Krittika Summer Project 2024

Pinpricks of the Vortex

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Abstract

Star clusters are gravitationally bound groups of stars from the same molecular cloud, are vital in studying stellar evolution and galactic dynamics.These were analysed using aperture photometry facilitated by the photutils library. This technique measures light flux from stars within specified apertures and accounts for background noise to calculate accurate brightness in magnitude. These measurements help to understand stars' properties and evolutionary stages in clusters, improving the knowledge of stellar and galactic evolution.

Contents

1. Stars

1.1 Stars

Stars are immense spheres composed primarily of hot gas, mainly hydrogen, along with helium and trace amounts of other elements. Each star follows a unique life cycle that spans from a few million to several trillion years, with its characteristics evolving over time.

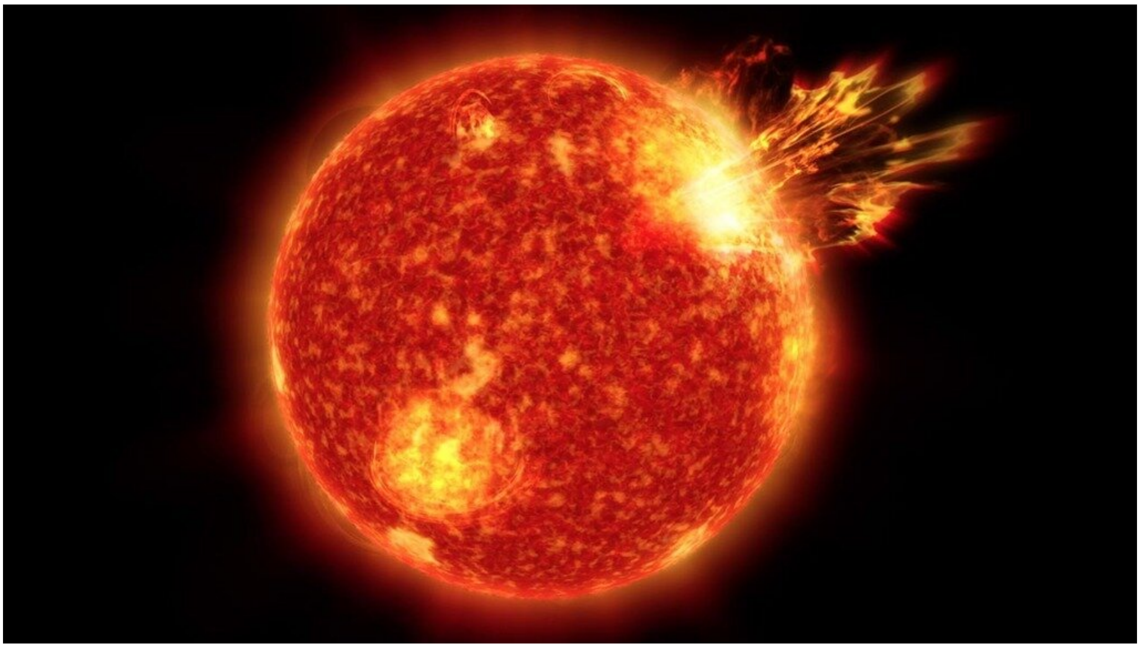


Figure 1.1: A Star

1.1.1 Stellar Population

Population I stars and **Population II** stars are two broad classes of stars and stellar assemblages defined in the early 1950s by the German-born astronomer Walter Baade.

Population I:

- Age: Population I consists of younger stars, clusters, and associations. These stars were formed about 1,000,000 to 1,000,000,000 years ago.
- Composition: They are relatively rich in heavier elements (such as iron, nickel, and carbon) compared to hydrogen and helium. These elements were created through processes like supernova explosions.
- Location: Population I stars occur near and in the arms of the Milky Way system and other spiral galaxies. They are also found in some young irregular galaxies.

Population II:

- Age: Population II consists of the oldest observed stars and clusters, which were formed about 1,000,000,000 to 15,000,000,000 years ago.
- Composition: These stars are relatively poor in heavier elements (elements heavier than helium). They contain 10 to 100 times less of these elements than Population I stars.
- Location: Population II stars are found in the halos of spiral galaxies and in globular clusters within the Milky Way system. They also occur in elliptical galaxies.

In summary, Population I stars are younger, metal-rich, and found in the disk of galaxies, while Population II stars are older, metal-poor, and often located in galactic halos and globular clusters.

1.2 Stellar Classification

Stellar classification is a system astronomers use to categorize stars based on their spectral characteristics, surface temperature, luminosity, and other properties.

O-Type Stars:

These are the hottest and most luminous stars, with surface temperatures exceeding 30,000 K. They appear blue-white in color and are relatively rare. O-type stars are typically found in young, massive star-forming regions.

B-Type Stars:

Slightly cooler than O-type stars, B-type stars have temperatures between 10,000 and 30,000 K. They are also blue-white in color and are known for their strong spectral lines of helium. B-type stars are massive and luminous, often found in young star clusters.

A-Type Stars:

These stars have surface temperatures between 7,500 and 10,000 K, appearing white or bluish-white. These stars are smaller and less massive than O and B-type stars but still relatively luminous. They are often used as standard stars for comparing other stars' properties due to their stability.

F-Type Stars:
With surface temperatures ranging from 6,000 to 7,500 K, they appear yellow-white. They are similar in size and mass to the Sun but are generally more luminous. Many nearby stars, including some visible to the naked eye, belong to this spectral class.

G-Type Stars:
The Sun's class. They have surface temperatures between 5,000 and 6,000 K, appearing yellow. G-type stars are often used as reference points for habitable zones and the search for exoplanets.

K-Type Stars:
Cooler than G-type stars, K-type stars have surface temperatures between 3,500 and 5,000 K, appearing orange in color. They are less massive and luminous than the Sun, including many red giants.

M-Type Stars:
These are the coolest and most common stars in the universe, with surface temperatures below 3,500 Kelvin. They appear red and are often called red dwarfs. M-type stars have long lifespans and are known to host many exoplanets.

1.3 Star Clusters

1.3.1 Introduction

A star cluster is defined to be an obvious concentration of several stars or more above the surrounding stellar background, apparently localized in space and identifiable on visual or infrared images covering a suitable field of view.

1.3.2 Types of Star Clusters

Star clusters are categorized primarily into two main types: **open clusters** and **globular clusters**. Additionally, there exist **stellar associations**, **moving groups**, and **embedded clusters**, each with distinct features.

Open Clusters

Open clusters are loosely bound groups of stars that usually contain a few dozen to a few thousand members. They are found primarily in the galactic plane and are relatively young, with ages ranging from a few million to a few billion years. Examples include the Pleiades and the Hyades clusters.

- **Formation and Characteristics**: Open clusters form from giant molecular clouds and are often associated with regions of active star formation. They exhibit a wide range of ages and stellar compositions but generally consist of Population I stars, which are metal-rich.
- **Stellar Density and Distribution**: These clusters have low stellar densities and can span a few parsecs in diameter. They tend to dissipate over time due to internal dynamical processes and external tidal forces from the galactic gravitational field.

Globular Clusters

Globular clusters are densely packed, roughly spherical collections of stars, containing tens of thousands to millions of members. They orbit the galactic core and are much older than open clusters, with ages exceeding 10 billion years.

- **Formation and Characteristics**: Globular clusters are among the oldest objects in the galaxy, formed during the early stages of galactic evolution. They consist mainly of Population II stars, which are metal-poor compared to younger stars.
- **Stellar Density and Distribution**: These clusters exhibit high stellar densities, particularly towards their centers, and have typical diameters of about 10 to 30 parsecs. Their stars are tightly bound by gravity, making them stable over long periods.

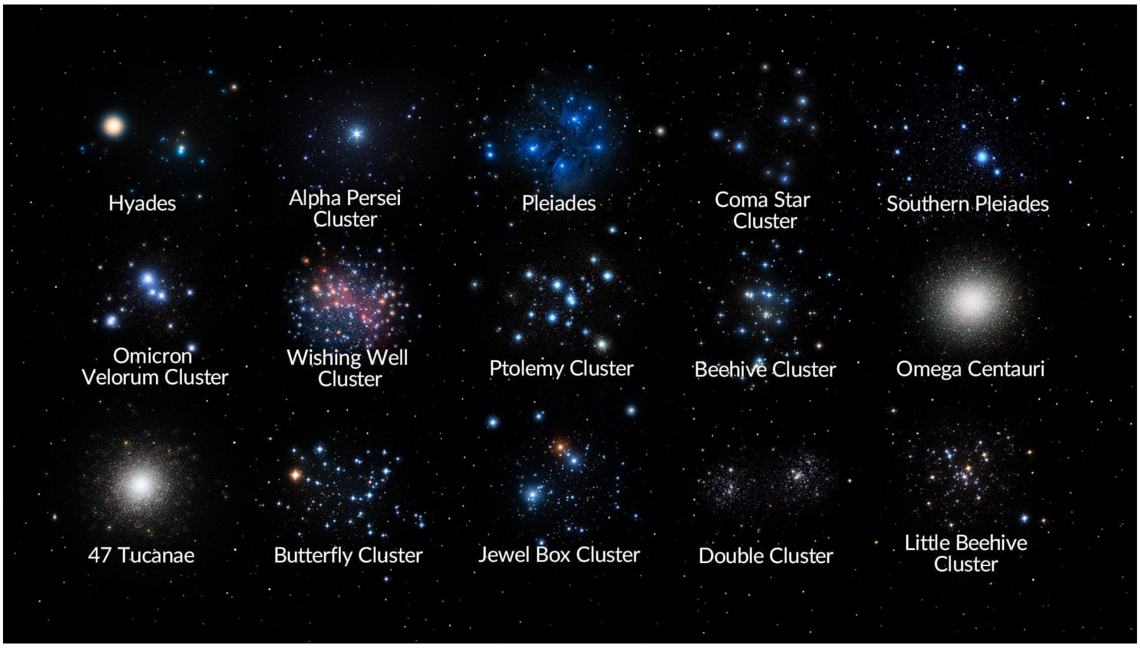


Figure 1.2: Some Prominent Clusters

Stellar Associations

Stellar associations are groups of stars that are not gravitationally bound and will disperse over time. They are primarily composed of young, massive stars, such as O and B types (OB associations), or young pre-main-sequence stars.

Moving Groups

Moving groups are collections of stars that share common motion through space, believed to have originated from the same star-forming region. Unlike stellar associations, moving groups can consist of older stars.

Embedded Clusters

Embedded clusters are groups of young stars still enshrouded in the gas and dust of their natal molecular cloud. They are often identified through infrared observations due to the obscuring effects of the surrounding material.

1.3.3 Significance of Star Clusters

Star clusters serve as fundamental laboratories for studying stellar evolution and dynamics. They allow astronomers to test models of star formation, calibrate distance measurements, and understand the chemical and dynamical evolution of the galaxy.

2. PHANGS

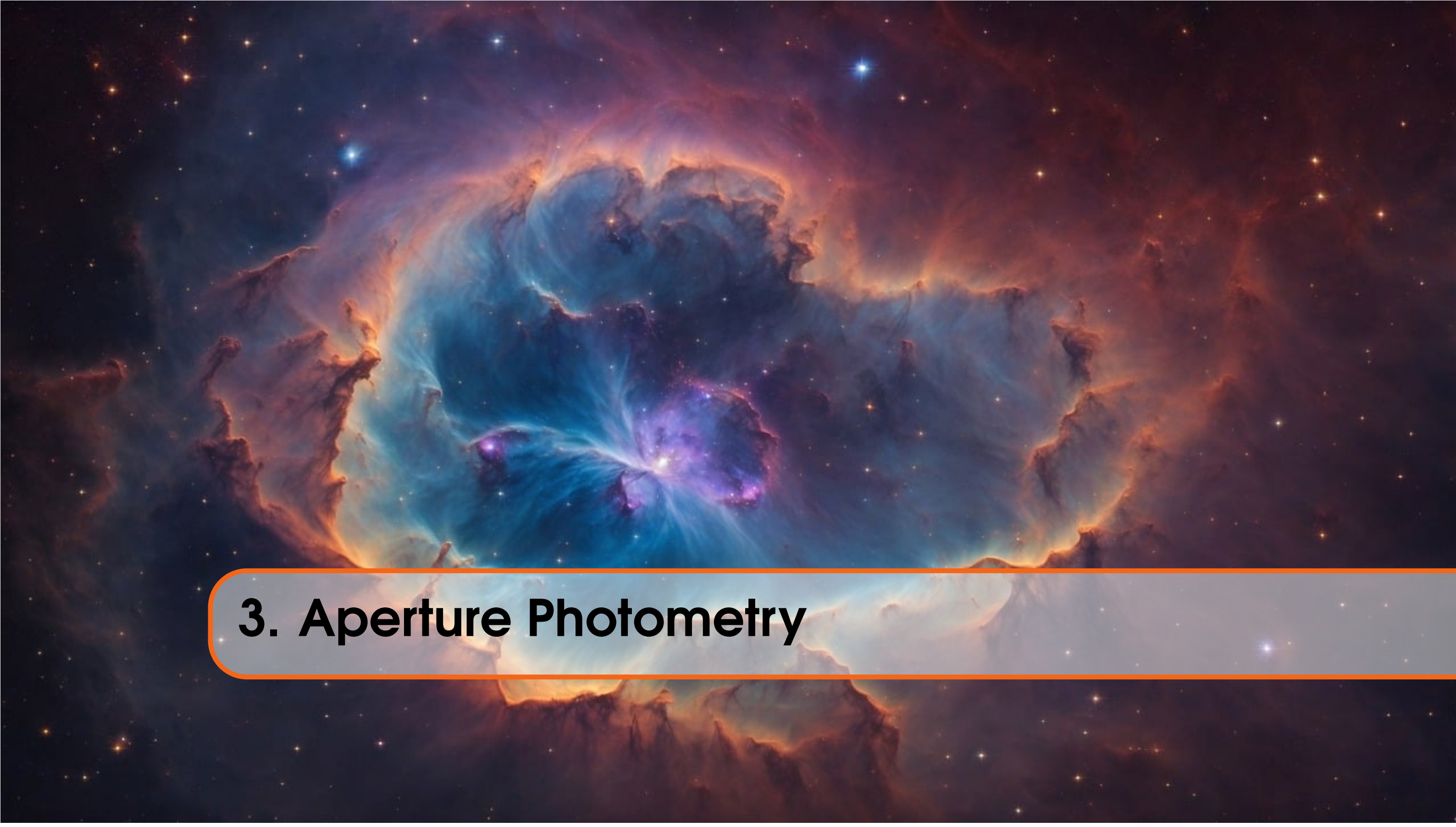
The PHANGS (Physics at High Angular Resolution in Nearby GalaxieS) survey is conducting high-resolution observations of nearby galaxies using multiple telescopes, including ALMA, Hubble, JWST, and the VLT. This survey aims to investigate the interplay between the small-scale physics of gas and star formation and the larger galactic structure and evolution. By studying nearby galaxies, the PHANGS survey seeks to understand how processes occurring at or near the "cloud" scale are influenced by galactic-scale conditions, how these processes impact even smaller-scale phenomena, and how they collectively drive the evolution of entire galaxies.

The catalog I am using is the Hubble Space Catalog(HSC). [1]

The galaxy I am working on is NGC 1365, commonly known as the Great Barred Spiral Galaxy. Situated in the constellation Fornax, NGC 1365 is distinguished by its double-barred spiral structure, a rare and notable feature among galaxies. This galaxy is renowned for its prominent central bar, which is flanked by an additional inner bar, giving it a striking appearance in observational images.
NGC 1365 hosts a supermassive black hole at its core, which is currently in an active state of accretion. The intense gravitational forces exerted by this black hole are pulling in surrounding material, leading to significant radiation emission. This high-energy activity classifies NGC 1365 as an active galactic nucleus (AGN). The AGN's radiation spans a broad spectrum, including X-rays and other high-energy emissions, providing valuable insights into the dynamics of supermassive black holes and their impact on their host galaxies.

[1] For more information, `https://catalogs.mast.stsci.edu/hsc`

Figure 2.1: NGC 1365



3. Aperture Photometry

Photometry is the technique of measuring the brightness of astronomical objects. To do so, we quantify the signal from a given source collected on our camera during the exposure. In other words, we only measure the instrumental flux of a source. One of the techniques used is Aperture Photometry.

In this, The signal is integrated over a circular aperture defined around the star of interest. To compensate for a non-zero background brightness (e.g. due to natural night sky emission or artificial light pollution), the sky brightness is estimated in a concentric annulus around the aperture and subtracted from the object signal.

3.1 Radius of aperture

The specific radii were determined using the WCS module from the Astropy library. The computed aperture radius is $4.28052672532827 \approx 4$ pixels. The annulus radii I took is 7 pixels for inner and 8 pixels for outer radius.

3.2 Corrections

The corrections made are:-

1. Background Corrections: Adjustments to account for background noise in the observations.
2. Aperture Corrections: Adjustments to account for the diffraction pattern of the instrument's aperture.
3. Extinction Factor: Adjustments to correct for scattering losses caused by dust and gas.
4. PHOTNU Factor: Inverse sensitivity correction provided in the catalog.
5. Adjustments to convert flux measurements to magnitudes accurately.
6. Adjustments to convert Vega magnitudes to absolute magnitudes accurately.

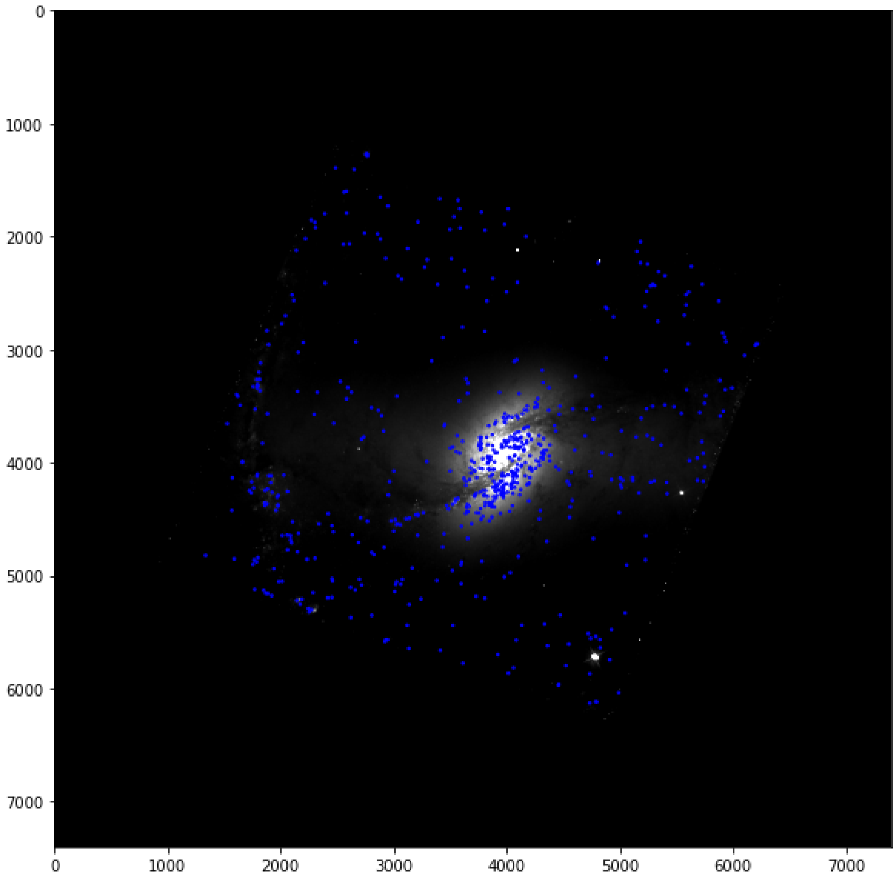


Figure 3.1: Positions of Clusters in NGC 1365

3.3 Photometric Plot

The plot of my photometry vs catalogue photometry for each filter after applying the corrections are -

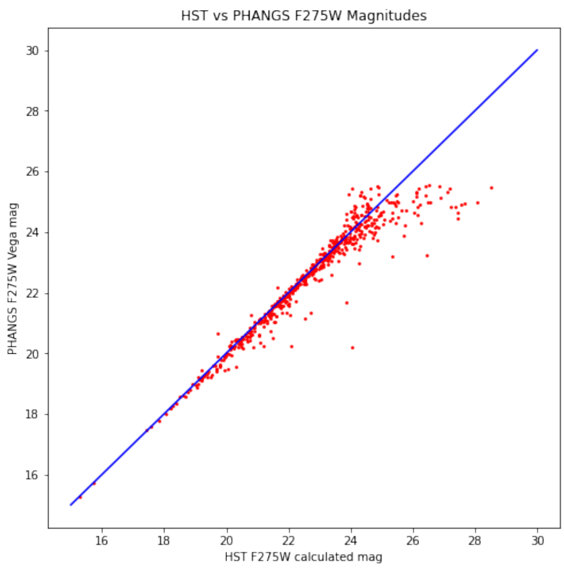


Figure 3.2: Filter 275

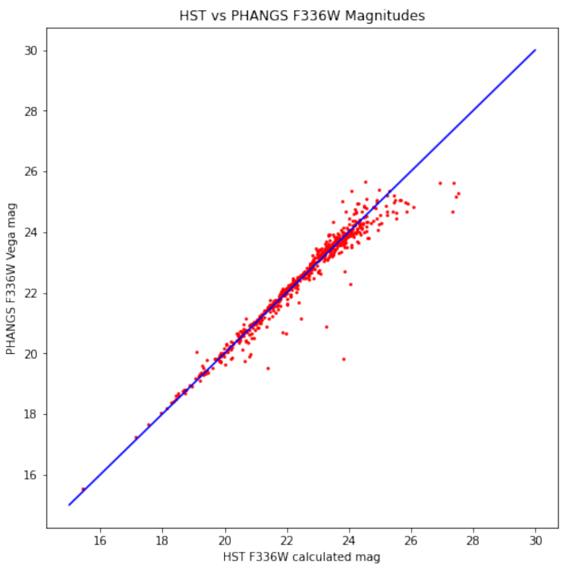


Figure 3.3: Filter 336

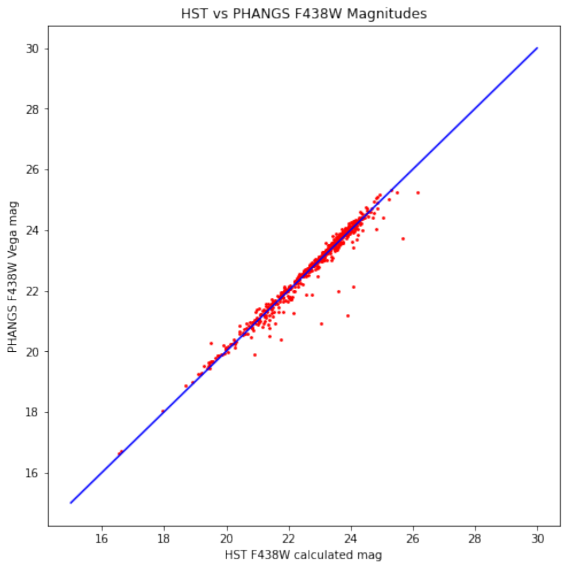


Figure 3.4: Filter 438

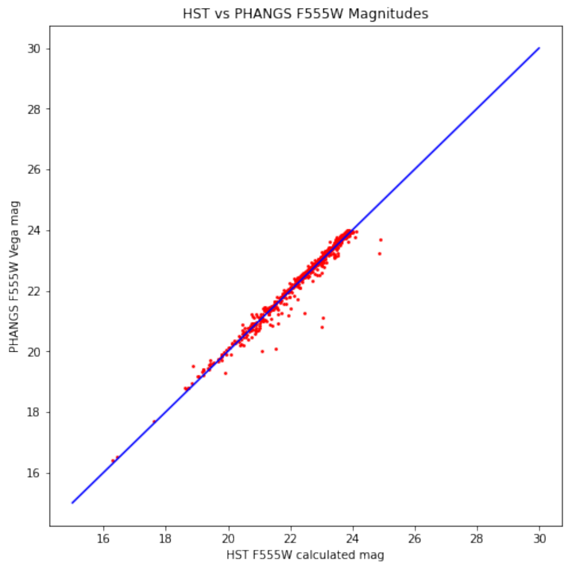


Figure 3.5: Filter 555

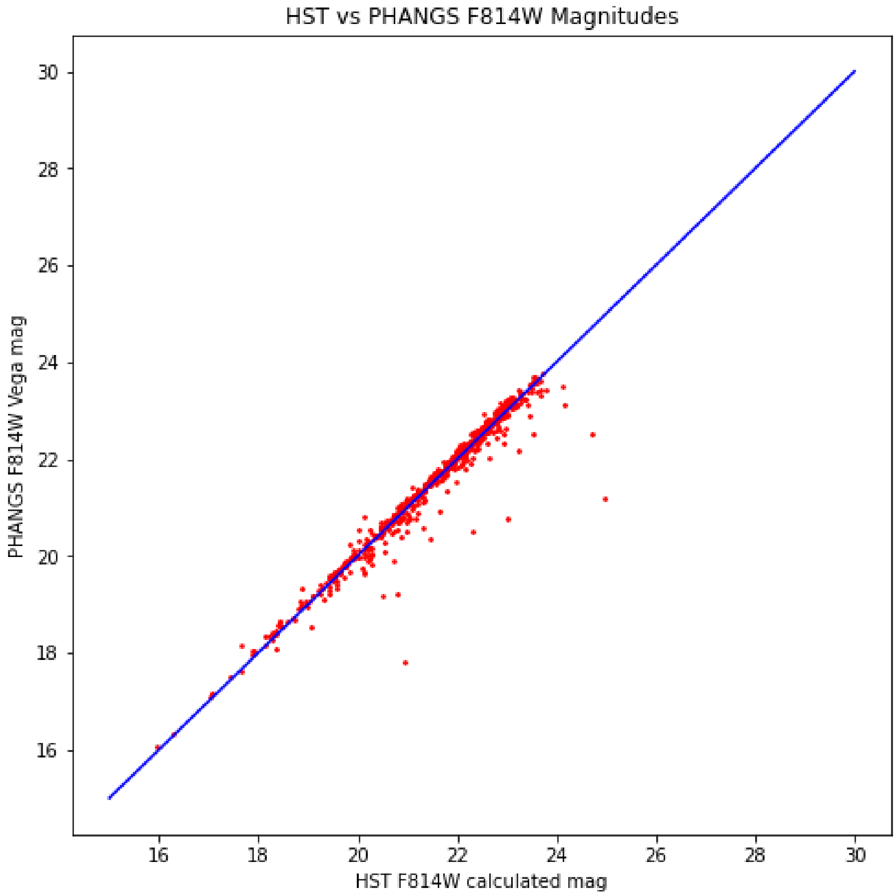


Figure 3.6: Filter 814

4. Colour-Colour Diagrams

Color-color diagrams are a tool in observational astronomy, used to investigate the properties and classifications of celestial objects. They plot the difference in magnitudes (or colors) between two different filters, creating a graph where each point represents an object under consideration.

To construct a color-color diagram, multiple photometric bands are utilized.

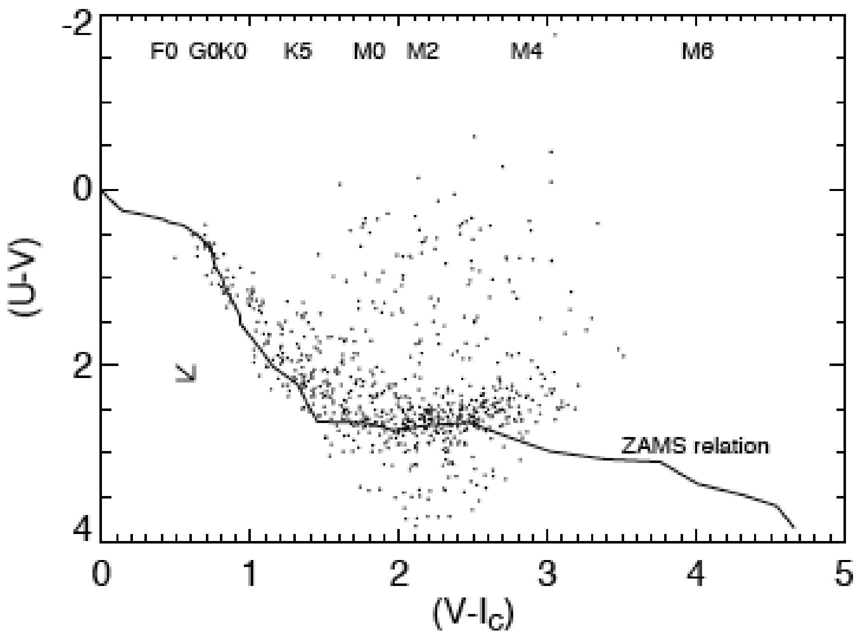


Figure 4.1: Example Colour Colour Diagram

Here I plotted the color index derived from the band (555-814) on the x-axis and

the color index derived from the band (336-438) on the y-axis. Each point on the diagram represents the colors of an object as measured in these bands, plotted with the x-axis representing the band (555-814) and the y-axis representing the band (336-438).
To provide a framework for interpreting the color-color diagram, theoretical evolutionary tracks of star clusters were overlaid. These tracks are derived from models of stellar evolution and illustrate the expected color indices of star clusters at various ages. By comparing the observed data points with these theoretical tracks, the ages of the star clusters can be estimated. The intersections between the observed data and the theoretical tracks offer insights into the evolutionary stages and ages of the clusters.

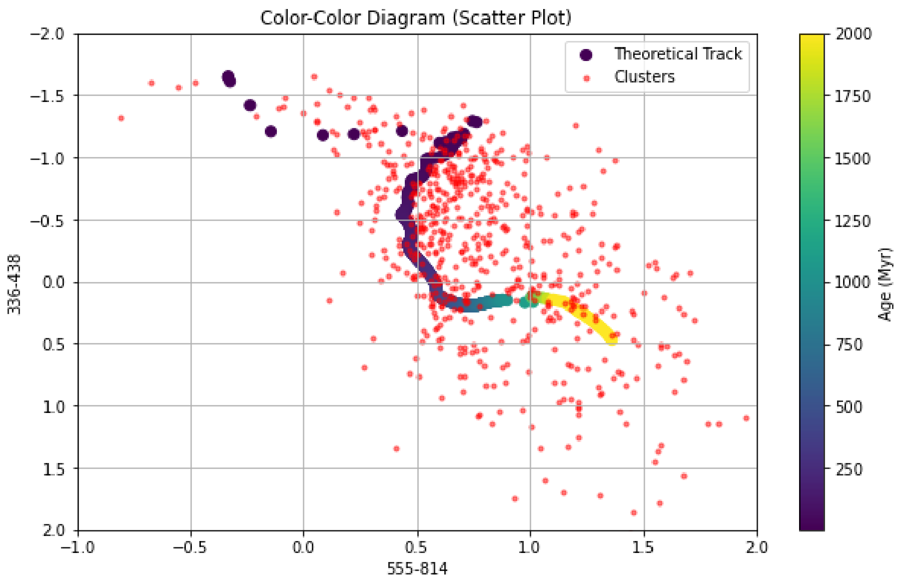


Figure 4.2: Scatter Plot for Clusters, with age track

Based on the age classifications of the star clusters, which were categorized as young, middle-aged, and old, I observed that the spatial distribution of these clusters within the galaxy varies significantly. Specifically, young clusters are predominantly located towards the outer regions of the galaxy, often along the spiral arms. In contrast, older clusters are more commonly found near the galactic center. This distribution pattern can be attributed to the effects of the supermassive black hole (SMBH) at the galactic core, which generates substantial gas turbulence. This turbulence inhibits star formation close to the center by preventing the gravitational collapse of gas clouds.

4.1 ALMA Gas Density Plots

I also plotted the ALMA gas data to further analyze the spatial distribution of star clusters. ALMA (Atacama Large Millimeter/submillimeter Array) provides detailed observations of molecular gas in galaxies, which are crucial for understanding star formation. The data includes measurements of various gas components such as carbon monoxide (CO) and dust emission, which trace the distribution and density of the interstellar medium. This high-resolution imaging allows for a comprehensive

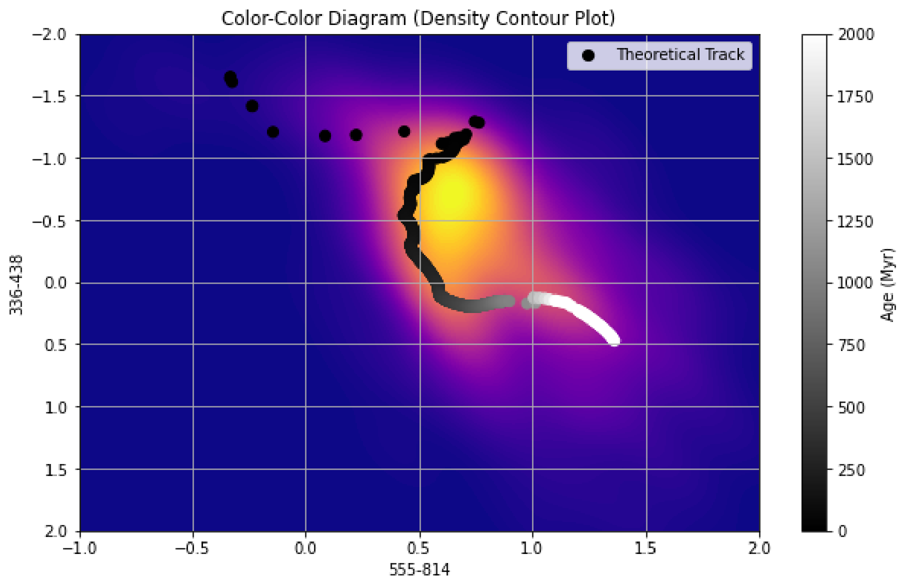


Figure 4.3: Density Plot for Clusters, with age track

view of the gas structure within the galaxy, aiding in the investigation of star formation processes and their relation to the observed cluster distributions

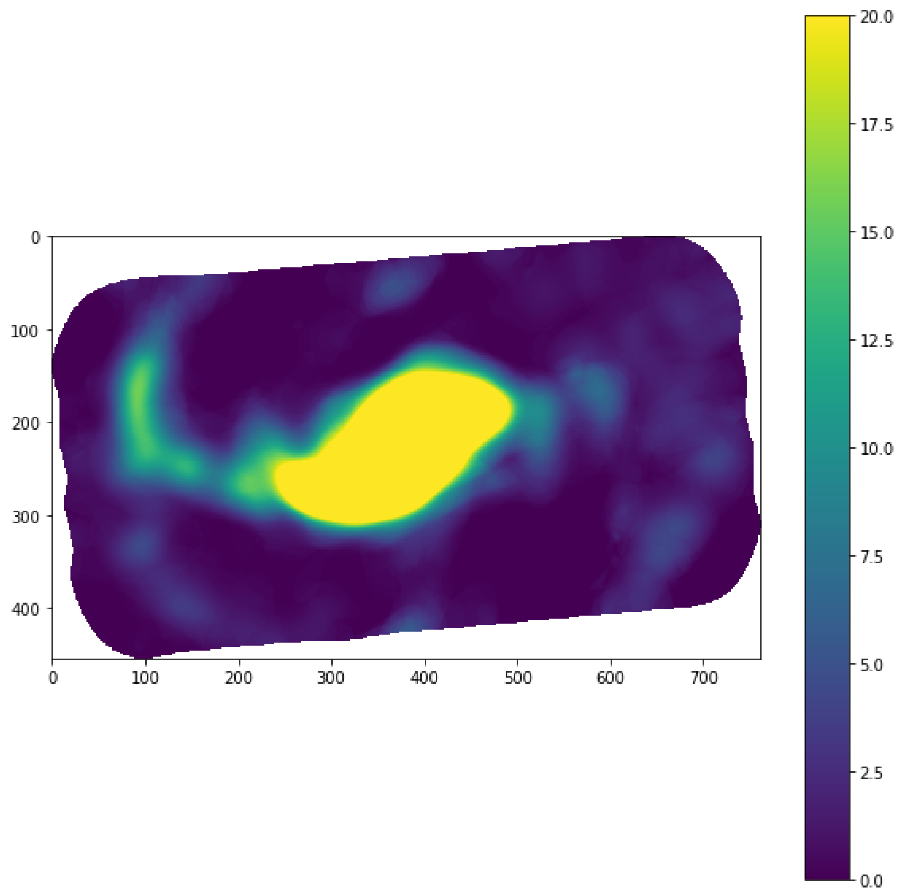


Figure 4.4: ALMA Plot

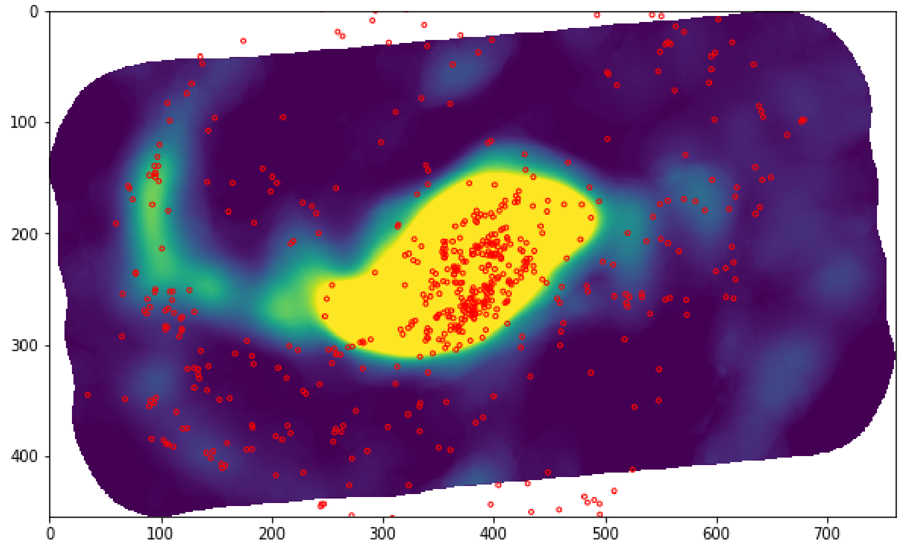


Figure 4.5: Position of Star Clusters on the gas plot

4.2 Cluster - Gas Density Plots

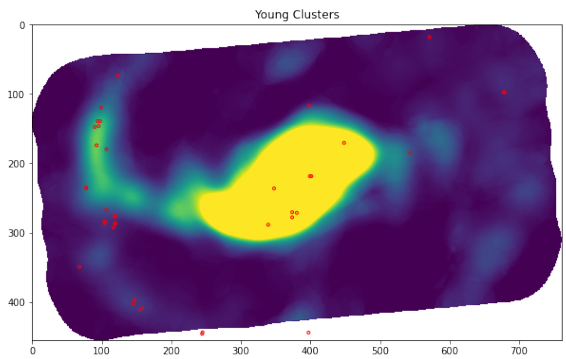


Figure 4.6: Young Clusters

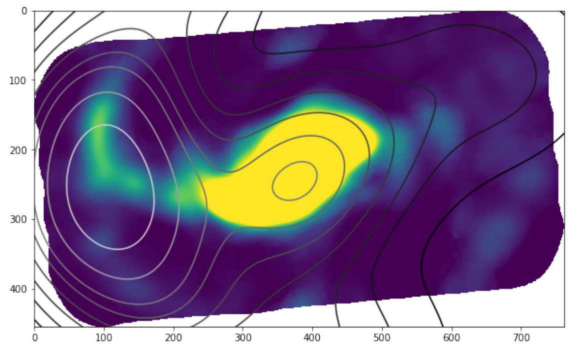


Figure 4.7: Contour Map

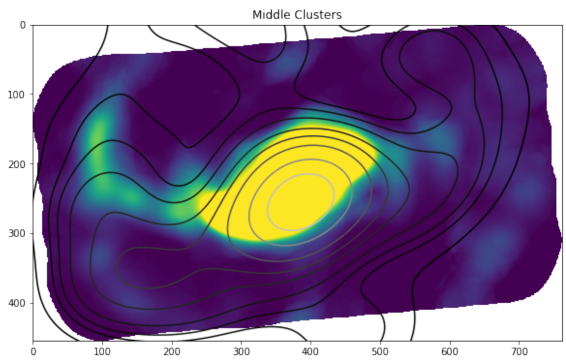


Figure 4.8: Middle Clusters

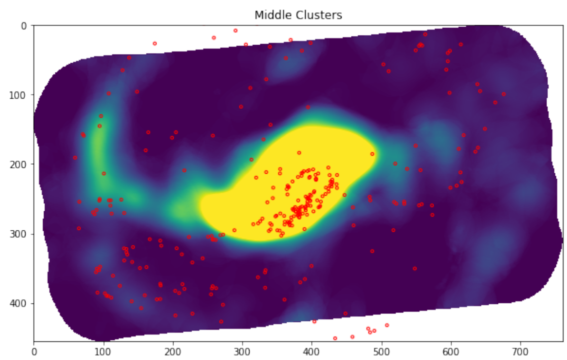


Figure 4.9: Contour Map

I superimposed the age classification of the star clusters onto the ALMA gas plots to further investigate their spatial relationship with the molecular gas distribution. The

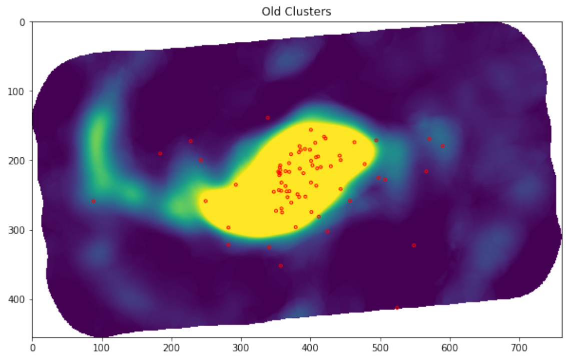


Figure 4.10: Old Clusters

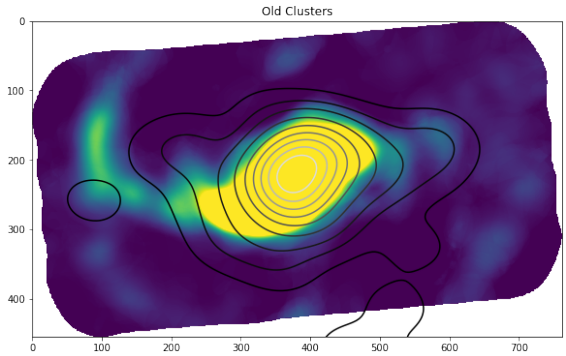


Figure 4.11: Contour Map

analysis corroborates the earlier findings, showing that young clusters are primarily situated along the spiral arms, where star formation is more active. Conversely, older clusters are predominantly located near the galactic center, within the thicker halo region. This pattern aligns with the understanding that the central regions, influenced by the supermassive black hole, are less conducive to star formation, while the spiral arms provide a more favorable environment for the formation of younger star clusters.

5. Further Classifications

In the analysis of star clusters within the galaxy, PHANGS categorized them into two distinct classes (actually four) based on their spatial and morphological characteristics.

5.1 Classes:

5.1.1 Class 1 (C1): Single Peak Circularly Symmetric Clusters

- **Description:** Class 1 star clusters exhibit a well-defined, single peak in their spatial distribution. These clusters are characterized by a circularly symmetric radial profile, indicating a uniform distribution of stars around a central point.
- **Radial Profile:** The radial profile of Class 1 clusters is more extended compared to a point source. This means that the density of stars in these clusters decreases gradually with distance from the center, forming a smooth, symmetric gradient. The extended profile suggests a more dispersed and evenly distributed structure.
- **Visual Characteristics:** On imaging, Class 1 clusters appear as round or nearly round structures with a smooth intensity gradient from the center to the periphery. The circular symmetry implies that the distribution of stars is uniform in all directions from the center.
- **Implications:** The circular symmetry and extended radial profile of Class 1 clusters indicate a stable star formation environment. These clusters likely formed under conditions that allowed for an isotropic distribution of stars, leading to a more homogeneous and stable cluster structure.

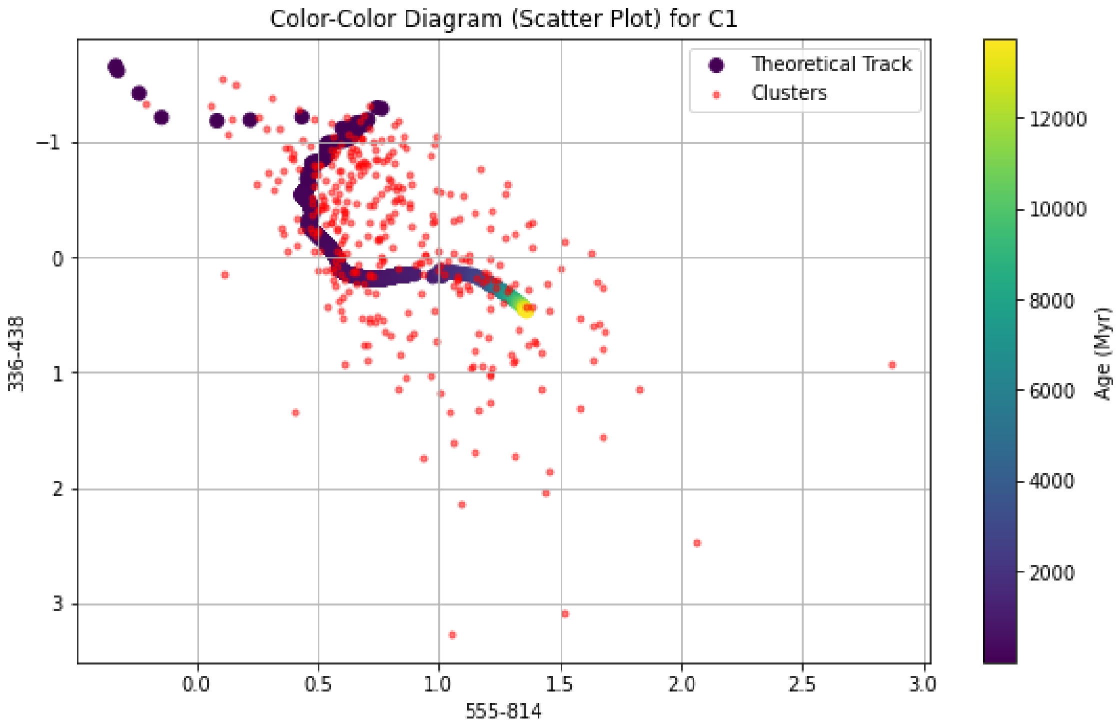


Figure 5.1: C1 Scatter Plot

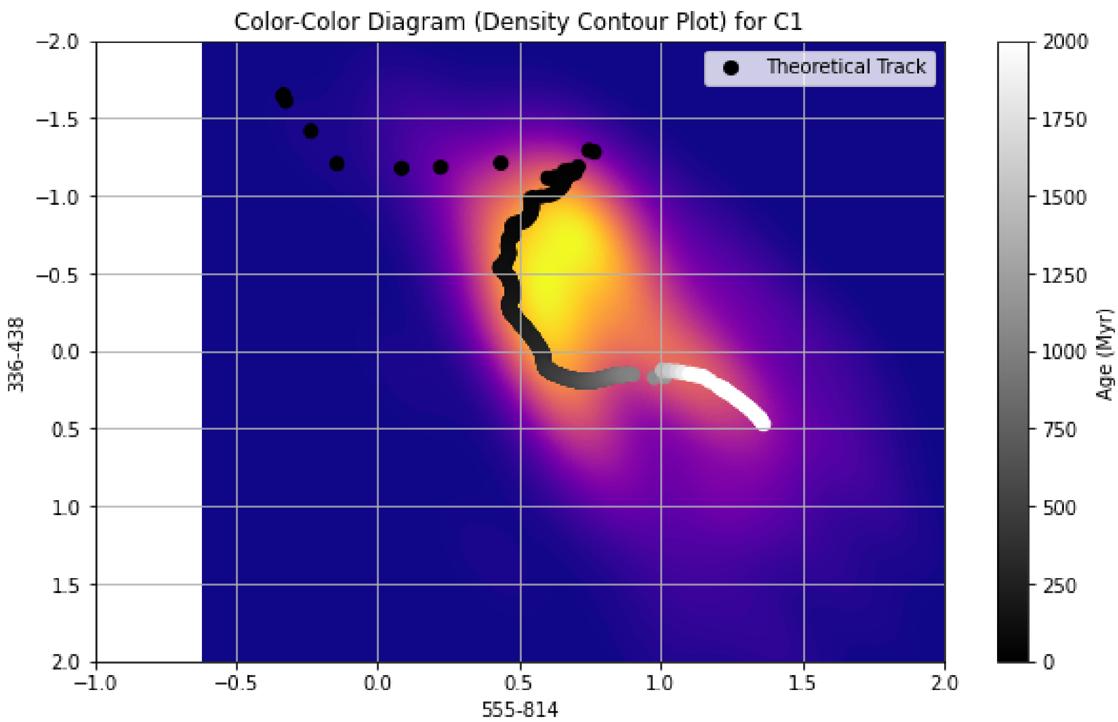


Figure 5.2: C1 Density Plot

5.1.2 Class 2 (C2): Elongated or Asymmetric Clusters

- **Description:** Class 2 star clusters are similar to Class 1 in that they feature a peak in their spatial distribution but differ in their morphology. These clusters are characterized by elongation or asymmetry, meaning that their spatial distribution deviates from perfect circular symmetry.
- **Radial Profile:** The radial profile of Class 2 clusters may vary in different directions. Unlike Class 1, where the density distribution is uniformly radial, Class 2 clusters exhibit variations in density along different axes. This results in an elongated or irregular shape, reflecting an asymmetric distribution of stars.
- **Visual Characteristics:** On imaging, Class 2 clusters appear as elongated or irregularly shaped structures. The asymmetry or elongation can be seen as a deviation from the circular profile, indicating that the cluster's density is higher along certain directions and more diffuse in others.
- **Implications:** The elongation or asymmetry observed in Class 2 clusters suggests that these star clusters may have experienced non-uniform star formation processes or interactions with their environment. Such clusters could be influenced by tidal forces, interactions with other clusters or galactic structures, or internal dynamical processes that lead to their non-circular shape.

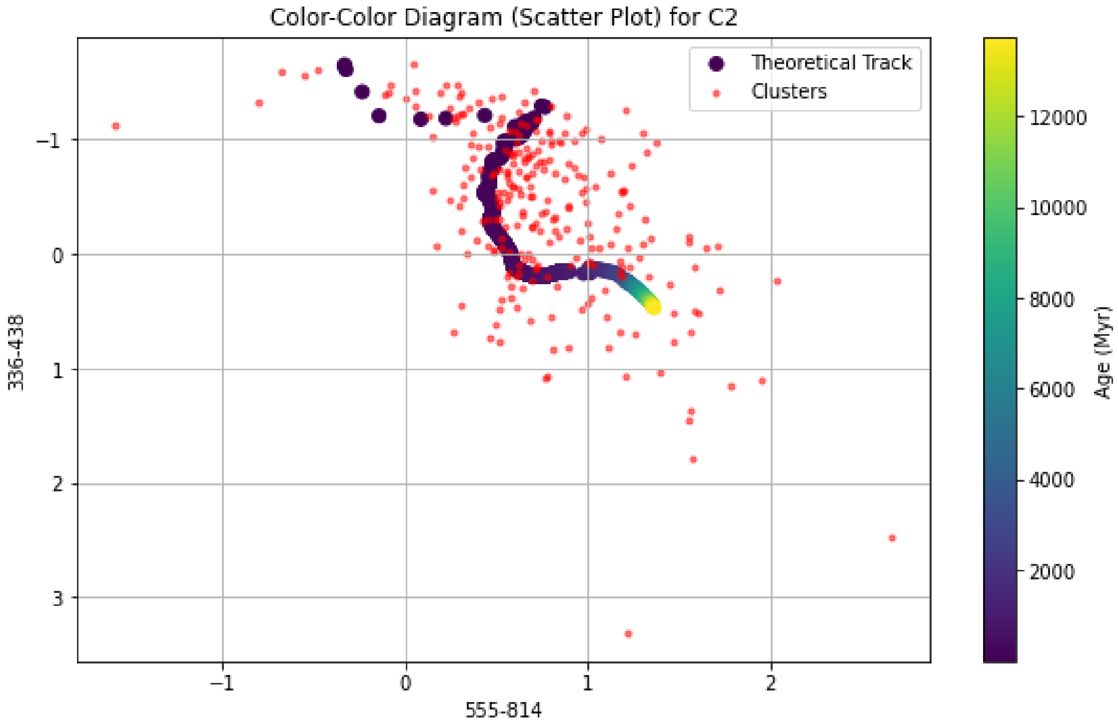


Figure 5.3: C2 Scatter Plot

In this galaxy, the analysis indicates that Class 2 (C2) star clusters are younger than Class 1 (C1) star clusters, as shown by the age distribution in the plotted data.

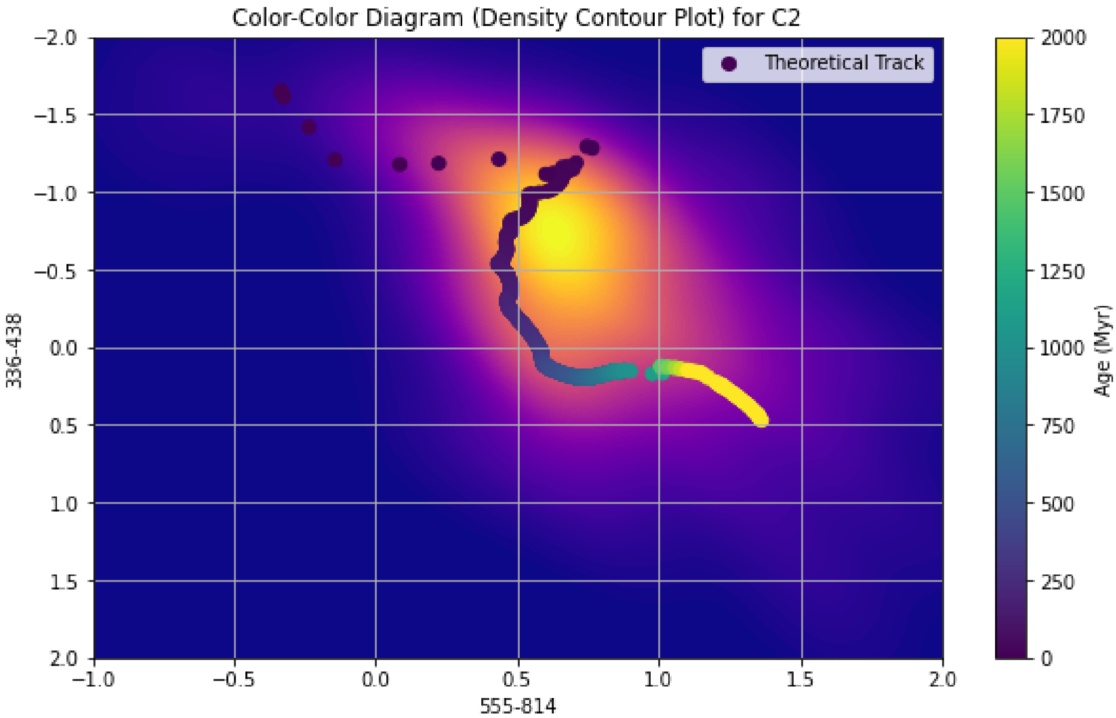


Figure 5.4: C2 Density Plot

6. NGC 4303

To further validate and refine the results obtained from the analysis of the first galaxy, I conducted a detailed study on galaxy NGC 4303, also known as Messier 61. Messier 61 is a barred spiral galaxy located in the constellation Virgo, approximately 52 million light-years from Earth. It is part of the Virgo Cluster and is notable for its large, well-defined spiral arms and high surface brightness. This galaxy was chosen as a test case to ensure the robustness of my methodology and findings. The analysis included generating and interpreting various plots, which have confirmed the consistency and accuracy of the results derived from the initial galaxy.

Figure 6.1: NGC 4303

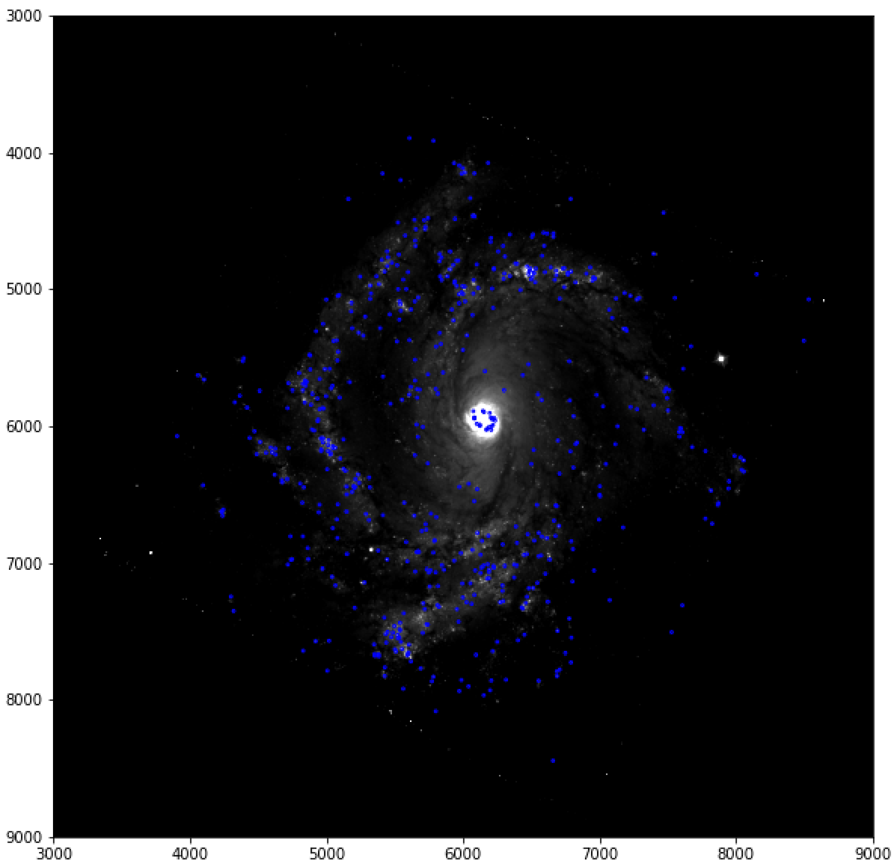


Figure 6.2: Positions of Clusters in NGC 4303

6.1 Photometric Plots

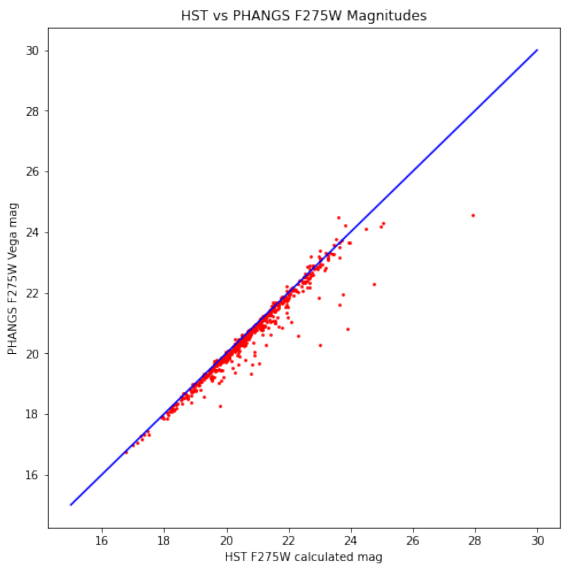


Figure 6.3: Filter 275

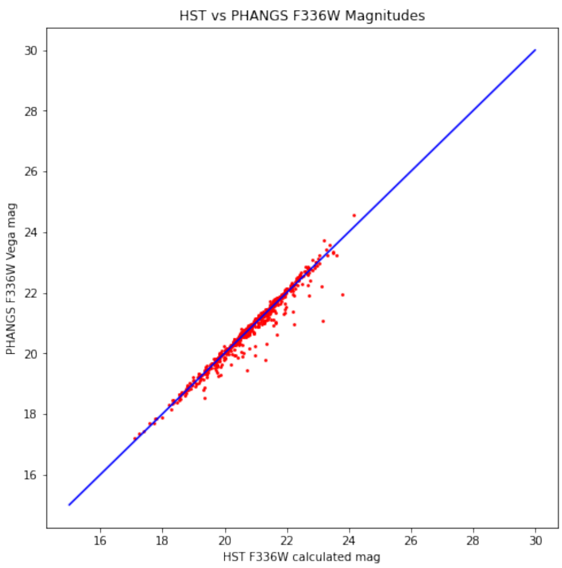


Figure 6.4: Filter 336

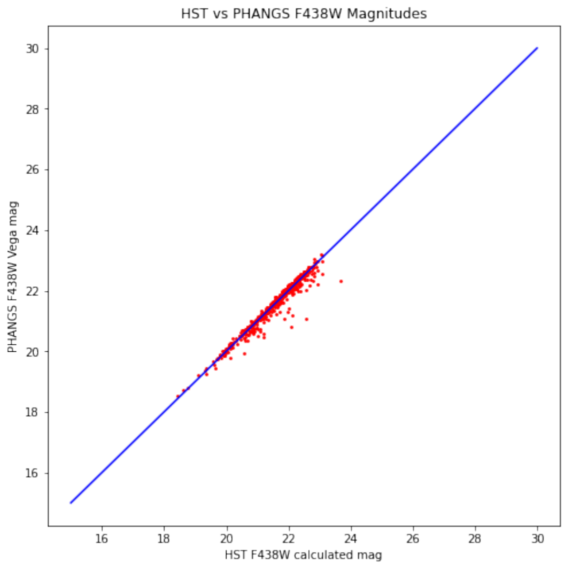


Figure 6.5: Filter 438

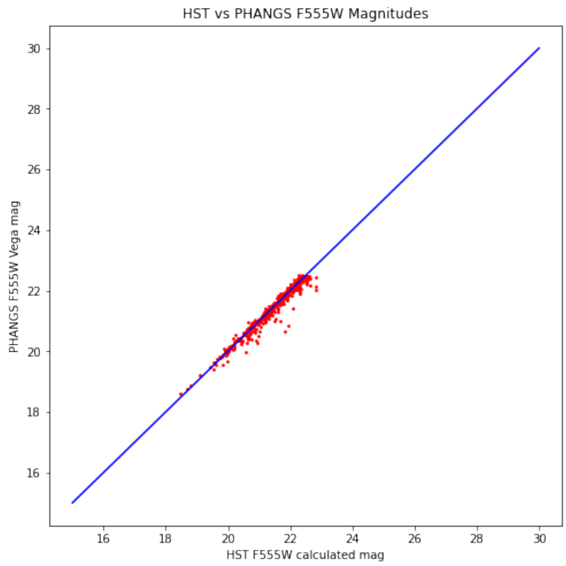


Figure 6.6: Filter 555

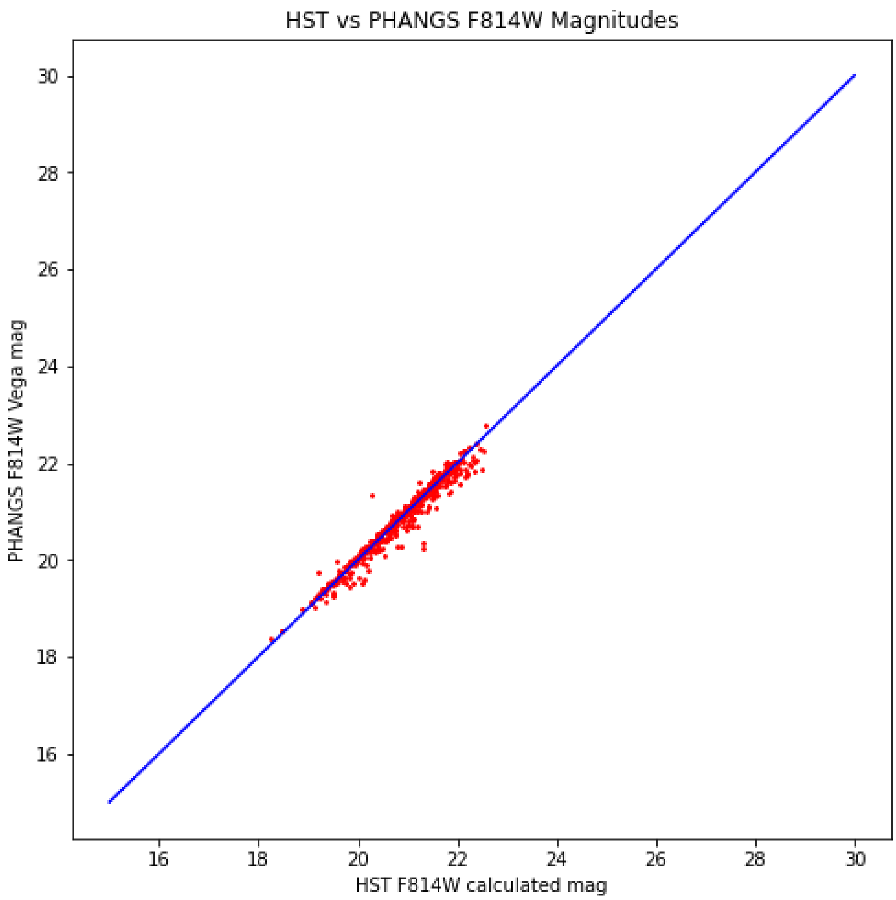


Figure 6.7: Filter 814

6.2 Colour Colour Diagrams

The color-color diagrams for galaxy NGC 4303 indicate that it is considerably younger than galaxy NGC 1365. The density plot distinctly shows that the majority of the galaxy's star clusters are concentrated in the younger regions of the diagram, with a notable paucity of clusters in the older regions.

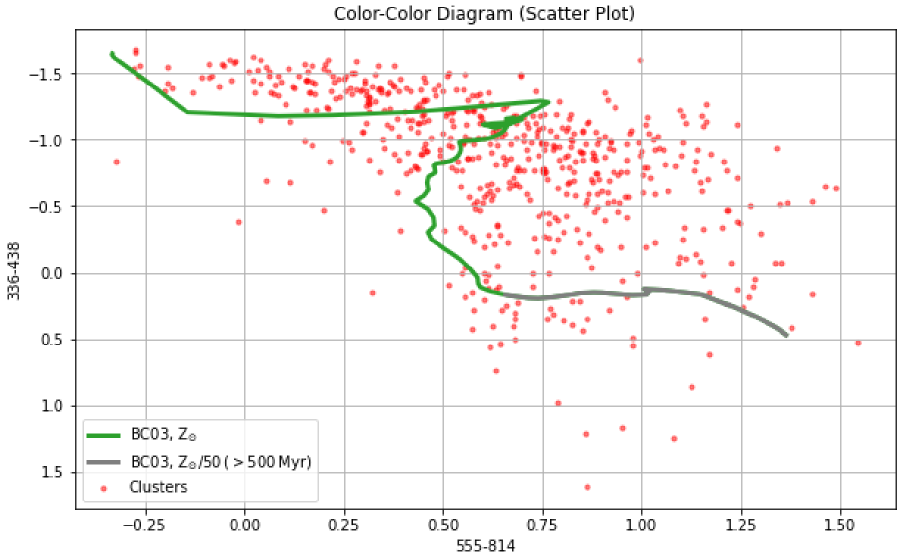


Figure 6.8: Scatter Plot

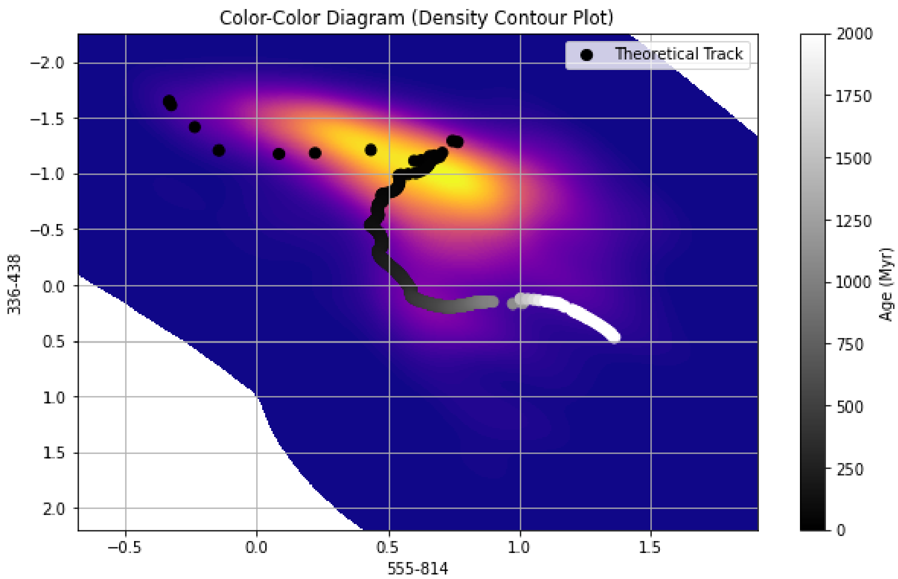


Figure 6.9: Density Plots

6.3 ALMA Gas Density Plots

The ALMA plots of galaxy NGC 4303 reveal a distinct gas distribution pattern, with the majority of the gas concentrated along the spiral arms and a pronounced, thick halo at the center. Additionally, cluster plots further validate that younger stars are predominantly located along the spiral bars, away from the central region.

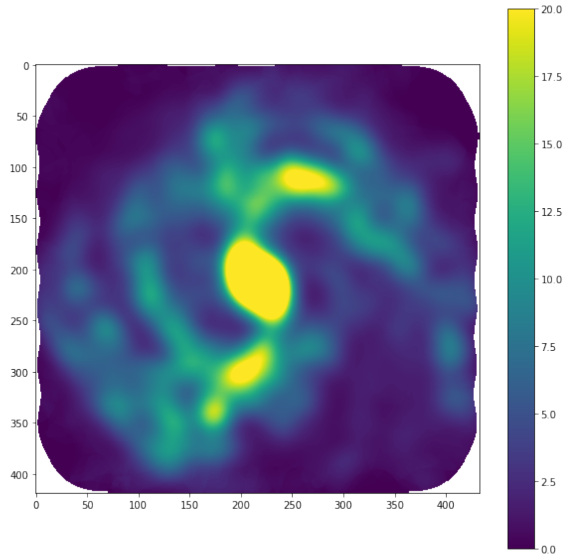


Figure 6.10: ALMA Plot

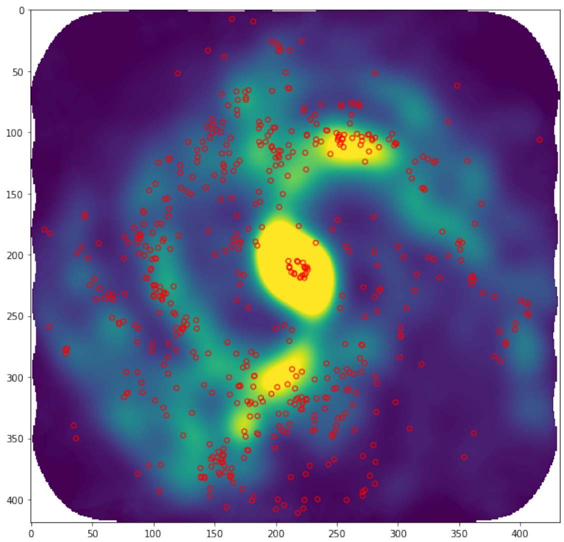


Figure 6.11: Position of Star Clusters on the gas plot

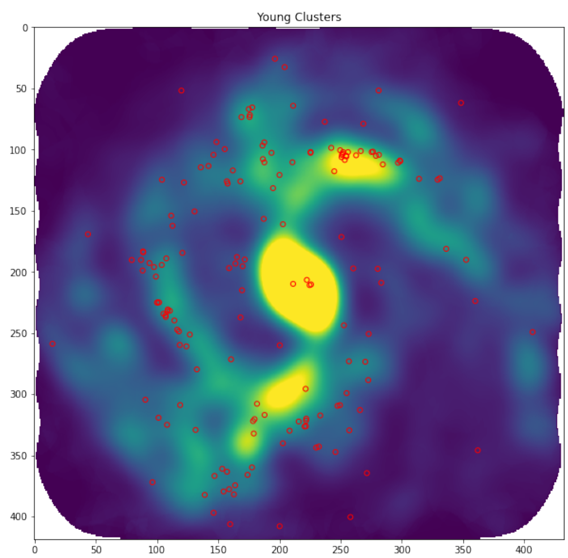


Figure 6.12: Young Clusters

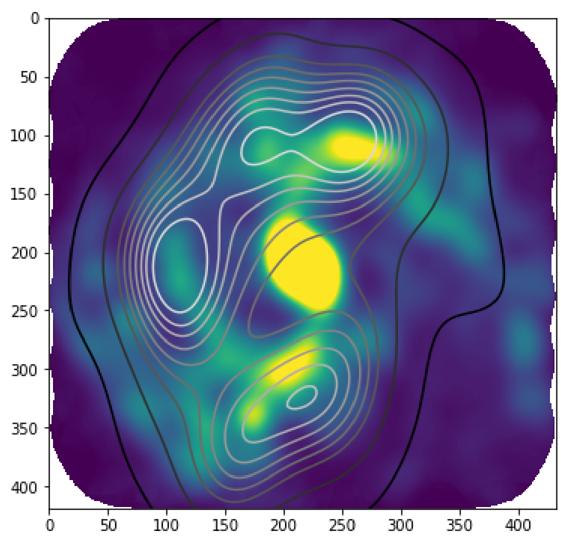


Figure 6.13: Contour Map

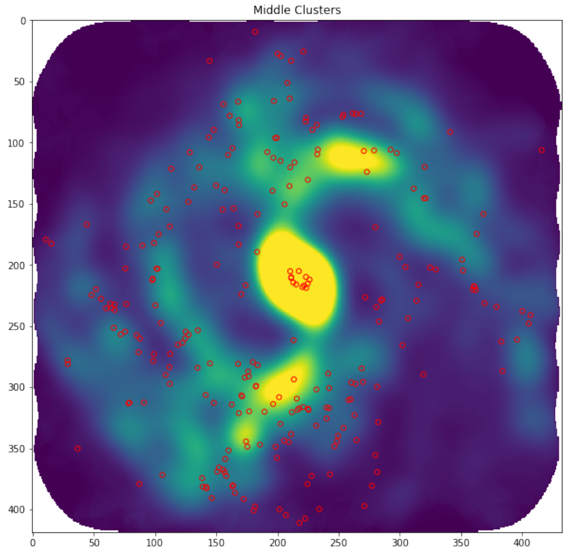


Figure 6.14: Middle Clusters

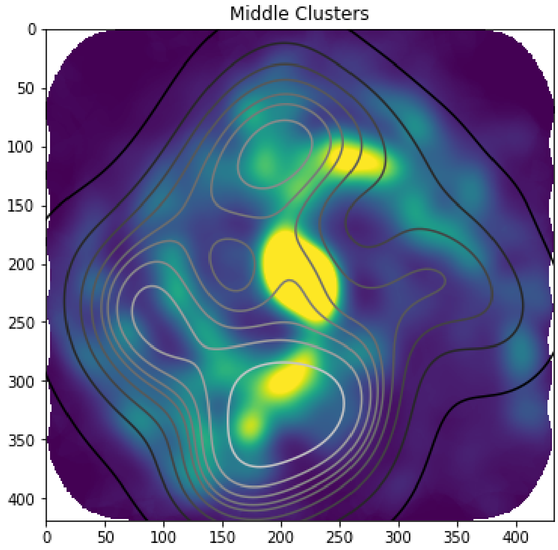


Figure 6.15: Contour Map

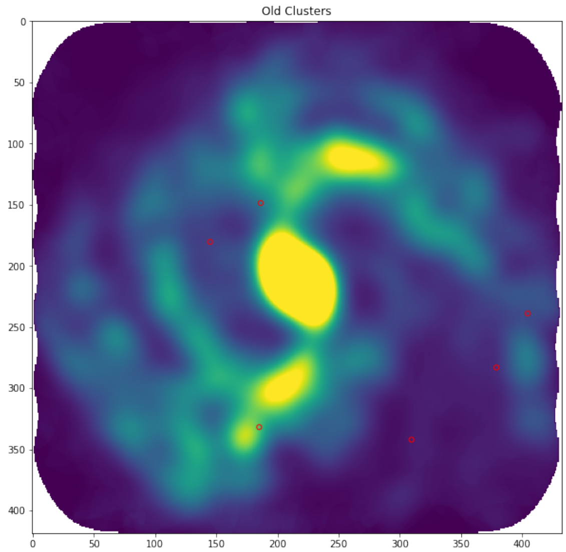


Figure 6.16: Old Clusters

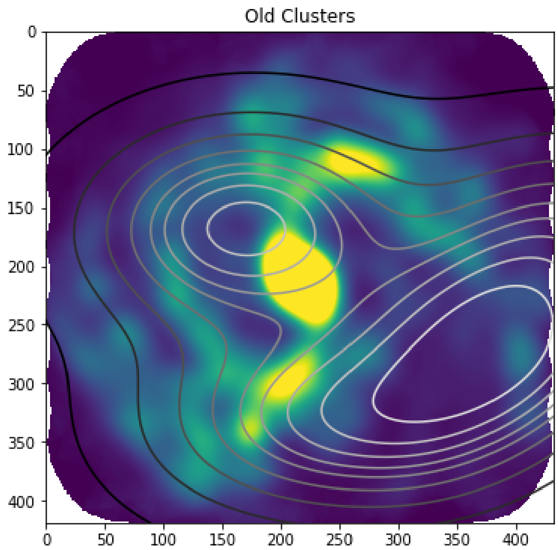


Figure 6.17: Contour Map

6.4 Density Plots for C1 C2

The density plot clearly indicates a shift towards younger clusters in C2 compared to C1. Consequently, C2 contains a higher concentration of younger clusters, in contrast to the older clusters predominantly found in C1. This observation reinforces the notion that C2 represents a more youthful stellar population.

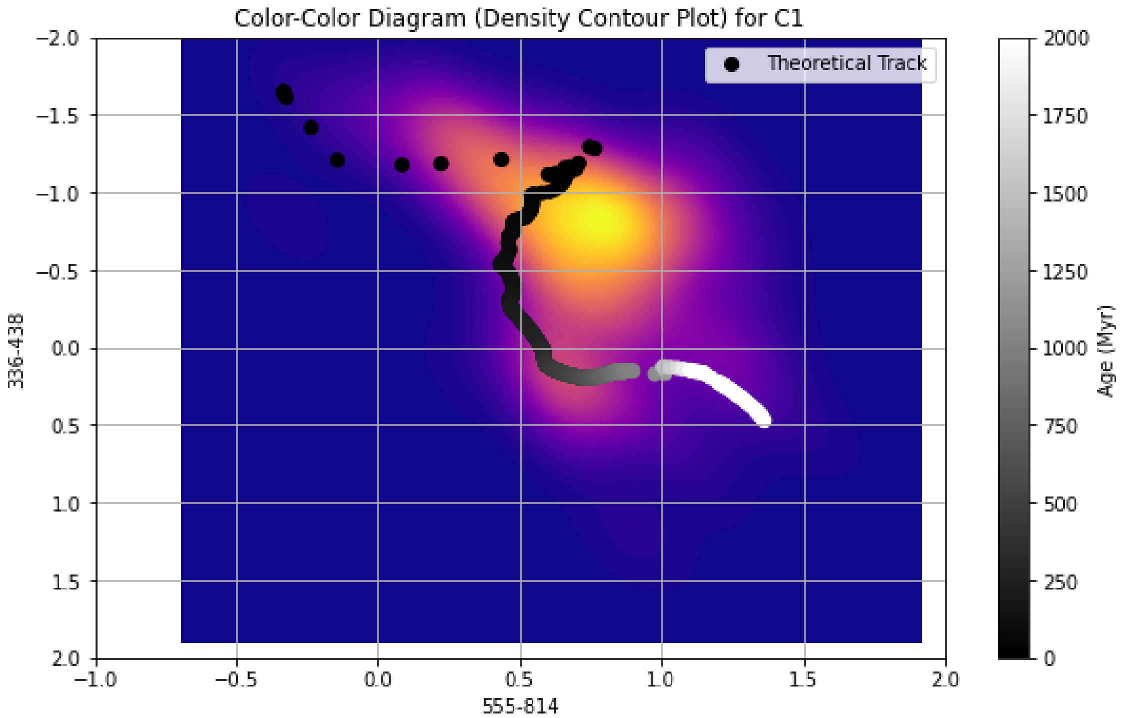


Figure 6.18: C1 Clusters

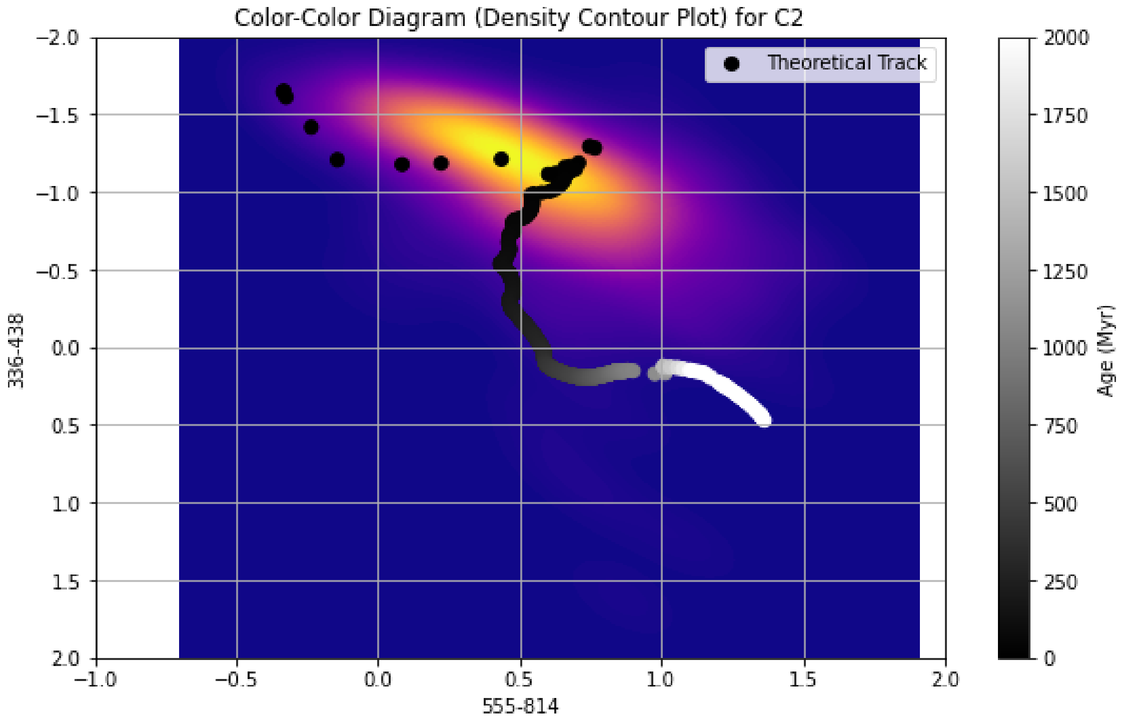


Figure 6.19: C2 Clusters

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