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A Study of the Centaurus Cluster of Galaxies

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ABSTRACT

Galaxy clusters are one of the largest gravitationally bound structures in the universe known to scientists. By modelling how gravitational structures interact with each other, we can also understand its structure and dynamics. This paper is an in depth study of the morphology, colour, velocity distribution and redshift of the galaxies in the Centaurus cluster. The Virial Theorem is applied to estimate the mass of the Centaurus Cluster.

Background

By determining the distances to Cepheids in the Andromeda Galaxy, Hubble proved that there are other galaxies beyond the Milky Way. Following the discovery of extragalactic objects, Holmberg (1962) estimated that 53% of the galaxies are in a cluster. Since then, data about galaxies have been made available in the Catalogue of Rich Clusters (Abel, 1958) and the Catalogue of Galaxies and Clusters of Galaxies (Zwicky et al., 1968).

Bahcall investigated the various aspects of galaxy clusters, such as their morphology or mass. Researchers were able to simulate the environment of massive galaxy clusters and their surroundings to study the evolution and origin of galaxies with central supermassive black holes (Lieke et al, 2019). The abundance of galaxy clusters as a function of mass and redshift are also used to explore the universe on a large scale, construct a universal scaling relation and study the distribution of luminous matter in clusters of galaxies(Singh et al, 2020).

Clusters of galaxies are hence the best samplers of matter on the largest scales and are sensitive probes of structure formation (Zward et al, 2008). Therefore, examining the structures and physics of clusters, their mass function and their evolution is vital to astronomers.

Centaurus Cluster

The Centaurus Cluster (A3526) is a cluster of at least 204 galaxies, located approximately 52 megaparsecs, or 170 million light years away in the Centaurus constellation. The centre of the galaxy is located at a right ascension of 192.20° and a declination of 41.10°.

Figure 1. The Centaurus Cluster. Credit: Wikipedia/Pablo Carlos Budassi

The density of galaxies in the Centaurus Cluster can be modelled as a function of the distance from the densest region. The densest region can be shown in Figure 2, where the density of the galaxies increases to a huge value in the centre. Other than the dense core, the density of the cluster remains roughly constant.

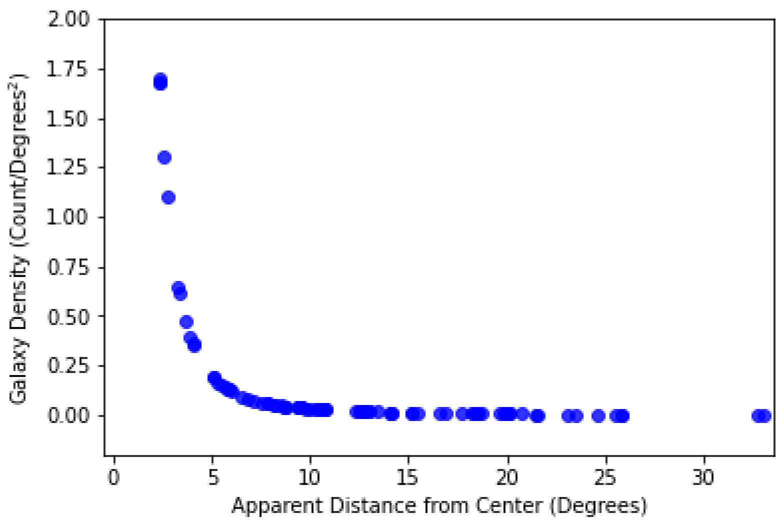

Figure 2. Galaxy Density Vs Apparent Distance

Analogous to the classification of galaxies or stars, clusters of galaxies can be organised into categories. According to Zwicky's classification, the Centaurus cluster is an irregular cluster because it shows little circular symmetry, and no strong central concentration (Bahcall, 1977). The Centaurus Cluster displays no circular symmetry, and has an irregular distribution of galaxies. Instead of having a bright centre, there are two brighter concentrations (see Figure 1).

Methods

All the data from the galaxies in the table below are from the NASA/IPAC Extragalactic Database, a list of extragalactic objects which have been cross-identified, and where the data are accurate to the greatest extent possible.

Table 1. Data from NASA/IPAC Extragalactic Database

Parameter	Total	Min	Max	Range	Mean	Median	Standard Deviation
RA (degrees)	204	166.5	224.7	58.2	194.9	192.6	8.7
DEC (degrees)	204	-50.7	-30.3	20.1	-40.1	-41.3	4.2
Redshift (z)	178	0.001	0.132	0.131	0.018	0.011	0.023
Velocity (km/s)	155	1219.0	5302.1	4083.2	3376.8	3250.9	865.6
Apparent Magnitude (mag)	155	8.18	18.6	10.4	12.8	12.3	2.30
Absolute Magnitude (mag)	155	-24.8	-14.9	9.9	-20.5	-21.2	2.1

From the NASA/IPAC Extragalactic Database, we gather 7 different parameters for these galaxies: Right Ascension, Declination, Redshift, Velocity (km/s), Morphology, Apparent magnitude and Absolute Magnitude. I then used the apparent and absolute magnitude to evaluate the distance of the galaxy using the distance modulus formula.

Results

Morphology of Constituent Galaxies

Table 2. The morphology of known member galaxies of the Centaurus Cluster classified according to the de Vaucouleurs class from NED.

Morphological Types	Total	Sub-types	Sub-Total
Elliptical	16	cE	8
		E	8
Spiral	90	S0	14
		SA	48
		SB	28
Irregular	1	I0	1
Unclassified	97	~	97
Total	204		204

The Centaurus Cluster has a high abundance of spiral and elliptical galaxies among the bright cluster members (see Table 2). Most galaxies are centred in the declination -35.0 to -37.5 degrees, and in the right ascension of 185 to 190 degrees, and they tend to be Spiral or Elliptical galaxies. Due to its distance from earth, the morphology of some galaxies of low surface brightness may be hard to analyse or ever detect.

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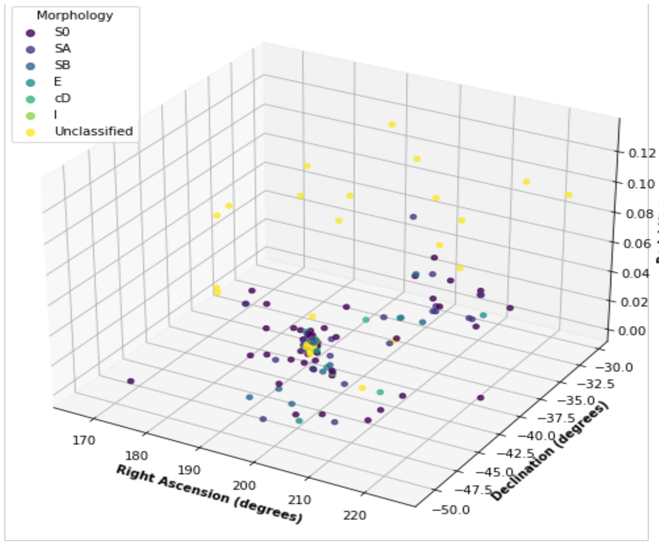

Figure 3. A 3D Plot of the Centaurus Cluster. A 3D Plot of the Centaurus Cluster using matplotlib, with different colours of the galaxies indicating different morphological types. Bright spiral and elliptical galaxies tend to cluster in the core. Distant galaxies are faint and unable to be classified.

According to NED, only one out of 204 galaxies is identified as irregular. Irregular galaxies tend to be fainter, so they may not be detected easily, which explains for the lack of galaxies of this type. There may be more faint irregular galaxies in the outskirts of the Centaurus Cluster awaiting discovery.

Colour

The following diagram shows the distribution of the colour B-V in the Centaurus Cluster:

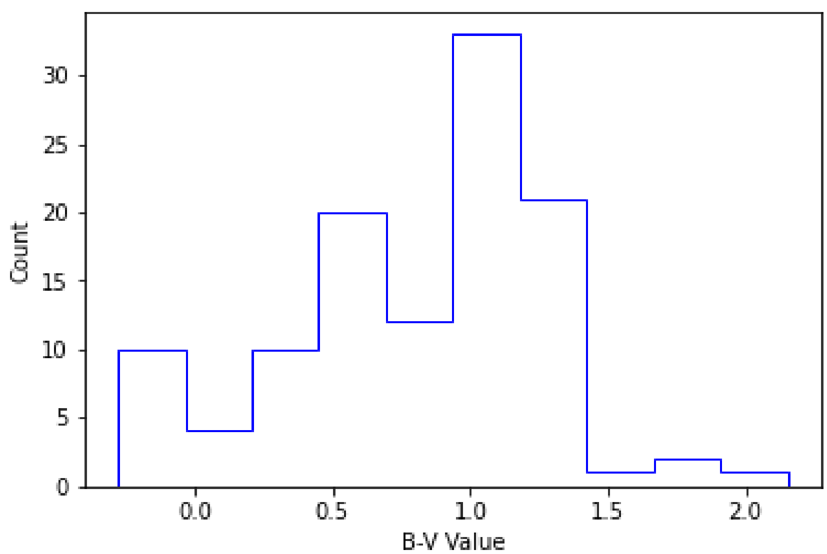

Figure 4. B-V Value of Galaxies in the Centaurus Cluster

As a reference, the B-V value for stars are listed in the table below:

Table 3. B-V Value for stars

Class	O5V	B0V	A0V	F0V	G0V	K0V	M0V

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B-V Value	-0.33	-0.30	-0.02	0.30	0.58	0.81	1.40

Not all data is available because the Centaurus Cluster is very far. Hence, I only used the data where both B and V values are present. A blue tilt is observed in the Centaurus Cluster. This may be interpreted as a mass-metallicity relationship caused by the galaxy cluster's self-enrichment: more massive galaxy clusters retain more enriched gas emitted by evolving stars, which causes the formation of more stars that are metal-rich (Bastian et al, 2018).

Velocity Distribution

As other investigators have suggested, there may be a bimodal velocity distribution in the Centaurus cluster. The Centaurus Cluster is hypothesised to be composed of two components: Cen 30 with a mean velocity of 3000 km/s and Cen 45 with a mean velocity of 4500 km/s. (Currie, 1986). The graph is especially dense in the regions with velocities of 3000 and 4500 km/s.

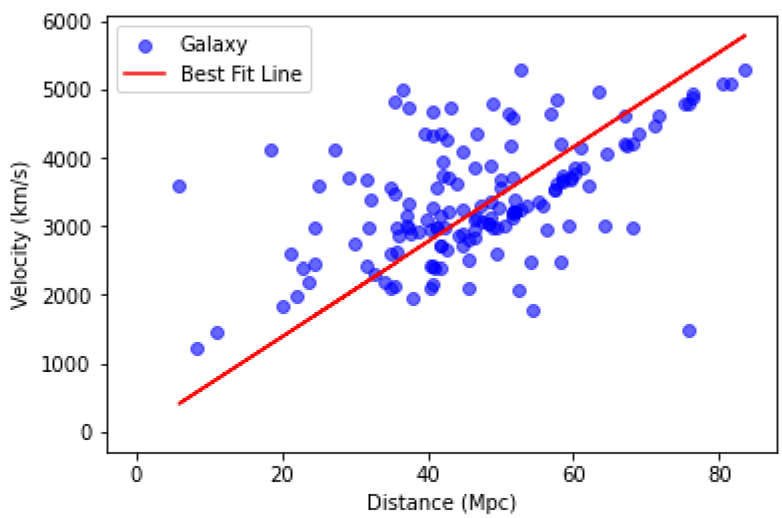

Figure 5. Velocity vs Distance of the Galaxies in the Centaurus Cluster

Cen 30 is more dominated by elliptical galaxies, while Cen 45 contains more spiral galaxies and fewer dwarfs (Hilker et al, 2003).

$$H_0 = \frac{v}{d} = slope \ \ldots (1)$$

We may construct a line of best fit to determine the Hubble's constant in the Centaurus Cluster. The value we evaluated is 69.3 km/s/Mpc; however, our data may be skewed due to the bimodal distribution of galaxies. Additionally, we can only obtain the data of luminous galaxies, so if we factor in the darker galaxies, our results should be consistent with the accepted value of the Hubble's constant.

Luminosity

The luminosity function of galaxies in a cluster allows us to study the properties of the cluster. The luminosity function's axes are defined by the magnitude of the certain galaxy against the logarithm of the number of galaxies brighter than or equal to the corresponding magnitude (Bahcall, 1977).

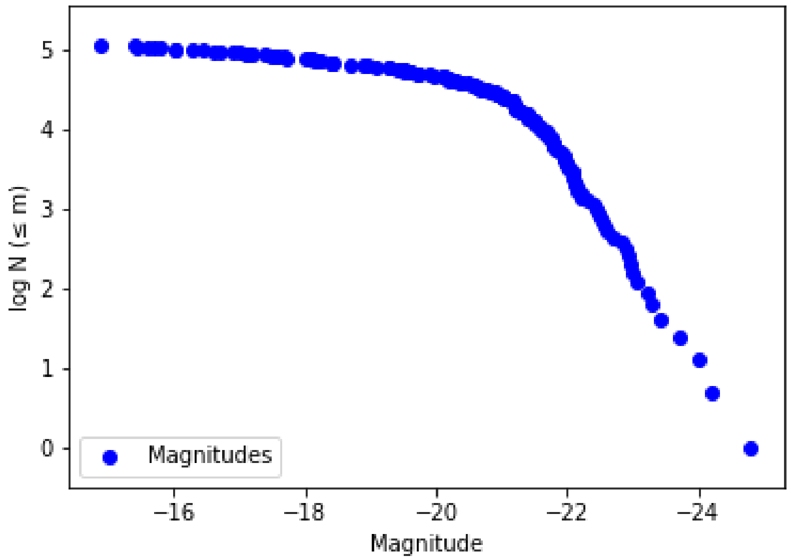

Figure 6. Logarithm integrated luminosity function for the Centaurus Cluster

We can see that the plot follows the general shape of a luminosity function for a galaxy cluster. The plot seems to follow a smooth shape for the dimmer magnitudes. From -22 to -24 magnitudes, the curve tends to deviate a bit. The right end represents the brightest galaxies that are scarce, which causes the variation.

Redshift

Redshift, denoted by z, is defined as an increase in the wavelength of electromagnetic radiation. In vast scales, redshift is caused by the expansion of the universe. Thus, studying redshift allows us to model and predict the expansion of the fabric of space time. Redshift is defined as delta lambda / lambda, where delta lambda refers to the change in wavelength while lambda_0 refers to the original.

In order to study the redshift of the Centaurus Cluster, we plot the distance of the galaxies against their redshift.

We may evaluate the distance of the galaxies from Earth with the distance modulus.

$$m - M = 5\, log\, log\, \left(\frac{d}{10\, pc}\right) \ldots (6)$$

By rearranging the terms, we get:

$$d = (10\, pc)\left(10^{\frac{m-M}{5}}\right) \ldots (7)$$

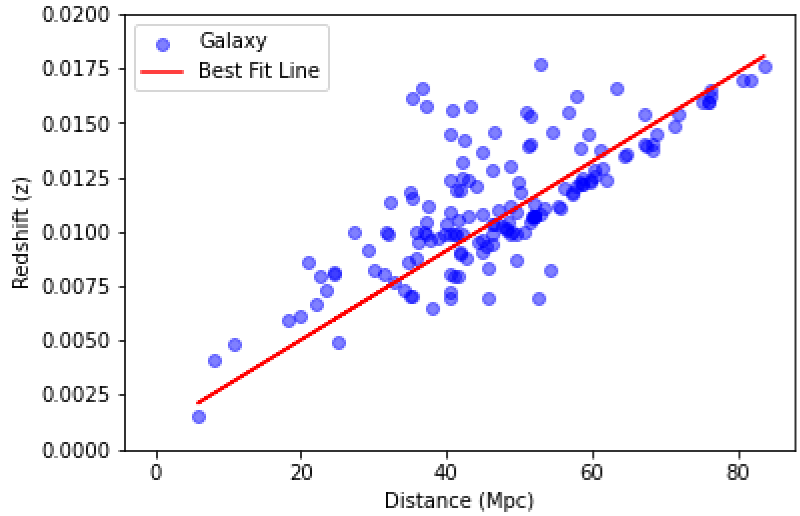

Figure 7. Distance versus Redshift

We observe a positive correlation between the distance and the redshift. The further away the galaxy is from us, the higher the redshift and the faster it is receding from Earth. The galaxies moving away from Earth demonstrates the fabric of space is expanding.

Mass

The Virial Theorem allows astronomers to determine the mass of clusters of stars or bodies. An important assumption about the Virial Theorem is that the galaxy cluster is a uniform sphere and is relaxed. Except for the dense core, the density of the galaxy core remains constant, so the Virial Theorem may be applied (See Fig. 2). The result we evaluate in the following section will only be a rough estimate of the actual accepted value.

Another assumption of the Virial Theorem is that the cluster is in virial equilibrium. That is, the system must be roughly in a stable state. For example, individual bodies may be moving inwards and outwards, but a roughly equal number must be moving inwards and outwards. The virial equation relates the kinetic energy (K) and potential energy (U) of a system in equilibrium as: 2K + U = 0.

The cluster has a kinetic energy of the following, where m_i and v_i denote the mass and velocity of every substituent galaxy:

$$K = \sum_{i=1}^{N} \frac{1}{2} m_i {v_i}^2 \ldots (2)$$

We may denote the net mass as M; we substitute each individual velocity with the full space velocity, which is equal to 3 times the line of sight velocity dispersion v, because the velocity is in three dimensions.

$$K = \frac{1}{2} M\vec{v} \ldots (3)$$

If we assume that the galaxy cluster is a sphere of uniform density, we evaluate U to equal:

$$U = -\frac{3}{5}\frac{GM}{R^2} \ldots (4)$$

We may continue the derivation by substituting the values of U and K into the Virial Equation:

$$2K + U = 02\left(\frac{3}{2}M\sigma^2\right) = -(-\frac{3}{5}\frac{GM}{R^2})$$

$$M = 5\frac{R\sigma^2}{G} \dots (5)$$

We may use the result of Equation 5 to estimate the mass of the Centaurus Cluster. There is no evidence of rotation of the Centaurus Cluster, so the cluster will roughly be in equilibrium. The value of R may be obtained by multiplying the angular measure of the Centaurus Cluster by the distance. According to Figure 3, the angular diameter roughly equals 20 degrees, while the average distance of the Centaurus Cluster is around 52 megaparsecs (Fig. 5), and obtain the value of r to be roughly equal 18.15 megaparsecs. We then obtain σ by calculating the average velocity of the galaxies, which is around 3500 km/s (Fig. 5). We obtained the result to be 5.14×10^{47} kilograms, or 2.57×10^{17} $M_\odot$.

However, this estimate would only apply to luminous matter. The actual mass of the cluster would be vastly greater, as we failed to take into account dark matter which is believed to account for around 80% of matter, so the total mass of the cluster could be up to 1.29×10^{18} $M_\odot$. Nevertheless, this estimate is still less than the actual value, because we neglect the mass stored by other energy such as the energy caused by the centrifugal force or dark energy.

Discussion

I answered my research question well as I was able to identify various aspects of the Centaurus Cluster and look into them in detail. I also estimated the mass of the Centaurus Cluster to be roughly equal to 2.57 x 10^17 solar masses, which is a reasonable guess considering that the mass of the Milky Way is 1.5 x 10^12 solar masses.

I also presented the data in various graphs and plots so that trends can be spotted easily. I then analysed the trends, and found them to be consistent with current data. For example, I discovered that the slope of the best fit line in Figure 5 is 69.3 km/s/Mpc, which corresponds to the accepted value of the Hubble's Constant. In Figure 5, I also found out that most of the velocities of the galaxies tend to be around 3000 or 4500 km/s, which matches current theories about Centaurus to be composed of Cen30 and Cen45 (Currie, 1986).

Conclusion

Throughout this paper, we achieved a deeper understanding of the structure of the Centaurus Cluster and the distribution of its constituent galaxies. We also evaluated the velocity distribution and a value of the Hubble's Constant for this particular galaxy. By using the Virial Theorem, we could estimate the mass of the cluster. The relationship between redshift and distance demonstrates that space is expanding.

Limitations

Multiple sources of error may exist in the paper. As seen in NED, sometimes only the Right Ascension and Declination parameters exist. This is because the light that reaches Earth from these galaxies is very weak. A few reasons may cause this. Firstly, there may be galactic extinction, so that the light of the galaxies could not be detected from Earth. Furthermore, since the Centaurus Cluster is inherently far away from the Earth, the light of some faint or dim galaxies may not approach the Earth.

Studies done on the Virgo cluster show that the Hubble's constant range from 71.8 km/s/Mpc to 77.0 km/s/Mpc (Kenworthy et al, 2022). An explanation for this discrepancy is that Kenworthy's team measured Hubble's Constant by 35 extragalactic Cepheid hosts, but this study plotted the velocity of certain galaxies against their distance away from Earth. The distances between the Earth and the galaxies may be overestimated due to calibration errors, which accounts for why my result for the Hubble's Constant, 69.3 km/s/Mpc, is slightly less than the newest measurements.

I compared my empirically determined luminosity function with that of Bahcall's (1977). I observed that my function had a less steeper curve for the galaxies with dimmer absolute magnitudes, and a steeper curve for galaxies with brighter absolute magnitudes. Bahcall used the comprehensive data points for four rich clusters, while I was only able to use the data points for the Centaurus cluster. This is why in my plot, the curve deviates on the right end (i.e., the brighter galaxies) because they are scarcer compared to that of the quantity of bright galaxies in four rich clusters.

Lucey et al. pointed out that applying the Virial Theorem generates considerable uncertainty because some galaxies may be mistakenly identified as a member of the Centaurus cluster (1980). These non-members may be not easily recognized, unless they have redshifts significantly different from the cluster mean redshift (Lucey et al, 1980). To filter the data for contaminants, I made sure to remove outlier data points which are greater than or less than two standard deviations of redshift before processing the data. Lucey et al. also mentioned how it would be rare for the Centaurus cluster's velocity distribution to be bimodal, but modern scientists found that Centaurus is made of two subclusters, Cen30 and Cen45. Hence, these confounding factors do not influence the accuracy of my estimate, although it would not be precise.

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