KRITTIKA SUMMER PROJECTS 2024

Studying Cluster-properties-in-NGC1566

Sanidhya Katiyar, author's name, author's name, author's name, and author's name

Pictures/background.pdf

KRITTIKA SUMMER PROJECTS 2024

Studying Cluster-properties-in-NGC1566

Sanidhya Katiyar[1], author's name[2], author's name[3], author's name[4], and author's name[5]

[1]IIT Bombay

[2]college name

[3]college name

[4]college name

[5]college name

PUBLISHED BY KRITTIKA: THE ASTRONOMY CLUB OF IIT BOMBAY

GITHUB.COM/KRITTIKAIITB

Sample Repository: Type project name

First Release, August 2024

Abstract (Sample abstract)

Gravitational Waves are ripples in spacetime, which were first predicted by Albert Einstein in 1916 using the General Theory of Relativity and observed experimentally in 2015 by the Laser Interferometer Gravitational wave Observatory (LIGO). The modeling of gravitational wave signals detected by LIGO requires solving the Einstein Field Equations to theoretically generate the gravitational waveforms. However, due to their highly non-linear and complicated nature we use certain approximation methods. In this project, we employed the Quadrupole Approximation and Post Newtonian Expansions to generate gravitational waveforms of Compact Binary Coalescence (CBC) for varying source parameters. A delay in the coalescence time was observed for Post Newtonian (PN) Waveform as compared to the Newtonian waveform because of the PN correction terms. The delay was found to vary with the masses of the binary components and choice of initial gravitational wave frequency. Matched Filtering of the GW150914 strain data was done with the generated waveforms as templates. A higher Signal to Noise Ratio (SNR) was obtained for the PN Waveform compared to the Newtonian waveform, which suggests its effectiveness in finding gravitational wave signals.

Contents

chapter_head_1.pdf

1. Star clusters

chapter_head_2.pdf

1.1 What are Star Clusters?

Star clusters are groups of stars that are gravitationally bound and are believed to have formed from the same molecular cloud.

Star clusters are groupings of stars that form physical systems, typically situated at the same distance and likely of the same origin. Trumpler in 1930 defined open clusters as those star groupings rich enough in stars for statistical investigation. Clusters are usually discovered through visual inspection or photographic/electronic images in visual or infrared wavelengths.

An operational definition of a star cluster is an obvious concentration of several stars or more above the surrounding stellar background, identifiable on suitable field-of-view images. This definition is practical and includes most objects listed in existing cluster catalogs, excluding galaxy-sized systems or objects with insignificant numbers of stars. Most clusters defined this way are likely physical systems, though they may not always be gravitationally bound.

Theoretically, a cluster can be defined as a self-gravitating system of stars within the Galactic gravitational potential. By this definition, unbound clusters or young clusters in the process of dispersing would not be considered true clusters. Additionally, stars that have achieved escape velocity but are still within the tidal radius would be nonmembers by the theoretical definition but members by the observational definition.

There have been numerous attempts to search for and catalog star clusters, leading to a variety of cluster catalogs. The large number of partly redundant catalogs has caused confusion regarding cluster names, with some clusters having multiple aliases. Existing catalogs are biased, and any statistical results based on them are subject to systematic errors and selection effects.

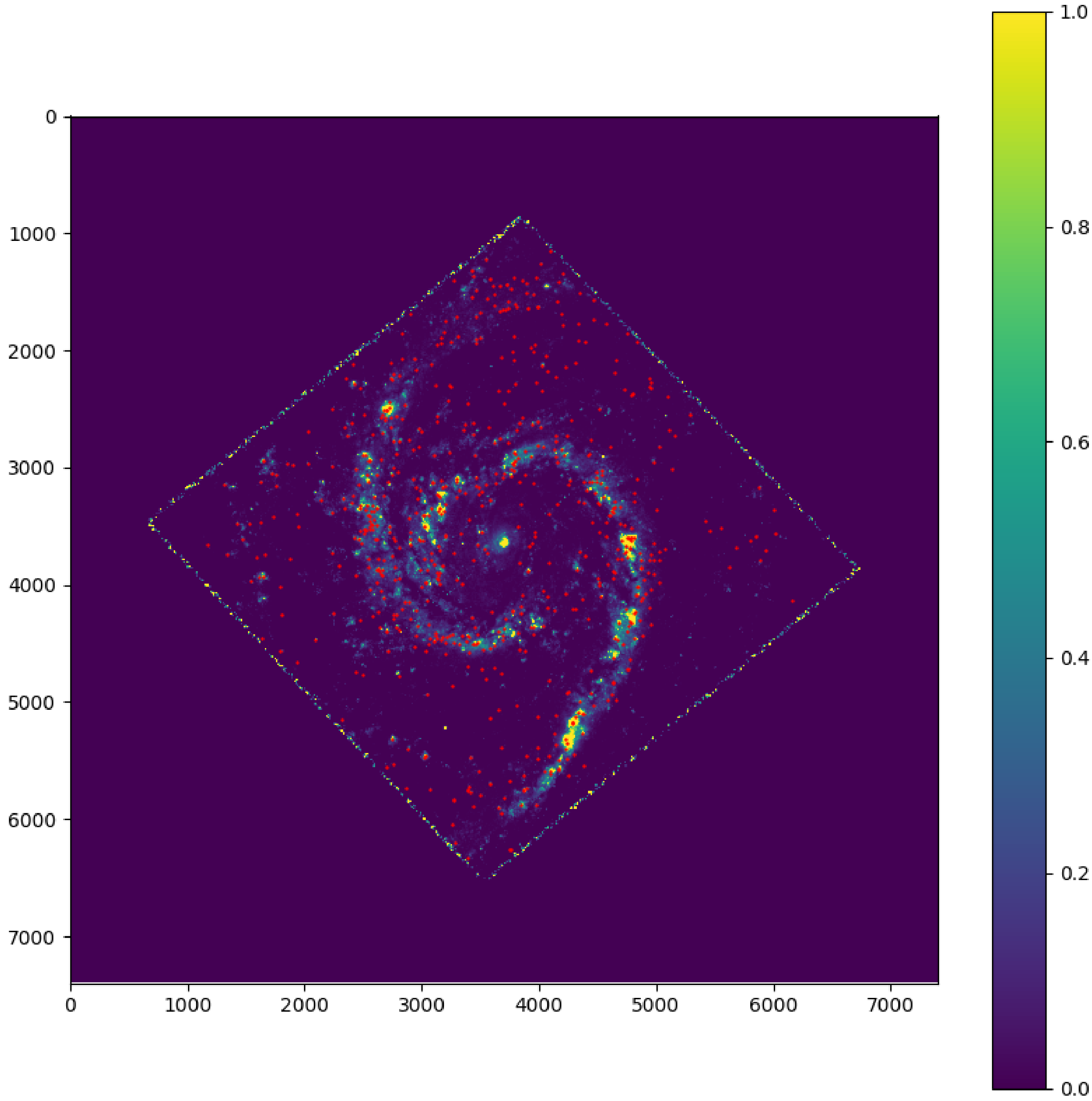


Figure 1.1: Galaxy - NGC1566 and its Star Clusters

1.2 Types of Star Clusters

They can be categorized into two main types: globular clusters and open clusters, each with distinct characteristics and significance in the study of stellar and galactic evolution.

Globular Clusters

Globular clusters are ancient, massive stellar systems predominantly composed of Population II stars. The Milky Way hosts around 147 known globular clusters, with an estimated total population of about 200, accounting for those obscured by the Galactic center and plane. These clusters contain at least 10,000 solar masses, with some, like M22 and Omega Centauri, exceeding one million solar masses. The stellar distribution within a globular cluster is well represented by King models, characterized by central surface brightness and core radius, which typically measures around 1 parsec. The median tidal radius is about 35 parsecs, although some clusters in the outer halo of the Galaxy have much larger tidal radii.

1.2.1 Open Clusters

Open clusters, which include OB associations, moving groups, and embedded clusters, are composed of Population I stars. About 1,200 open clusters have been cataloged, though some are merely enhancements in stellar density or asterisms of unrelated stars. Most open clusters lie near the Galactic plane, often obscured by interstellar dust, suggesting that the actual number may exceed 105. Open clusters range significantly in size and mass, from small clusters with fewer than a dozen stars to massive ones like NGC 6791 with more than 10,000 members. Typically, open clusters are 4-5 parsecs in diameter with core radii around 1 parsec. These clusters show no strong correlation between size, age, Galactic location, or number of members.

1.2.2 OB Associations

OB associations are large, diffuse regions with a higher-than-normal density of O and B stars. These associations, covering tens of parsecs, often contain one or more discrete clusters. Approximately 70 OB associations have been cataloged, each ranging from a dozen to several dozen luminous O and B stars. The total mass of an OB association can range from about 1,000 solar masses to more than ten times that number, depending on the number and mass of its constituent stars.

1.2.3 Moving Groups

Moving groups are collections of stars that share common motion through space, suggesting a common origin. However, because these groups can be spread over large regions of the Galaxy, identifying all members is challenging, and reliable total mass estimates are difficult to obtain. The membership of a moving group is often incomplete, complicating the understanding of their total extent and significance.

1.2.4 Embedded Clusters

Embedded clusters are newly formed groups of stars still deeply enshrouded in the nebulosity from which they formed. These clusters, identified through infrared imaging, range from a few tenths of a parsec to about two parsecs in diameter. Despite their compact size, embedded clusters can contain hundreds to thousands of solar masses of stars. Notably, the stars in these clusters have not yet reached the main sequence, making even relatively low-mass stars quite luminous in the infrared. The question of whether these embedded clusters evolve into open clusters or dissipate along with their surrounding gas remains unresolved, leading to ongoing discussion and research in the field.

1.3 Galactic Distribution

1.3.1 Globular Clusters

Globular clusters, containing the oldest stars in the Galaxy, are distributed in a nearly spherical shape around the Galactic center, defining the stellar halo. Harlow Shapley used these clusters to determine the Galactic center's direction and distance in the 1920s. These clusters are identified as Population II stars. They can be categorized into three subpopulations based on composition and horizontal branch shapes: old halo clusters with horizontal branches indicating great age, young halo clusters with slightly younger horizontal branches, and disk globular clusters that are more metal-rich and arranged in a thick disk shape. The old halo clusters likely formed during the Galaxy's initial collapse, while disk globular clusters belong to the thick disk population, suggesting they are younger and more metal-rich. Young halo clusters may have originated from nearby dwarf spheroidal galaxies that merged with our Galaxy, showing no correlation between Galactic position and composition, unlike the old halo and disk subsystems which do show such correlations, hinting at a possible single system formation with a systematic trend between composition, position, and age.

1.3.2 Open Clusters

Open clusters, including associations, moving groups, and embedded clusters, belong to the disk population of the Galaxy (Population I stars). They are predominantly located near the Galactic plane, with most known open clusters situated within a couple of kiloparsecs from the Sun.

2. PHANGS

chapter_head_2.pdf

2.1 The Collaboration

PHANGS (Physics at High Angular resolution in Nearby GalaxieS) is an international collaboration aimed at understanding the physics of star formation and the interstellar medium in nearby galaxies. The collaboration utilizes data from multiple observatories including the Atacama Large Millimeter/submillimeter Array (ALMA), the Very Large Telescope (VLT), and the Hubble Space Telescope (HST).

PHANGS observes galaxies at multiple wavelengths, providing a comprehensive view of the gas, dust, and stars within these galaxies. The data collected is used to study the physical processes driving star formation, the role of the interstellar medium, and the interplay between stars and their environment.

The main scientific goals of PHANGS include:

- Understanding the star formation process at high resolution.
- Investigating the role of galactic dynamics in shaping the interstellar medium.
- Studying the feedback processes from young stars on their natal environment.

PHANGS has already provided significant insights into these areas and continues to be a valuable resource for the astrophysical community.

2.2 Galaxy

For this project, I'll be using the PHANGS-HST catalogue and focusing on the galaxy NGC 1566. The PHANGS-HST survey is an integral part of the broader PHANGS project, which aims to understand the physics of star formation and the interstellar medium in nearby galaxies. This catalogue leverages the unparalleled resolution and sensitivity of the Hubble Space Telescope to capture high-quality images in the ultraviolet (UV), optical, and near-infrared (NIR) bands.

2.2.1 PHANGS-HST Catalogue

The PHANGS-HST catalogue provides extensive data on star-forming regions within nearby galaxies. It includes:
Multi-wavelength Imaging: High-resolution images in UV, optical, and NIR bands, crucial for studying different phases of star formation and the characteristics of stellar populations.
Star Cluster Identification: Detailed maps of young stellar clusters and associations, offering insights into the initial conditions of star formation and the early evolution of star clusters.
Dust and Gas Interaction: Information on the distribution and properties of interstellar dust, which plays a vital role in cooling gas and facilitating star formation.
Stellar Populations: Data on the ages, masses, and spatial distributions of stellar populations, essential for understanding the star formation history and evolution of galaxies.

2.2.2 Galaxy NGC 1566

NGC 1566, also known as the Spanish Dancer Galaxy, is a prominent face-on spiral galaxy located approximately 60 million light-years away in the constellation Dorado. It is one of the brightest and most well-studied galaxies in the southern hemisphere. Key features of NGC 1566 include:
Type: Intermediate spiral galaxy (SABbc), characterized by its well-defined spiral arms and a small central bar.
Star Formation: NGC 1566 is noted for its vigorous star formation, particularly in its spiral arms, making it an excellent candidate for studying the star formation process in detail.
Nucleus: It harbors an active galactic nucleus (AGN), classified as a Seyfert type, which exhibits variability and emits strong radiation across the electromagnetic spectrum.
Dynamics: The galaxy's well-defined structure and relatively face-on orientation allow for precise studies of its dynamics, including rotation curves and the distribution of different stellar populations.
Proximity: At around 60 million light-years, NGC 1566 is close enough to resolve individual star clusters and star-forming regions with high resolution, yet far enough to provide a broad view of galactic structures and processes.
By utilizing the PHANGS-HST catalogue, this project will delve into the rich data available for NGC 1566, exploring its star formation regions, stellar clusters, and the interplay between stars, gas, and dust. The high-quality HST images will facilitate a detailed analysis of the star formation processes and the galactic environment, contributing to our understanding of how galaxies evolve and form stars.

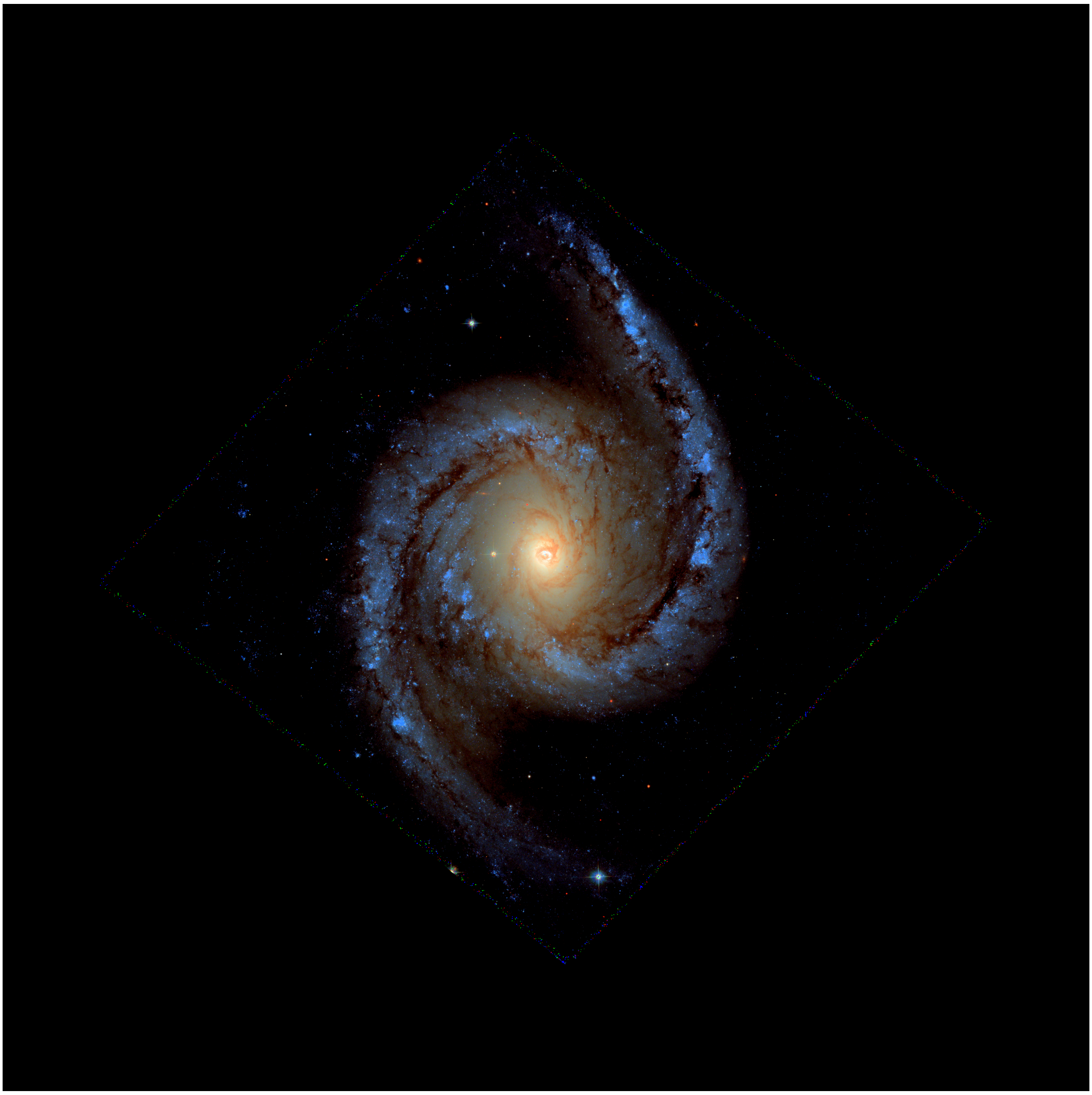


Figure 2.1: NGC 1566 Stacked Image

3. Aperture Photometry

chapter_head_2.pdf

3.1 What is meant by Aperture Photometry?

Aperture photometry is a fundamental technique in observational astronomy used to measure the flux or brightness of astronomical objects within a specified circular aperture. This method involves summing the light within a defined circular region centered on the target object and subtracting the background light, which is estimated from an annular region surrounding the aperture. In this project, aperture photometry is performed using the photutils library on data from the PHANGS-HST survey.

3.1.1 Selecting the Right Aperture

Selecting the appropriate aperture size is crucial for accurate photometric measurements. The aperture must be large enough to encompass the majority of the object's light but small enough to minimize contamination from nearby sources and the sky background. The size of the aperture can significantly affect the accuracy of the photometry:

Undersized Aperture: A too-small aperture may miss a significant portion of the object's light, leading to an underestimation of its brightness.
Oversized Aperture: A too-large aperture may include excess background light and light from neighboring stars, leading to an overestimation of the object's brightness.
In this project, a circular aperture with a radius of 4 pixels is used for measuring the light from the target stars. This radius is chosen based on the point spread function (PSF) of the stars in the images, ensuring that most of the star's light is captured while minimizing contamination from the background.

Measuring Instrumental Magnitudes with Photutils Instrumental magnitudes are measured by summing the pixel values within the selected aperture and subtracting the average background level. The process involves several steps using photutils:
Loading the Data: The PHANGS-HST data is loaded using the astropy.io.fits module.
Defining the Aperture and Annulus: The circular aperture of 4 pixels radius and the annular region with inner radius of 7 pixels and outer radius of 8 pixels are defined.
Performing Aperture Photometry: The flux within the aperture and the background flux in the annulus are measured.
By carefully selecting the aperture and background annulus radii, accurate instrumental magnitudes can be obtained, which are essential for further analysis such as determining the absolute magnitudes or colors of stars. The specific radii of 4 pixels for the circular aperture and 7 and 8 pixels for the inner and outer radius of the annulus are chosen to balance the trade-off between capturing sufficient star light and minimizing background noise.

3.2 My Plot WITHOUT CORRECTIONS

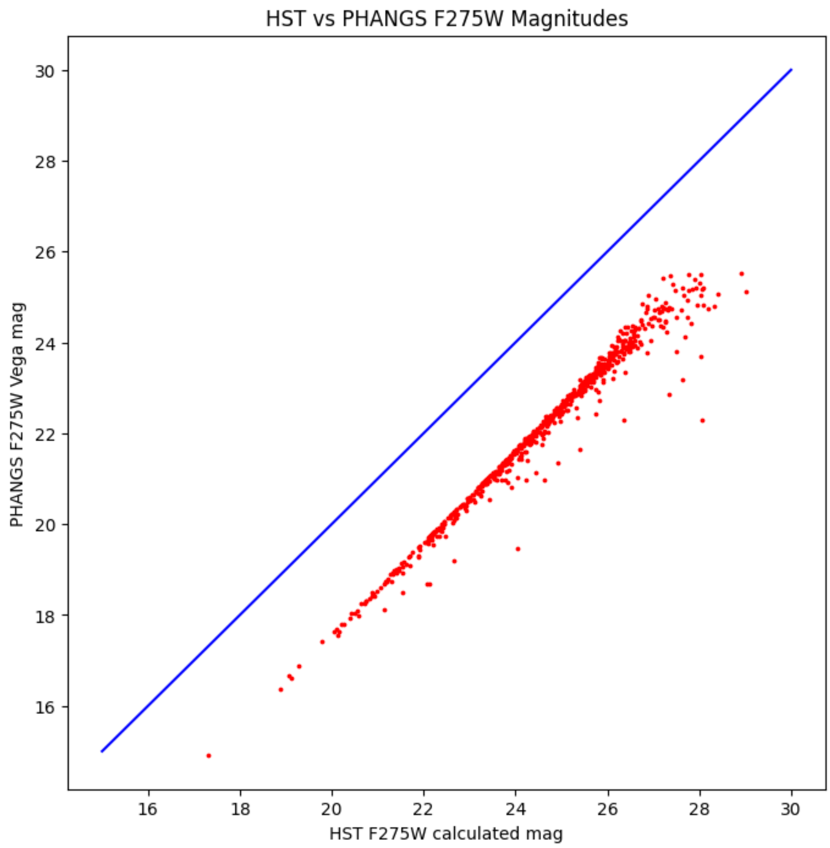
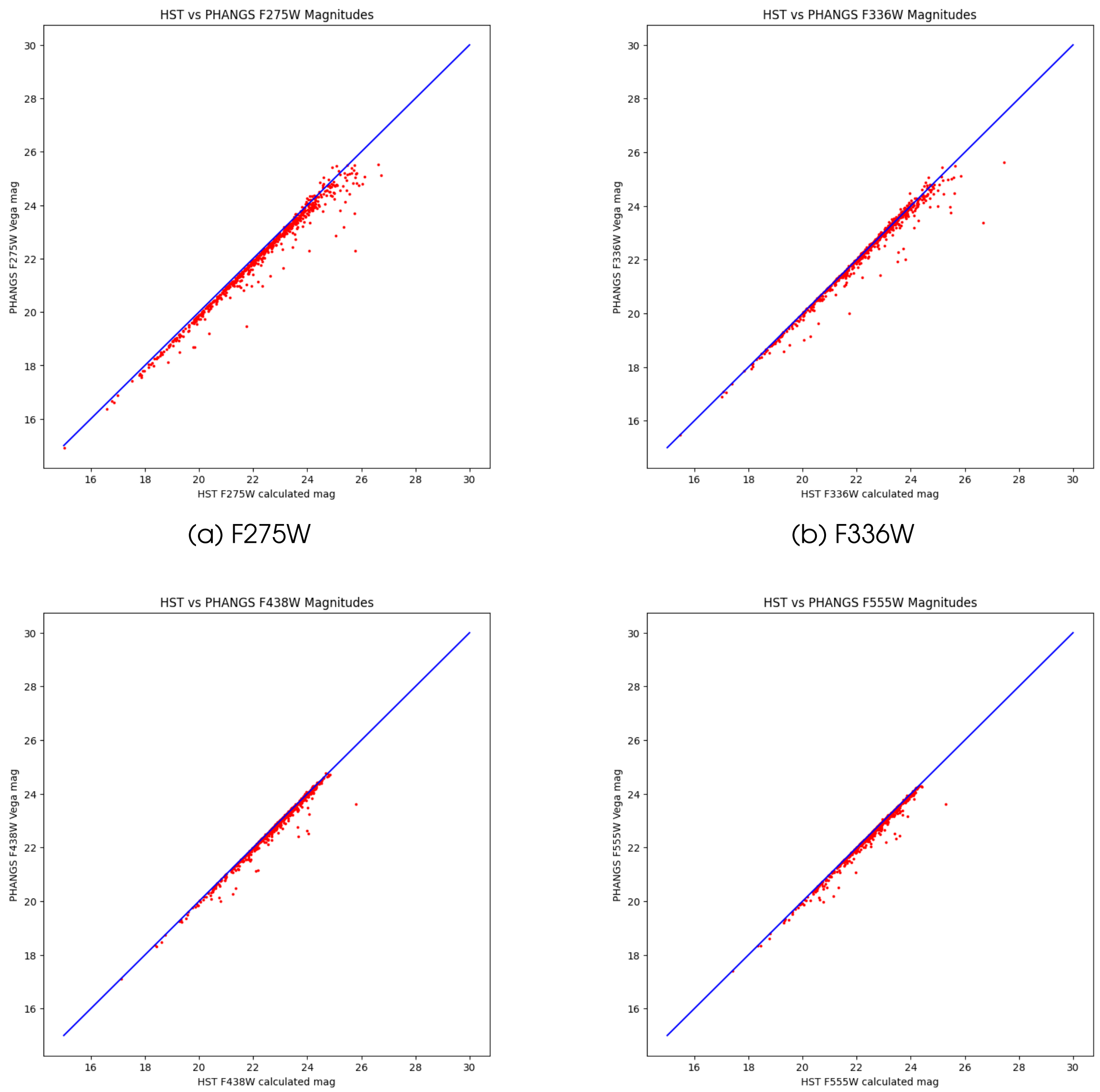


Figure 3.1: HST vs PHANGS F275W Magnitudes

3.3 Applying 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



(a) F275W (b) F336W

(c) F438W (d) F555W

Figure 3.2: After applying corrections in different bands.

4. Color-Color Diagrams

chapter_head_2.pdf

4.1 Introduction

Color-color diagrams (CCDs) are essential tools for studying the properties of astronomical objects, such as clusters, by examining their colors derived from magnitudes in different filters. The diagrams in the context of this code use specific filter combinations to explore the properties of star clusters in nearby galaxies.

4.2 Filters and Color Indices

4.2.1 Filter Combinations

The filters used here are F275W, F336W, F438W, F555W, and F814W, which span a range from ultraviolet to visual wavelengths. Color indices are created by subtracting magnitudes in one filter from another, providing a measure of color.

4.2.2 Color Indices

- **(F275W - F438W)**: This index combines ultraviolet and blue light, sensitive to hot, young stars and star-forming regions.
- **(F336W - F438W)**: This index spans near-ultraviolet to blue light, useful for studying slightly older stellar populations.
- **(F438W - F555W)**: This index includes blue to visual light, highlighting differences in stars' temperatures and compositions.
- **(F555W - F814W)**: This visual-to-near-infrared index is sensitive to older, cooler stars and is less affected by interstellar extinction.

4.3 Theoretical Model Track

- **Model Track**: The code plots a theoretical model track on the CCDs, representing the expected path of stellar evolution under certain assumptions

(e.g., solar metallicity, indicated by BC03, $Z_\odot$).
- **Evolutionary States**: The model track helps compare observational data to theoretical predictions, indicating stages of cluster evolution, age, and composition.

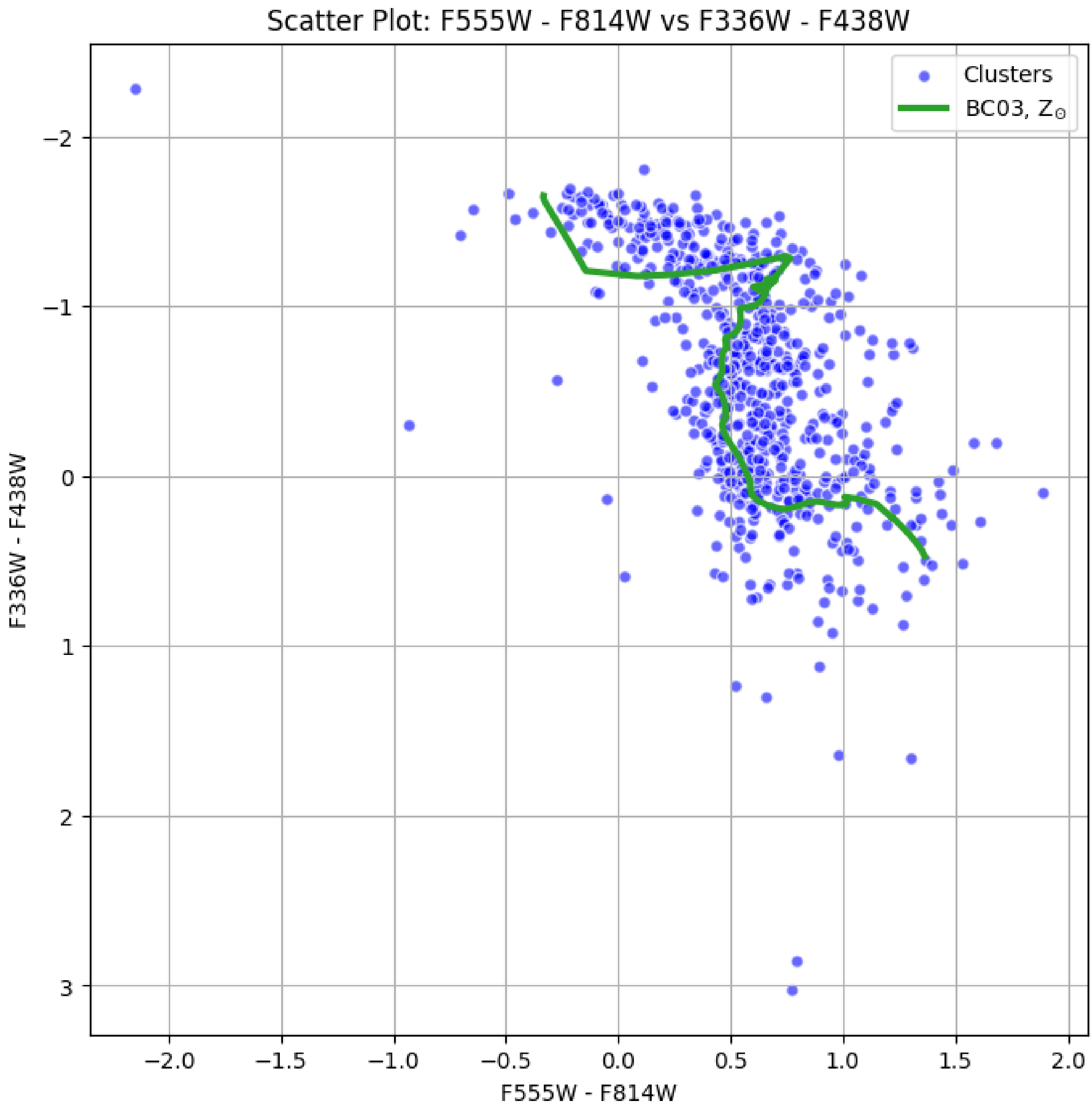


Figure 4.1: Scatter Plot: F336W-F438W vs F555W-F814W

4.4 Purpose and Interpretation

4.4.1 Stellar Populations

CCDs reveal different stellar populations within the clusters, distinguishing between young, hot stars and older, cooler stars. The positions of clusters on the CCDs indicate their ages and evolutionary stages.

4.4.2 Reddening and Extinction

Interstellar dust affects the observed colors of clusters, causing reddening. This shift can be observed on the CCDs. Theoretical tracks allow for the correction and study of these effects, providing a clearer picture of intrinsic cluster properties.

4.4.3 Star Formation Histories

By comparing clusters' positions on the CCDs with the model track, astronomers can infer star formation histories. Clusters off the main sequence or model track may indicate ongoing star formation or unique evolutionary histories.

4.5 Understanding Clusters in a Galaxy through CCDs

Color-color diagrams are instrumental in understanding the characteristics and evolution of star clusters within a galaxy. They provide insights into several key aspects:

4.5.1 Age Distribution

By locating clusters on the CCDs, we can estimate their ages. Young clusters with hot, blue stars will appear in different regions compared to older clusters with cooler, red stars. The spread of clusters along the theoretical model track provides information on the age distribution of clusters within the galaxy.

4.5.2 Metallicity

The position and spread of clusters on the CCDs can also give clues about their metallicity, which is the abundance of elements heavier than hydrogen and helium. Clusters with different metallicities will follow different paths on the CCDs, allowing for a comparative study.

4.5.3 Star Formation History

By analyzing the positions of clusters on CCDs, we can reconstruct the star formation history of the galaxy. Clusters located in regions indicative of recent star formation provide evidence of ongoing or recent star formation activities within the galaxy.

4.5.4 Interstellar Reddening

CCDs help in identifying the effects of interstellar reddening, which is the dimming and reddening of starlight due to interstellar dust. By comparing the observed cluster positions with the theoretical model tracks, we can correct for reddening effects and obtain a clearer understanding of the clusters' intrinsic properties.

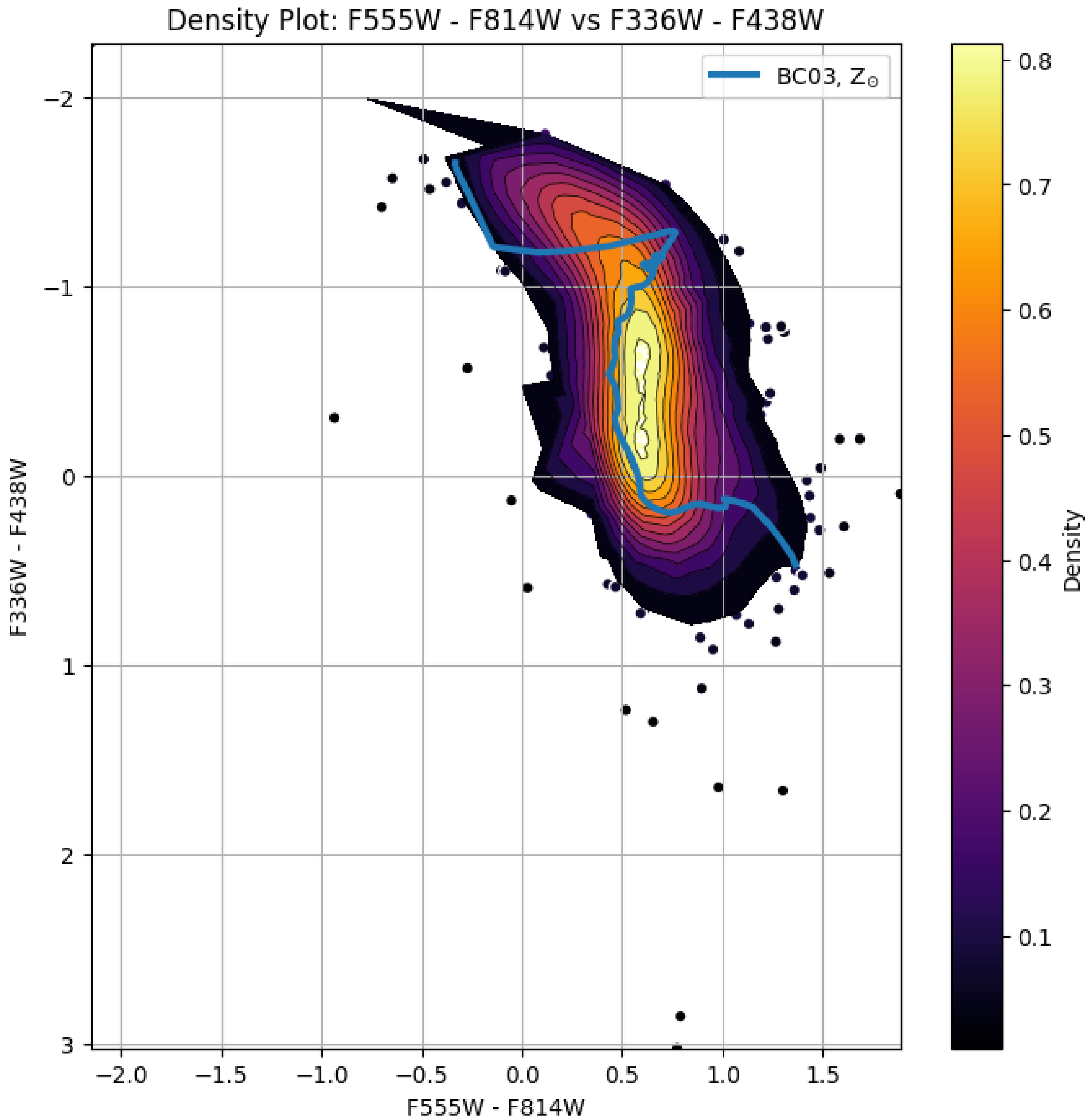


Figure 4.2: Density Plot for Clusters in NGC 1566 with Theoretical Track

4.6 Specific Color-Color Diagrams

4.6.1 (F555W - F814W) vs. (F275W - F438W)

This CCD combines a visual-to-near-infrared index with an ultraviolet-to-blue index, providing a broad view of stellar populations from young, hot stars to older, cooler stars.

4.6.2 (F555W - F814W) vs. (F336W - F438W)

This CCD combines a visual-to-near-infrared index with a near-ultraviolet-to-blue index, focusing more on intermediate-age stellar populations.

4.6.3 (F555W - F814W) vs. (F438W - F555W)

This CCD combines a visual-to-near-infrared index with a blue-to-visual index, providing detailed insights into stellar temperatures and compositions.

4.7 Conclusion

The color-color diagrams generated using these specific indices and model tracks allow for a detailed analysis of cluster properties in nearby galaxies. By examining the colors and comparing them to theoretical models, astronomers can deduce information about the age, composition, and evolutionary state of the clusters, as well as the effects of interstellar dust. This detailed understanding helps build a comprehensive picture of the star formation history and the overall evolution of galaxies.

We will be studying the (F555W - F814W) vs. (F336W - F438W) color-color diagram for our galaxy, NGC 1566. This specific CCD is chosen because it combines a visual-to-near-infrared index with a near-ultraviolet-to-blue index, which allows for a detailed analysis of intermediate-age stellar populations. NGC 1566 is known for its active star formation regions and diverse stellar populations, making it an ideal candidate for this analysis. By focusing on these indices, we aim to gain insights into the star formation history, age distribution, and metallicity variations within the galaxy. Additionally, the chosen color indices are less affected by interstellar reddening, providing a clearer understanding of the intrinsic properties of the clusters within NGC 1566.

5. Further Classifications

chapter_head_2.pdf

5.1 C1 and C2 Clusters

In our study, we focus on two specific clusters within NGC 1566, referred to as C1 and C2. These clusters exhibit distinct properties that make them significant for our analysis.

5.1.1 C1 Cluster

The C1 cluster is characterized by its young, hot stars predominantly found in star-forming regions. Its properties are as follows:

- **Age**: The C1 cluster is relatively young, with an estimated age of around 10 million years. This youthfulness is indicated by the presence of hot, blue stars.
- **Metallicity**: The C1 cluster has a high metallicity, reflecting the enriched environment typical of active star-forming regions. This high metallicity is consistent with the presence of massive, young stars that have undergone rapid evolution.
- **Stellar Population**: The cluster is dominated by massive, hot stars, which contribute to its blue color in the CCDs. These stars are often in the early stages of their evolutionary pathways.
- **Location**: C1 is located in a region of NGC 1566 known for vigorous star formation activity, contributing to its distinctive properties.

5.1.2 C2 Cluster

The C2 cluster, in contrast, is older and exhibits different characteristics:

- **Age**: The C2 cluster is significantly older than C1, with an estimated age of around 1 billion years. Its older age is indicated by the presence of cooler, red stars.
- **Metallicity**: The C2 cluster has a lower metallicity compared to C1, reflecting a different star formation epoch and chemical enrichment history.
- **Stellar Population**: C2 is dominated by older, cooler stars, which contribute to its red color in the CCDs. These stars are in later stages of their evolutionary paths.
- **Location**: C2 is found in a more quiescent region of NGC 1566, with less active star formation compared to the region housing C1.

5.1.3 Significance of C1 and C2 in CCD Analysis

By analyzing the C1 and C2 clusters using the (F555W - F814W) vs. (F336W - F438W) CCD, we can gain valuable insights into the diverse stellar populations and evolutionary histories within NGC 1566. The contrast between the young, metal-rich C1 cluster and the older, metal-poor C2 cluster highlights the variety of star formation and chemical enrichment processes in the galaxy.
Understanding the properties of these clusters helps us build a comprehensive picture of NGC 1566's star formation history and the interplay between different stellar populations within the galaxy. This analysis contributes to our broader understanding of galaxy evolution and the factors influencing star cluster development.

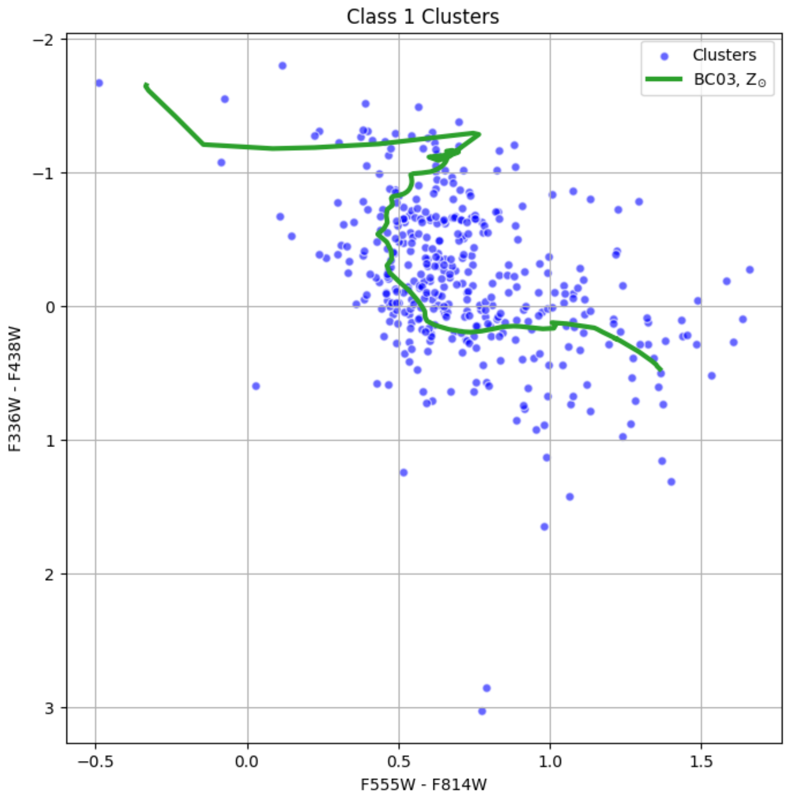


Figure 5.1: Scatter Plot

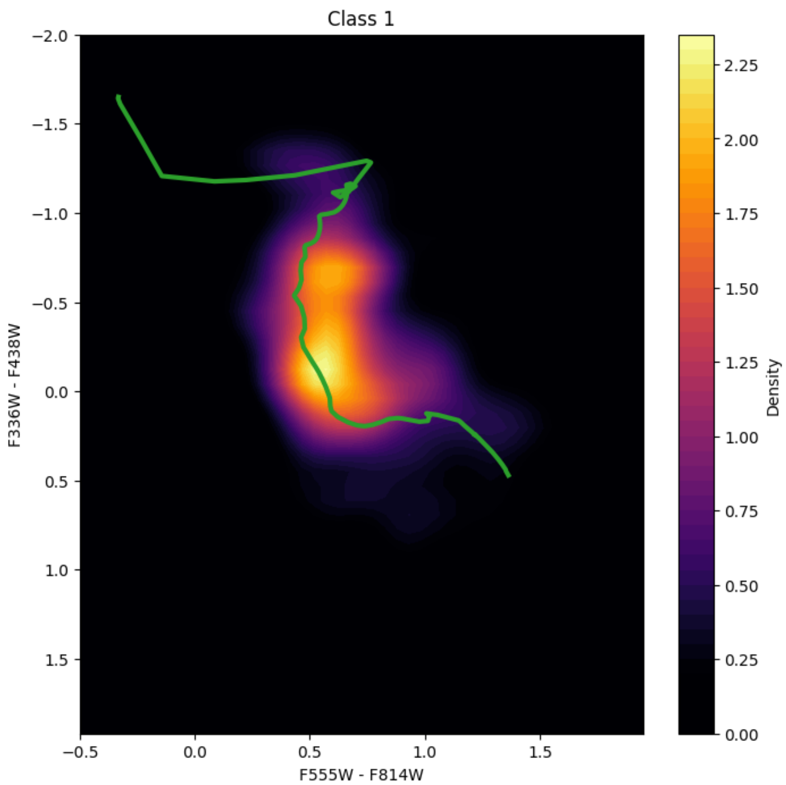


Figure 5.2: Density Plot

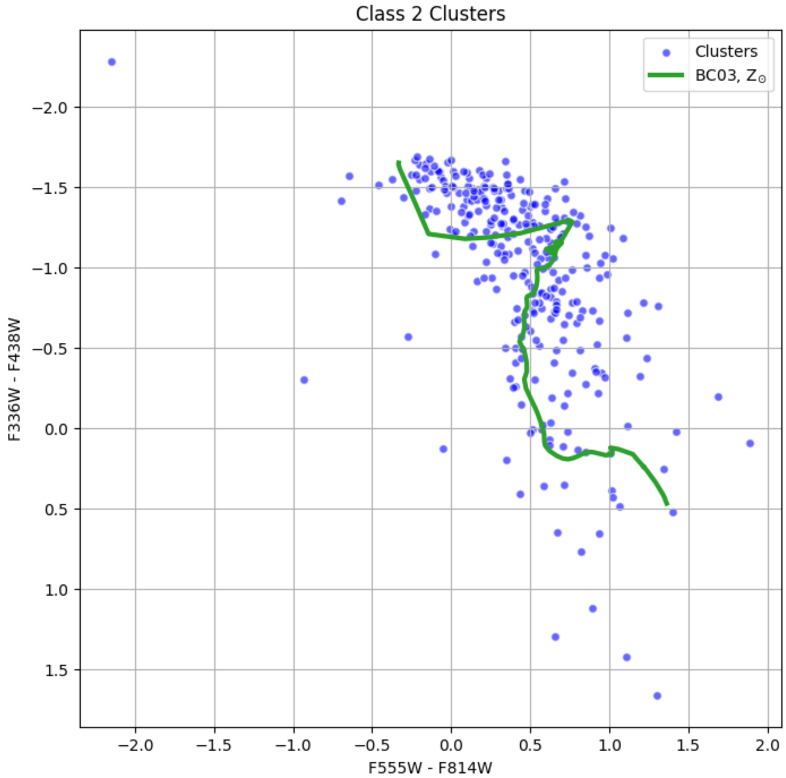


Figure 5.3: Scatter Plot

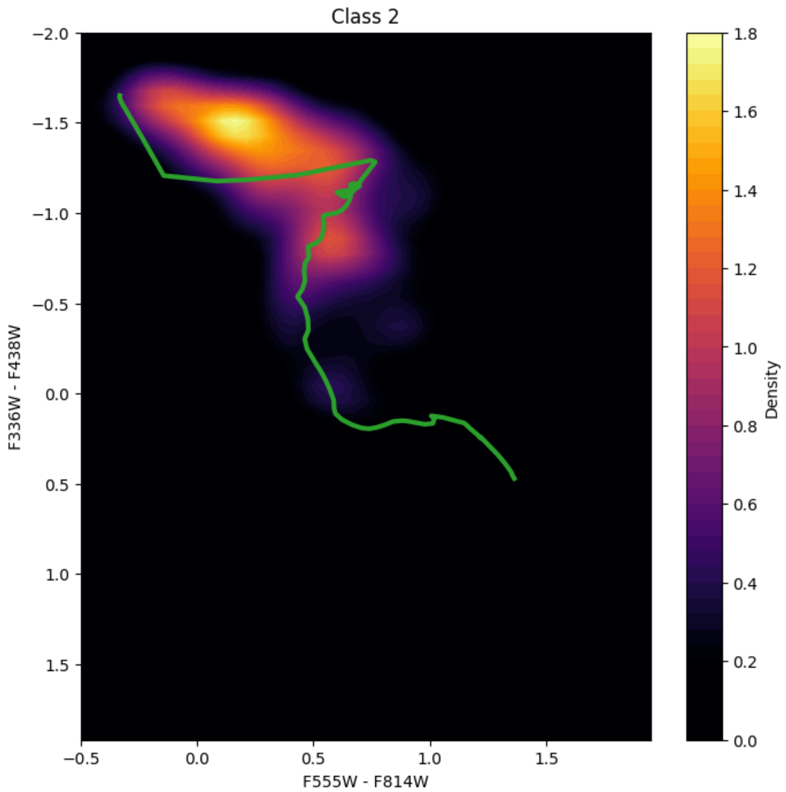


Figure 5.4: Density Plot

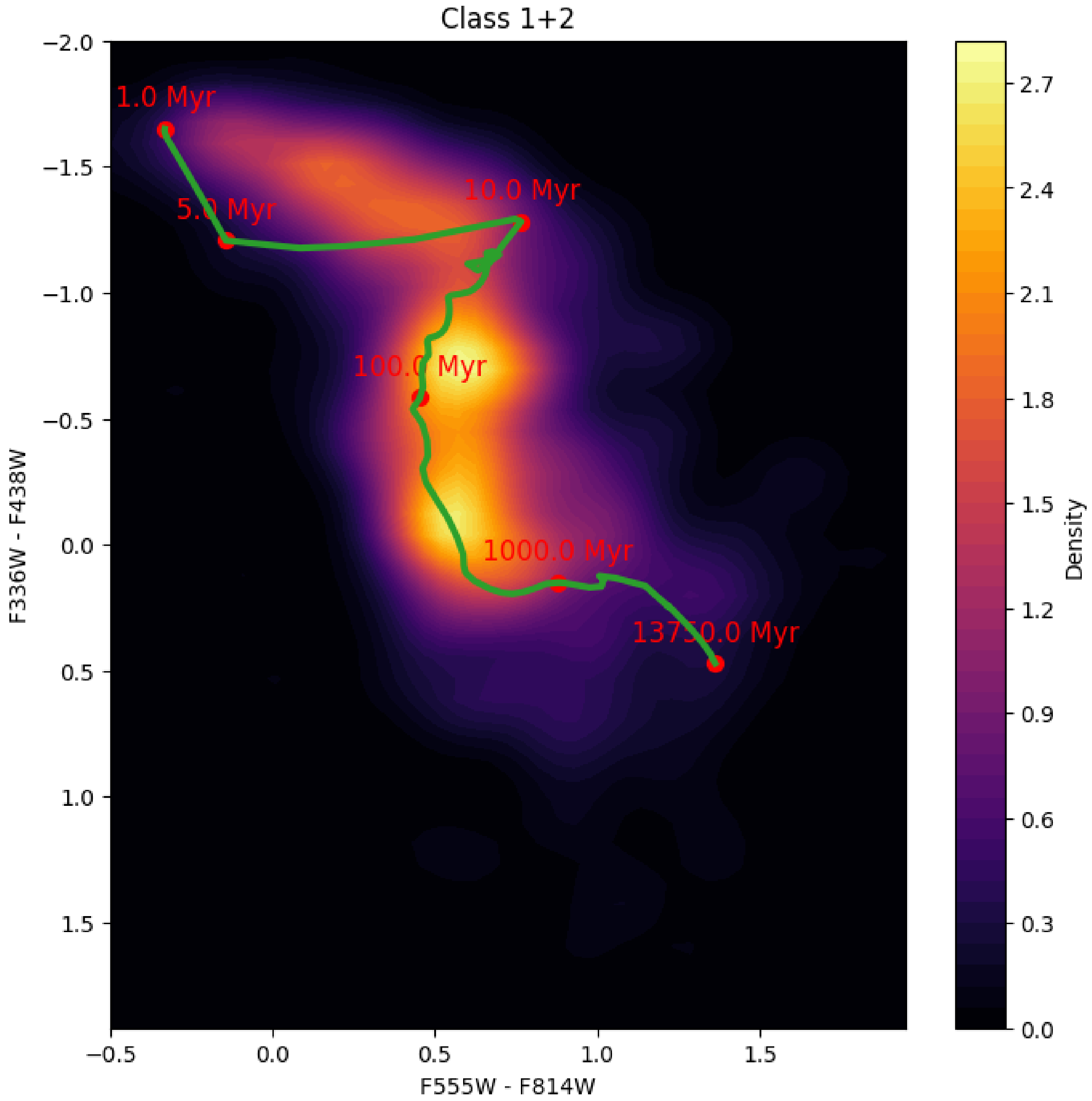


Figure 5.5: Density Plot with Theoretical Track

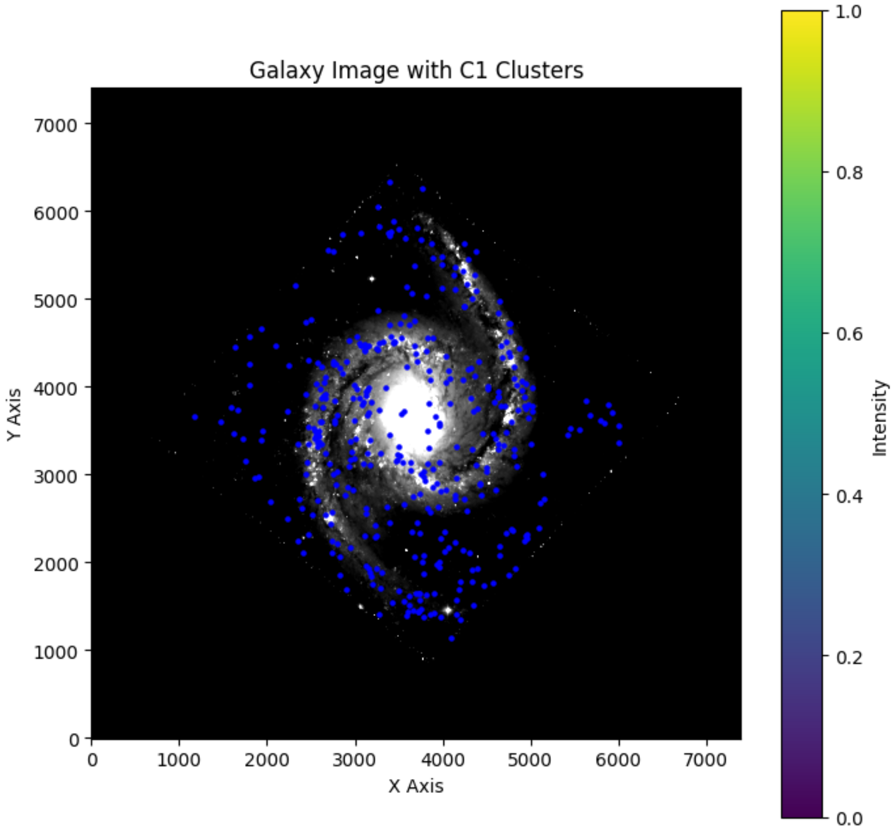


Figure 5.6: C1

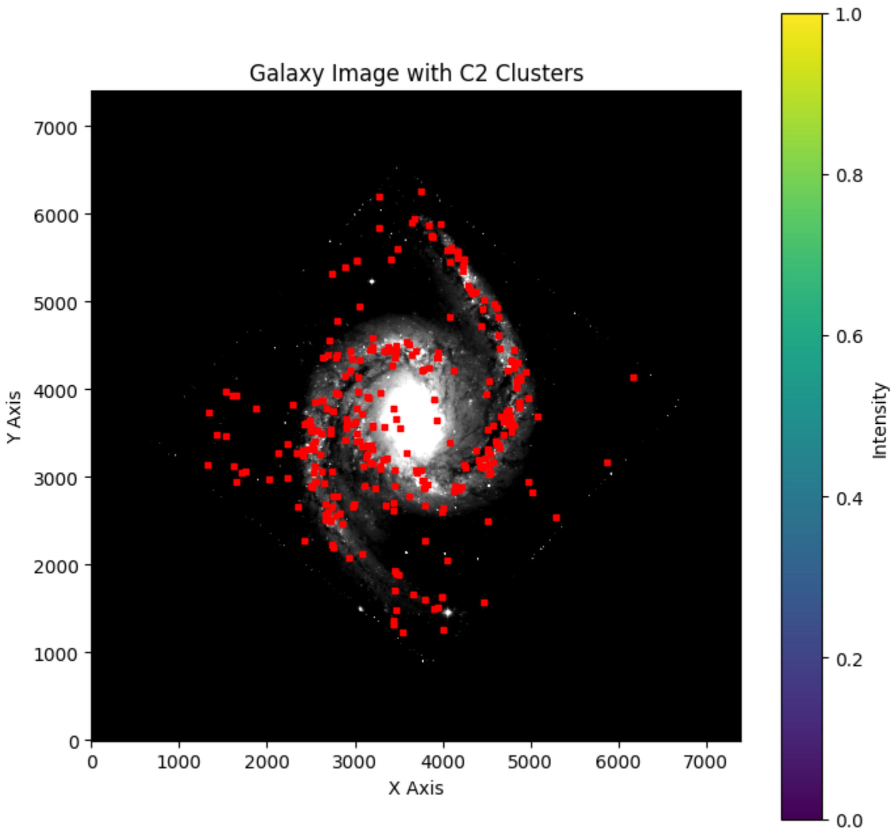


Figure 5.7: C2

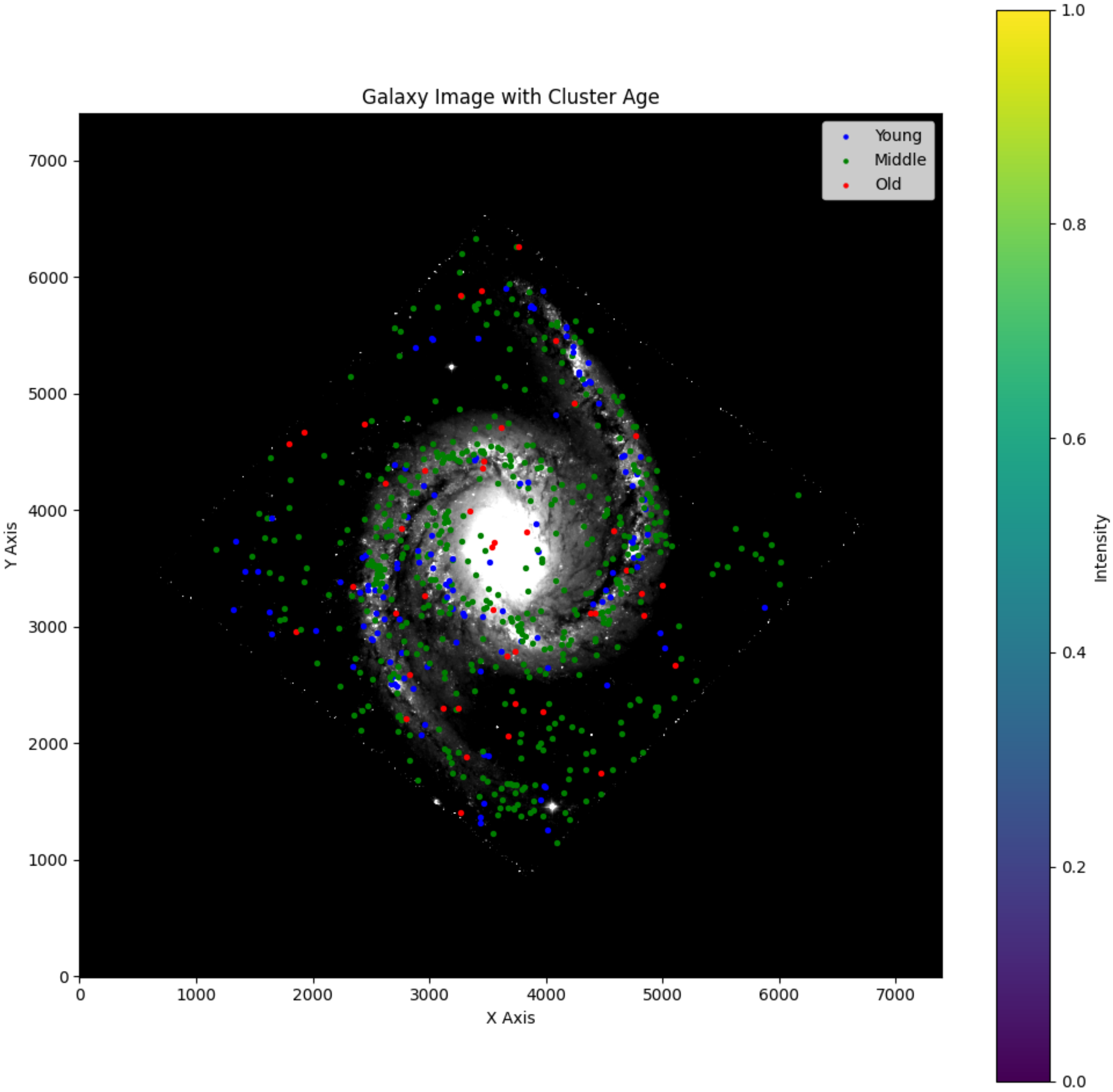


Figure 5.8: Age-wise Distribution

6. Gas Distribution

chapter_head_2.pdf

Understanding the distribution of gas within a galaxy provides crucial insights into the processes of star formation and cluster evolution. Gas distribution influences the formation and dynamics of star clusters, as well as the overall structure of the galaxy.

6.0.1 ALMA Gas Distribution

The Atacama Large Millimeter/submillimeter Array (ALMA) offers high-resolution observations of molecular gas in galaxies. ALMA's capabilities allow for detailed mapping of gas distributions, including:

- **Molecular Clouds**: ALMA detects the distribution of molecular clouds, which are the primary sites of star formation. These clouds are composed of gas and dust and play a critical role in the formation of new stars and clusters.
- **Gas Density and Kinematics**: ALMA provides information on the density and motion of the gas, helping to understand the dynamics of gas inflows and outflows within the galaxy.
- **Star-Forming Regions**: The gas distribution observed by ALMA helps identify regions of active star formation, correlating with areas where young star clusters are likely to form.

6.0.2 Age-Wise Correlation with Gas Distribution

By analyzing the gas distribution data obtained from ALMA and correlating it with the ages of star clusters, we can gain insights into the relationship between gas availability and cluster formation:

- **Young Clusters**: Young clusters, such as the C2 cluster, are typically found in regions with high gas density and molecular clouds. The availability of abundant gas in these regions provides the necessary conditions for the formation of new, young star clusters. The correlation with high gas density indicates that these clusters are forming in areas with significant star-forming activity.

- **Intermediate-Age Clusters**: Clusters of intermediate age are often located in areas where gas density has decreased compared to the regions of active star formation. This suggests that these clusters formed when gas was more available but are now in regions where gas has been partially consumed or dispersed.
- **Old Clusters**: Older clusters, such as the C1 cluster, are usually found in regions with low gas density. Over time, the gas in these regions has been largely consumed or expelled, reflecting the fact that these clusters formed in the past when the gas was more abundant. The low gas density in these areas is consistent with the more evolved state of these older clusters.

Correlating the age of the clusters with the gas distribution helps in understanding how changes in gas availability over time influence the formation and evolution of star clusters within the galaxy.

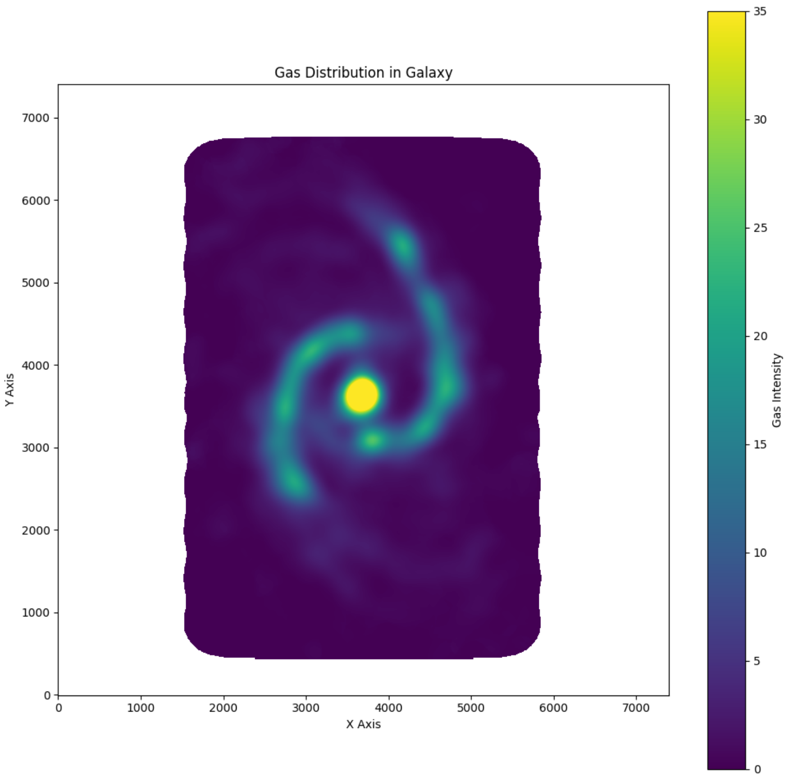


Figure 6.1: Scatter Plot

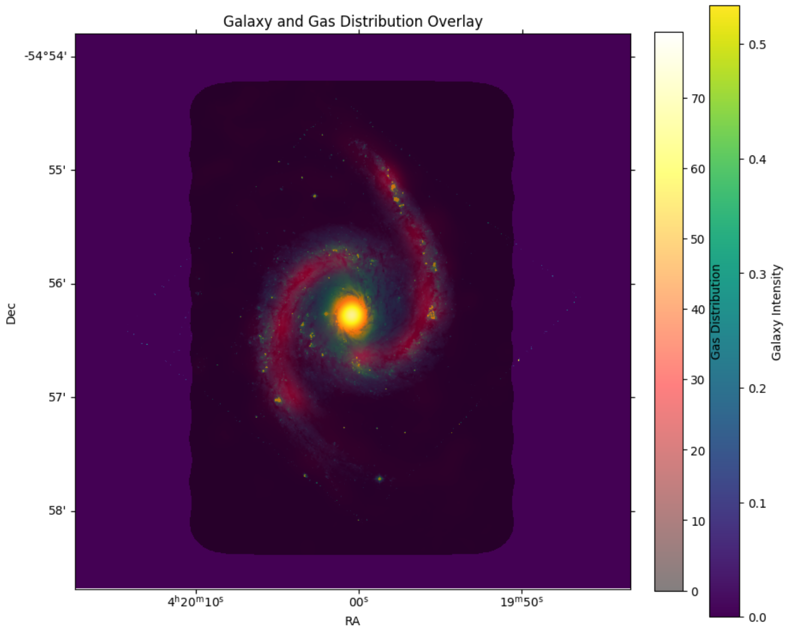


Figure 6.2: Density Plot

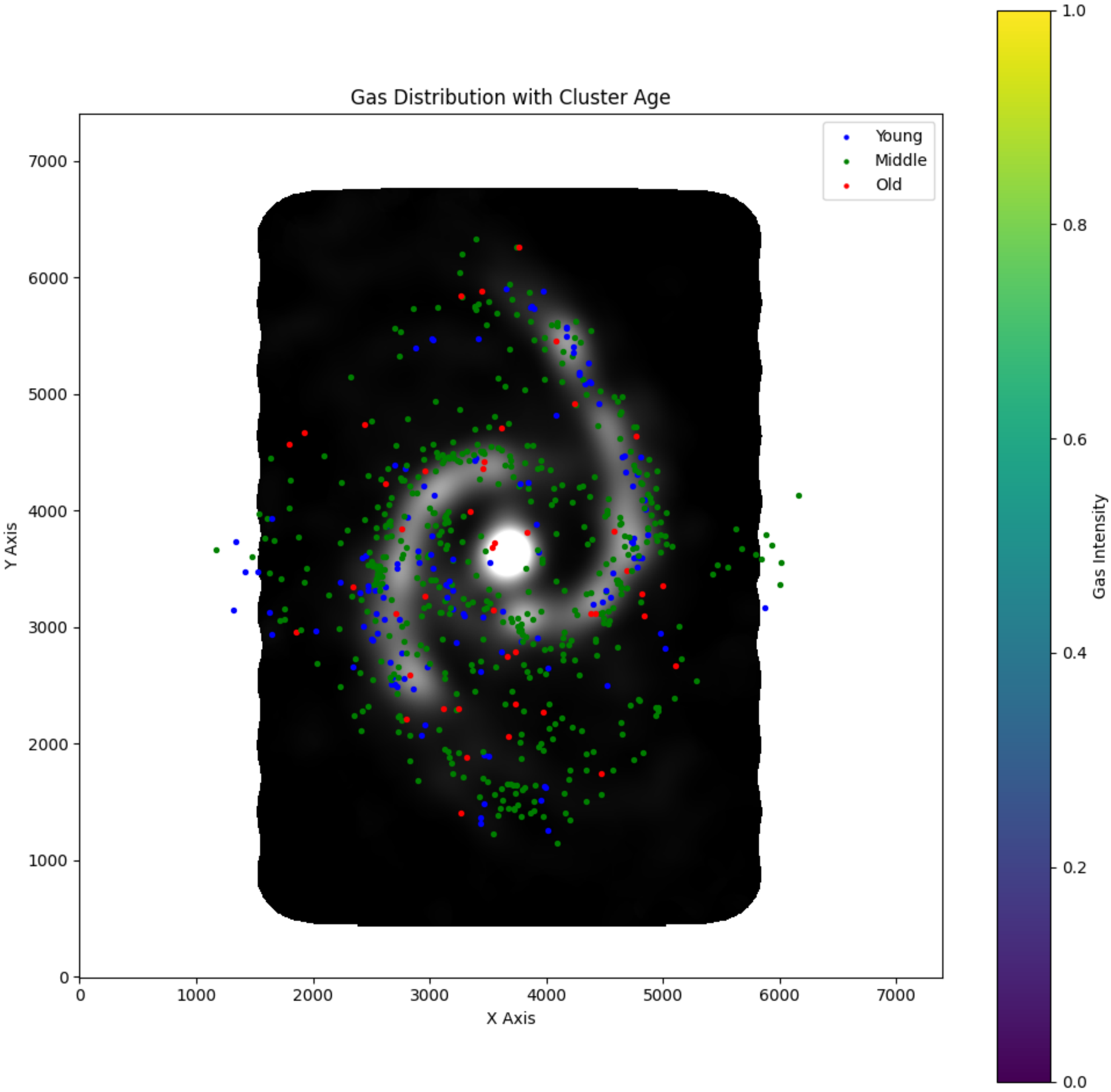


Figure 6.3: Scatter Plot

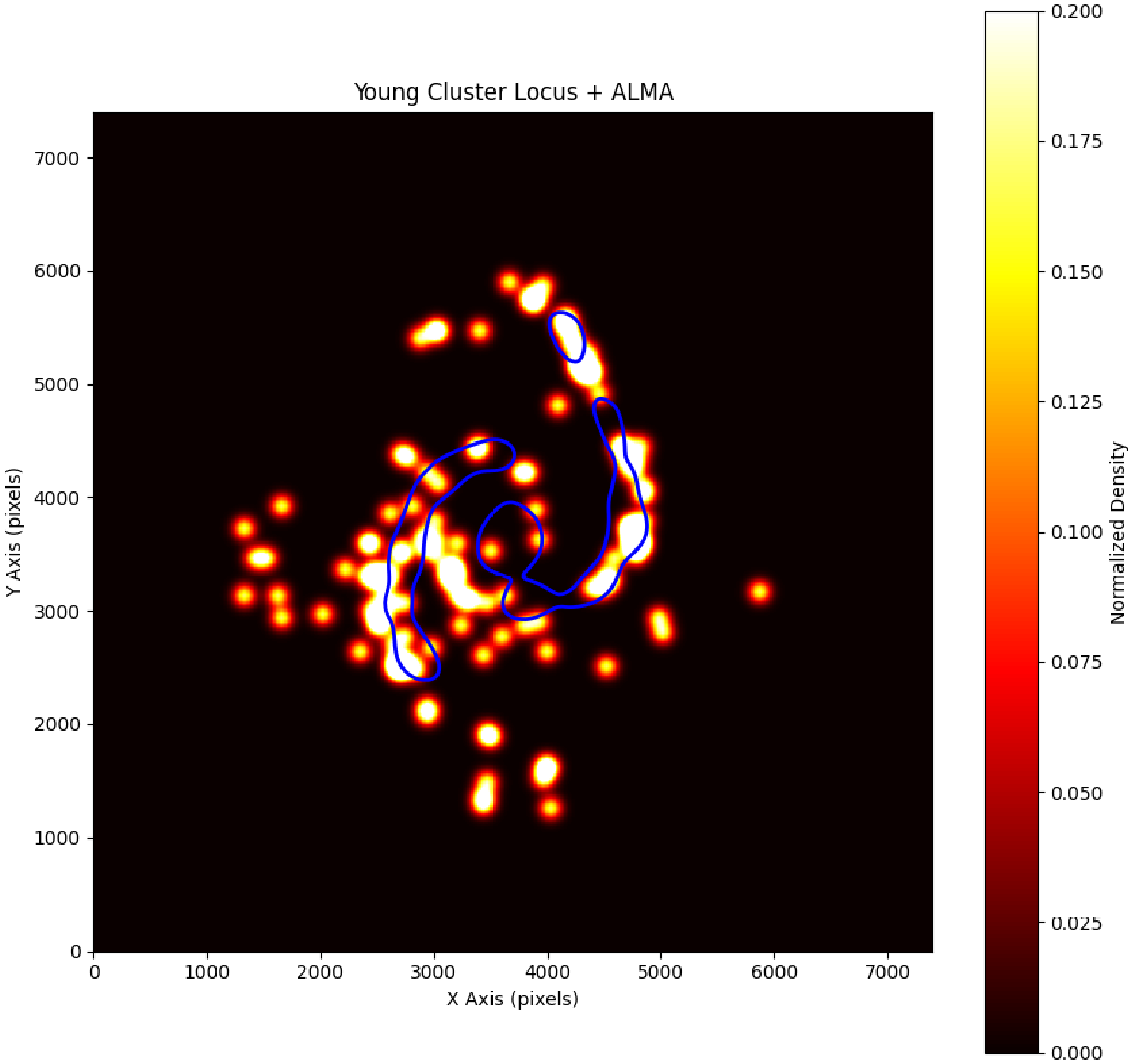


Figure 6.4: Scatter Plot

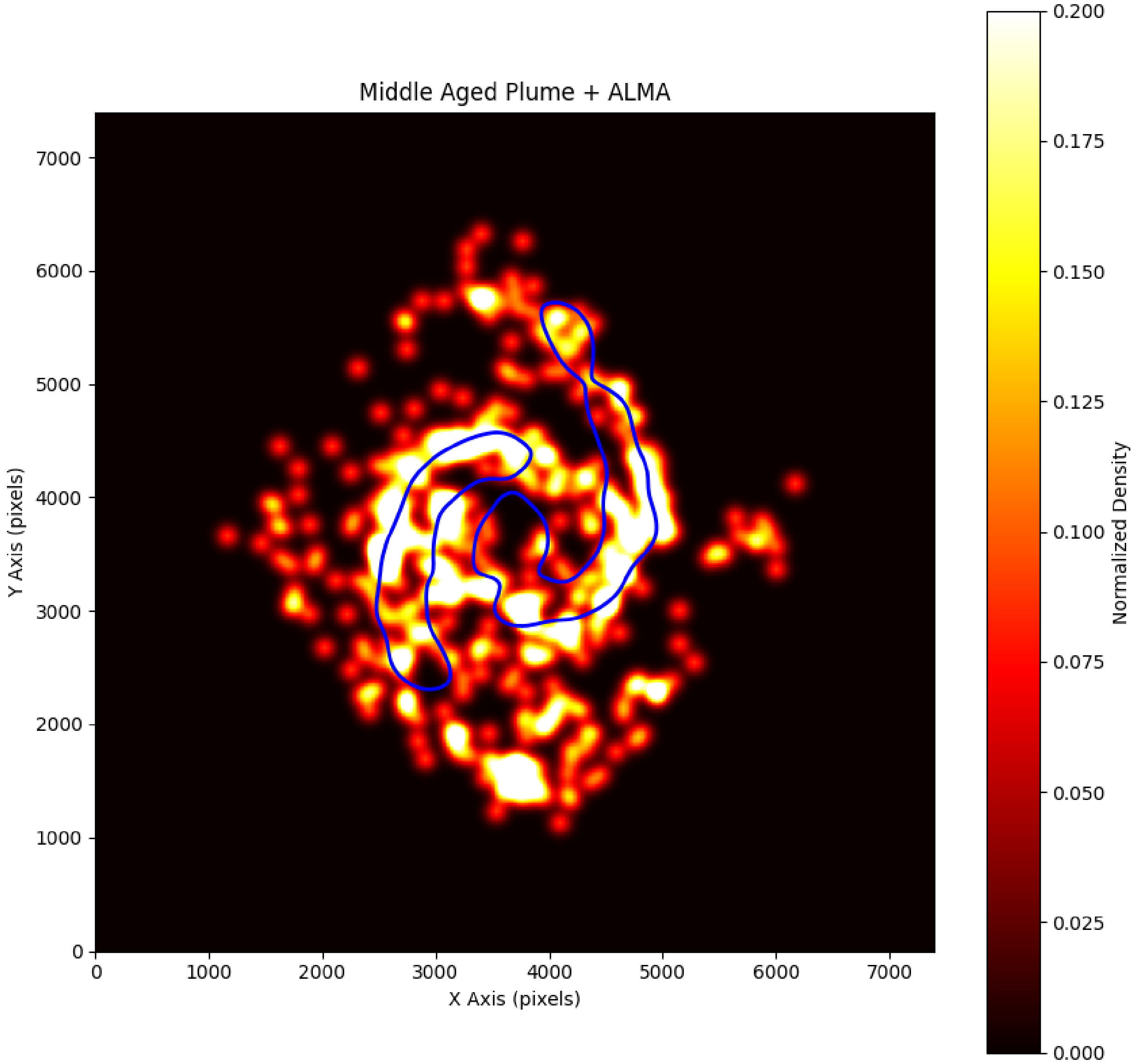


Figure 6.5: Scatter Plot

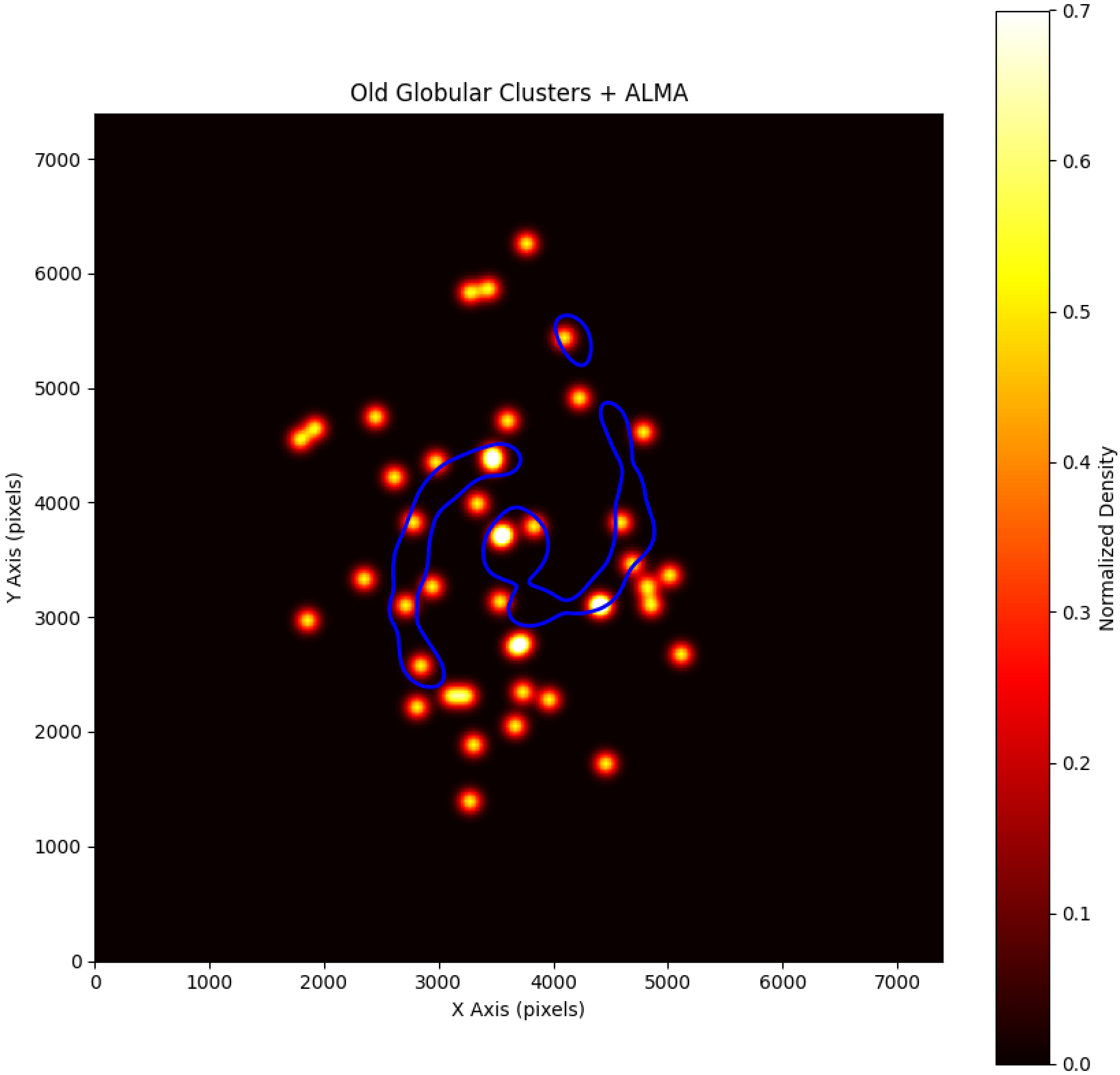


Figure 6.6: Scatter Plot