Smoking Gun in the Milky Way Galaxy: Dwarf Galaxies and Open Clusters

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Abstract

Although many open clusters (OCs) have been found to date, little has been done with them to investigate problems and questions about the Milky Way Galaxy (MWG) itself. This project found clues regarding the Milky Way's formation process and the role of open clusters and dwarf galaxies in it. The project was conducted using data on 520 OCs published by Kharchenko et al. in 2005, which includes distance, spherical coordinates, radial velocity, proper motion, measurement error, and other data on the clusters. In the process of discovering connections between the astronomical bodies, several mathematical and analytical techniques were used, including coordinate transforms and 2D and 3D scatter plotting. With data analysis, new evidence for connections between dwarf galaxies and open clusters were discovered, including the transfer of open clusters during galactic collisions in general, and for collisions between dwarf galaxies and the Milky Way in particular.

Contents

1 Introduction

Open clusters, as opposed to globular clusters (GCs), are large groups of stars that formed around the same place, and around the same time. These two facts make them perfect candidates for research objects, because any foreign member of the cluster that does not belong can be more easily identified, and the correct age of all stars in the cluster can be derived. The composition of the stars are often very similar due to their formation times and locations. Open clusters are typically found in the disk of the galaxy, rather than in the "halo" region (see Figure 1) of the galaxy. There are usually between 50 and several thousand stars in an open cluster, while globular clusters have many more members and are also larger in radius. The open clusters are relatively younger and hence, have a greater level of metallicity (Mihos 2015). Figure 2 is an image of open cluster M36, which is approximately 25 million years old, has over 60 members, and is located in the arms of the MWG. In contrast, Figure 3 is an image of globular cluster M15, which is 12.0 billion years old, has over 100,000 members, and is located in the halo region.

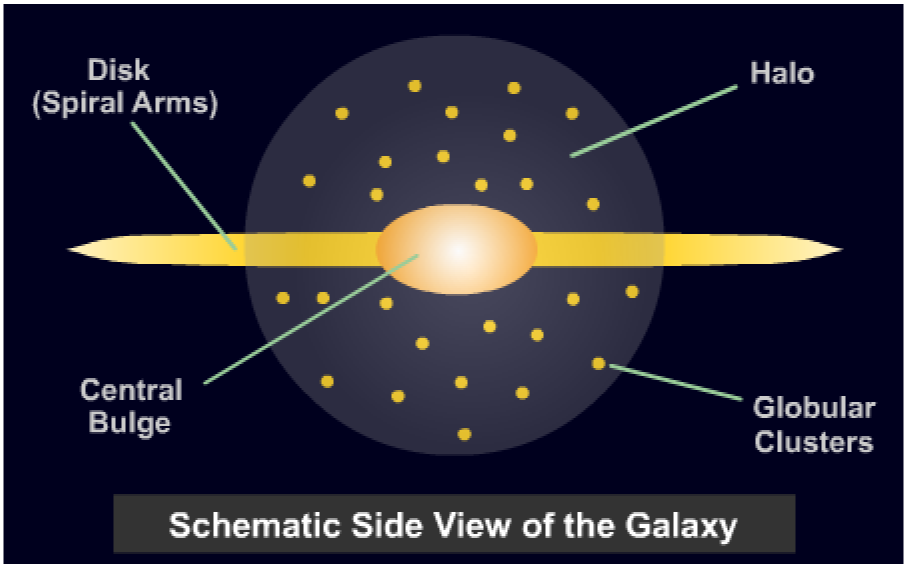

Figure 1: Schematic Side View of the Galaxy (Terao et al. 2013)

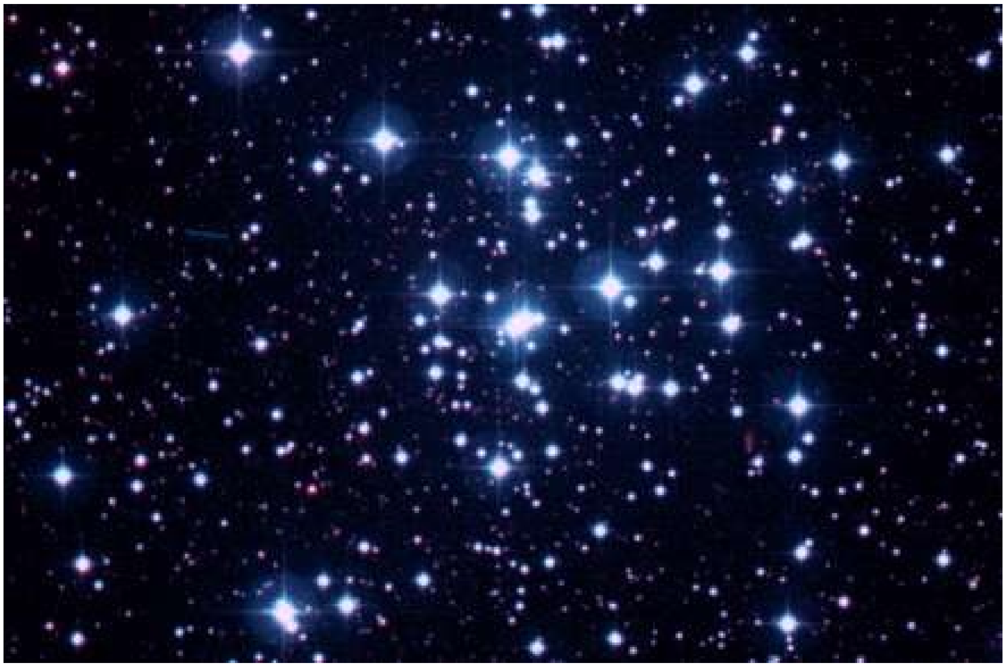

Figure 2: M36 Open Cluster (Kohlert 2008)

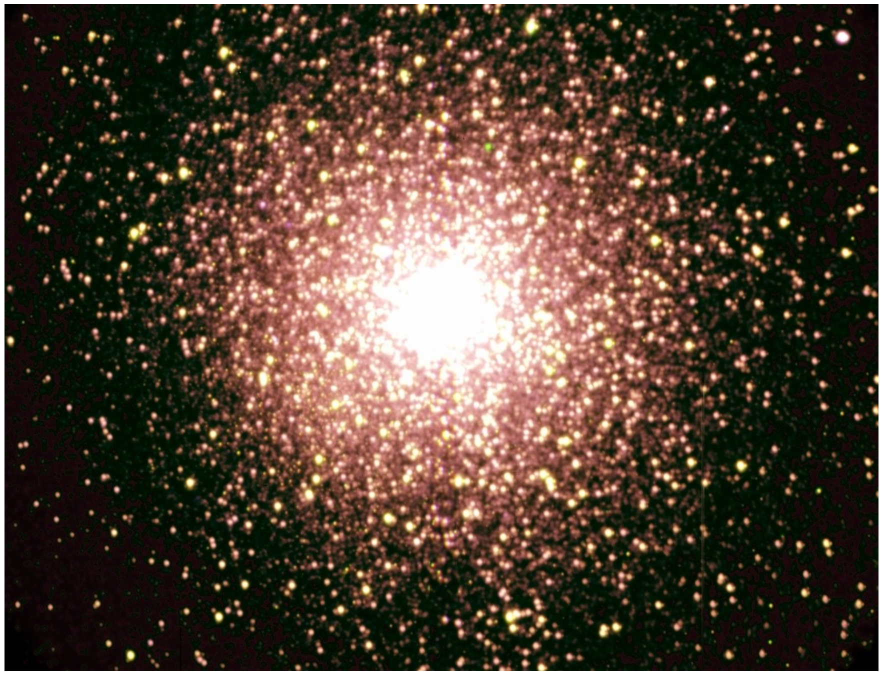

Figure 3: M15 Globular Cluster (”M15: A Great Globular Cluster.”)

Dwarf galaxies with large quantities of dark matter have been simulated (Figure 4) to collide with the MWG, with the interaction playing a key role in the MWG’s structural development process (Purcell et al. 2011). Also, possible dwarf galaxy remnants have been observed to float around the MWG, titled “tidal streams” of dwarf galaxies (Figure 5). In addition, other simulations have shown the Andromeda Galaxy colliding with a dwarf galaxy in a similar fashion to Purcell et al.’s simulation, shown in Figure 6 (Dierickx et al. 2014). The main goal of this project was to use large amounts of open cluster data in conjunction with dwarf galaxy information to find new evidence and information on the MWG’s formation process.

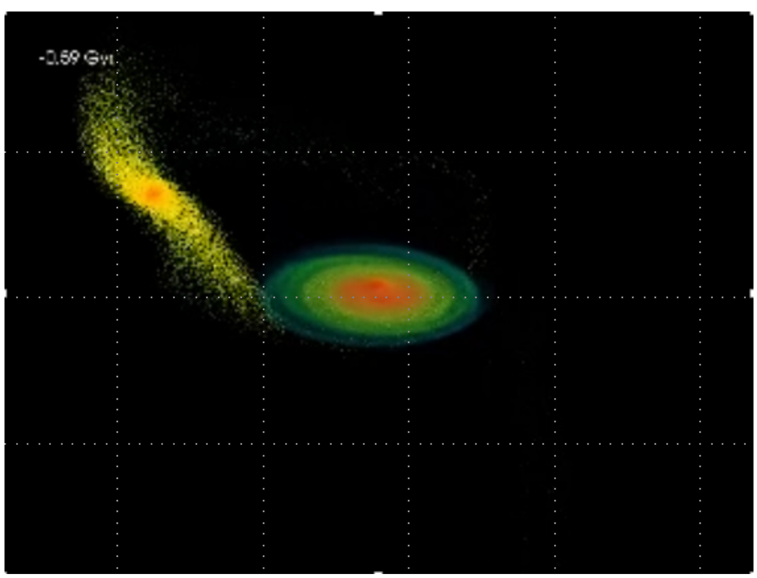

Figure 4: A snapshot of a computer simulation of the Milky Way Galaxy’s (shown in red and green) cannibalization of the Sagittarius Dwarf Elliptical Galaxy (shown in yellow) (Purcell 2011).

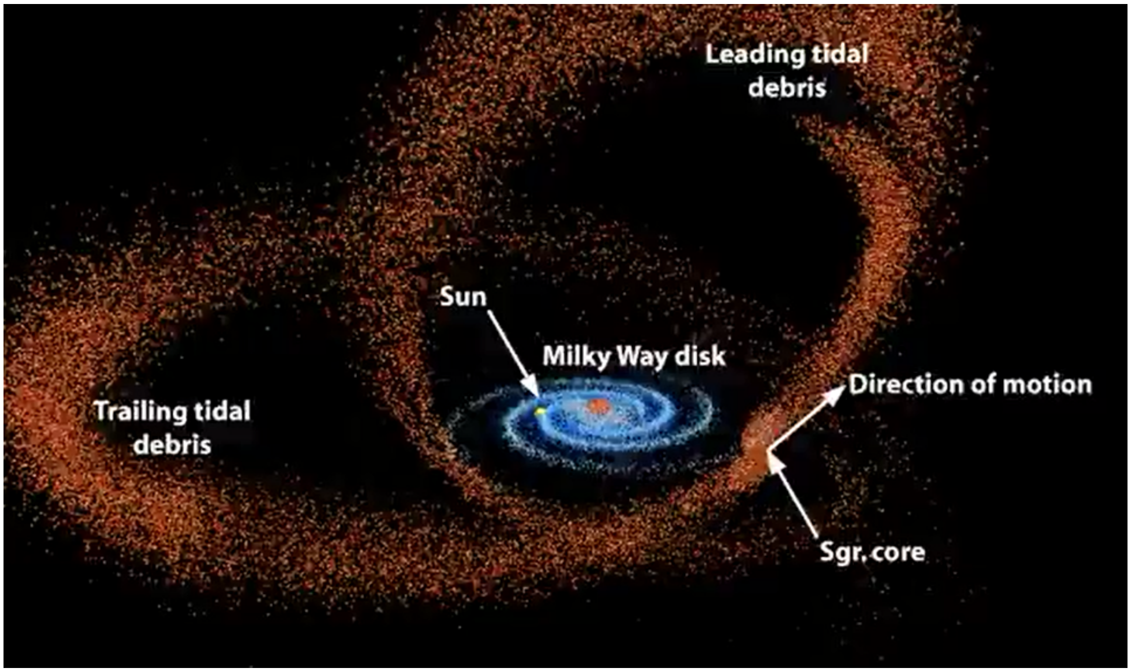

Figure 5: Sagittarius Dwarf Elliptical Galaxy "Tidal Stream" Illustration (Law 2010).

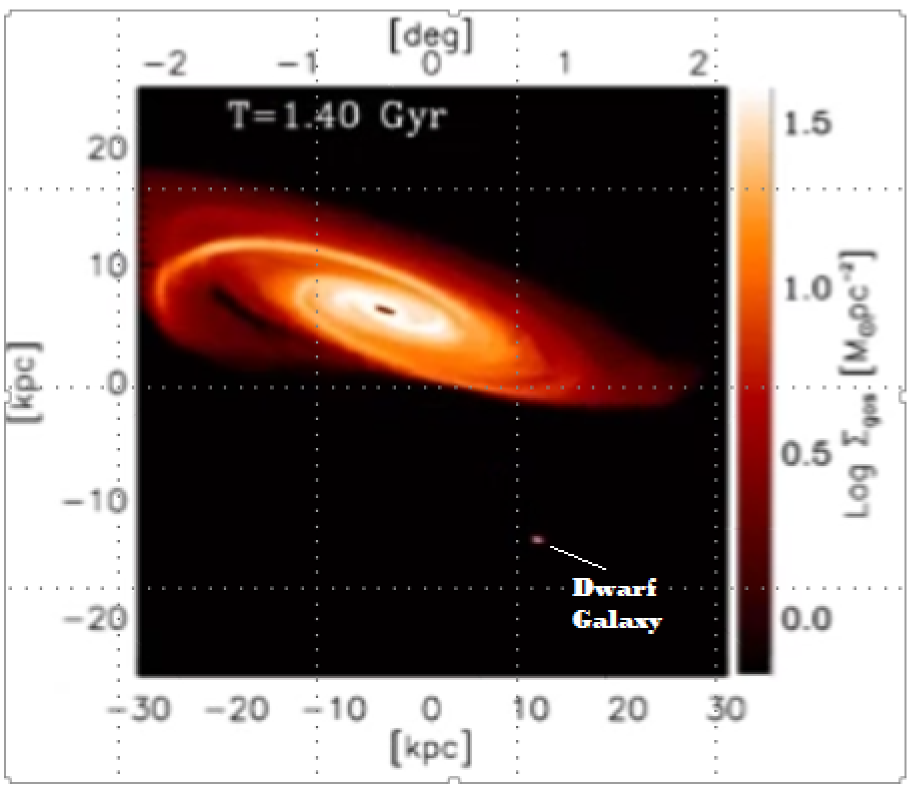

Figure 6: A snapshot of a computer simulation clip of the Andromeda Galaxy's cannibalization of a dwarf galaxy (Dierickx 2014).

2 Equipment and Description of Data

To conduct this research project, a laptop was used together with Microsoft Excel and gnuplot. Data was taken from Kharchenko et al.'s "Catalogue of Open Cluster Data (COCD)" found in the VizieR astronomical database. (Kharchenko et al. 2005). A large contribution to the creation of the COCD was the Tycho-2 catalogue from the Hipparcos mission. Example of data types included in the COCD were the sizes of clusters, cluster cores, heliocentric distances, proper motions, radial velocities, and approximate ages, as well as the amount of measurement errors included in the data. Information on the gathering techniques of the data types can be found in the Appendix. The data included 520 open clusters. Mathematical coordinate transforms (spherical to Cartesian) were performed on cluster position data and the results plotted in a 3-dimensional scatter plot using gnuplot. Currently, the proper motions and radial velocities are also being plotted using similar transforms in order to find even more information. Error was prominent in the radial velocity data, so the exclusion of certain clusters in the data analysis was necessary. In addition to coordinate transforms, the heliocentric distances of star clusters were converted to galactic center-centric distances for data analysis, to find relationships between galactic center-centric distance and other variables.

3 Research Process

Starting with the COCD data, the first goal was to plot the positions of the open clusters in a 3-D scatter plot. Important data types were distance, right ascension, and declination. The 3 data types discussed previously is in spherical coordinates (radial distance, azimuth angle, and zenith angle). The conversion of normal spherical coordinates (r, θ, ϕ) (Figure 7) to Cartesian coordinates (x, y, z) is

$$x = r \sin\theta \cos\phi \tag{1}$$

$$y = r \sin\theta \sin\phi \tag{2}$$

$$z = r \cos\theta \tag{3}$$

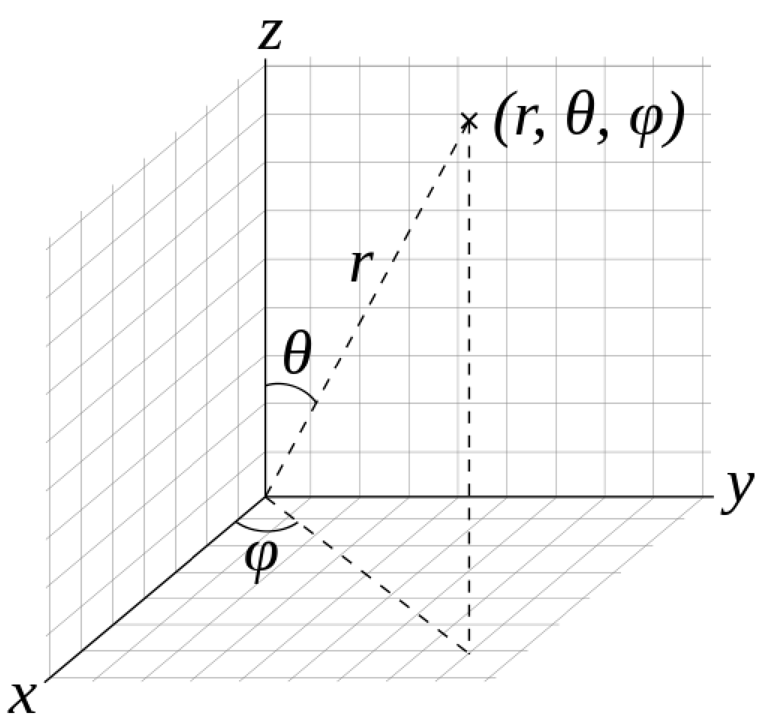

Figure 7: Illustration of Spherical Coordinates (Andeggs 2009).

However, astronomical declination (δ) is $90 - \theta$. Therefore, the transformation of astronomical spherical coordinates (d, δ, α) to Cartesian coordinates is

$$x = d \cos \delta \cos \alpha \tag{4}$$

$$y = d \cos \delta \sin \alpha \tag{5}$$

$$z = d \sin \delta \tag{6}$$

After performing unit conversions and coordinate transformations, the position data was plotted on gnuplot using the `splot` command. The completed scatter plot was compared with previous illustrations of dwarf galaxy remnants, as well as with illustrations of the MWG to check for accuracy.

In addition to position data plotting, graphs were created to plot galactic center-centric distance vs. cluster membership count, approximate age of cluster, and radius of cluster. Clusters over 1 billion years old and containing red M giants were given special attention due to their age connection with Purcell et al.'s simulation, as well as their content connection with the Canis Major Dwarf Galaxy (CMDG)—the CMDG has a large percentage of red M giant clusters (Martin et al. 2003).

Future procedures include performing coordinate transformations on the velocities of the star clusters based on proper motion and radial velocity, and plotting as a vector plot with the size of the direction arrow proportional to the magnitude of velocity.

4 Results and Data

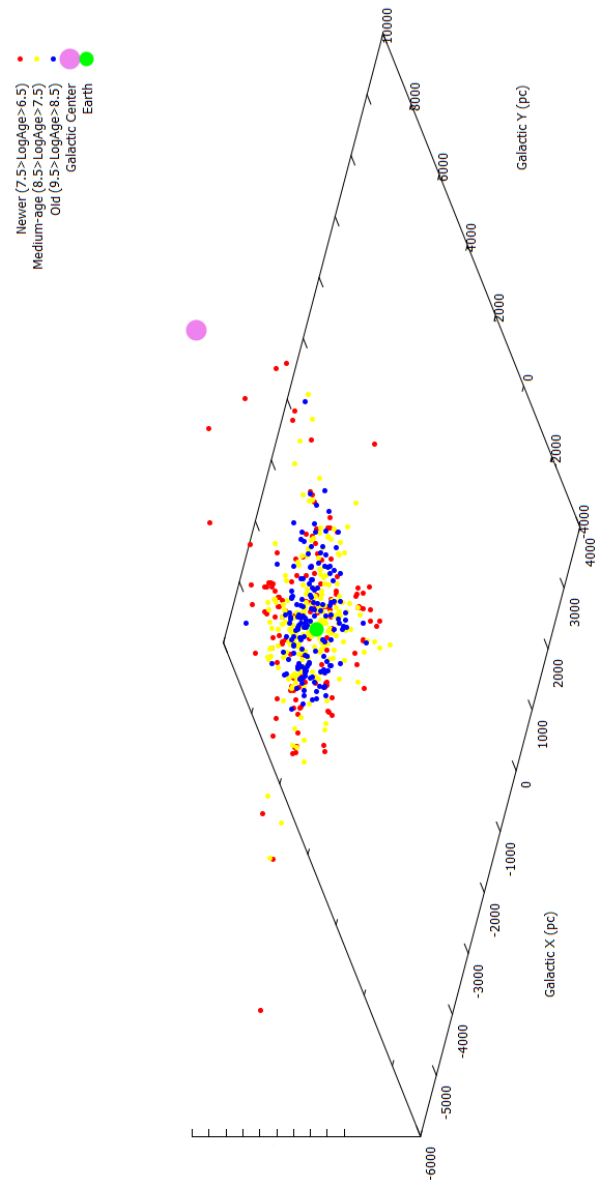

Figure 8: A gnuplot 3D scatter plot of all 520 star clusters.

Figure 8 is the result of carrying out the spherical coordinate transformations and plotting the results in a 3D scatter plot. 3 brackets (Figure 10) have been made for the logarithm of ages of the star clusters, and it is clear from Figure 11 that the older star clusters are distributed more vertically (z axis) with respect to the galactic plane, and the newer star clusters are distributed more in the x-y plane of the galaxy.

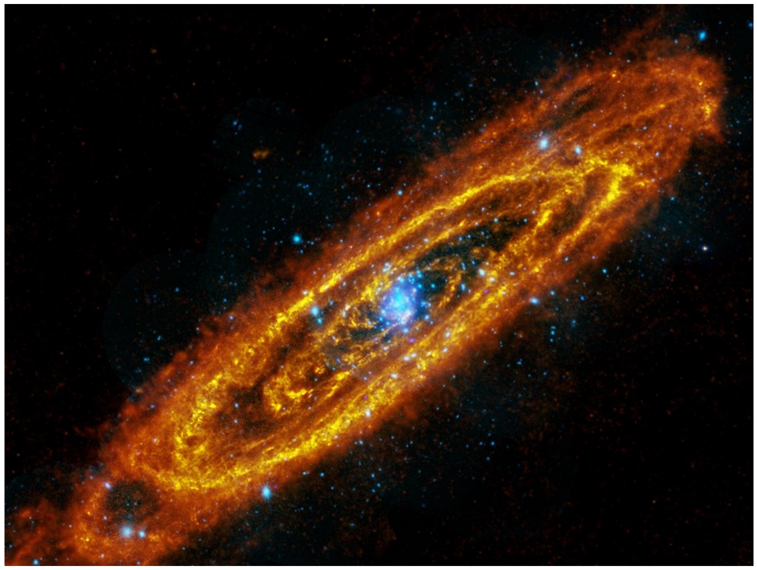

Figure 9: X-ray and infrared photograph of the Andromeda Galaxy, European Space Agency.

It is inconvenient to observe our own galaxy because of our position inside it: we cannot look through the dust and gas. However, we can look at other galaxies for clues. Figure 8.5 is an infrared (orange) and X-ray (blue) composite photograph of the Andromeda Galaxy, the Milky Way's neighbor that is predicted to collide with it. We see that the older stars which emit X-rays are clustered in the center, while the younger stars, which emit large quantities of infrared and visible light are in the dusty arms of the galaxy. When compared to Figure 8, we see a very similar distribution of stars in our galaxy: older on the inside, younger on the outside. This suggests that the Andromeda Galaxy is a perhaps good object of study if knowledge on the MWG is to be obtained. Thus, the simulation found in Figure 6 about the Andromeda Galaxy is most likely applicable and similar to the dwarf galaxy collisions in the MWG.

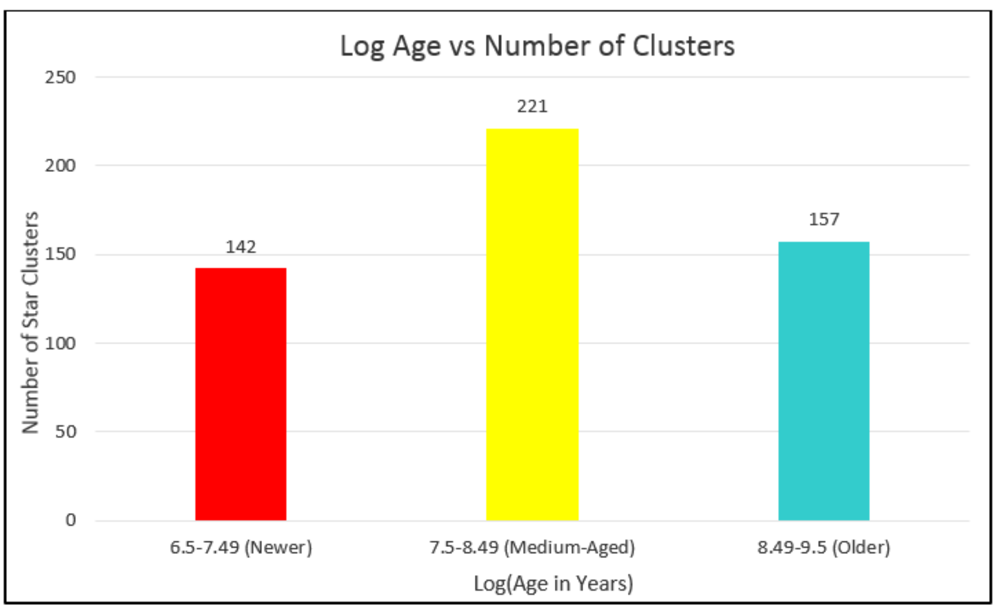

Figure 10: A bar graph of the plotted cluster age brackets, showing the age distribution.

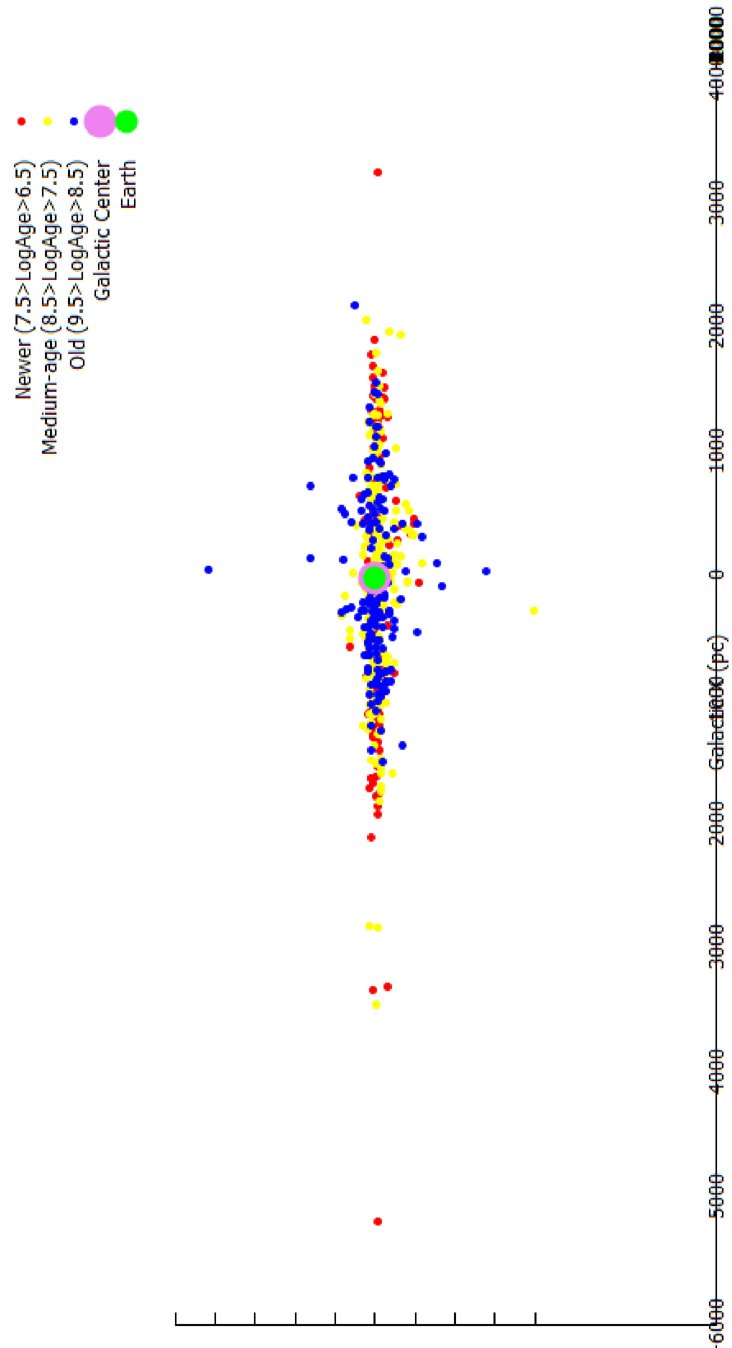

Figure 11: An alternate (side) view of the plot, looking from behind the earth towards the galactic center.

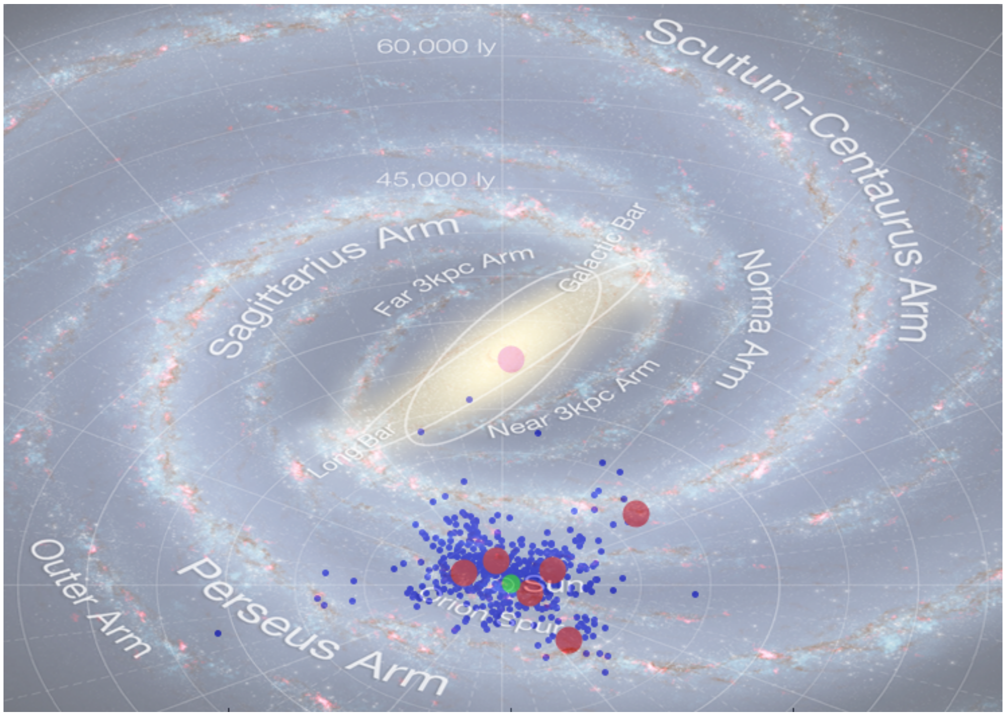

Figure 12: A gnuplot 2D representation of all 520 star clusters, with prominent red giant population clusters highlighted in red. The plot was superimposed on an illustration of the Milky Way Galaxy by NASA ("Milky Way Annotated.")

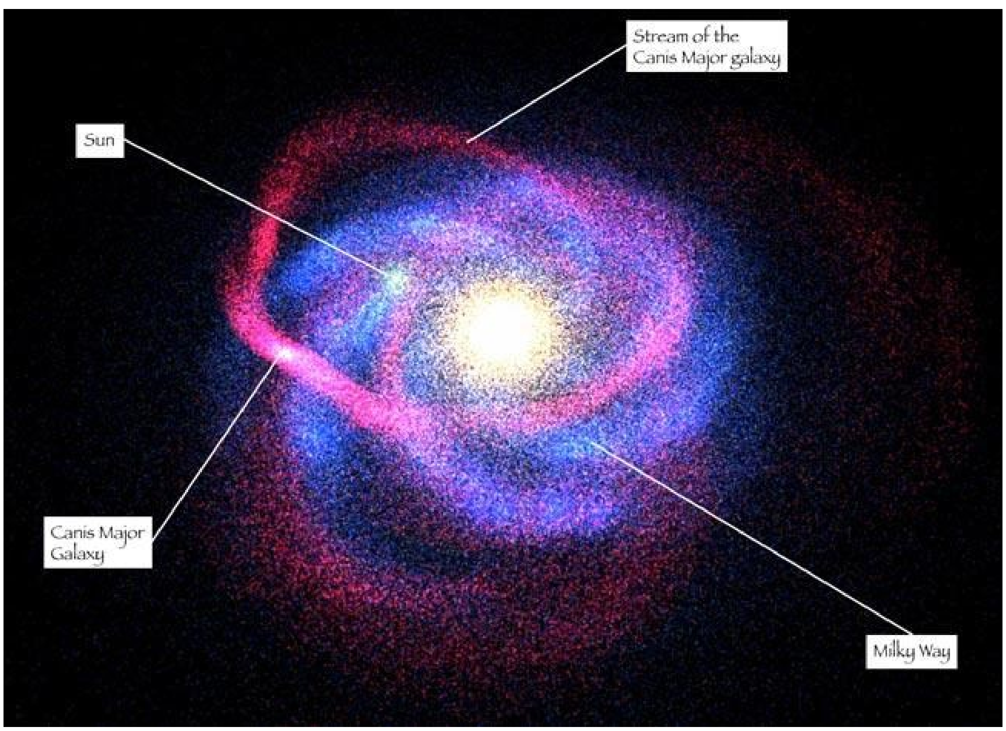

Figure 13: An illustration of the Canis Major Dwarf Galaxy remnants by R. Ibata (Strasbourg Observatory, ULP) et al. (Ibata).

Figure 12 shows the distribution of observed open clusters around the Earth. A notable observation is that there are no clusters observed outside a certain distance from the Earth. This fact is most likely explained by the dust and other material in the MWG that prevents telescopes from observing any farther. A close observation shows that the clusters containing red M giants are very close to the Earth—when looking at Figure 13, the CMDG stream also passes through the galactic plane in a region close to Earth. As mentioned previously, the CMDG has a large percentage population of red M giants, and the position data provides evidence that these star clusters were transferred from the dwarf galaxy to the MWG, most likely in a collision.

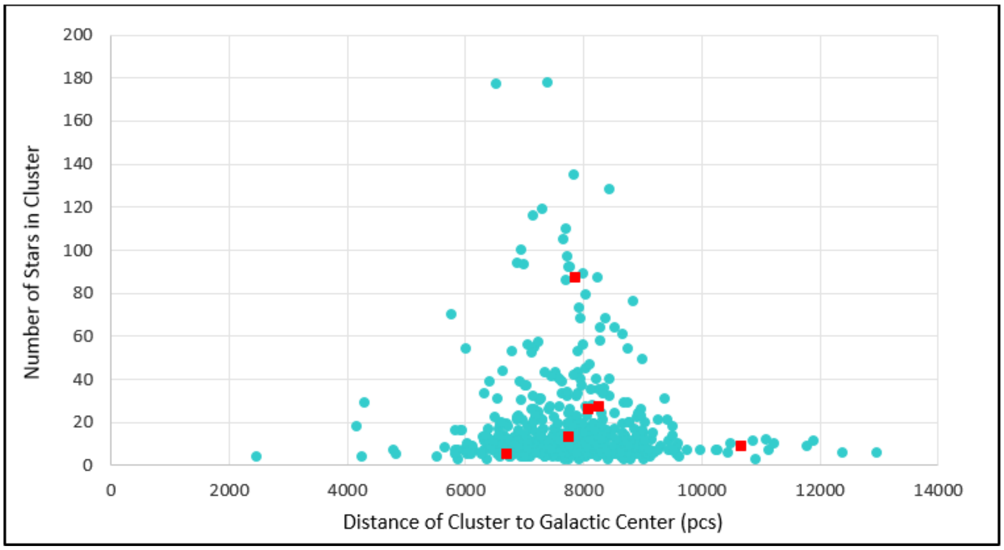

Figure 14: A graph of Galactic Center-centric distance vs. Cluster membership count.

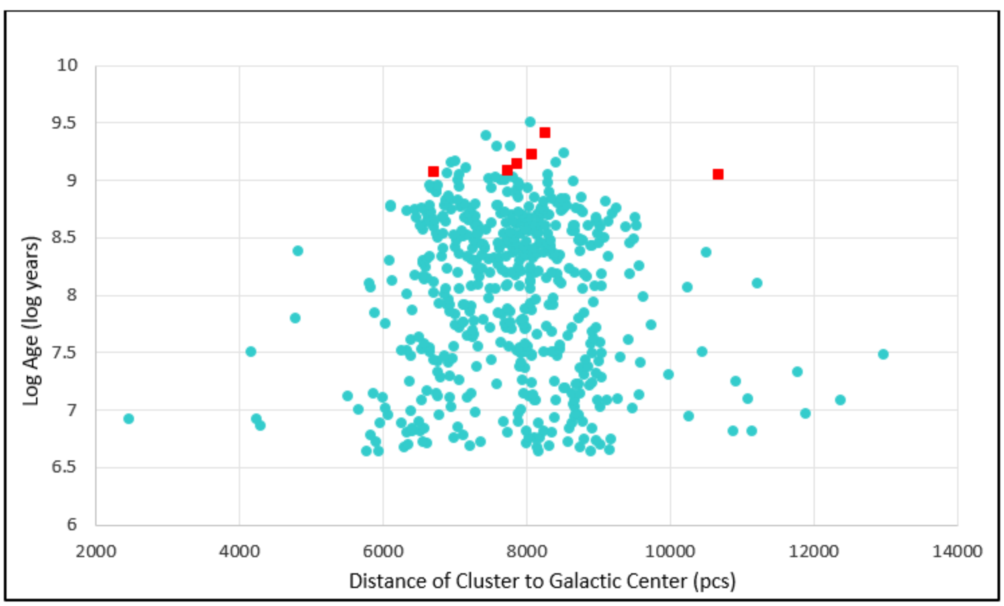

Figure 15: A graph of Galactic Center-centric distance vs. log(Age).

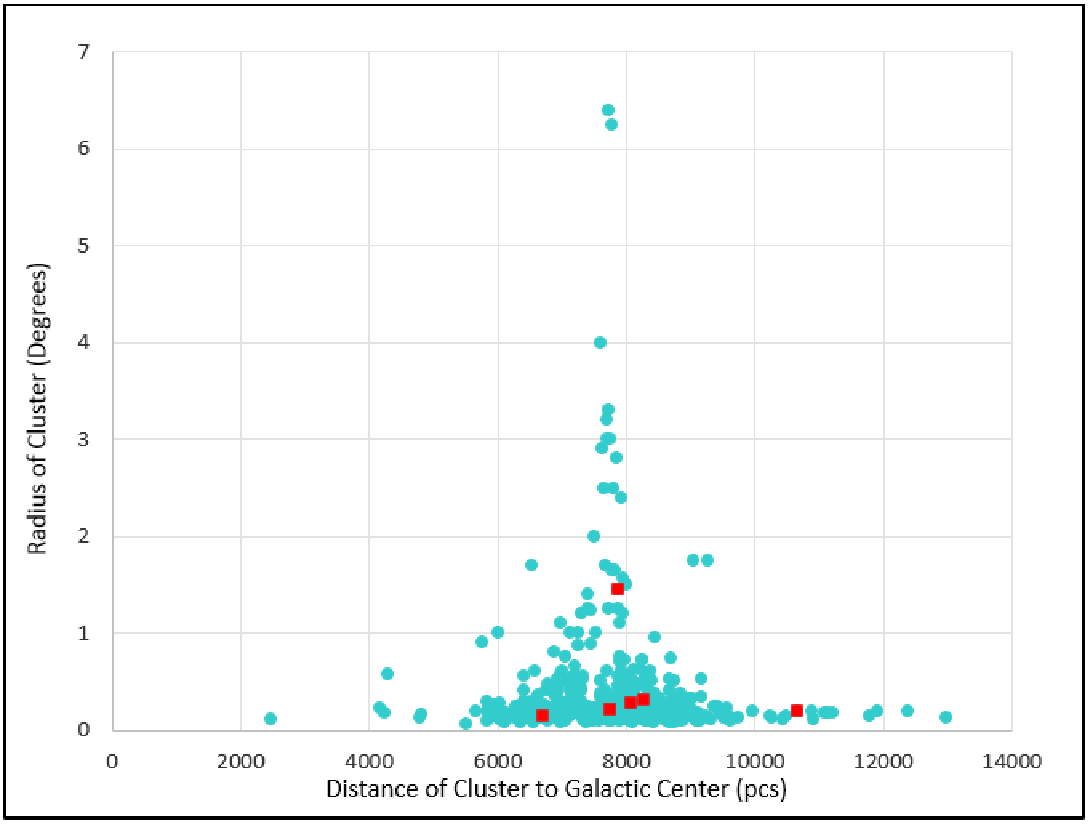

Figure 16: A graph of Galactic Center-centric distance vs. Radius of Cluster.

In Figure 14, there does not seem to be a noticeable pattern in the distribution of star clusters versus their membership counts, except for the fact that most clusters have under 60 members. The red points resemble the clusters with over 1 billion years of age and a large amount of red M giants. It is interesting to note that the clusters containing large numbers of red M giants are among the oldest in the MWG.

In Figure 15, there is no clear pattern of age versus distance from the center. The red M giants were selected based on their age (greater than 1 billion years), so the fact that they all have a log(Age) of greater than 9 is no surprise.

In Figure 16, most of the old clusters have a small radius. This suggests that as age of a cluster increases, its radius shrinks due to loss of its outermost member stars.

5 Implications, Discussion, and Conclusions

After the review of earlier studies on dwarf galaxy remnants, the appearance of rare red M-giant stars in various star clusters suggests that the cannibalized Canis Major Dwarf Galaxy has contributed to membership of star clusters in the MWG (namely NGC 2506, 6208, 3680, 752, 7789, 2682). Figures 12 and 13 agree with each other in that the approximate location of the red giant-containing clusters coincides with the location of the Canis Major Dwarf Galaxy tidal stream near the solar system. Because of the newly discovered fact that red M giants can be taken from other dwarf galaxies and deposited in star clusters of the MWG, it is likely that other foreign stars have been deposited in star clusters as well. The assumption that all open clusters contain stars created around the same time period as other members is not always valid, and previous open cluster studies involving Hertzsprung-Russell diagram fitting to find the age of clusters should be edited to discard clear outlier stars that likely originated outside the cluster itself. The discovery of red giant star exchange confirms the possibility of simulations by Purcell et al. (Figure 4) and Dierickx et al. (Figure 6) involving dwarf galaxy cannibalization by both the MWG and the Andromeda Galaxy, and suggests that these interactions indeed existed and, if these simulations are physically correct, contributed to spiral arm formation of both galaxies. There is also a large possibility of observing contributions of guest stars and clusters from the Sagittarius Dwarf Galaxy, but there is currently no identifying trait to those contributions, unlike the red M giant stars that came from the CMDG. Since these contributions originated in a foreign place, their elemental abundances should be different from the typical open cluster native to the MWG. Identifying these elemental differences will be crucial to identifying these foreign stars and OCs. Along with their elemental composition differences, the range of their ages may be constrained using the simulation found in Figure 4—it is likely that the contributions are older than the time of galaxy collision.

6 Further Research

Currently, vector calculations based on the velocities of the individual star clusters are being performed (Figure 17), so that any non-uniform directional movement of clusters can be plotted and pointed out visually and the cluster labeled a foreign cluster originating from outside the MWG. A mathematical approach can also be implemented, in which the magnitude of velocity can be plotted, and anything going too fast or too slow can be investigated individually. Also, the possibility of using cluster velocity data to determine the dark matter halo density profile of the MWG is being explored.
Use of the GAIA mission (approx. 2018) to collect more data on stars and star clusters can help identify more likely candidates for the Milky Way's shaping process. There are much more than 520 star clusters in the Milky Way, and the arm across the galactic center has not been identified yet.

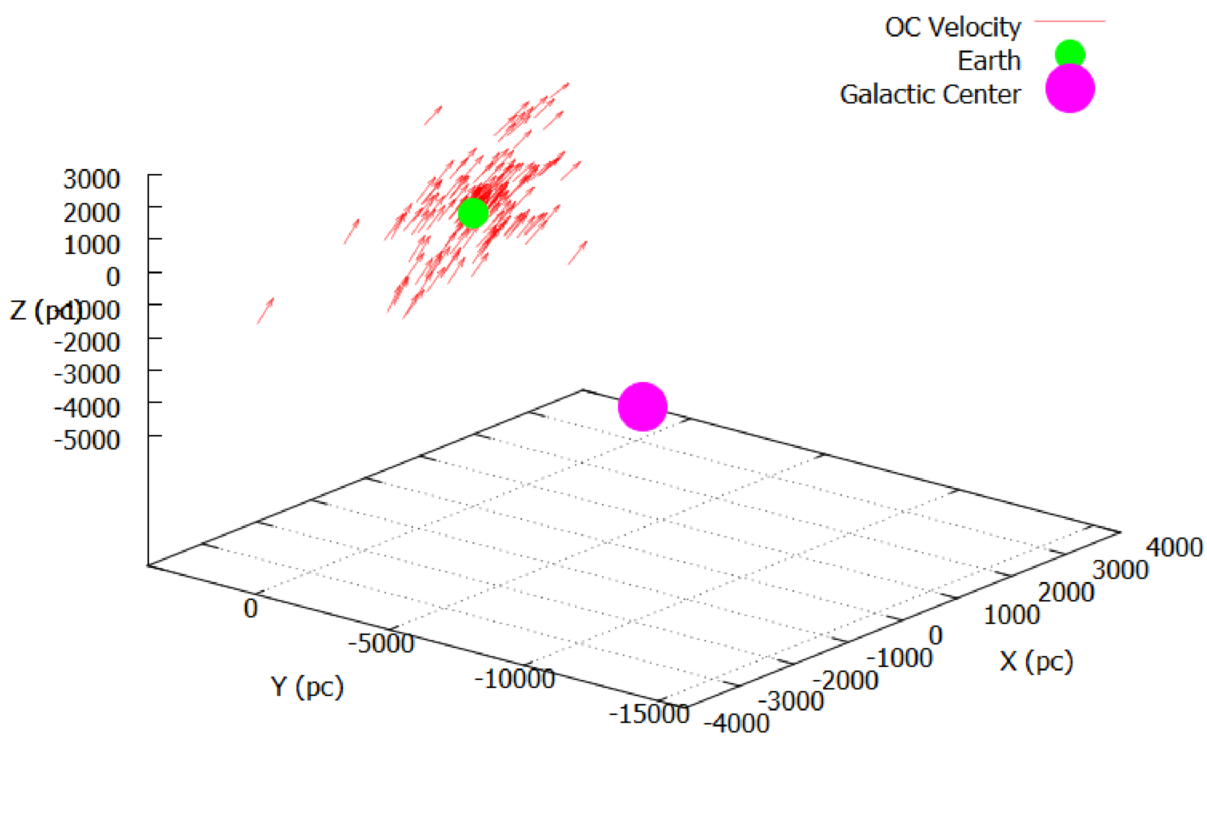

Figure 17: A 3D Vector Plot of OC Velocities.

7 Appendix: Methods of data measurement

7.1 Distance

Distance measurements to stars or clusters can be performed using parallax observations for closer objects, or Main Sequence fitting for more distant stars. Main Sequence fitting is especially effective on open clusters due to the large number of members available to plot.

7.2 Mass

The mass of a star can be found using the mass-luminosity relation, in the following equation:

$$\frac{L}{L_{\odot}} = (\frac{M}{M_{\odot}})^{a} \tag{7}$$

where a is 3.5 for main sequence stars.

7.3 Temperature

Temperature can be found using the Hertzsprung-Russell (HR) diagram or the Plank Law.

7.4 Age

The age of a cluster can be found using a combination of mass, luminosity, and turnoff star data. The mass of the first turnoff stars in a sequence of plotted stars (as in the case of an OC) can be used to determine the current age of the entire OC.

7.5 Velocity and Position

Velocity and position measurements can be acquired from observation over time.

8 Acknowledgements

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The University of Connecticut Mentor Connection Programme

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