Investigating the Effects of Milky Way Globular Clusters' Galactocentric Distances on Their Rotational Velocities about the Galactic Center

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Abstract

This investigation examines the kinematics and locations of globular clusters in the Milky Way to answer the question: "how do the galactocentric distances of Milky Way globular clusters affect their rotational velocities about the galactic center?". The investigation was carried out under the hypothesis that no relationship exists between galactocentric distances and rotational velocities of Milky Way globular clusters. All of the data was extracted from the article "Space Velocities of Globular Clusters. III. Cluster Orbits and Halo Substructure," which was written by Dana I. Dinescu, Terrence M. Gerard, and William F. Van Altena, and published in *The Astronomical Journal*, Volume 117 in 1999. The data was next processed into a graph and the mean and standard deviation statistical analysis was applied to determine whether there was no relationship between the variables. Then the data was linearized and a second statistical analysis--correlation coefficient analysis--was applied to verify the lack of relationship between the two variables. This investigation concludes that there is no relationship between the galactocentric distance of a Milky Way globular cluster and its galactic rotational velocity. This suggests that a substantial amount of dark matter is present in the halo of the Milky Way.

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Table of Contents

1. **Introduction……………………………………………………………………..……………4**

2. **Research Question…………………………………………………………..……….….5**

3. **Background Information**

    3.1. **Definition of Globular Clusters…………………………………..………………..5**

    3.2. **Nature of the Milky Way Galaxy……………………………………..………...6**

    3.3. **Distances to Globular Clusters……………………………………….…...….6-7**

    3.4. **Kinematics of Globular Clusters………………………………….……….….7-8**

    3.5. **Rotation Curves and the Scientific Principles Behind Them………….….…….8-9**

    3.6. **Dark Matter……………………………………………………………….……….10**

    3.7. **Statistics………………………………………………………………….…….10-11**

4. **Hypothesis………………………………………………………………………..……11-12**

5. **Data Collection**

    5.1. **Resources and Data Extraction…………………………………………….....12-13**

    5.2. **Data Processing……………………………………………………………......13**

6. **Data Results**

    6.1. **Raw Data: Galactocentric Distance, Rotational Velocity, and Uncertainty…....14-15**

    6.2. **Processed Data: Graphs and Statistical Analyses…………………………………..16**

        6.2.1. **Mean and Standard Deviation Analysis…………………………………17-18**

        6.2.2. **Correlation Coefficient Analysis…………………………………………18-20**

7. **Conclusion and Interpretation**

    7.1. **Explanation of Results……………………………………………………...…...21**

    7.2. **Implications………………………………………………………...………21-22**

8. **Evaluation………………………………………………………………...………..22-23**

    8.1. **Suggestions for Further Study……………………………………...…………..23**

9. **Works Cited……………………………………………………………...………...24-25**

1. Introduction

One of the most fascinating topics in the realm of astrophysics is that of dark matter. Dark matter is believed to be matter that gives off so little light, if any at all, that we are unable to detect its presence (Weintraub 261). However, scientists have been able to infer its existence from numerous observations and calculations surrounding the nature of the Milky Way galaxy, other galaxies, galactic clusters, and even the universe as a whole. One such method that has been used as an indicator of the presence of dark matter within the Milky Way is the rotation curve of stars in the galaxy. In 1962, astrophysicist Vera Rubin generated a rotation curve for the Milky Way and found that at distances greater than 8.5 kiloparsecs from the galactic center, the rotation curve was flat and did not decrease (Rubin). The flat nature of the graph was very surprising to physicists because the amount of luminous mass in the Milky Way is such that as the distance from the galactic center increases, there is not enough mass to offset the effects of basic gravitational principles (Weintraub 274). The graph therefore suggests that there is far more mass present in the galaxy than is currently detectable: dark matter.

This investigation aims to generate a rotation curve similar to that of Milky Way disk stars for a sample of thirty-seven globular clusters in the Milky Way galaxy, and determine how the galactocentric distances of Milky Way globular clusters affect their rotational velocities about the galactic center. Because globular clusters are located in the halo of the Milky Way and not in the disk, they are not impacted the initial effects of additional mass as their distances from the galactic center increase as disk stars do. Thus, they may provide an interesting indication for the presence of dark matter within the halo of the Milky Way galaxy, particularly because most of the dark matter in the Milky Way is believed to be located in the halo (Oppenheimer).

2. Research Question

How do the galactocentric distances of Milky Way globular clusters affect their rotational velocities about the galactic center?

3. Background Information

3.1. Definition of Globular Clusters

Globular clusters are largely-spherical clusters of gravitationally-bound stars that contain anywhere from 10^4-10^6 stars (Fusi-Pecci, Flavio, Clementini 1). Stars in globular clusters most likely originated from the same interstellar cloud and all share the motion of the cloud from which they were created. The sheer number of stars in these clusters and, consequently, their centrally-condensed nature differentiate them from open clusters, which contain far fewer stars. Because there are so many stars in globular clusters, gravity's effects are significant, and can hold the stars in the clusters for billions of years (Weintraub 112-118). There are, as of 2010, 157 identified globular clusters in the Milky Way galaxy (Harris "A Catalog of Globular Clusters"). These clusters are distributed evenly above and below the disk of the Milky Way, but none come within 1,300 parsecs of its mid-plane, or the central line of its disk (Weintraub 198). Additionally, these clusters are separated into two distinct globular cluster systems based on their metallicities (or the amount of elements they contain that are heavier than hydrogen and helium) and kinematics. The first Milky Way globular cluster system consists of metal-poor globular clusters and contains about three-fourths of the globular clusters in a roughly spherical system. The second globular cluster system consists of metal-rich globular clusters and contains the remaining one-fourth in a roughly disk-like system (Harris, "Globular Cluster Systems" 2).

3.2. Nature of the Milky Way Galaxy

The Milky Way Galaxy is a galaxy in which virtually all of the visible mass is concentrated toward the center of the galaxy (Weintraub 274). The Milky Way consists of two parts: the disk and the halo. Figure 1 below shows the layout of the galaxy as well as the locations of globular clusters versus disk stars.

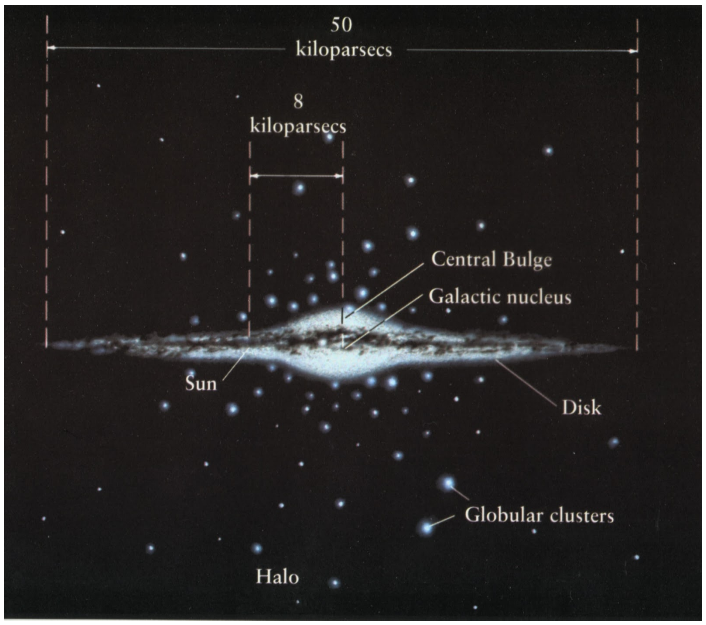


Figure 1. Milky Way Diagram (National Tsing Hua University, n.d.)

All globular clusters are located in the halo, while younger stars such as our sun are located in the disk and participate in the disk rotation about the galactic center. Globular clusters do not participate in the disk rotation, and revolve around the galaxy in highly-eccentric orbits.

3.3. Distances to Globular Clusters

Because the distances between stars in a cluster are much smaller than the distance from the cluster to the Sun, it is reasonable to think of all the stars in a cluster as being equidistant from the Sun (Weintraub 118). One means to measure the average distance to a globular cluster is using geometry derived from the convergent point phenomenon, which states that when the average motion of a globular cluster is in a direction away from Earth, the stars eventually appear to converge to a point in that direction. The stars in clusters that are closer appear to converge faster, while stars in clusters that are farther away appear to converge slower (Weintraub 115). Another way to determine the distance to globular clusters is through main-sequence fitting, in which the apparent magnitudes of main-sequence stars in the cluster are compared to the absolute magnitudes of main-sequence stars in clusters of known distances (Weintraub 121). After determining the distance from the cluster to the sun, the cluster's galactocentric distance, or distance from the center of the galaxy, can also be calculated. While the distances in this investigation were not directly measured, it is important to have a good idea as to how those distances may have been derived.

3.4. Kinematics of Globular Clusters

Stars in globular clusters share an average motion, while inside the cluster, stars are free to move about randomly and interact with one another (Fusi-Pecci, Flavio, Clementini 1). Halo stars have highly elliptical orbits unlike disk stars; consequently, they typically travel at higher velocities than disk stars (Oppenheimer). Figure 2 below shows the orbits of Milky Way globular clusters in green, compared to disk stars' orbits (yellow) and bulge stars' orbits (red).

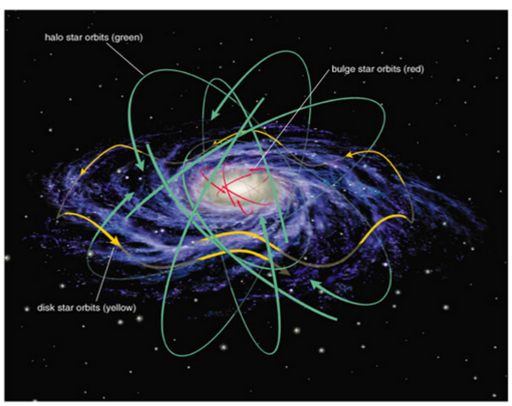


Figure 2. Globular Cluster Orbits (Harrison, New Mexico State University n.d.)

There are many different reference points from which to measure velocity. For any given globular cluster, there are numerous, differing velocity measurements that are dependent only on what the velocity is measured with respect to. For this investigation, the rotational velocity of a globular cluster with respect to the galactic center was used to determine whether the distance from the galactic center affects the speed at which a globular cluster revolves around it.

3.5. Rotation Curves and the Scientific Principles Behind Them

Rotation curves are graphs that plot celestial bodies' distances from their orbital center against their rotational velocities (Palma). An example of a rotation curve for the disk stars in the Milky Way is included below in Figure 3:

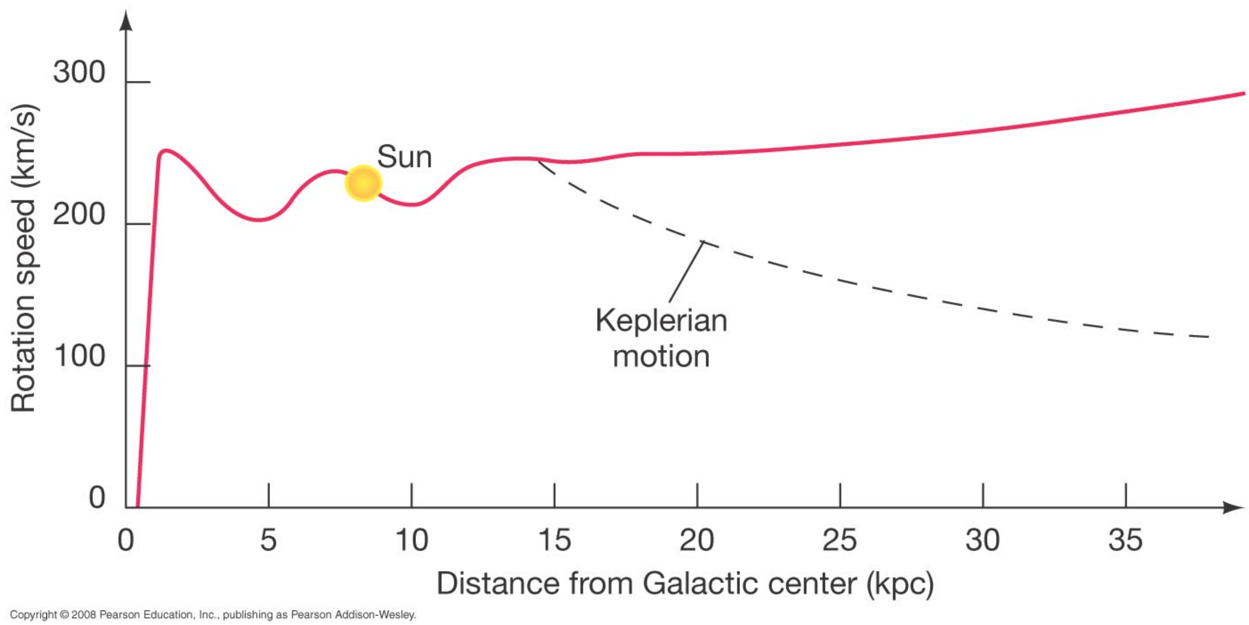


Figure 3. Milky Way Rotation Curve (University of Oregon, 2010)

Because the majority of the detectable mass in the Milky Way is concentrated toward the center, the rotation speed initially increases as distance from the galactic center increases. This is because greater mass within the orbit of the disk stars increases the effects of gravity on their rotation speed. However, as the distance from the galactic center continues to increase, the mass stops increasing and should have less of a gravitational effect on disk stars further away. The dotted line represents the expected rotation curve for the Milky Way Galaxy when all of the detectable matter is taken into account. Without the presence of dark matter, the Milky Way rotation curve should exhibit Keplerian motion. Keplerian motion refers to the phenomenon in which as the distance from the galactic center increases, there is not enough mass to offset the effects of Kepler's Third Law (Weintraub 273, 279). Kepler's Third Law is represented mathematically as follows:

$$\frac{{P_1}^2}{{P_2}^2} = \frac{{R_1}^3}{{R_2}^3}$$

In which P_1 and P_2 are the orbital periods of two celestial bodies respectively and R_1 and R_2 are the two objects' semi-major axes. Note that the period of a body is directly affected by the velocity at which the body travels.

This law dictates that in a system in which most of the mass is concentrated around the center, a planet or star's velocity should decrease in proportion to the square root of its orbital radius (Haynes). Additionally, Newton's Universal Law of Gravitation, which is represented mathematically below, states that the force of gravity felt between two objects is inversely proportional to the square of the distance between them. Thus, as the distance between two objects increases, the force of gravity that they exert on each other decreases by a factor of the square root of the distance.

$$F_g = G\frac{m_1 m_2}{r^2}$$

In which F_g is the force of gravity felt between two objects, G is the universal gravitational constant ($6.637 \times 10^{-11} Nm^2 kg^{-2}$), m_1 and m_2 are the masses of the two objects respectively, and r^2 is the square of the distance separating the center of the two objects.

3.6. Dark Matter

Dark matter is a mysterious phenomena that has never been directly detected. Some theories suggest that this is because it gives off too little electromagnetic radiation to be detected while other theories suggest that it gives off no electromagnetic radiation at all. Possible forms of dark matter are bodies that we cannot detect because of their small size or distance from us, such as white dwarf stars, unseen planets, and black holes (Weintraub 264-265). Other forms of dark matter are made of particles that have only been predicted, such as axioms (low-mass particles that are hypothesized to have been created in abundance during the Big Bang) and WIMPs (Weakly Interacting Massive Particles) (Weintraub 283).

When examining the flat rotation curve of the Milky Way, astrophysicists such as Professor David Weintraub of Vanderbilt University argue that the only way such a curve is possible in a system in which most of the mass is concentrated toward the center is for at least 90% of the galaxy's total mass to be dark matter (Weintraub 280).

3.7. Statistics

Two methods of determining whether there is no relationship between the variables are applied in this essay. The first is referred to as the "mean and standard deviation analysis" and the second is referred to as the "correlation coefficient analysis." The mean and standard deviation analysis is operated off the basis that if there exists no relationship between two variables, all or most of the data points on a graph should lie between the margins of the mean and one standard deviation above and below the mean. If they do, then it is reasonable to conclude that there is no relationship between the variables and any differences are within the margin of error.

The second method is the correlation coefficient analysis. The correlation coefficient is a value used to measure the strength of a linear association between two variables. The graphing program Logger Pro, from which the correlation coefficient was calculated in this investigation, uses the following equation to calculate correlation coefficient:

$$r = \frac{\Sigma(x_i - \bar{x})(y_i - \bar{y})}{(n-1)(s_x)(s_y)}$$

In which r is the correlation coefficient, x_i refers to all individual independent variable measurements, $\bar{x}$ refers to the mean of the independent variable measurements, y_i refers to all individual dependent variable measurements, $\bar{y}$ refers to the mean of the dependent variable measurements, n refers to the number of data points, and s_x and s_y refer to the standard deviations of the independent and dependent variables respectively ("Q: Logger Pro and Logger Lite"). According to Pennsylvania State University's Department of Statistics, correlation coefficient values between 0 and ±0.1 indicate that there is no relationship between the variables (Schafer 11).

4. Hypothesis

This investigation was carried out under the hypothesis that no relationship exists between the sample of Milky Way globular clusters' galactocentric distances and their galactic rotational velocities. This hypothesis was formulated after examining all the evidence presented in the background about the flat rotation curve of the Milky Way disk stars and the dark matter content of the Milky Way. Because disk stars closer to the center of the galaxy feel the initial effects of increased mass from other disk stars within their orbits and globular clusters do not, this investigation expected globular clusters to show a completely flat rotation curve with no relationship whatsoever between galactocentric distance and rotational velocity.

5. Data Collection

5.1. Resources and Data Extraction

The investigation was originally attempted through using a number of equations for globular cluster kinematics obtained from the paper "Globular Clusters Systems: Formation Models and Case Studies--Case Studies: The Milky Way GCS" written by Dr. William E. Harris of McMaster University. However, the data derived from the formulas listed in the paper yielded rotational velocities in the thousands of kilometers per second, which are extremely improbable values in the given situation. Upon calling Dr. Harris and discussing the issue with him, it was discovered that the equations listed in his paper only work for globular cluster systems in which the orbits are relatively circular, and not for individual globular clusters, which can have highly eccentric orbits. Dr. Harris then referred the investigator the article “Space Velocities of Globular Clusters. III. Cluster Orbits and Halo Substructure” (Dinescu, Gerard, Van Altena), from which all of the data in this investigation was extracted. The article was originally published in *The Astronomical Journal*, Volume 117 in 1999. All data points were obtained from Table 2, which lists the kinematic data for thirty-eight Milky Way globular clusters (Dinescu, Gerard, Van Altena 1795). The data used was listed under R_{GC} and Θ, where R_{GC} refers to “Galactocentric radii,” or distance from the galactic center, and Θ refers to “the positive velocity “in the direction of Galactic rotation” (Dinescu, Gerard, Van Altena 1793). Thirty-seven of the listed globular clusters are examined in this investigation; the one that was excluded, Pal 3, has a galactocentric distance of 84.9 kiloparsecs, which, for the purposes of this investigation, is beyond the scope of Milky Way globular clusters. This investigation only examines globular clusters within 30 kiloparsecs of the galactic center because 30 kiloparsecs is the accepted size of the Milky Way according to the National Aeronautics and Space Administration's (NASA) High Energy Astrophysics Science Archive Research Center ("The Milky Way Galaxy").

5.2. Data Processing

The data in this paper was processed through the use of Logger Pro, a graphing program. The galactocentric distances, rotational velocities, and rotational velocity uncertainties were inputted into the program and then plotted on a graph. Microsoft Excel was used to arrange the data in increasing galactocentric distance order. Next, a TI-84 Plus calculator was used to compute the average rotational velocity and the standard deviation for the rotational velocity data. To determine whether there exists no relationship between galactocentric distances and rotational velocities of the clusters, two methods were used. First, three horizontal lines were added to the graph: one at the mean, one located one standard deviation above the mean, and one located one standard deviation below the mean, and the number of data points (including uncertainty bars) falling within that range was determined. Second, the galactocentric distance values were squared using Microsoft Excel's squaring computation capabilities to linearize the data, and the correlation coefficient of the linearized data was calculated using Logger Pro.

6. Data Results

6.1. Raw Data: Table of Galactocentric Distance, Rotational Velocity, and Uncertainty

Table 1

The Effect of Galactocentric Distance on Galactic Rotational Velocity

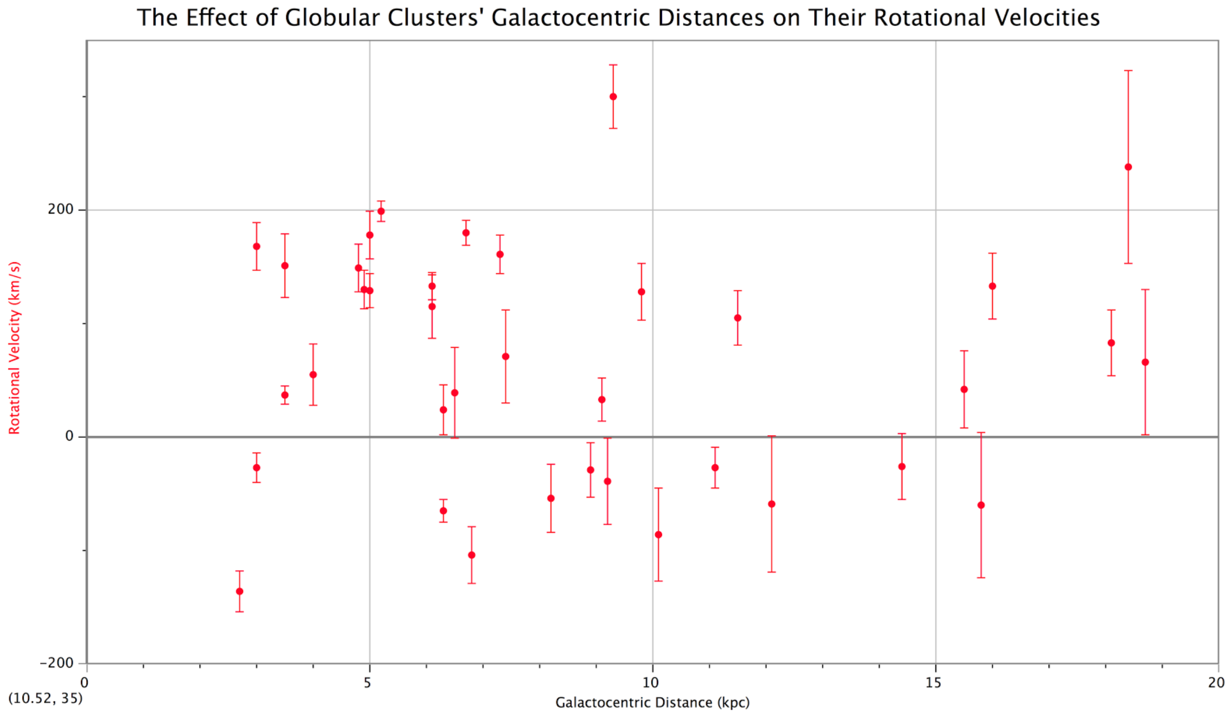
Identification	Galactocentric Distance (kpc)*	Galactic Rotational Velocity (kms^{-1})	Uncertainty of Galactic Rotational Velocity ($\pm kms^{-1}$)
NGC 6144	2.7	-136	18
NGC 6093	3.0	-27	13
NGC 6626	3.0	168	21
NGC 6171	3.5	151	28
NGC 6712	3.5	37	8
NGC 6809	4.0	55	27
NGC 6254	4.8	149	21
NGC 6218	4.9	130	17
NGC 6362	5.0	129	15
NGC 6656	5.0	178	21
NGC 6752	5.2	199	9
NGC 5904	6.1	115	28
NGC 6397	6.1	133	12
NGC 5139	6.3	-65	10
NGC 6121	6.3	24	22
NGC 6584	6.5	39	40
NGC 6838	6.7	180	11

NGC 7099	6.8	-104	25
NGC 104	7.3	161	17
NGC 5897	7.4	71	41
NGC 6205	8.2	-54	30
NGC 362	8.9	-29	24
NGC 6341	9.1	33	19
NGC 6779	9.2	-39	38
NGC 4590	9.3	300	28
NGC 7078	9.8	128	25
NGC 7089	10.1	-86	41
NGC 288	11.1	-27	18
NGC 5272	11.5	105	24
NGC 6934	12.1	-59	60
NGC 2298	14.4	-26	29
Pal 5	15.5	42	34
NGC 5466	15.8	-60	64
NGC 1851	16.0	133	29
NGC 1904	18.1	83	29
NGC 5024	18.4	238	85
NGC 4147	18.7	66	64

*Note: The uncertainties for galactocentric distance are negligible compared to the uncertainties of the rotational velocity, and were not even listed in the paper from which the data was obtained.

6.2. Processed Data: Graphs and Statistical Analyses

Graph 1 (Rotation Curve)

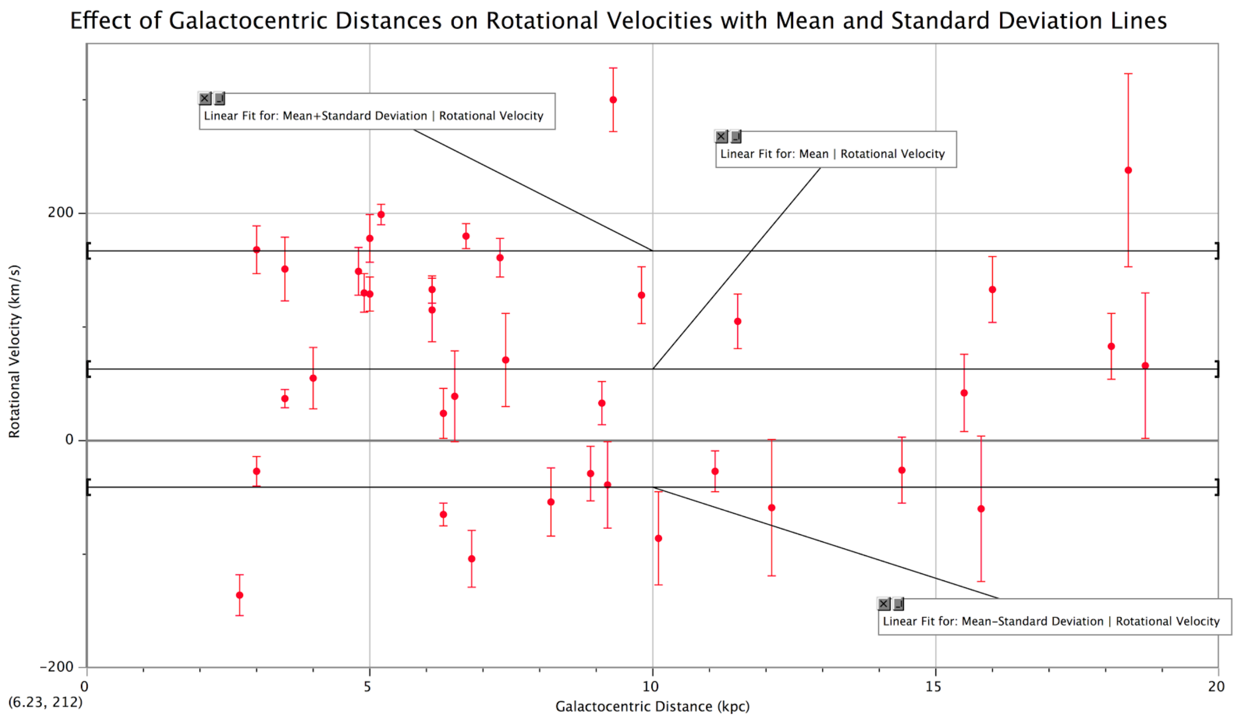


The graph above has the same axes labels and units as the Milky Way disk star rotation curve, and as such is comparable to disk stars' rotation curve. The rotational velocities included in the graph do not seem to exhibit any relationship with galactocentric radii whatsoever. In fact, when all curved and linear fits were attempted on the data, the smallest root mean square error was still over 100. Root mean square error is a statistical measure of the differences between predicted models and observed values. The closer it is to zero, the more closely the expected and observed values match each other (Karen). A root mean square error of 100 is significantly larger than zero. That suggests that the rotational velocities of globular clusters in the Milky Way are not related to the clusters' galactocentric distances by any curved or linear relationship.

6.2.1 Mean and Standard Deviation Analysis

The mean rotational velocity for the data points is 63 km/s. The standard deviation for this sample of globular clusters' rotational velocities is 104km/s.

Graph 2



In Graph 2 above, the highest added horizontal line represents one standard deviation above the mean rotational velocity, the central added horizontal line represents the mean rotational velocity, and the lowest added horizontal line represents one standard deviation below the mean rotational velocity. If there is truly no relationship between the two variables, most of the data points (excluding outliers), or at least their uncertainty bars, should fall between the margins of plus or minus one standard deviation away from the mean rotational velocity.

According to Graph 2, seven out of the thirty-seven globular clusters do not lie within that margin, nor do their uncertainty bars. That amounts to just about 19% of the clusters.

However, the data points which do not lie within those prescribed margins could be outliers, and it seems significant that thirty of the globular clusters are within the bounds of the mean and one standard deviation above and below it.

6.2.2 Correlation Coefficient Analysis

Another way to determine whether there is no relationship between the two variables is by calculating the correlation coefficient for the data, though this method only determines the existence or lack of a linear relationship between variables. Therefore, the correlation coefficient was calculated by first linearizing the data. Because both Kepler's Third Law and Newton's Universal Law of Gravitation show that the orbital velocity and the effects of gravity are related to the square roots of distance proponents of the cluster (either the semi-major axis or the radius to the galactic center), the data can be linearized by squaring all the values of the galactocentric distances. These linearized values are found in Table 2 below:

Table 2

The Effect of Squared Galactocentric Distance on Galactic Rotational Velocity

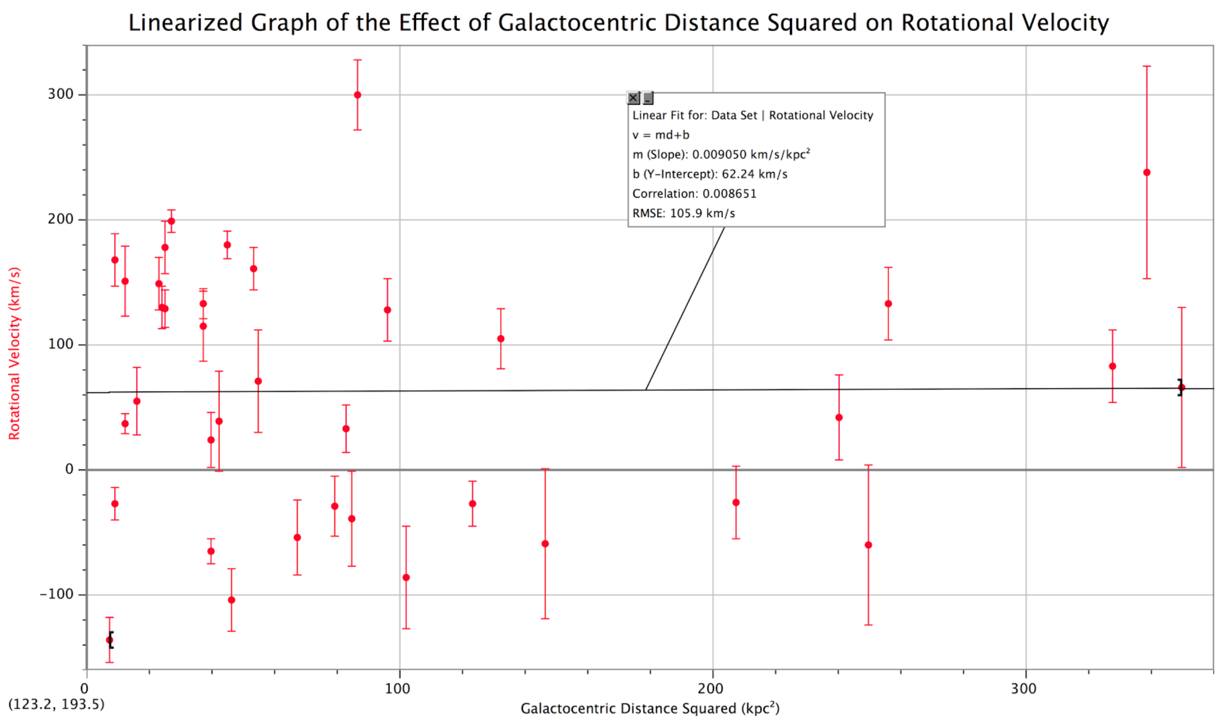
Identification	Galactocentric Distance Squared (kpc^2)*	Galactic Rotational Velocity (kms^{-1})	Uncertainty of Galactic Rotational Velocity ($\pm kms^{-1}$)
NGC 6144	7.29	-136	18
NGC 6093	9	-27	13
NGC 6626	9	168	21
NGC 6171	12.25	151	28
NGC 6712	12.25	37	8
NGC 6809	16	55	27
NGC 6254	23.04	149	21

NGC 6218	24.01	130	17
NGC 6362	25	129	15
NGC 6656	25	178	21
NGC 6752	27.04	199	9
NGC 5904	37.21	115	28
NGC 6397	37.21	133	12
NGC 5139	39.69	-65	10
NGC 6121	39.69	24	22
NGC 6584	42.25	39	40
NGC 6838	44.89	180	11
NGC 7099	46.24	-104	25
NGC 104	53.29	161	17
NGC 5897	54.76	71	41
NGC 6205	67.24	-54	30
NGC 362	79.21	-29	24
NGC 6341	82.81	33	19
NGC 6779	84.64	-39	38
NGC 4590	86.49	300	28
NGC 7078	96.04	128	25
NGC 7089	102.01	-86	41
NGC 288	123.21	-27	18
NGC 5272	132.25	105	24
NGC 6934	146.41	-59	60
NGC 2298	207.36	-26	29
Pal 5	240.25	42	34

NGC 5466	249.64	-60	64
NGC 1851	256	133	29
NGC 1904	327.61	83	29
NGC 5024	338.56	238	85
NGC 4147	349.69	66	64

*Note: Again, the uncertainties for the galactic distance squared are negligible compared to the uncertainties for rotational velocities, and were not even listed in the paper from which the data was extracted.

Graph 3



According to the Logger Pro graph, on which a linear fit model was applied, the correlation between the variables is 0.008651.

7. Conclusion and Interpretation

7.1. Explanation of Results

Based on the above findings, it seems reasonable to conclude that there is no relationship between the galactocentric distances of Milky Way globular clusters and their galactic rotational velocities. As described in section 3.7 of the background, correlation coefficient values between 0 and ±0.1 indicate that there is no relationship between the variables. 0.008651 is far closer to 0 than it is to 0.1, which strongly supports the claim that the galactocentric distance of a globular clusters does not affect its rotational velocity.

The mean and standard deviation method supports this conclusion as well, although to a lesser extent. Even though 19% of the clusters in the sample do not fall within one standard deviation on either side of the mean, 81% of the clusters do. That becomes significant when considering the logic that if there is a relationship between galactocentric distance and rotational velocity, one would expect a far lower percentage of the clusters to fall within the margin of just one standard deviation on either side of the mean.

7.2. Implications

The potential implications for the conclusions drawn above are important to our knowledge of galactic kinematics. Clearly, at least for the sample of Milky Way globular clusters studied in this investigation, globular clusters do not follow the laws of Keplerian motion and do not have a decreasing rotation curve. One possible explanation for why this might be lies in the concept of dark matter. If our galaxy is surrounded by a halo of dark matter and filled with it, as most astrophysicists believe, then that could account for the relative consistency of globular clusters' rotational velocities. A halo of dark matter would be enough mass to counterbalance the reduced effects of gravity due to the centrally-condensed density of visible matter in the Milky Way. There would have to be great amounts of dark matter to offset the laws of Keplerian motion, so it is astounding that physicists and astronomers still have not been able to detect any of it directly. Instead, they are forced to infer its pervasive existence through indirect methods, such as through generating rotation curves similar to the one created in this investigation. The significance of dark matter is a topic for another essay, but its inferred presence through this analysis holds implications not only for the kinematics of Milky Way globular clusters, but also for the ways in which we view the universe and the fascinating phenomena it contains.

8. Evaluation

This investigation is limited in a number of ways. First, out of the 157 total globular clusters identified in the Milky Way, only thirty-seven were investigated and analyzed. This limitation stems from the issue that rotational velocity measurements were only recorded for thirty-seven of the clusters in the paper referred by Dr. Harris, who explained over the phone that it is far more common to measure the galactic rotational velocities for systems of globular clusters in the Milky Way.

Second, the eccentricities and natures of the globular clusters' orbits were not examined. The shapes and eccentricities of these orbits could have offered alternative explanations for the lack of relationship between the galactocentric distance and galactic rotational velocity of the clusters.

Third, the globular cluster systems were not examined or taken into account in this investigation, despite the fact that different cluster systems contain clusters with different metallicities and kinematical properties.

One final limitation to this investigation is that all of the data was extracted from the article "Space Velocities of Globular Clusters. III. Cluster Orbits and Halo Substructure" (Dinescu, Gerard, Van Altena). Thus, there was no way to understand the methods the authors used to obtain their measurements, as they did not offer any substantial explanations, nor was there a reasonable way to apply the methods and obtain independently-measured data to analyze.

8.1. Suggestions for Further Study

Many steps can be taken to further study the rotation curves of Milky Way globular clusters. The kinematics of more individual globular clusters can be analyzed to be compared to those studied in this investigation. Or, researchers can study globular cluster systems' kinematics and examine their net rotational velocity as opposed to investigating rotational velocities for individual clusters. Researchers can also examine the individual orbits of the globular clusters and take a closer look at whether eccentricity and the shape of the orbit plays a role in the rotational velocity of the cluster. One final suggestion for researchers interested in furthering this investigation is to examine the kinematics of globular clusters in other galaxies, some of which are well-documented in scientific literature.

Overall, the data collected in this experiment is tentative and has many limitations. But its potential implications for the nature of our galaxy are enough to set the mind spinning faster than any of the globular clusters in the Milky Way.

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