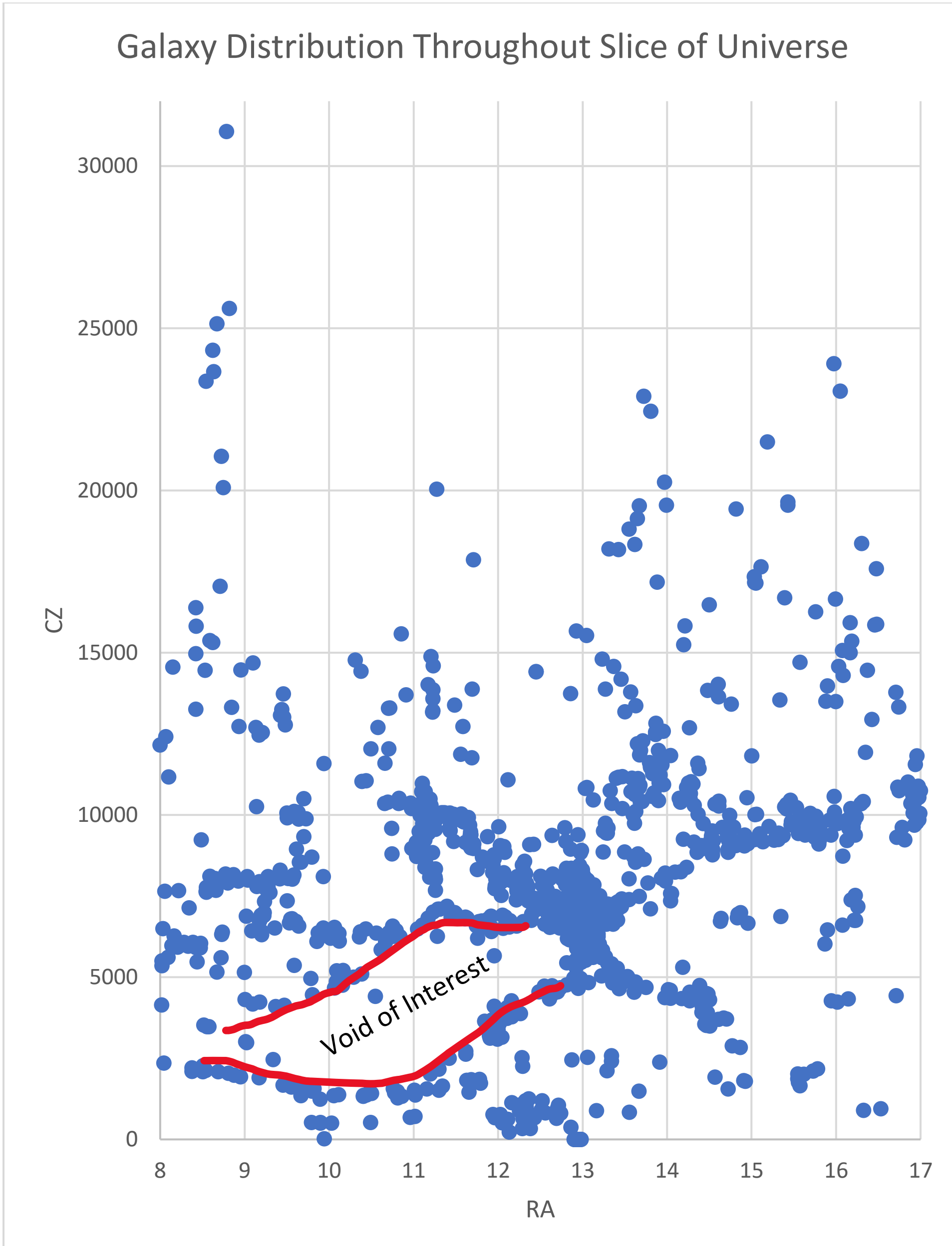


Figure 3: Diagram of spatial positions of galaxies throughout Universe. The red lines indicate the filaments whose approximate lengths were calculated.

$$d = \frac{c}{H_0}\left(\frac{(z+1)^2-1}{(z+1)^2+1}\right) \quad \text{when } z > 0.8$$

$c = 3\times10^8 \frac{m}{s}$ $\quad H_0 = 70 \text{ Km s}^{-1}\text{Mpc}^{-1}$

$$\frac{v}{c} = \frac{(z+1)^2-1}{(z+1)^2+1}$$

Calculation Of Void Area

For radial diameter of void,

top → 6487 (in cz)

Bottom → 1511

$6487 - 1511 = 4976$

$4976\times10^3 \frac{m}{s} = (3\times10^8 m)\, z \qquad z = 0.0165$

when $z \ll 1$ $\qquad d = \frac{cz}{H_0} = \frac{4976 \text{ Km/s}}{70 \text{Km s}^{-1}\text{Mpc}^{-1}}$

$$d_r = 71.0857 \text{ Mpc}$$

For diameter along RA,

$6487 - 1511 = 4976$ $\qquad 1511 + 2488 = 3999$

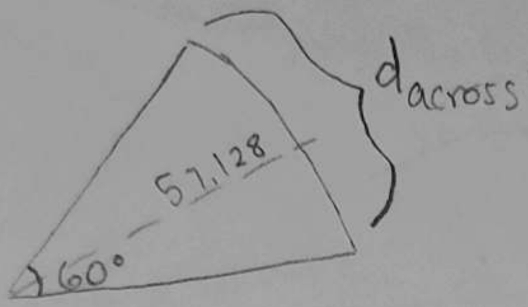
$4976/2 = 2488$

center point of void (radially)

$d = \frac{cz}{H_0} = \frac{3999 \text{ Km/s}}{H_0} = 57.1286 \text{ Mpc}$

distance to center

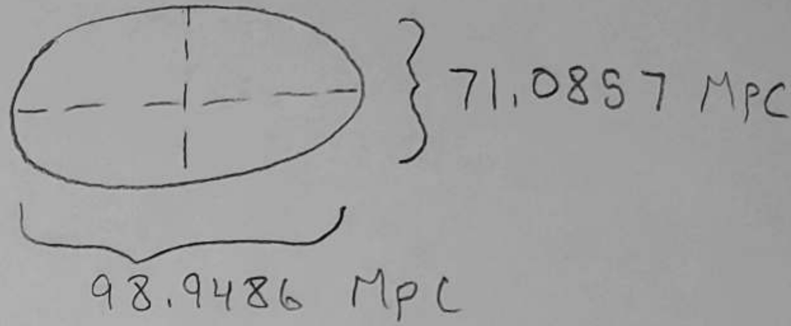
RA difference across void: $13 - 9 = 4$ hours $= 60°$



$$\tan\theta = \frac{d_{across}}{57.128}$$

$$d_{across} = 98.9486 \text{ Mpc}$$

Thus we have



$$\text{Area} = \pi ab = \pi(98.9486/2)(71.0857/2)$$

$$\boxed{\text{Area of void} \approx 5524.36 \text{ Mpc}^2}$$

Approximate filament sizes

$$P \approx 2\pi\sqrt{\frac{a^2+b^2}{2}} = 270.651 \text{ Mpc}$$

$$\frac{270.651}{2} = \boxed{135.326 \text{ Mpc}}$$