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Variations of Hubble's Parameter Across Galaxy Clusters

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AUTHOR BIOGRAPHY

Hasini Mandapati and Shreya Manoj Kumar are both Texas high schoolers with a passion for physics and astronomy. They became intrigued by Hubble tension - the discrepancy in measured values of Hubble's constant, also known as the Hubble parameter. Under the guidance of Professor Shyamal Mitra, they investigated possible causes of this tension and developed their own estimate to compare with existing values.

ABSTRACT

Over the years, there has been a dispute over the exact value of Hubble's constant and the factors that cause variance. Through our research, we intend to answer the question, "To what extent does cluster density impact the calculated Hubble parameter and lead to variations in the value?" We hypothesized that higher galaxy cluster densities (i.e., the estimated number of galaxies within a cluster) would correspond to smaller values of Hubble's constant due to local gravitational interactions between galaxies. We selected approximately twenty galaxies each from sixteen galaxy clusters of varying distances. Using the NASA/IPAC Extragalactic Database (NED), SIMBAD, and the *A catalog of rich clusters of galaxies*, we compiled data on recessional velocities, distances, and densities. We then used Hubble's law to derive each galaxy's Hubble constant, which allowed us to calculate its range for each cluster and average the Hubble parameters to get the overall constant for each cluster. We used linear regression models to visualize the relationship between each galaxy's distance from Earth and its recessional velocity, with the slope of the line of best fit providing us with an estimate for Hubble's constant. We concluded that the correlations between densities and H range, densities and H average, distance and H range, and Hubble parameter and cluster density are all weak to moderately correlated, with p-values of 0.4841, 0.3916, 0.0778, and 0.03, respectively.

Keywords: *Hubble Constant, Universal Expansion, Galaxies, Astronomy, Cluster Density, Computational Astrophysics, Recessional Velocity, Linear Regression, NED Database, SIMBAD*

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INTRODUCTION

This study aims to explore the correlation between the density of galaxy clusters and Hubble's constant. In addition to this, we will also estimate a value for Hubble's constant based on our data set and determine the range of Hubble's constant for galaxy clusters.

In 1929, Edwin Hubble observed a relationship between the distance to a galaxy and the speed at which it recedes from Earth (Bahcall, 2015). This relationship, known as Hubble's law, can be modeled by the equation $v = H_0 \times d$, where v represents the recessional velocity, H_0 is the Hubble constant (or the rate of expansion of the universe), and d is the distance of the galaxy from Earth (Bahcall, 2015). While this formula provided groundbreaking insight into the universe, it was later revealed that H_0 does not stay constant. Rather, Hubble's "constant" is variable, and subsequent observations have shown that the rate of the universe's expansion is accelerating (Riess et al., 1998). Early values of Hubble's constant yielded a value of approximately 500 km/s/Mpc, a result heavily influenced by the limitations of the experimental methods of the time (Bahcall, 2015). For example, because the calibration for the luminosities was incorrect, Hubble's reference point was faulty (Bahcall, 2015). Beyond that point, other methods, such as using Type 1a supernovae, would have resulted in more accurate results, but Hubble was unaware of such distance indicators (Bahcall, 2015). Since then, scientists have come a long way in refining and developing the methods used to calculate H_0.

Recently, cosmologists and astrophysicists have attempted to utilize the Early Dark Energy model, which considers the role dark energy plays in accelerating the rate of expansion of the universe (Li & Shafieloo, 2019). The exact value of H_0 still remains uncertain, however, with estimates typically around 70±~2 km/s/Mpc (Bahcall, 2015). This margin of error, called Hubble tension, arises from different methods of calculating Hubble's constant - such as those based on analyses of the motion of nearby galaxies, measurements from the cosmic microwave background (CMB), and data from gravitational wave observations of neutron star and black hole collisions (3, 4). These discrepancies suggest that our understanding of the universe's expansion is still incomplete. Resolving the causes for this tension is crucial, as it may give us insight into fundamental cosmological phenomena, including the nature of dark energy and the universe's overall structure and evolution.

METHODS AND MATERIALS

To calculate our own value for Hubble's parameter, we made our own dataset using information from NED and SIMBAD. We selected a total of sixteen different galaxy clusters of varying distances and collected the data of 204 different galaxies, including their recessional velocities, redshift-independent distances, and densities of the clusters. Then, using Hubble's formula:

$$v = H_0 d$$

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We derived each galaxy's Hubble parameter. Averaging that value gave us each cluster's Hubble parameter, while the individual values gave us the range.

We used Jupyter Notebook and Python libraries such as NumPy, SciPy, Matplotlib, Seaborn, and Pandas to simulate our data and create graphs so that we could observe possible correlations between cluster distance and density and the calculated average Hubble's parameter and range across different galaxy clusters.

Using Python, we graphed a linear regression model that showed the relation between each galaxy's distance from us and its recessional velocity. After drawing the line of best fit for these data points and taking its slope, we calculated Hubble's "constant." After computing the p-value, we determined that there was an association between the density of a galaxy cluster and its Hubble parameter. Understanding the characteristics that affect the Hubble parameter is essential for creating more precise and accurate calculations in the future.

Figure 1
Abridged table of raw data for galaxy clusters analyzed

Cluster	Sample Size (Galaxies)	Cluster Distance (Mpc)	Minimum H (km/s/Mpc)	Maximum H (km/s/Mpc)	H Range (km/s/Mpc)	H Average (km/s/Mpc)
Abell 1060	20	79.7	40	103	63	69
Abell 426	16	71.7	44	111	67	69
Abell 2151	13	148.8	65	90	25	76
Abell 3526	14	40.1	51	133	82	87
ACO S 373	11	17.6	46	85	39	68
Abell 1656	13	109.4	57	79	22	66
Abell 262	20	64.6	48	171	123	78
Abell 3742	5	64.4	39	70	31	61.6
Abell 1185	11	161	52	89	37	65
Abell 2162	3	166	61	66	5	64
Abell 1367	20	95.2	36	75	39	59
Abell 2199	20	118	60	99	39	70
Abell 400	19	101.1	54	122	68	83
Abell 569	9	83.4	56	68	12	62
Abell 671	8	206	64	100	36	75

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Abell 2256	3	237.3	70	98	28	80

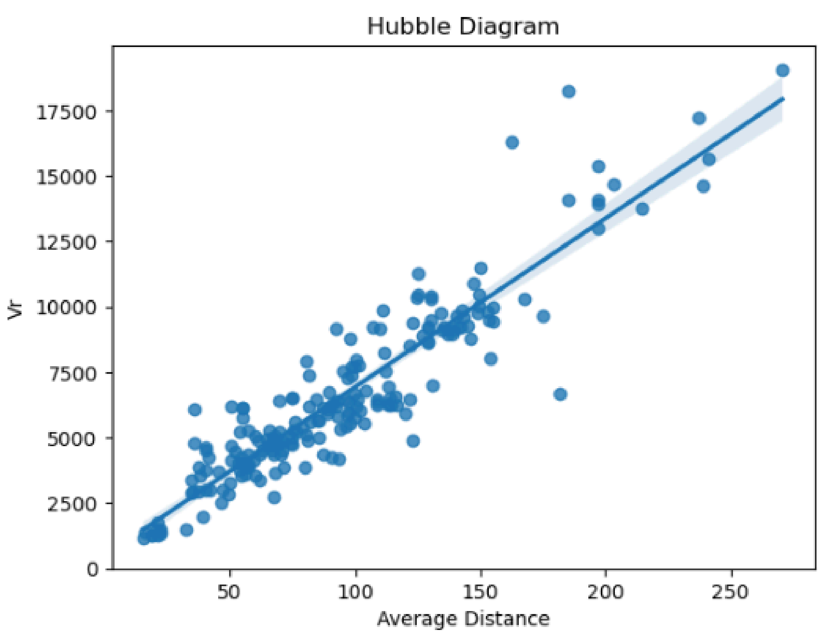
Note. A table summarizing the key properties of each galaxy cluster used in analysis, including cluster name, sample size (number of galaxies), cluster distance (Mpc), minimum and maximum calculated Hubble parameter (H), H range, and H average for each cluster. The table includes data for 16 galaxy clusters. These clusters were chosen to represent a range of distances and densities to provide a diverse dataset for more reliable statistical analysis and regression modeling.

RESULTS

The rationale behind this research was based on the hypothesis that higher galaxy cluster densities would correlate with smaller values of Hubble's constant due to the influence of local gravitational interactions between galaxies within the cluster. By understanding how galaxy cluster densities, among other factors, relate to Hubble's constant, we can better understand what causes variance in Hubble's constant and take one step closer to finding a more definitive answer. To test this hypothesis, we selected 204 galaxies from 16 galaxy clusters of varying distances and recessional velocities, with clusters ranging from 17.6 Mpc in distance to 237.25 Mpc away (Figure 2). Using Hubble's law, we calculated Hubble's constant for each galaxy and graphed these values in a fitted linear regression plot. From our data, we found our calculated Hubble's constant to be 64.4±2 km/s/Mpc.

Figure 2

Relationship between the average distance of galaxies and their recessional velocities



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Note. A scatter plot with a fitted linear regression line reveals a strong positive correlation between average distance (x-axis) and recessional velocity (y-axis), indicating the Hubble parameter in accordance with the universal expansion. Data was analyzed using linear regression (slope = 64.38, intercept = 499.88). Statistical analysis includes Pearson correlation (r = 0.92) and p-value < 0.001 (n = 204).

After calculating our overall value for Hubble's constant, we averaged the H_0 for each galaxy in the cluster to get the Hubble parameter average for each galaxy cluster. Using this information, we examined how factors such as the density of a cluster might correlate with the average H_0 calculated per cluster. For simplicity, the densities used to compare galaxy clusters were derived from the number of galaxies present per cluster as recorded in the SIMBAD astronomical database and cross-checked with data from the *Abell Catalog of Rich Clusters of Galaxies*. By graphing our data on a scatter plot and fitting a linear regression line, we found a weak negative correlation between cluster density and the calculated H_0 average, with a Pearson correlation coefficient of r = -0.23 and a probability value of 0.39 (Figure 3). A correlation coefficient of -0.23 indicates a weak negative relationship and implies that as cluster density increases, the calculated H_0 value tends to decrease slightly. The p-value of 0.39 is greater than 0.1, suggesting that the found trend may not be statistically significant and could be due to chance or other factors at play.

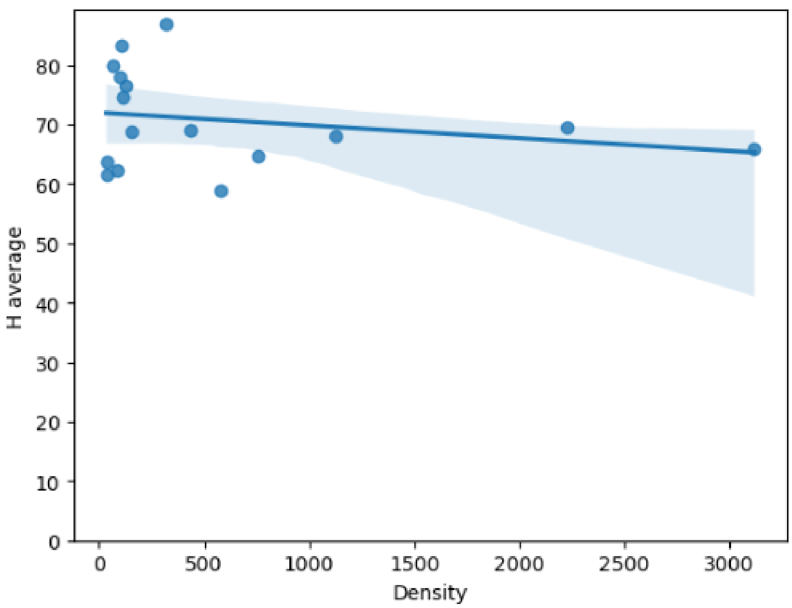
We additionally found the range of the calculated Hubble parameter in each cluster by finding the difference between the minimum and maximum calculated H_0 values of the galaxies. We used this to uncover any relationships between cluster density and cluster H_0 range. Through our research and after plotting a linear regression graph, we found weak evidence against the null hypothesis, implying that there is likely no significant relationship between the density of a cluster and the average Hubble parameter range. The Pearson correlation coefficient derived from the graph was r = -0.19, and the probability value was 0.48, indicating that there is a 48% chance that the weakly negative observed correlation was due to chance (Figure 4).

After looking at the relationships that density might have with the overall Hubble parameter of the cluster, we looked into what other factors might have caused a discrepancy in the range of Hubble's parameters calculated. We used the distances and Hubble range of each cluster to identify if there was any correlation between the two. We found a moderate and weakly statistically significant negative relationship between cluster distance and Hubble range, with clusters at greater distances exhibiting a weaker range. Through analyzing the data using a linear regression model, we found a Pearson correlation coefficient of r = -0.45 and a probability value of 0.08, indicating that the correlation was likely not due to chance and that a noticeable correlation exists between the two (Figure 5). This relationship reinforces the idea that factors other than cluster density likely have a greater role in causing variations in Hubble's parameter.

Lastly, we explored the direct relationship between the calculated Hubble parameter of each galaxy with the cluster's overall density to identify if there is any possible effect of cluster density on the calculated H_0 value on a smaller scale. We found there to be a weak but statistically significant relationship between the two variables, implying that while it is true that cluster density plays a role in calculating the Hubble parameter, the effect of density is negligible on a larger scale. We reached this conclusion by analyzing the data from the linear regression model and deriving a Pearson coefficient of r = -0.15, indicating a weak negative correlation, and a probability value of 0.03, suggesting that the correlation is unlikely to be due to chance (Figure 6).

Figure 3

Relationship between the Hubble Parameter average and cluster density



Note. A scatter plot with a linear regression line featuring the negative correlation between the H average of each cluster and the density. The data was analyzed using linear regression, and statistical analysis revealed a correlation coefficient (r = -0.23) and p-value = 0.39 (n=16).

Figure 4

Relationship between Hubble Parameter Range and cluster density

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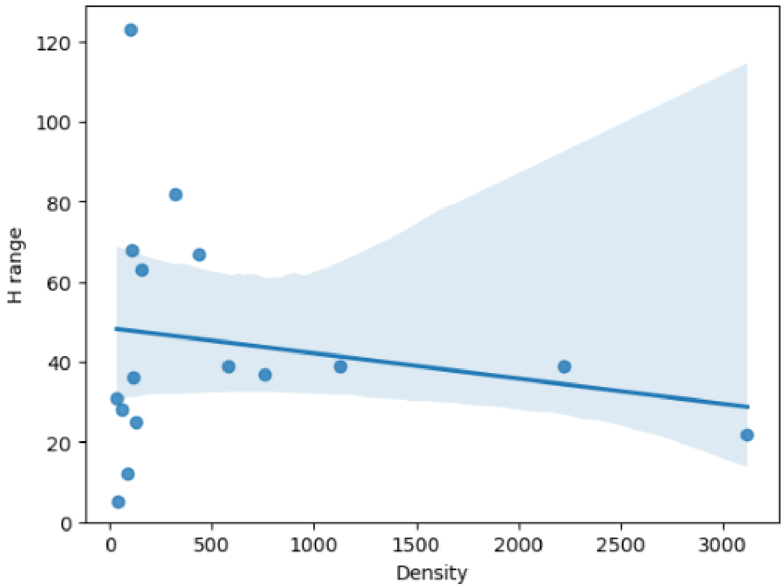
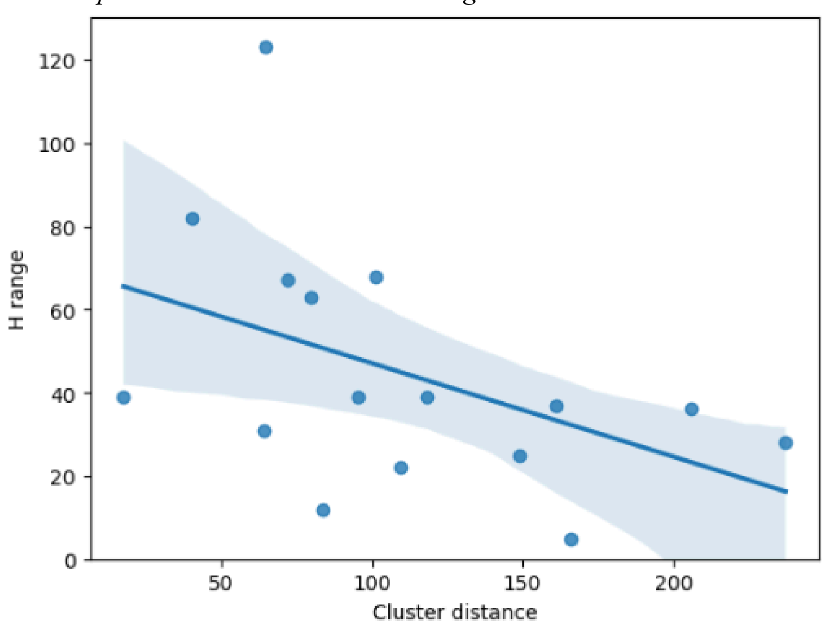


Note. A scatter plot with a linear regression line featuring the negative correlation between the H range of each cluster and the density. The data was analyzed using linear regression, and statistical analysis revealed a correlation coefficient (r = -0.19) and p-value = 0.48 (n=16).

Figure 5

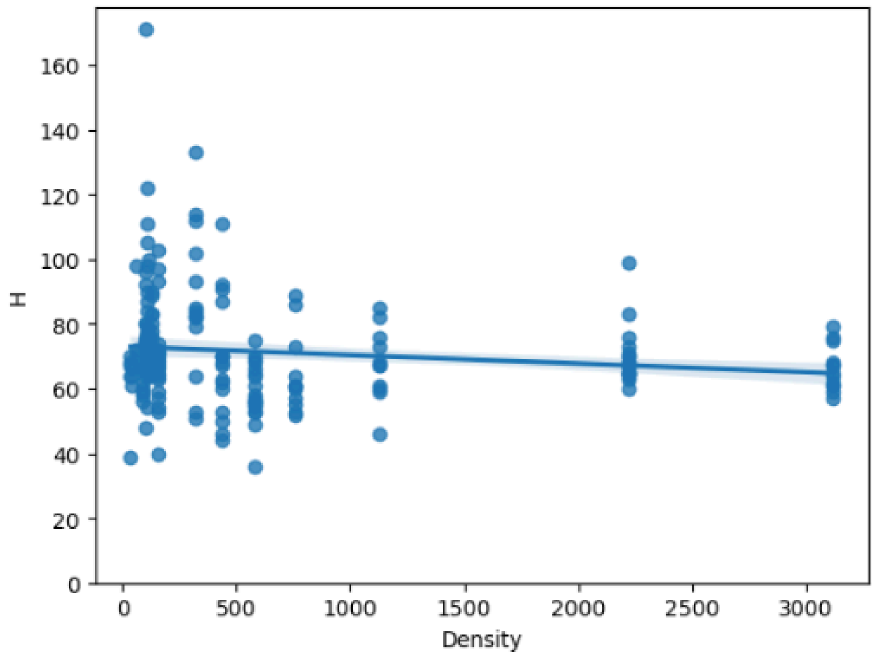
Relationship between Hubble Parameter Range and cluster distance



Note. A scatter plot with a linear regression line featuring the negative correlation between the H range of each cluster and the distance. The data were analyzed using linear regression, and statistical analysis revealed a correlation coefficient (r = -0.45) and a p-value of 0.08 (n=16).

Figure 6

Relationship between the Hubble Parameter of galaxies and cluster density



Note. A scatter plot with a linear regression line featuring the negative correlation between calculated H values for all galaxies overall and cluster density. The data was analyzed using linear regression, and statistical analysis revealed a correlation coefficient (r = -0.15) and p-value = 0.03 (n=204).

DISCUSSION

We concluded that the correlations between densities and H range, densities and H average, distance and H range, and Hubble parameter and cluster density are all weakly to moderately negative, with p-values of 0.4841, 0.3916, 0.0778, and 0.03, respectively. Most of our results can be attributed to random variation, with the exception of the Hubble parameter and cluster density, where the p-value suggests a strong, statistically significant relationship, and distance and H-range, where the p-value suggests a weak, but plausible, statistically significant relationship. This indicates that there is a 3% probability that the observed correlation between the Hubble parameter and cluster density, and a 7% probability that the observed correlation between distance and H range, could have occurred by random chance. This suggests that both correlations are unlikely to be solely due to chance. Our value of 64.38 km/s/Mpc indicates that while we were close to the typical range of values for Hubble's constant, there may have been errors that skewed the accuracy of the result.

One factor that could have impacted our research was the choice of galaxies sampled from each cluster. The distribution of galaxy types and the different physical properties of the individual galaxies (such as galaxy morphology) could influence their peculiar velocities (M. Einasto et al., 2014). Focusing on homogeneity for the galaxy populations we choose to analyze could reduce these additional variables, allowing us to isolate the effects of cluster densities more effectively.

In dense clusters, the gravitational interactions between galaxies will cause peculiar velocities, which can deviate from the expected rate of cosmic expansion (Kopylova & Kopylov, 2017). These peculiar velocities can introduce scatter to the redshift measurements, which could reduce the accuracy of the calculated radial velocities, and thus Hubble's constant.

Gravitational redshift is another potential source of error. In dense clusters, light from galaxies must escape the gravitational potential well, leading to a redshift of the light (Wojtak et al., 2011). This effect can lead to a bias in redshift measurements, which would affect the radial velocities we used to calculate Hubble's constant. Thus, although our findings show a weak to moderate correlation between Hubble's constant and density, they suggest that peculiar velocities may be contributing to the observed correlation.

Another factor that could have introduced some uncertainty to our research results was the uniform distances that we selected. The databases that we used to collect our data, NED, the NASA/IPAC Extragalactic Database, and SIMBAD, often lacked information on more distant galaxy clusters, forcing us to limit our sample to nearby clusters, which could have skewed our results.

CONCLUSION

Hubble tension remains a prevalent topic that is widely discussed in modern cosmology, reflecting the ongoing debate on the true rate of the universe's expansion. In this study, we explored how the cluster density, among other potential factors, might relate to Hubble's constant, with the goal of identifying behaviors that could contribute to discrepancies in its measured value. Regarding our hypothesis, our research showed that the density of galaxy clusters had a weak but statistically significant relationship with the Hubble parameter, indicating that while cluster density may influence calculations, its overall effects are minimal. While additional research is needed, our work contributes to the growing effort to better understand the reasons behind the Hubble tension and address the deeper questions about the universe's fundamental nature, including the role of dark energy and the processes driving the evolution of the universe.

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