Project 1: Estimating the Dynamical Mass of a Galaxy Cluster – Summary Report

- **Introduction -** In this study, we analyze a galaxy cluster using spectroscopic data from the Sloan Digital Sky Survey (SDSS). Our goal is to estimate the dynamical mass of the cluster by identifying member galaxies, calculating their redshift statistics, and applying the virial theorem to derive the mass from their motion. This helps us understand how much of the cluster's mass comes from visible matter, and how much is likely due to dark matter.

- **Observations –**

  - **Dataset -** We used a dataset from SDSS DR16 that includes galaxy properties like: spectroscopic redshift (specz), Right Ascension (RA), Declination (Dec), Projected separation (proj_sep) and R-band magnitude (rmag).

    Following are the Index of ('Skyserver_SQL6_26_2025 3_38_22 PM.csv') file
    Index(['objid', 'ra', 'dec', 'photoz', 'photozerr', 'specz', 'speczerr', 'proj_sep', 'umag', 'umagerr', 'gmag', 'gmagerr', 'rmag', 'rmagerr', 'obj_type', 'velocity'])
  - **Redshift Statistics –** Mean redshift (z) = 0.08105
    Standard Deviation of redshift = 0.00950
    3-sigma limits of redshift = 0.05255 to 0.10954
    137 out of 139 galaxies were selected as cluster members.
    Clustered redshift = 0.08003
  - **Velocity Dispersion –** 1202.5763 km/s
  - **Projected Separation (arcmin) –** count = 139.0
    mean = 6.079801
    std = 2.517581
    min = 0.429175
    25% = 4.045745
    50% = 6.405518
    75% = 8.347733
    max = 9.844519
  - **Size and Mass of galaxy cluster -** Cluster Diameter: 0.919 Mpc

    Dynamical Mass of the cluster is 4.48e+14 solar mass

    Total luminous mass: 7.42e+12 solar mass

    Stellar mass fraction = 0.0166 ~ 1.6565 %

Interpretations – In this project, we aimed to estimate the dynamical mass of a galaxy cluster using spectroscopic data obtained from the SDSS DR16 server. First, we extracted all relevant data from the downloaded CSV file which contained properties of 139 individual galaxies in the observed field. To perform the analysis, we used Python in a Jupyter Notebook environment and imported all the necessary libraries, such as numpy, pandas, astropy, and matplotlib. These tools helped us efficiently process the dataset and visualize the results.

One of the first steps was to identify the galaxies that are actually part of the cluster. For this, we analyzed the spectroscopic redshift (specz) values. Since galaxy clusters often show a peak in redshift distribution, we applied a $\pm 3\sigma$ (sigma) rule, a method used by astronomers to filter out outliers. We calculated the mean redshift and standard deviation, then used the formula:

Limits of redshift = mean of redshift ± 3 * (Standard deviation of the redshift)

Where,

Mean redshift (z) = 0.08105

Standard Deviation of redshift = 0.00950

3-sigma limits of redshift = 0.05255 to 0.10954

To define the range within which galaxies are considered cluster members. Using Python's comparison operators, we filtered the dataset accordingly. Out of the original 139 galaxies, 137 galaxies remained within this 3σ region, and were treated as true cluster members.

Next, we calculated the cluster redshift, which is the mean redshift of the filtered members, and found it to be:

Clustered redshift = 0.08003

To calculate the velocity dispersion, first we have to calculate velocity for all datasets by using v = c * z. And by the help of pandas library, velocity column added to existing dataset.

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

After determining the cluster membership, we moved on to calculating the velocity dispersion using the relativistic formula that compares the redshift of each galaxy to the mean cluster redshift. The standard deviation, resulting velocity dispersion was:

Velocity dispersion = 1202.5763 km/s

To estimate the physical size of the cluster, we used the maximum projected separation of member galaxies, converted the angular size from arcminutes to radians, and applied an approximation of the co-moving distance to find the diameter. We found the characteristic diameter of the cluster to be:

Cluster Diameter: 0.919 Mpc

Then, using the virial theorem, we calculated the dynamical mass of the cluster:

$$M_{dyn} = \frac{3\sigma^2 R}{G}$$

Where,

σ = velocity dispersion in m/s

R = Cluster radius in meters

G = Gravitational constant in SI unit.

After converting the final result to solar masses by dividing by 2 x 10^{30} kg., we found:

$$M_{dynamical} = 4.48 \times 10^{14}\ M_{\odot}$$

We also compared this with the luminous (stellar) mass, which was estimated to be:

$$M_{luminous} = 7.42 \times 10^{12}\ M_{\odot}$$

This gives a stellar mass fraction of:

$$f_* = \frac{M_{luminous}}{M_{dynamical}} = 0.0166 \sim 1.65\ \%$$

This means that only a tiny fraction of the cluster's mass comes from visible matter like stars and gas, while the rest is most likely dark matter, which doesn't emit light but has a significant gravitational influence.

References –

- Astropy: https://docs.astropy.org
- Geeks For Geeks: https://www.geeksforgeeks.org/python/python-programming-language-tutorial/
- Pandas: https://pandas.pydata.org/docs/reference/api/pandas.read_csv.html