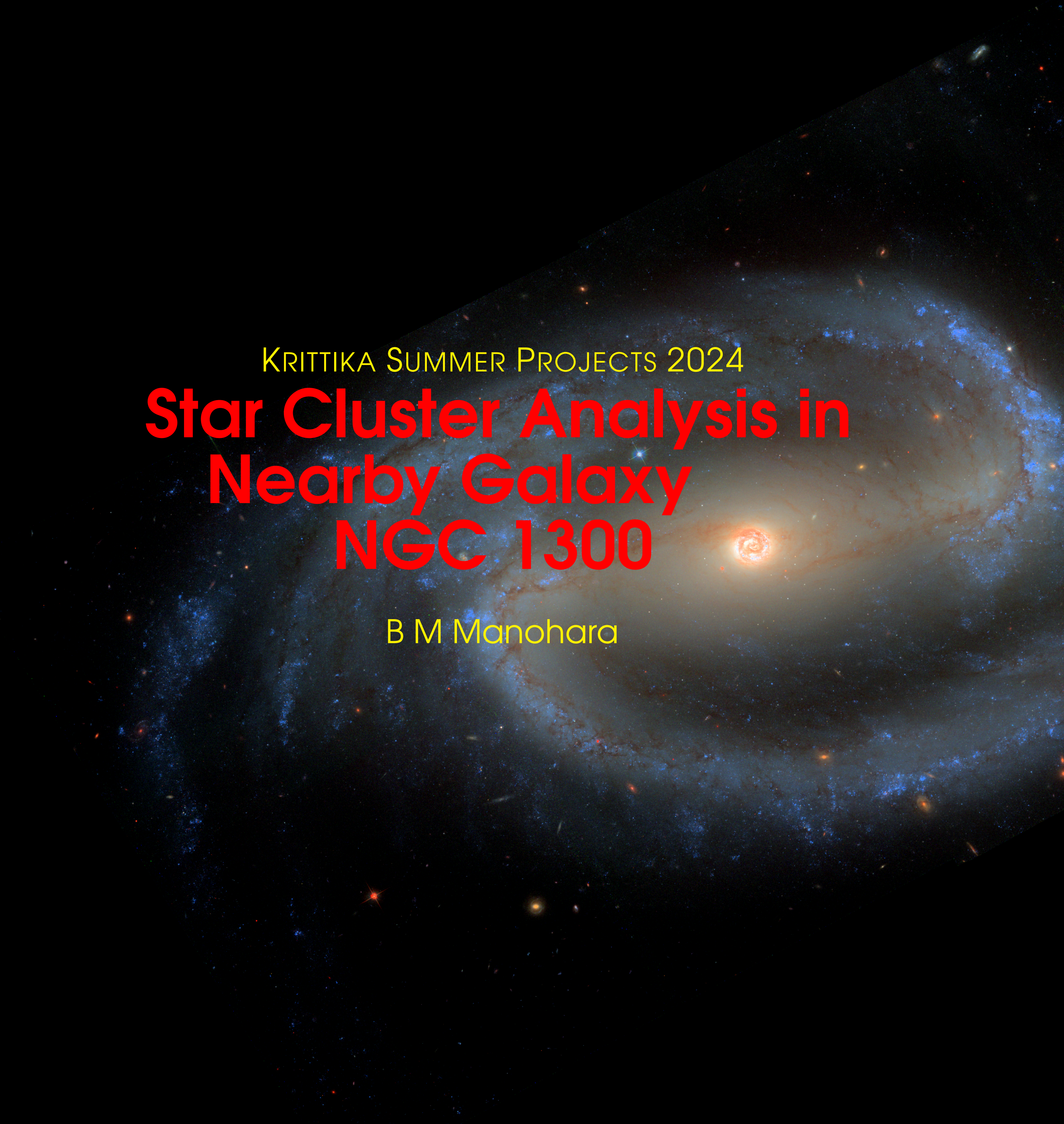

KRITTIKA SUMMER PROJECTS 2024

Star Cluster Analysis in Nearby Galaxy NGC 1300

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Abstract

This project involves the analysis of star clusters within a galaxy using data obtained from the Hubble Space Telescope (HST) and the Atacama Large Millimeter/submillimeter Array (ALMA). The primary objective is to study the properties of star clusters in detail. The approach includes several key methods: performing photometric analysis to obtain magnitudes, drawing color-color diagrams to investigate cluster properties, and classifying star clusters into young, middle-aged, and old categories. The clusters are further classified based on morphology into symmetric, asymmetric, and compact groups, examining how these morphological variations correlate with age. Additionally, the star clusters are overlaid on galaxy images to study their spatial distribution and on ALMA data to identify areas of active star formation. By comparing the findings with those of the PHANGS (Physics at High Angular resolution in Nearby GalaxieS) collaboration, the study aims to validate the methodologies and contribute to a deeper understanding of star cluster properties and their evolution within galaxies.

Objectives

The main objective of this project report is to discuss about:

- Perform photometry to obtain the magnitudes of star clusters.
- Draw color-color diagrams to analyze the properties of the clusters.
- Overlay young, middle-aged, and old clusters on a galaxy image to study their distribution within the galaxy.
- Classify star clusters as symmetric, asymmetric, or compact and further categorize them into young, middle-aged, and old to observe variations in morphology.
- Overlay clusters on ALMA data to identify areas of active star formation.

Acknowledgments

I would like to extend my heartfelt gratitude to all those who have contributed to the success of this project.
First and foremost, I am deeply thankful to **Krittika** and the **Astronomy Club of IIT Bombay** for providing me with the exciting and wonderful opportunity to undertake this summer project. Your support and encouragement have been invaluable throughout this journey.
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A special thank you to **Dhruva** from the **Astronomy Club of RV College of Engineering** for introducing me to the KSP initiative, which paved the way for this project. Your support was a crucial first step in this rewarding journey.
Lastly, I am grateful to **Aryan Namboodari** for his continuous support and discussions regarding related astronomy information, from the recruitment test through to the completion of the project. Your insights and assistance have greatly enhanced my understanding and contributed to the work.
Thank you all for your contributions, support, and encouragement. This project would not have been possible without each one of you.
B M Manohara

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I Part One

Part One

1. Introduction

1.1 Galaxy Morphology

Galaxies are fundamental building blocks of the universe, serving as the vast, complex systems where stars, planets, and other cosmic phenomena are born and evolve. Understanding galaxies is crucial before delving into the specifics of star clusters, as it provides the broader context for their formation and behavior.

The classification of galaxies based on morphology primarily follows the Hubble Sequence, introduced by Edwin Hubble in 1926. This system classifies galaxies into three main categories: elliptical, spiral, and irregular, with subcategories within each. Here's an overview of each type:

1.1.1 Elliptical Galaxies (E)

Elliptical galaxies are characterized by their smooth, featureless light distribution and ellipsoidal shape. They range from nearly spherical (E0) to highly elongated (E7).

- E0: Almost spherical
- E7: Highly elongated.

Figure 1.1: Elliptical Galaxy

These galaxies contain older, red stars and have little to no interstellar gas and dust, indicating minimal star formation activity.

1.1.2 Spiral Galaxies (S)

Spiral galaxies have a flat, rotating disk with spiral arms winding outwards from a central bulge. They are further classified based on the tightness of their spiral arms and the size of the central bulge.

- Sa: Tightly wound arms and large central bulge.
- Sb: Moderately wound arms and medium-sized bulge.
- Sc: Loosely wound arms and small bulge.

Figure 1.2: Spiral Galaxy

1.1.3 Barred Spiral Galaxies (S)

Similar to spiral galaxies but with a central bar structure extending from the nucleus, from which the spiral arms emerge.

- SBa: Tightly wound arms and large bar.
- SBb: Moderately wound arms and medium-sized bar.
- SBc: Loosely wound arms and small bar.

Figure 1.3: Barred Spiral Galaxy

1.1.4 Irregular Galaxies (Irr)

Irregular galaxies lack a distinct shape or structure and do not fit into the elliptical or spiral categories. They often have chaotic appearances with no clear symmetry.

- Irr I: Some structure, hinting at a disk or spiral arms but still irregular.
- Irr II: Completely chaotic without any hint of structure.

Figure 1.4: Irregular Galaxy

1.1.5 Lenticular Galaxies (S0)

Lenticular galaxies are intermediate between elliptical and spiral galaxies. They have a prominent central bulge and a disklike structure but lack significant spiral arms. They can be further divided based on whether they show a bar structure:

- S0: No bar.
- SB0: Bar present.

Figure 1.5: Lenticular Galaxy

1.2 The Hubble Tuning Fork Diagram

Hubble's classification is often visualized as a tuning fork diagram: The left fork represents elliptical galaxies (E0 to E7). The right fork splits into normal spiral galaxies (Sa to Sc) and barred spiral galaxies (SBa to SBc). The stem of the fork includes lenticular galaxies (S0 and SB0).

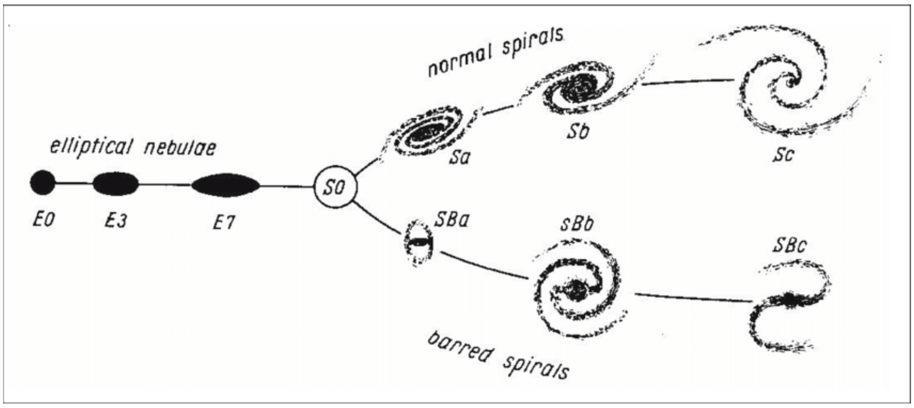

Figure 1.6: Hubble Tuning Fork Diagram

1.3 Typical Features of Barred Spiral Galaxies

1. **Central Bar Structure:**
   - A prominent elongated bar of stars extends from the nucleus, crossing the central bulge.
   - The bar structure can influence the motion of stars and gas within the galaxy.
2. **Spiral Arms:**
   - Spiral arms extend from the ends of the bar rather than from the nucleus.
   - These arms are sites of active star formation, containing young, hot stars, star clusters, and nebulae.
3. **Central Bulge:**
   - A dense, spherical concentration of older stars located at the galaxy's center.
   - The bulge can vary in size and brightness.
4. **Disk:**
   - The flat, rotating disk contains the spiral arms and the majority of the galaxy's gas and dust.
   - The disk often contains a mix of young and old stars.
5. **Halo:**
   - A roughly spherical region surrounding the galaxy, containing older stars, star clusters, and dark matter.
   - The halo may also include globular clusters.
6. **Active Star Formation:**
   - The spiral arms are rich in gas and dust, providing the raw materials for new stars to form.
   - Star formation regions, such as H II regions and molecular clouds, are common in the arms.

7. **Rotation:**
    - The galaxy exhibits differential rotation, where the inner regions rotate faster than the outer regions.
    - The bar and the spiral arms rotate around the central bulge.
8. **Color:**
    - The spiral arms often appear blue due to the presence of young, hot stars.
    - The central bulge and bar may appear redder due to the older stellar population.
9. **Gas and Dust Content:**
    - Barred spiral galaxies typically contain significant amounts of interstellar gas and dust.
    - This material is concentrated in the spiral arms and the central bar.
10. **Examples:**
    - Well-known examples of barred spiral galaxies include the Milky Way, the Andromeda Galaxy (M31), and the galaxy NGC 1300.

Figure 1.7: NGC1300

1.4 Star Clusters

Star clusters are groups of stars that are gravitationally bound and share a common origin. They can be broadly classified into two main types: open clusters and globular clusters. Here's a detailed look at each type:

1.4.1 Open Star Clusters

Characteristics of Open Star Clusters are:

1. **Age:** Relatively young, ranging from a few million to a few billion years old.
2. **Stars:** Composed of a few hundred to a few thousand stars
3. **Distribution:** Stars in open clusters are loosely bound and spread out over a larger area.
4. **Composition:** Often contain many blue, hot, young stars, indicating active star formation.
5. **Shape:** Irregular in shape due to the weaker gravitational binding.

Examples: The Pleiades (also known as the Seven Sisters) and the Hyades in the constellation Taurus.

Formed from giant molecular clouds, open clusters are sites of active star formation. Over time, gravitational interactions with other stars and molecular clouds can disperse the stars in an open cluster, leading to its eventual dissolution.

Figure 1.8: Open Star Cluster

1.4.2 Globular Star Clusters

Characteristics of Globular Star Clusters are:

1. **Age:** Typically very old, ranging from around 10 to 13 billion years.
2. **Stars:** Composed of tens of thousands to hundreds of thousands of stars.
3. **Distribution:** Stars in globular clusters are tightly bound and concentrated in a spherical shape, occupying a relatively small volume of space.
4. **Composition:** Generally contain older stars with low metal content (population II stars), and often show a more uniform color distribution, typically redder due to the older stellar population.
5. **Shape:** Spherical in shape with a dense core, reflecting strong gravitational binding.

Examples: M13 (the Hercules Cluster) and Omega Centauri (NGC 5139).

Globular clusters are among the oldest stellar systems in the universe, believed to have formed early in the galaxy's history. They are typically found in the halo of a galaxy and are crucial for studying the early stages of galaxy formation and the evolution of stars. Due to their high stellar density and old age, globular clusters offer valuable insights into the formation and evolution of the Milky Way and other galaxies.

Figure 1.9: Globular Star Cluster

1.5 PHANGS Collaboration

The Physics at High Angular resolution in Nearby GalaxieS (PHANGS) collaboration is an international research project focused on understanding the interplay between the small-scale physical processes that govern star formation and the large-scale properties of galaxies. The PHANGS team uses data from various telescopes, including the Hubble Space Telescope (HST), the Atacama Large Millimeter/submillimeter Array (ALMA), and the Very Large Telescope (VLT), to study nearby galaxies at high resolution.

About the Galaxy Under Study: The specific galaxy being analyzed in this project is part of the PHANGS sample, which includes over 90 nearby galaxies. These galaxies are selected to cover a range of morphologies, star formation rates, and environments, providing a comprehensive view of star formation across different galactic contexts. The high-resolution data from HST allows for detailed analysis of individual star clusters within these galaxies, helping to elucidate the conditions and processes that lead to star formation.

PHANGS aims to create a multi-wavelength dataset that can be used to study the physical conditions of the interstellar medium, the formation and evolution of star clusters, and the feedback processes that regulate star formation. By comparing our results with the PHANGS catalog, we can validate our analytical methods and contribute to the broader understanding of galactic star formation.

1.6 NGC 1300

NGC 1300 is a prominent barred spiral galaxy located approximately 61 million light-years away in the constellation Eridanus. This galaxy is known for its well-defined bar structure and striking spiral arms, making it an excellent example of the morphological type in galactic studies. Observations of NGC 1300 provide valuable insights into the dynamics of barred spiral galaxies and their star formation processes.

Characteristics: NGC 1300 features a central bar that extends across its bulge, with spiral arms emerging from the ends of the bar. The galaxy exhibits active star formation, particularly in its spiral arms, where young, hot stars and star clusters are prominent. The detailed structure of NGC 1300 is often studied using high-resolution imaging from telescopes such as the Hubble Space Telescope (HST) and ground-based observatories.

Significance: As a member of the Hubble Sequence of galaxy types, NGC 1300 helps astronomers understand the impact of the central bar on spiral arm formation and galactic dynamics. Its detailed morphology and active star-forming regions provide a rich field for studying the interplay between different components of a galaxy and the processes driving galactic evolution.

2. Data Analysis Techniques

2.1 Aperture Photometry

Aperture photometry is a widely used technique in astronomical imaging for measuring the total light emitted by an astronomical object. This method involves summing the pixel values within a defined circular region, known as the aperture, centered on the object of interest.

Steps and Considerations:

1. **Define Aperture:** Choose a circular region around the object to capture its light. The size of the aperture is critical for accurate measurement. If the aperture is too small, it may miss some of the object's light, leading to an underestimation of its flux. Conversely, if the aperture is too large, it may include excessive background noise, resulting in an overestimation.
2. **Sky Background:** Measure the average background light from an annular region surrounding the aperture, known as the sky annulus. This background measurement is necessary to correct for the light contamination from the surrounding environment. Subtract the estimated background flux from the total flux within the aperture to isolate the object's true flux.
3. **Total Flux Calculation:** Sum the pixel values within the defined aperture. Then, subtract the background flux, derived from the sky annulus, to obtain the net flux of the object.

Advantages:

- Simple and straightforward to implement.
- Efficient for use in isolated fields where objects are not overlapping.

Disadvantages:

- Less accurate in crowded fields where the light from neighboring stars can contaminate the aperture.
- The choice of aperture size can significantly impact the results, requiring careful optimization to balance between capturing all the light from the object and minimizing background noise.

Aperture photometry remains a fundamental technique in astronomical research, particularly in scenarios where simplicity and efficiency are essential. However, it is important to carefully select the aperture size and consider background contamination to ensure accurate measurements.

2.2 Corrections in Photometry

Accurate photometry requires several corrections to ensure that the measured fluxes of star clusters are precise and comparable. The main corrections applied include background correction, extinction correction, and unit conversion.

2.2.1 Background Correction

Background correction is crucial for isolating the flux of star clusters by accounting for the light from surrounding areas.

1. **Annulus Method:** The annulus photometry technique was employed to estimate the background light. This method involves measuring the flux in a circular annulus around the star cluster. The annulus provides an estimate of the background contribution affecting the aperture containing the star cluster.
2. **Background Subtraction:** The average background flux obtained from the annulus was subtracted from the total flux measured within the circular aperture. This subtraction helps isolate the true flux of the star cluster by removing the background light contribution.

2.2.2 Extinction Correction

Extinction refers to the absorption and scattering of light by interstellar dust and gas between the star clusters and the observer. This effect can significantly alter the observed brightness of the objects.

- **Correction Approach:** Extinction correction factors were applied to adjust the measured fluxes. These factors, derived from models or empirical data, estimate the amount of light lost due to interstellar material.

2.2.3 Unit Conversion

To ensure consistency in photometric analysis, it is necessary to convert measured flux values into standard units.

- **Flux to Magnitude Conversion:** The flux values were converted to magnitudes using zero points calculated from calibration objects. This conversion is essential for comparing the photometric results with values from the PHANGS catalog and other standard references.

2.3 Color-Color Diagram

A color-color diagram is a graphical tool used in astronomy to analyze the colors of astronomical objects, providing insights into their physical properties and evolutionary stages. The diagram plots the difference between two different color indices (typically in magnitudes) on the x-axis and y-axis.

2.3.1 Concept and Construction

- **Color Indices:** Color indices are derived from the difference in magnitudes measured through different filters. For example, $(B-V)$ and $(V-I)$ are common color indices where B, V, and I represent magnitudes in the blue, visible, and infrared filters, respectively. These indices reflect the object's color and can indicate its temperature, age, and composition.
- **Diagram Construction:** To construct a color-color diagram, astronomical objects are plotted according to their color indices. Each point on the diagram represents an object, with its position revealing information about its stellar properties. For instance, the x-axis may represent $(B-V)$ and the y-axis $(V-I)$, allowing the examination of correlations between different colors.

2.3.2 Applications and Interpretation

- **Stellar Populations:** The diagram helps distinguish between different stellar populations, such as young, middle-aged, and old stars, by comparing their color indices. Young, hot stars will appear in one region, while cooler, older stars will be located elsewhere on the diagram.
- **Reddening and Extinction:** The diagram can also be used to study the effects of interstellar reddening and extinction. By comparing the observed colors with those expected from stellar models, researchers can infer the amount of dust and gas along the line of sight.
- **Star Formation Regions:** Color-color diagrams are useful for identifying and analyzing star-forming regions. The diagram can reveal the presence of young, massive stars and the extent of star formation activity within a region.

2.3.3 Examples and Models

- **Stellar Isochrones:** Isochrones representing theoretical models of stellar evolution can be overlaid on the color-color diagram. These models help interpret the observed colors in terms of stellar age and composition.
- **Comparative Studies:** By comparing the color-color diagrams of different star clusters or regions, researchers can investigate variations in stellar populations and star formation processes across different environments.

II

Part Two

3. Methodology, Results and Discussion

3.1 Photometry Analysis of Star Clusters in NGC 1300

The analysis of star clusters in NGC 1300 is conducted through the following key steps:

3.1.1 Data Acquisition and Visualization

- **Filter Images Obtained:** Various filter images covering ultraviolet (UV) to infrared (IR) wavelengths were acquired.
- **Data Visualized:** The data were visualized using `astropy.fits`, a library for manipulating and visualizing FITS files.

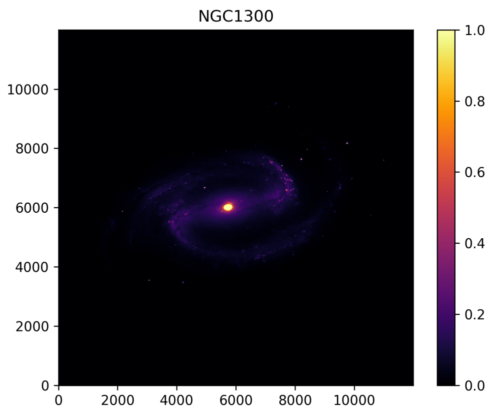

Figure 3.1: 555 Filter Image Visualized

3.1.2 Image Stacking

- **Filter Images Stacked:** The images were stacked to create a composite color image, with the extreme UV filter (435 nm) represented as blue, the middle-range filter (555 nm) as green, and the IR filter (814 nm) as red. This stacking was performed to enhance the visualization of the galaxy's structure and star clusters.

Figure 3.2: NGC1300

3.1.3 Star Cluster Identification

- **Star Clusters Marked:** The star clusters within NGC 1300 were marked on the stacked image using right ascension (RA) and declination (DEC) values. This marking was done to facilitate subsequent photometric analysis.

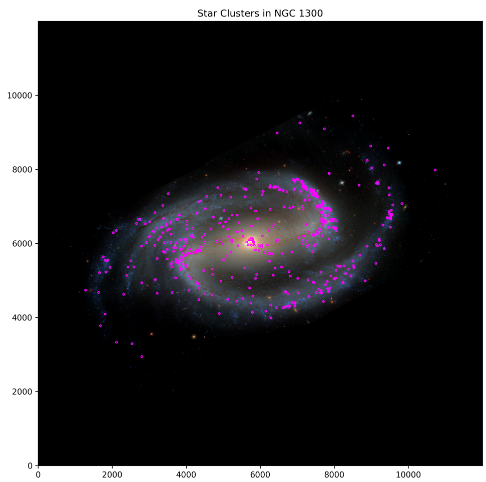

Figure 3.3: 318 Star Clusters Identified in NGC1300

3.1.4 Flux Measurement with Astroquery

- **Flux of Known Objects Obtained:** The flux of known constant sources (excluding supernovae) in the vicinity of NGC 1300 was obtained using `astroquery`. Measurements were taken for various filters (275, 336, 435, 555, and 814 nm). The constancy of these sources was ensured to maintain accurate flux calibration.

3.1.5 Photometry Calibration

- **Photometry on Calibration Objects Performed:** Photometric measurements were conducted on these calibration objects using both circular and annulus methods:
  - **Circular Photometry:** A radius of 4 pixels was used for the circular photometry.
  - **Annulus Photometry:** An inner radius of 7 pixels and an outer radius of 8 pixels were employed to aid in background subtraction and achieve accurate flux measurements.
- **Zero Point Determined:** The zero point for the filters was calculated from the photometric measurements.

3.1.6 Photometry on Star Clusters

- **Photometry on Star Clusters Performed:** The same photometric methods and radii were applied to the marked star clusters in NGC 1300 to obtain their flux values.

3.1.7 Data Comparison and Verification

- **Apparent Magnitude Plotted:** The apparent magnitudes, derived from the photometry analysis, were plotted against the values from the PHANGS catalog.
- **Results Verified:** This comparison facilitated the verification of the accuracy of the calculated values by checking for consistency with the standard values provided by the PHANGS collaboration.

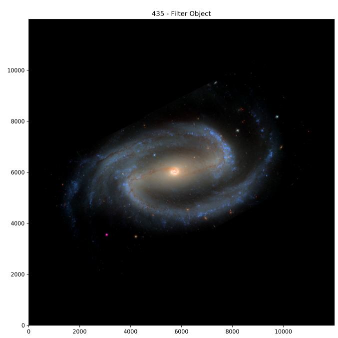

Figure 3.4: Object used for photometry calibration in 435 filter

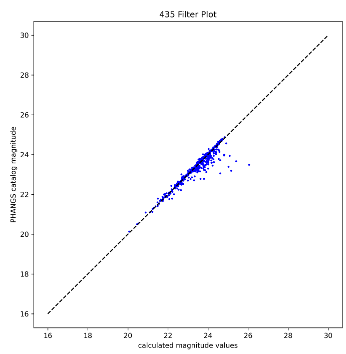

Figure 3.5: The plot shows almost 1:1 agreement with PHANGS catalog

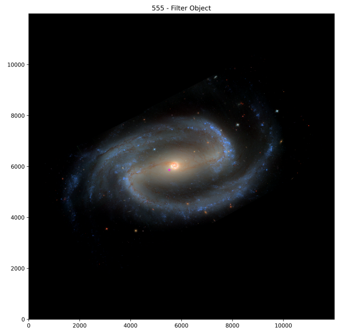

Figure 3.6: Object used for photometry calibration in 555 filter

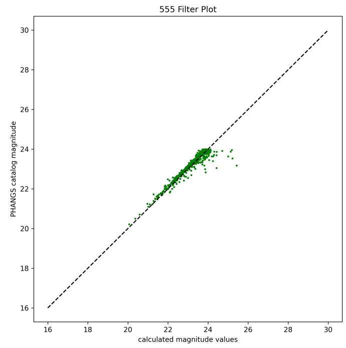

Figure 3.7: The plot shows almost 1:1 agreement with PHANGS catalog

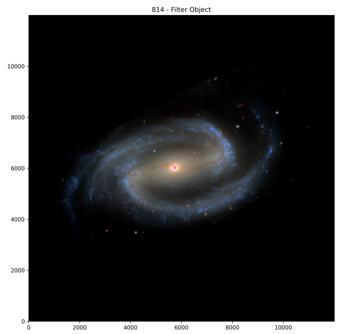

Figure 3.8: Object used for photometry calibration in 814 filter

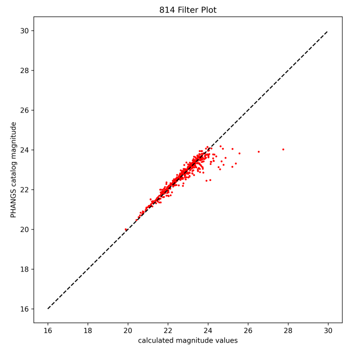

Figure 3.9: The plot shows almost 1:1 agreement with PHANGS catalog

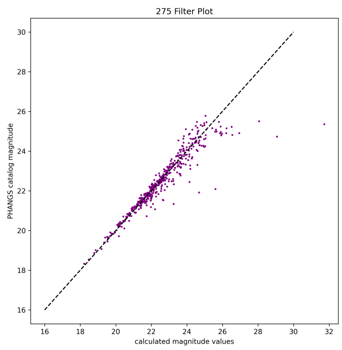

Figure 3.10: Magnitudes calculated by subtracting vega magnitude from different bands show 1:1 agreement with PHANGS catalog

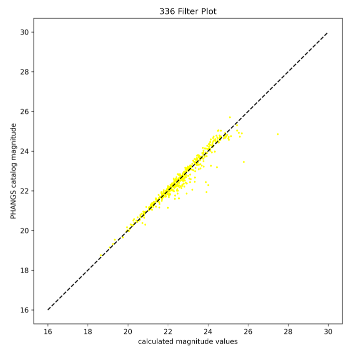

Figure 3.11: Magnitudes calculated by subtracting vega magnitude from different bands show 1:1 agreement with PHANGS catalog

3.2 Color-Color Diagram Analysis

To analyze the star clusters in NGC 1300, a color-color diagram was constructed using photometric data from various filters. Specifically, the diagram was created using the color indices $(336-435)$ versus $(555-814)$, which provide a means to differentiate between clusters of various ages and stellar populations.

3.2.1 Calculation of the Color-Color Diagram

1. **Data Extraction:** The flux measurements in the 336 nm, 435 nm, 555 nm, and 814 nm filters were obtained through photometric analysis of the star clusters. These measurements allowed the calculation of the color indices.
2. **Color Index Calculation:** The color indices were computed as follows:
   - $(336-435)$: Represents the difference in flux between the 336 nm and 435 nm bands.
   - $(555-814)$: Represents the difference in flux between the 555 nm and 814 nm bands.
3. **Color-Color Plot:** The calculated color indices were plotted on a color-color diagram. The $(336-435)$ index was plotted on the y-axis, while the $(555-814)$ index was plotted on the x-axis.
4. **Overlay of Theoretical Tracks:** The theoretical evolutionary tracks, which represent various stages of stellar evolution, were overlaid on the color-color diagram. These tracks, derived from stellar population models, provide a reference for distinguishing different age groups of star clusters.

3.2.2 Conclusion

The color-color diagram, with the theoretical tracks overlaid, indicated that the majority of star clusters in NGC 1300 fall within the region corresponding to young age clusters. Specifically, the diagram suggests that these star clusters are predominantly in the age range of 1 to 100 million years. This conclusion is based on the positions of the clusters relative to the theoretical tracks, which are used to interpret the age and evolutionary status of stellar populations.
The results from the color-color analysis provide insights into the star formation history and the current state of star clusters within NGC 1300, confirming the presence of active, young star clusters within the galaxy.

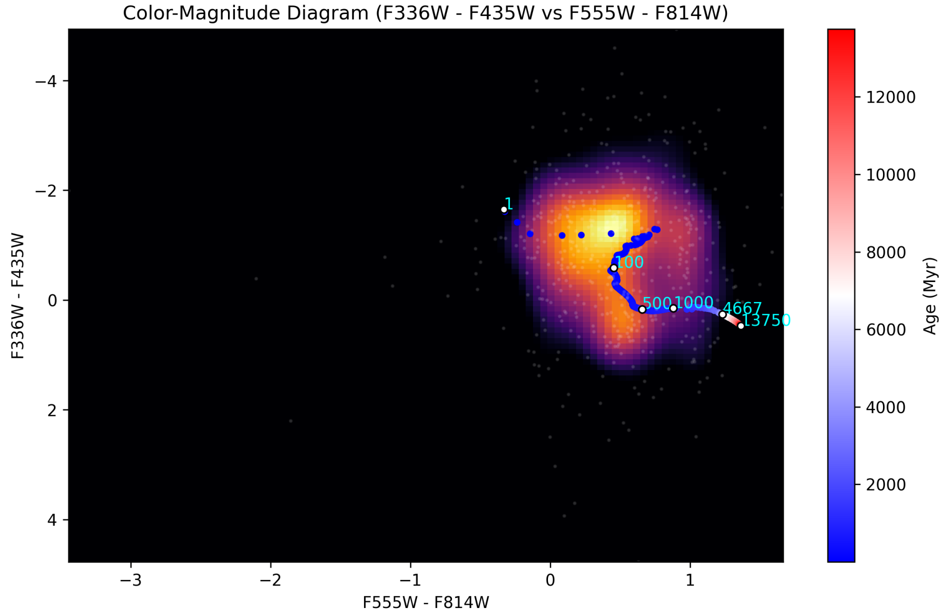

Figure 3.12: Color Magnitude Diagram

3.3 Cluster Symmetry Classification and Age Correlation

The catalog classified star clusters based on their symmetry, distinguishing them into symmetric clusters, asymmetric clusters, and compact associations. To further understand these classifications, theoretical tracks were employed to categorize the clusters into young, middle-aged, and old age groups.

3.3.1 Observations and Classification

- **Young and Middle-Aged Clusters:** These clusters were predominantly observed as asymmetric or in compact associations. This suggests that these clusters have not yet reached a stable state of equilibrium. The irregularity in their structure may be attributed to ongoing star formation and dynamic processes within the clusters.
- **Old-Aged Clusters:** In contrast, older clusters were more frequently found to be symmetric. This indicates that, over time, the random motion of gases and stars within the clusters tends to become more uniform. As the clusters evolve, they move towards a more stable configuration, resulting in a symmetric appearance.

3.3.2 Conclusions

The analysis reveals that the symmetric nature of old-age clusters results from the gradual stabilization of stellar and gaseous motion within the clusters. Conversely, young and middle-aged clusters exhibit more asymmetric features or compact associations due to ongoing evolutionary processes and lack of equilibrium.

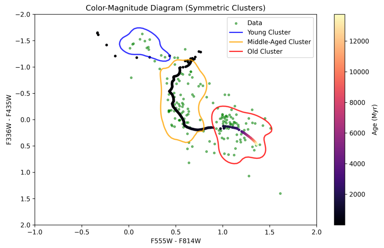

Figure 3.13: Distribution of Young, Middle and Old Aged Clusters in Symmetric Clusters

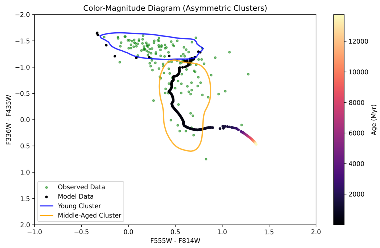

Figure 3.14: Distribution of Young, Middle and Old Aged Clusters in Asymmetric Clusters

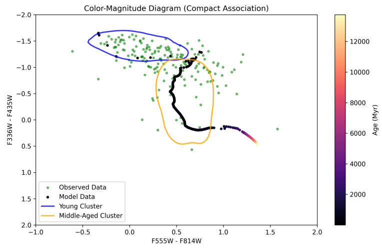

Figure 3.15: Distribution of Young, Middle and Old Aged Clusters in Compact Association

3.4 Overlay of Star Clusters on CO Moment Maps

The analysis included overlaying the classified star clusters—young, middle-aged, and old—on the CO moment maps from ALMA data. This approach helps in understanding the spatial distribution of star clusters relative to the hydrogen-rich regions of the galaxy.

3.4.1 Importance of CO Moments

CO moment maps are crucial in identifying regions rich in molecular hydrogen, which is a primary component for star formation. The CO emission traces the dense molecular clouds where star formation occurs. By examining these maps, areas with high CO intensity can be correlated with regions where hydrogen is abundant, indicating potential star-forming regions.

3.4.2 Overlay Analysis

The classified star clusters were overlaid on the CO moment maps, which revealed the following spatial distribution:

- **Young Star Clusters:** As anticipated, young star clusters were predominantly found in the spiral arms of the galaxy. These regions corresponded with the areas of highest CO intensity, indicating that star formation is most active where there is significant molecular gas concentration.
- **Middle-aged Star Clusters:** These clusters were observed between the arms and the galactic center. Their distribution suggests that, while still active,

the star formation rate has decreased compared to the younger clusters. The middle-aged clusters are located in regions of moderate CO intensity, reflecting a transition phase in their star formation history.

- **Old Star Clusters:** The old star clusters were largely concentrated towards the galactic center. This concentration indicates that, over time, clusters have migrated towards the central regions of the galaxy. The central area, while having lower CO intensity compared to the arms, supports the older clusters, which have likely passed through the more active star-forming phases and settled in the core.

The overlay of star clusters on CO moment maps thus provides valuable insight into the distribution of star clusters in relation to molecular gas regions, confirming that star formation patterns align with CO intensity distributions in the galaxy.

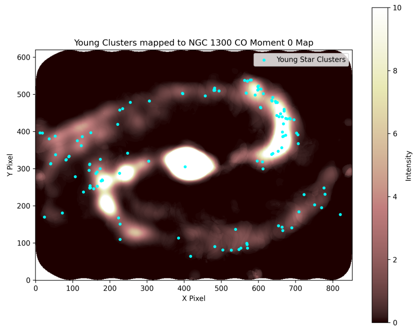

Figure 3.16: Distribution of Young Aged Clusters in Galaxy

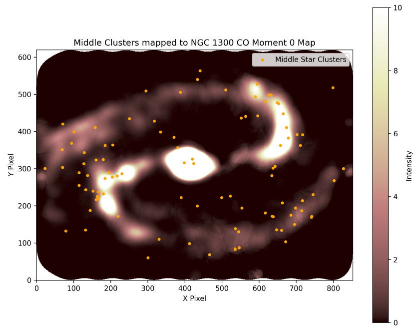

Figure 3.17: Distribution of Middle Aged Clusters in Galaxy

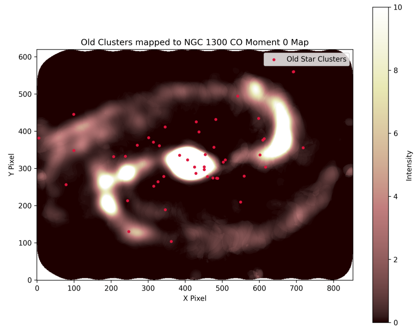

Figure 3.18: Distribution of Old Aged Clusters in Galaxy

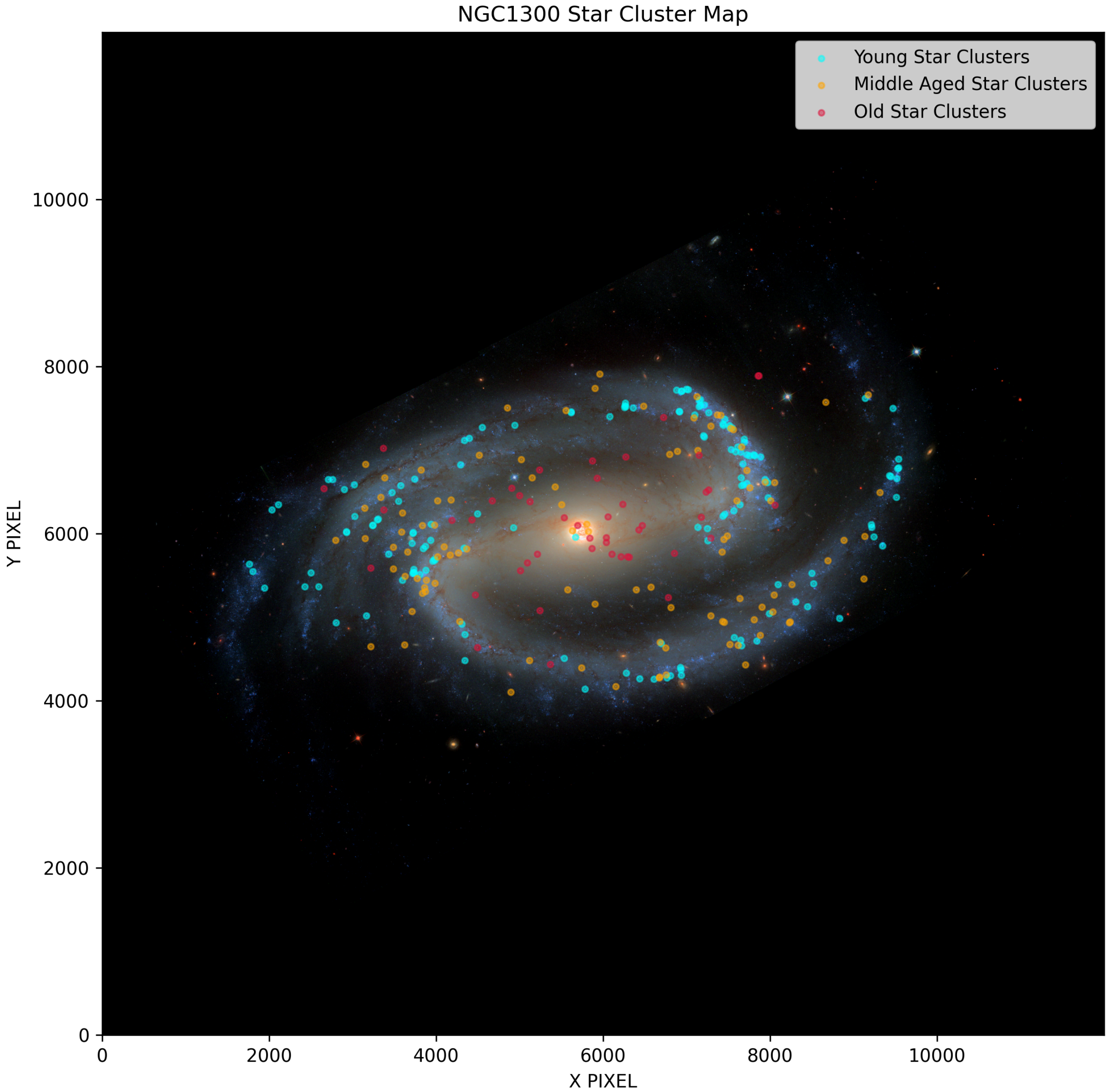

Figure 3.19: NGC 1300 Star Cluster Map

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