KRITTIKA SUMMER PROJECTS 2024

# Studying Cluster Properties In Nearby Galaxies

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# *Abstract*

The objective of this project is to use the data about galaxies and star clusters which has been collected by the PHANGS (Physics at High Angular resolution in Nearby GalaxieS) collaboration, and use it to obtain insights about star cluster systems. Data from the Hubble Space Telescope (HST) for NGC-4535 galaxy - a barred spiral galaxy in the constellation Virgo - is used and aperture photometry is performed on the star clusters of the galaxy. Various formulas and correction factors (aperture correction factor, dust extinction factor, etc.) are applied to the flux calculated through photometry to find out the magnitude of the clusters. Then we plot color-color diagrams to study the age distribution in the clusters across two morphological classes - C1 and C2, to divide them in to young clusters, middle age plume and old globular cluster clump. Finally we overlay these clusters on the HST and the ALMA galaxy images to study the spatial correlation of these clusters with different regions of the galaxy.

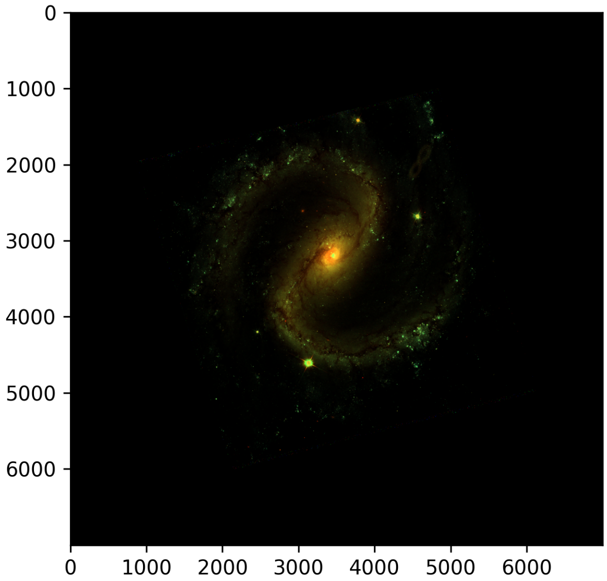



Figure 1: NGC-4535

# *Contents*

# Star clusters

## 2.1 Introduction

One widely accepted claim about the universe is that most stars form in groups and not in isolation. These groups evolve over time to produce various different kinds of gravitationally bound systems of stars, which we call star clusters. Based on their properties these clusters are broadly divided into globular clusters, open clusters and stellar associations.

## 2.2 Globular Clusters

Globular clusters are spherical associations of stars where the density of stars grows as we approach the center of the cluster. The strong gravitational pull in these clusters gives them their regular, spherical shape. They are typically older than open clusters, so they have a greater proportion of older, redder stars. They mostly contain Population-II stars (metal-poor stars, which generally have formed during an earlier time in the universe than metal-rich stars).

They are found in about all galaxies, and in case of spiral galaxies (like the Milky Way), they are found in the galactic halo, which is the extended spherical part of a galaxy, which extends beyond its main, visible part (which in case of spiral galaxies, is the disc).

The Hertzsprung-Russell diagram is a plot of stellar luminosity vs its spectral classification (effective temperature). The H-R diagram of a globular cluster shows many stars in the red-giant phase and the lower main-sequence phase, but with much fewer stars of O,B,A or F type main-sequence stars. They have a prominent red-giant branch and horizontal branch which sets them apart form open clusters. The horizontal branch consist of all those stars where helium fusion (to carbon) happens in the core and hydrogen fusion happens in a shell around the core. White dwarfs lie on the bottom-left of the diagram, and they can be used to find out the age of the globular cluster, which is much more than the age of open clusters.

## 2.3 Open Clusters

Open Clusters are loosely bound group of young stars. They contain about tens to a few thousands of stars and are associated with galactic centres. They are less stable than globular clusters and can loose/gain members during close encounters with other clusters. They too consist of a dense core of stars, which is surrounded by a diffuse corona.

Since they are mostly composed of young, hot and blue stars, they are found in regions of high gas density, which in case of spiral galaxies are the spiral arms. The stars share a common origin and hence have similar properties like age, distance, metallicity (abun-

dance of elements heavier than hydrogen and helium),etc. Open clusters consist mostly of Population-I stars (young, metal-rich stars).
The H-R diagram of open clusters shows us that most of the stars lie on the main-sequence branch, while some have evolved to become red giants. They have a higher main-sequence turnoff point than globular clusters.

## 2.4 Stellar Associations

Stellar associations are star clusters which are even more loosely bound than open clusters. When star formation is taking place in a gas-dense region of a galaxy, then the radiation pressure from the newly forming stars can disperse all the surrounding gas which negatively affects further star formation. If these stars are gravitationally unbound then this system is known as stellar association. Stellar associations are defined on basis of the velocity vectors, ages and chemical composition which indicate their common origin.

# *PHANGS Collaboration*

## 3.1 Introduction

The PHANGS (Physics at High Angular resolution in Nearby GalaxieS) collaboration aims to undertake high resolution observations of nearby galaxies with several telescopes, including ALMA, Hubble, JWST and the VLT. It's goal is to understand the various stages of stellar formation and evolution, and the effect that various properties of a galaxy have on those processes.
These telescopes can provide images of galaxies in a broad spectrum of wavelengths. The ALMA (Atacama Large Millimeter Array) is an interferometer consisting of 66 radio telescopes, which observe radiation at millimeter and sub-millimeter wavelengths (infrared and microwave region). Hubble telescope takes observations at near-ultraviolet, visible and near-infrared range. VLT (Very Large Telescope) can observe at both near-infrared and visible wavelengths. JWST (James Webb Space Telescope) has been primarily designed for taking observations in the near-infrared region.

## 3.2 Galaxy and Catalog

### 3.2.1 Galaxy Morphology

There are many different systems of galaxy morphology-classification which are used by astronomers to divide galaxies into various groups to make it easier to study them. Hubble sequence is a popular method of classification. According to it, galaxies can be divided into elliptical, spiral and lenticular galaxies.
Elliptical galaxies are seen as smooth and featureless ellipsoid-like distributions of light. They have lesser interstellar gas (than spiral galaxies) and hence have less open clusters. They contain a greater proportion of older and redder stars and have many globular clusters in their galactic halo.
Spiral galaxies consist of a flat disc of stars with prominent spiral arms. Most spiral galaxies rotate around the center, with the spiral arms generally trailing the direction of rotation. The shape of their central bulge divides spiral galaxies into two groups - barred (having a bar-shaped structure) and unbarred.
Lenticular galaxies have properties in between those of elliptical and spiral galaxies. They have a flat disc of stars, but unlike a spiral galaxy, they don't have spiral arms. They have a prominent central bulge resembling that of elliptical galaxies.

### 3.2.2 Star Cluster Catalog

The catalog which is being used for this project is the PHANGS-HST catalog which consists of all the data which has been collected by the Hubble Space Telescope and extensively processed before being provided to us.
The objects in the data are divided into 4 classes in the catalog to characterize the sources. These are :-

- Class 1 - star clusters - single peak, circularly symmetric, but with radial profile more extended than point source
- Class 2 - same as Class 1 but they are elongated or asymmetrical
- Class 3 - stellar associations - asssymetric and have multiple peaks
- Class 4 - not a star cluster or a stellar association (could be a background galaxy, image artefact,etc).

Data pertaining to 814nm, 555nm, 438nm, 336nm and 275nm for the galaxy NGC-4535 is used to study various properties of clusters in it.NGC-4535 is a barred-spiral galaxy which can be observed in the constellation Virgo. It is approximately 50 million light-years away from us and is a member of the Virgo Cluster.
Here we use data from Class 1 and Class 2 to study the star clusters in the galaxy.

# *Aperture Photometry*

## 4.1 Introduction

In aperture photometry, an aperture is centred on an object in the image and aperture radius is chosen and all the flux inside that aperture is summed up. This is then subtracted from the background flux, which is calculated by taking and annulus centred on the same location and choosing an inner and outer radius. The mean flux which exists between the inner and outer radius is considered to be the background flux and is subtracted from the flux from aperture to get the flux of the object. This is then converted to AB magnitude by applying a conversion formula and various correction factors.
Here, we calculate the magnitude of the star clusters in the galaxy NGC-4535. These magnitudes are then plotted alongside the magnitudes available in the PHANGS-HST catalog to verify them.

## 4.2 Methodology Used

The radius of aperture and annulus used in photometry can vary depending on the size of object and density of the location on which photometry is being done. The radius of aperture used in this case is 4 pixels, while the inner radius of annulus is taken to be 7 pixels and the outer radius is taken to be 8 pixels.
The flux calculated was then converted to the magnitude in the AB magnitude system by taking a reference star in the galaxy with a known magnitude, conducting aperture photometry on it to find its flux, and then using equation (1) to find the magnitude.

$$M = m_0 + 2.5 \cdot \log\left(\frac{f}{f_0}\right) \tag{1}$$

where $M$ is the magnitude of the star cluster, $m_0$ is the magnitude of the reference star $f_0$ is the flux of the reference star and $f$ is the flux of the star cluster.
These magnitudes were plotted against the catalog magnitudes and the graph obtained showed a linear $y = x + c$ relation. The reason for the offset from the $y = x$ line is considered to because of aperture corrections, dust extinction or also because of the reference star being a transient (having variable magnitude over some short period of time).

### 4.2.1 Aperture Corrections

The aperture sizes that we use for the photometry may not contain the entire flux of the star because of their small size. However increasing the size of the aperture is not an option as that would lead to significant amount of nearby stars' flux being in the annulus used

for the background correction. Therefore aperture corrections are applied to the data to compensate for the lost flux.
The correction factor for this can be calculated by approximating the source to be a point source and finding out the flux not in the radius of aperture by using a point-spread function. It has also been modeled in the paper [4] by applying aperture photometry on successive radii from 4 pixels upto 10 pixels (20 pixels in case of Class 1 objects) and using that to correct for the flux lost due to aperture radius being 4 pixels.
According to their calculations the aperture correction factor for the galaxy NGC-4535 is -0.71 in the V-band, which has to be added to the calculated magnitude. For the other bands constant offsets are added on the basis of their FHWM (Full Width at Half Maximum) of the WFC3 (Wide Field Camera - 3 present on the HST) point-spread function (PSF). On the basis of this, the offsets applied to the NUV, U, B ,I bands are -0.19, -0.12, -0.03 and -0.12 respectively. The values of the aperture corrections used here are given in Table 1.

| Values of aperture correction | | | | |
|---|---|---|---|---|
| 814 nm | 555 nm | 438 nm | 336 nm | 275 nm |
| -0.90 | -0.83 | -0.74 | -0.71 | -0.83 |

Table 1

### 4.2.2 Dust extinction

Extinction is the absorption and scattering of radiation of a source by the gas and dust present between the source and observer. This may happen due to the interstellar medium, the circumstellar dust (a shell/disk of cosmic dust around a star), and the Earth's atmosphere. Since absorption and scattering are also wavelength-dependent, the value of the correction for this factor depends on the wavelength band being used, with shorter wavelengths facing more extinction. This phenomena is known as interstellar reddening (as it leads to objects looking redder than they actually are). As the value of this factor depends on the line-of-sight, it depends on the galaxy being observed.
The values of the foreground extinction factors(for extinction caused by Milky Way) for the galaxy NGC-4535 for the bands NUV, U, B, V and I are provided in Table 2.

| Values of foreground extinction factor | | | | |
|---|---|---|---|---|
| 814 nm | 555 nm | 438 nm | 336 nm | 275 nm |
| 0.0285 | 0.0535 | 0.0692 | 0.0848 | 0.105 |

Table 2

#### 4.2.3 Transient reference star

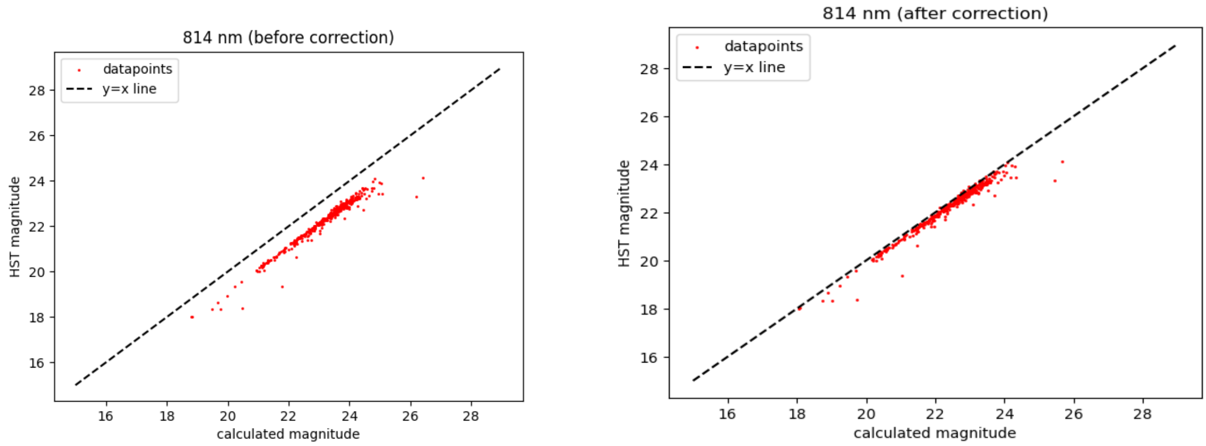
There is still the possibility that the star which was used was a transient star. To remove this dependence of using a reference star we can use equation (2) to convert the flux to magnitude:

$$M = -2.5 \cdot \log(f) + 8.9 \tag{2}$$

where $M$ is the AB magnitude of star cluster and $f$ is the flux converted from electron counts to Jansky unit.
This AB magnitude can then be converted to Vega magnitude (as the magnitude of clusters available in catalog is in Vega magnitude system, which sets the magnitude of Vega as the zero-point).

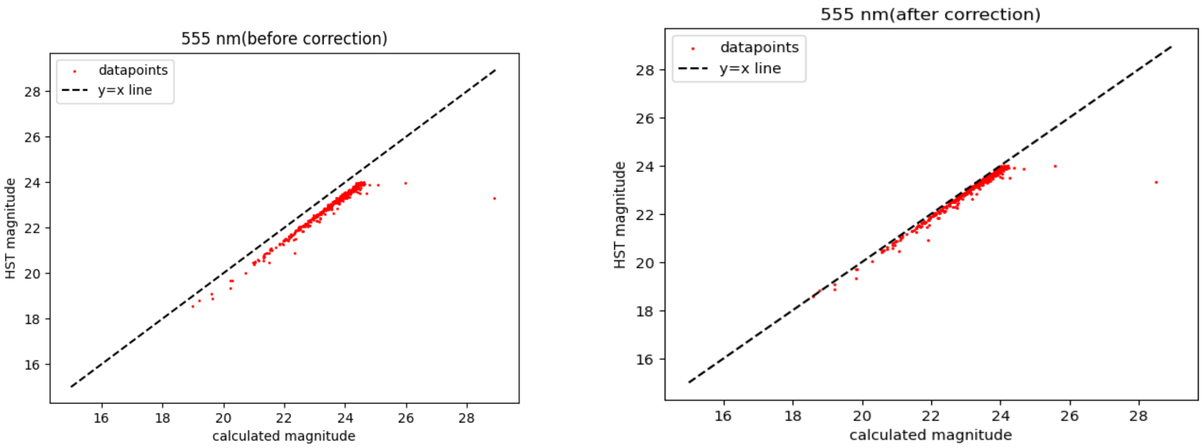
### 4.3 Results

After applying these corrections, a one-to-one correspondence was obtained with the Vega magnitudes of clusters available in the PHANGS-HST catalog as shown in the Figures 2-6 below, which show the magnitude plots before and after correction factors were applied. However in Figure 5 and Figure 6 we see that for magnitudes greater than 25, the datapoints become more scattered and the calculated magnitudes are slightly lower than the actual HST magnitudes. This could be because of errors in the aperture correction offsets being used or because of underestimating the dust extinction factor (as we only take into account the extinction caused by Milky Way).



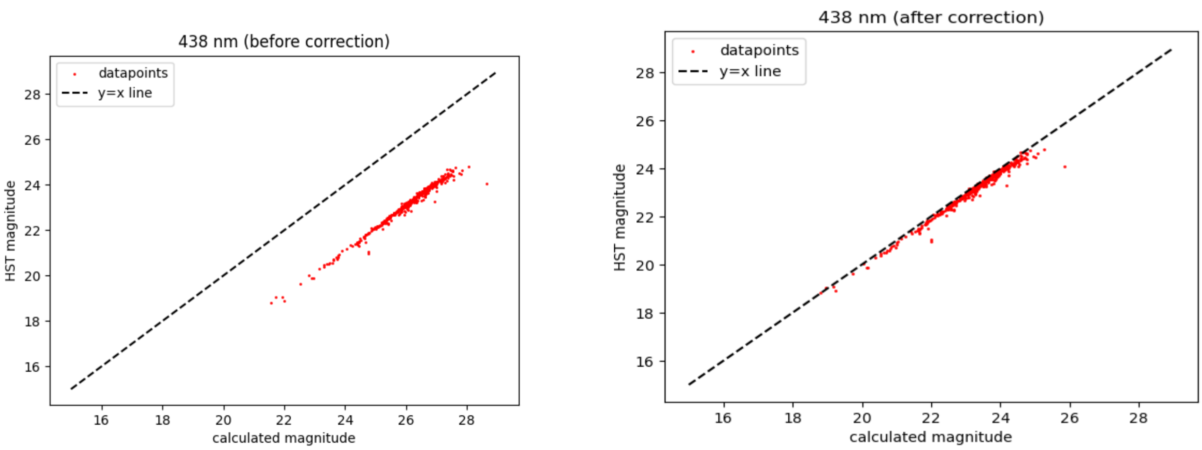

(a) before correction (b) after correction

Figure 2: 814 nm - I band



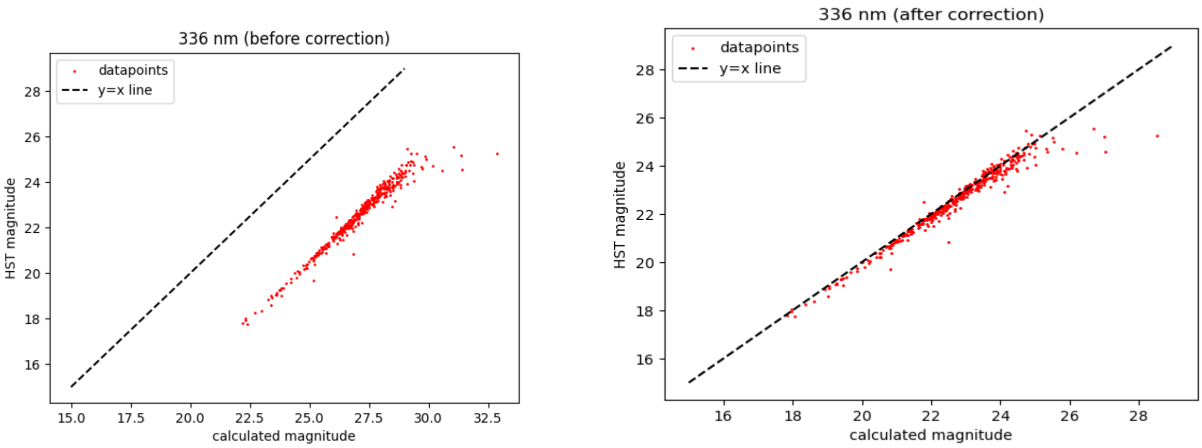

(a) before correction (b) after correction

Figure 3: 555 nm - V band




(a) before correction (b) after correction

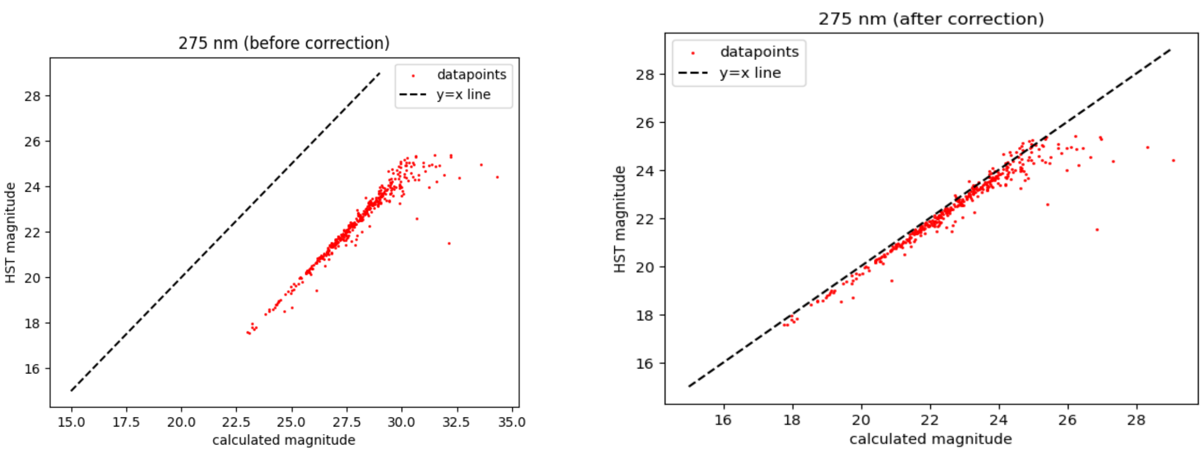
Figure 4: 438 nm - B band




(a) before correction

(b) after correction

Figure 5: 336 nm - U band




(a) before correction

(b) after correction

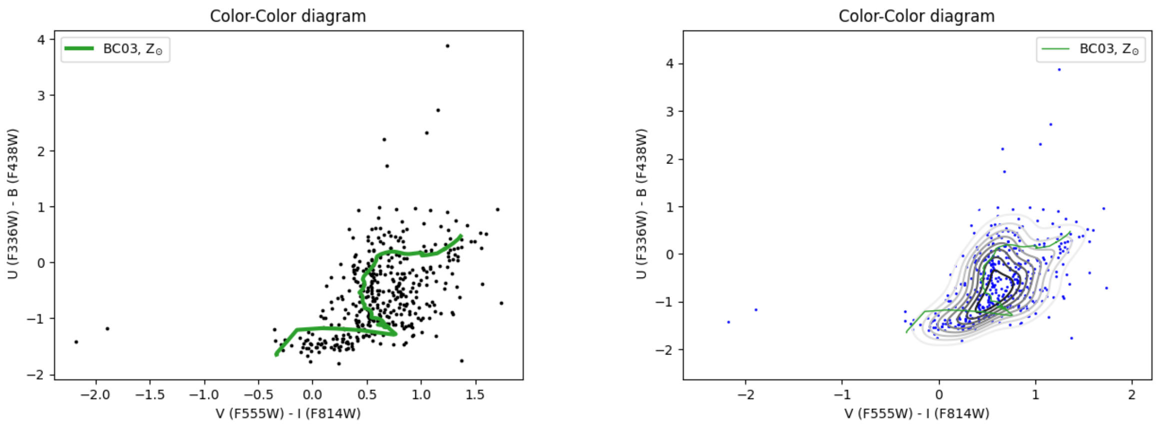
Figure 6: 275 nm - NUV band

# *Color Color diagrams*

## 5.1 Introduction

Color-color diagrams provide a means of comparing the magnitudes of the spectra of a stellar body, like a cluster, to find out various properties of the stellar body and its evolution.
The spectra of young stars is dominated by ultraviolet light (the NUV and the U bands), while that of old stars is dominated by infrared light (the I band). On the basis of this, a star cluster's spectra can be studied to find out the age groups of its stars. To do this we use color-color diagrams and compare them with the SSP (Single Stellar Population) model.
Single stellar population refers to a group of stars which have roughly the same age and the same metallicity. They are the building blocks of more complex stellar associations and provide us a model for understanding their properties. This uses the assumption that globular and open clusters can be represented by SSPs, which has been observed to be valid for nearby galaxies. Here we use the SSP model which was built by Bruzual and Charlot in the paper [1], to find out the ages of the clusters in the galaxy, which is labelled as Z in the color-color diagrams. Here Z refers to the metallicty used in the model, and it has been well established that the metallicities of nebulae in spiral galaxies is around Z.
The color-color diagrams have been created by plotting the V-I magnitudes against the U-B magnitudes of the star clusters, along with the SSP track to compare the track against the observed cluster locations on the diagram. These diagrams are then studied for the entire cluster as well as for the two different morphological classes of clusters - C1 and C2 clusters. For this purpose, the human classification of clusters, provided in the catalog is used.

## 5.2 Observations




(a) (b)

Figure 7: The VI-UB scatter plots presented above are of both C1 and C2 star clusters in the galaxy. The green line traced on the plot is the SSP model track. Figure (b) is a contour plot for the same

The SSP model, which is shown in Figure 7, helps us in dividing the star cluster of the galaxy in different age groups - old globular cluster locus, a middle aged plume and a young cluster locus. Old star clusters have spectra dominated by longer wavelengths therefore they present themselves closer to the right-hand side end of the SSP track, while the younger clusters have spectra dominated by shorter wavelengths and hence they show up on the left-hand side end of the track.
We have decided to classify clusters which are closer to the portion of the track before 10 MA as young clusters and the ones closer to the portion of the track after 1000 MA years as old clusters. On the basis of this, we see in Figure 7b most of the clusters are grouped near the middle and the young aged portion of the SSP track with fewer old globular clusters. To further study the distribution of ages of clusters in the galaxy, individual plots were made for the C1 and the C2 star clusters as shown in Figure 8 and Figure 9 respectively.
In those figures given below, the individual clusters are represented by black dots, and the places of high concentration of clusters have been marked by a Gaussian-smoothed contourf plot.

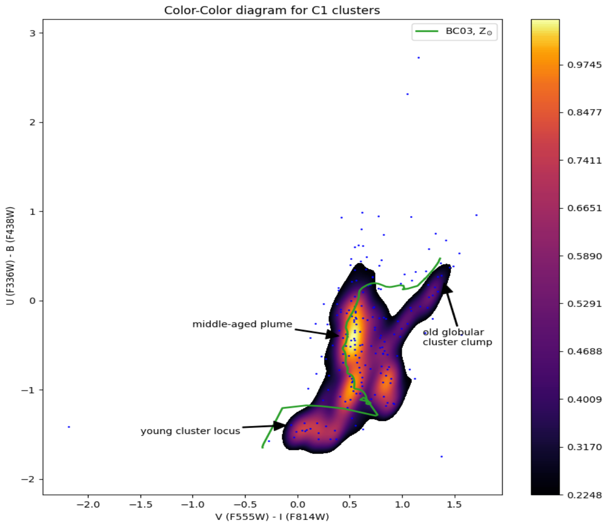



Figure 8: Color-color diagram for C1 clusters

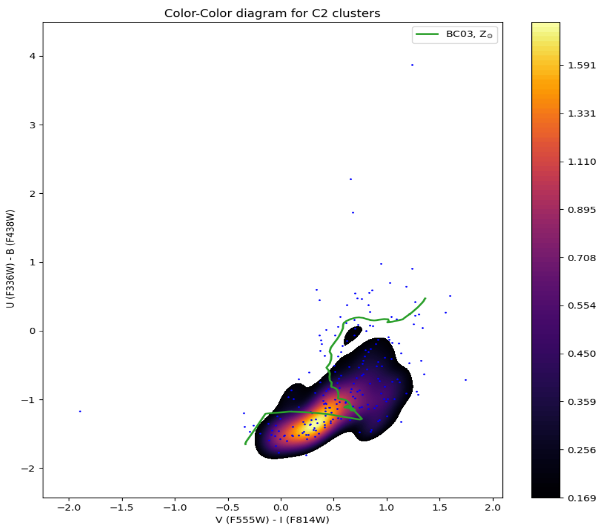



Figure 9: Color-color diagram for C2 clusters

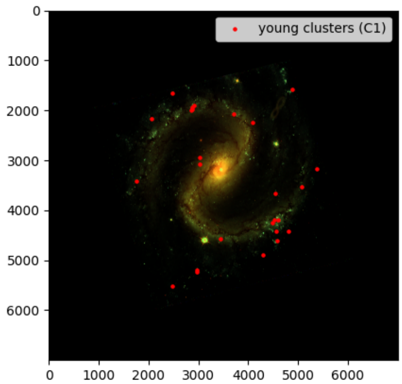
In Figure 8, we see that the population of the C1 single peaked symmetric clusters has a very prominent middle-aged plume, along with some clusters forming the young cluster locus and the old globular cluster clump. We see that these regions are distinctly defined in the diagram. While most of the clusters seem to lie along the SSP track, there is a significant portion of them, beyond the young cluster locus which have greater value of I band magnitude (and hence have lesser infrared emission and greater V-band emission) than predicted by the SSP model.

In Figure 9, we see the population of the C2 single peaked asymmetric clusters is predominantly young. It has a very defined young cluster locus which extends into the middle-aged plume, with no clear separation between the two. There are very few old globular clusters. Just like Figure 8, while most of the clusters lie along the track, a significant number of them have greater value of I-band magnitude (and hence have lesser infrared emission and more V-band emission) than predicted by the SSP model.

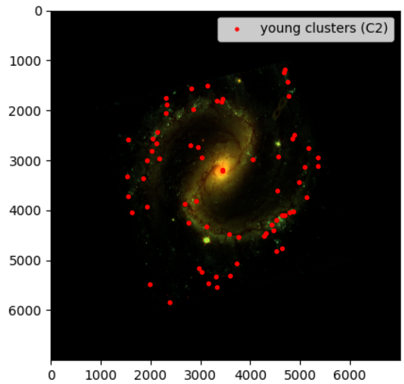
# *Spatial correlations of the clusters*

## 6.1 Correlations with the HST galaxy image

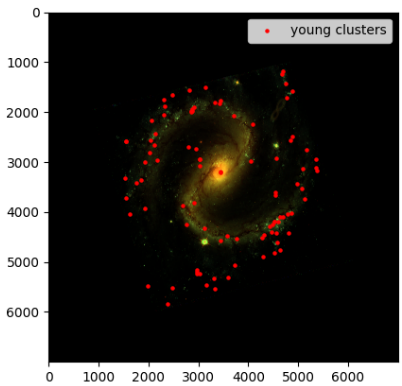
To study the spatial correlation of these clusters, we overlay images of these different age groups of the clusters on the the image of the galaxy, as shown below.




(a) young C1 clusters



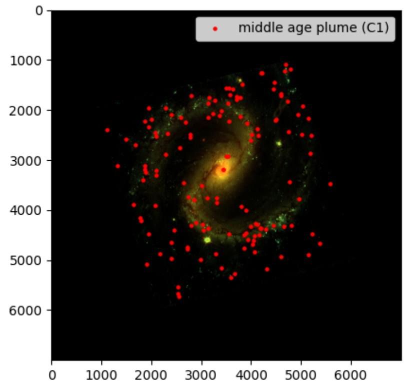

(b) young C2 clusters



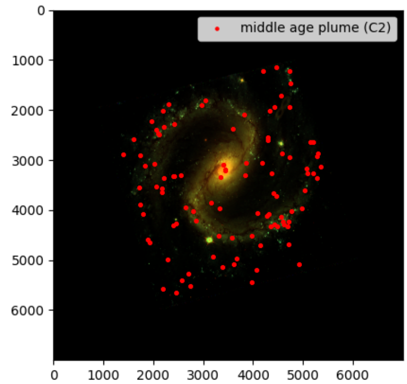

(c) young clusters (C1 + C2)

Figure 10: Young clusters of the two morphological classes overlayed on the galaxy image

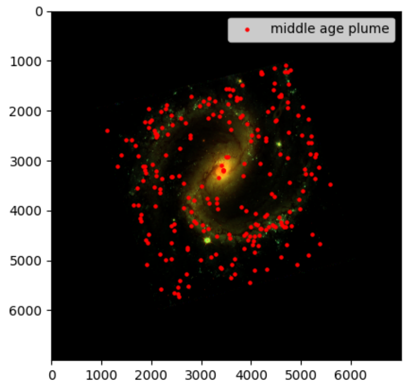
In Figure 10, we see that the young clusters of C1 and C2 star clusters follow the two spiral arms of the galaxy, with only a few outliers. As visible from the Figure 7 and 8, there are greater number of young C2 clusters than C1 clusters. This is the expected behaviour as young clusters (open clusters) in spiral galaxies are concentrated in the spiral arms comprise the majority of the star-forming regions of the galaxies. This is due to the high molecular gas densities in these regions.




(a) middle-aged C1 clusters



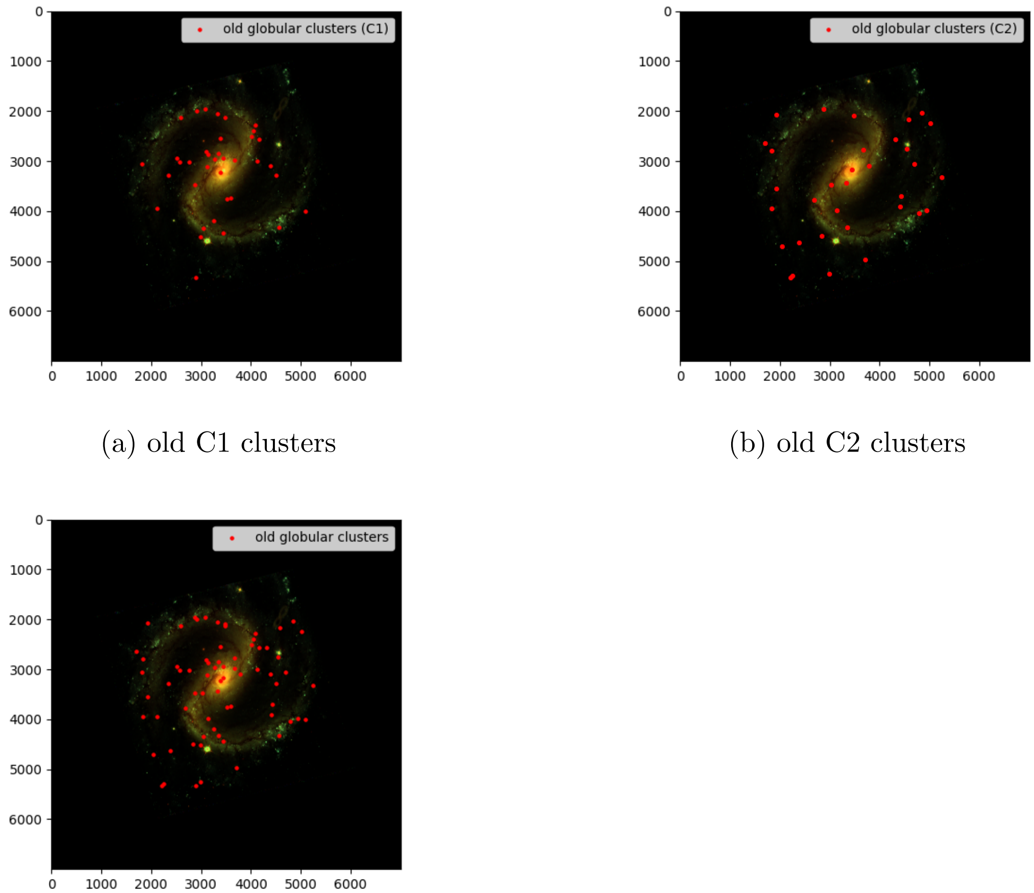

(b) middle-aged C2 clusters




(c) middle-aged clusters (C1 + C2)

Figure 11: Middle-aged plume of the two morphological classes overlayed on the galaxy image

In Figure 11, we see that there is a higher prominence of the C1 class in the middle-aged plume of the galaxy. While some of the middle-aged clusters can be seen to follow the spiral arms of the galaxy, most of them are scattered away from the center of the galaxy throughout the image. This can be rationalised as middle-aged plume consists of some open young clusters as well as some old globular clusters. These globular clusters are found to be concentrated in the galactic halo of spiral galaxies, which is observed in Figure 12.




(a) old C1 clusters

(b) old C2 clusters

(c) old clusters (C1 + C2)

Figure 12: Old globular cluster clump of the two morphological classes overlayed on the galaxy image

## 6.2 Correlations with the ALMA galaxy image

### 6.2.1 Introduction

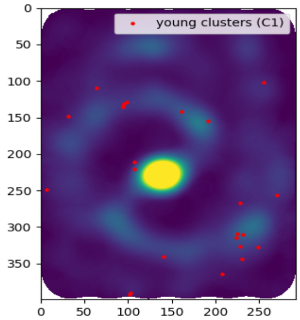
The ALMA telescope takes images of galaxies in the millimeter and submillimeter wavelengths. At these wavelengths, the spectra of molecular gas can be studied to find out regions of high densities of gas in the galaxy. The PHANGS-ALMA is a survey to map the electronic transition of Carbon Monoxide (CO J=2→1). This can be used to study the star forming regions of the galaxy.

In the dense molecular clouds of nebulae, where there is a high concentration of $H_2$ gas, are the birthplaces of stars. However $H_2$ gas has only high energy transitions possible which means that its density can only be probed in warm regions of the universe. This implies that most of the cold, dense regions of $H_2$ gas, which forms the dense, molecular phase of the interstellar medium (ISM), can't be observed. Due to this issue, CO gas transitions are used in place of $H_2$ gas, as CO has low-level energy transitions which lie in the millimeter wavelength. That is why CO is used as a tracer for $H_2$ in observational astronomy. Here there is an assumption that the conditions which favour CO formation are the same as the ones which favour $H_2$ formation, so they must be positively correlated (this claim is highly debated and a matter of active research).

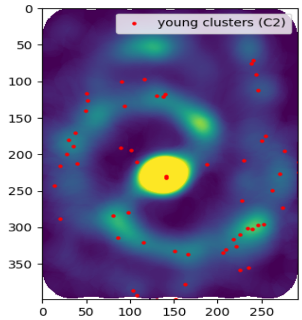
### 6.2.2 Observations

We see that in Figure 13 that young clusters of both morphological classes are concentrated on the two gas-dense spiral arms of the galaxy. The clusters which were seen to lie outside the spiral arms in the galaxy plots in Figure 9 are also seen to be lying on gas-dense regions. About 50% of the clusters lie in the 50 percentile contour of the ALMA gas density plot, which shows a strong correlation between the regions dense in CO gas and young cluster locus.

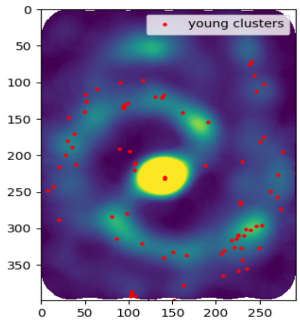
Figure 14 and Figure 15 show a less stronger correlation, with the star clusters spread throughout the image, even in gas-poor regions. This is especially true for the old globular clusters shown in Figure 15. The respective contour plots show less than half of the clusters lying in the 50 percentile contour line. This establishes the fact that while young, open clusters lie on the gas-dense regions of a galaxy, the old globular clusters lie in the galactic halo and are hence seen to be more spread out throughout the galaxy in the HST and ALMA galaxy images.



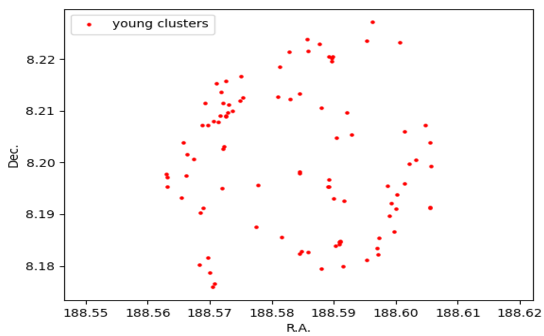

(a) young C1 clusters



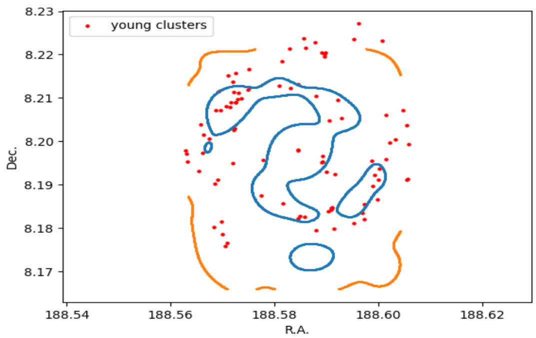

(b) young C2 clusters




(c) young clusters (C1 + C2)

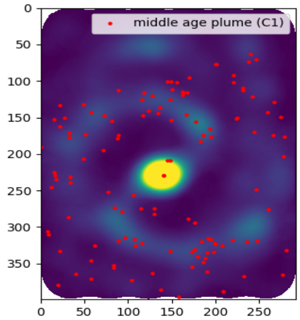



(d)

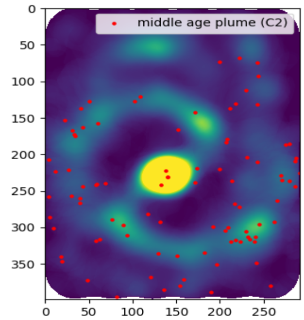



(e)

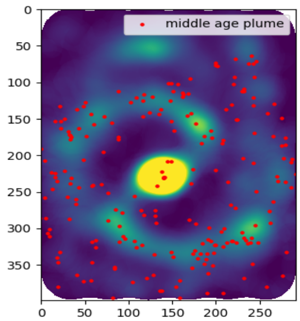
Figure 13: Plots a), b) and c) are the young clusters overlayed on the ALMA galaxy images. Plots d) is a RA-Dec image of the young clusters, with plot e) additionally having the 50 percentile ALMA contour plot (in blue), with the orange lines marking the boundaries of the ALMA image



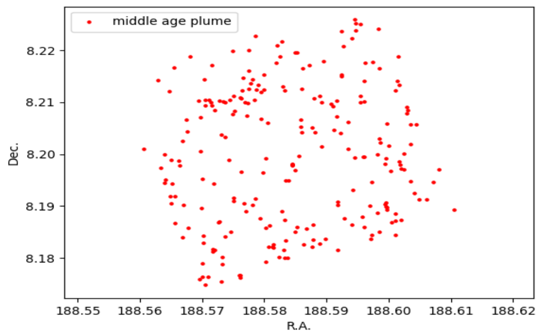

(a) middle-aged C1 clusters



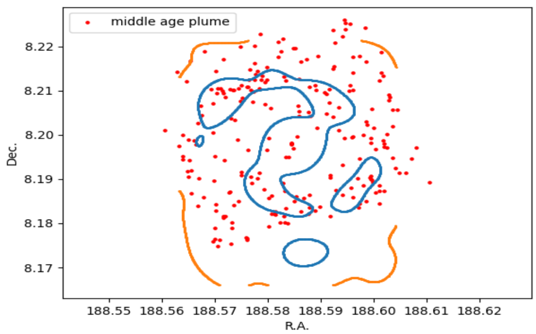

(b) middle-aged C2 clusters




(c) middle-aged clusters (C1 + C2)

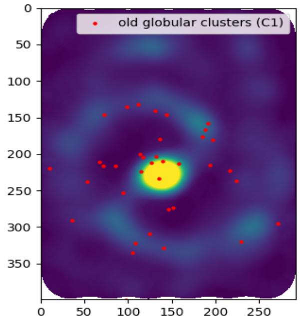



(d)

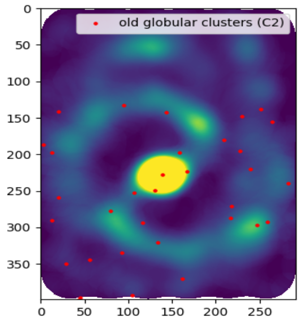



(e)

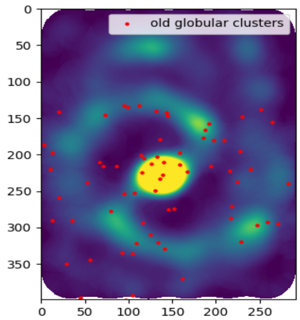
Figure 14: Plots a), b) and c) are the middle-aged clusters overlayed on the ALMA galaxy images. Plots d) is a RA-Dec image of the middle-aged clusters, with plot e) additionally having the 50 percentile ALMA contour plot (in blue), with the orange lines marking the boundaries of the ALMA image



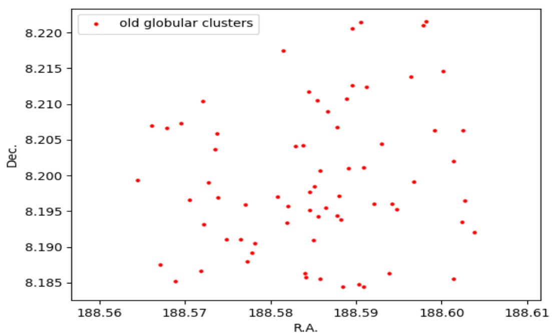

(a) old C1 clusters



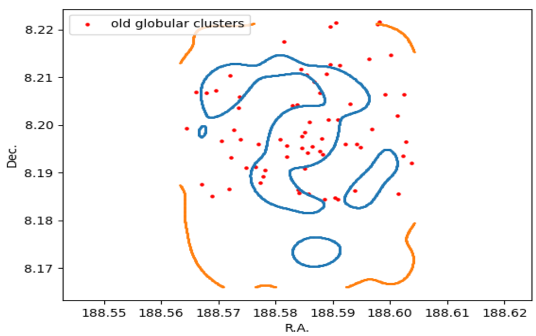

(b) old C2 clusters




(c) old clusters (C1 + C2)




(d)




(e)

Figure 15: Plots a), b) and c) are the old globular clusters overlayed on the ALMA galaxy images. Plots d) is a RA-Dec image of the old globular clusters, with plot e) additionally having the 50 percentile ALMA contour plot (in blue), with the orange lines marking the boundaries of the ALMA image

# *Summary*

This report was aimed towards discovering various properties of the star clusters in NGC-4535 and the findings can be summarised as done below:

- Aperture photometry is a useful tool for finding out the magnitudes of the astronomical bodies, however its accuracy is limited by variability in background noise (especially in the bright-central regions of the galaxy), interstellar reddening due to dust extinction and the need for aperture corrections. Aperture correction factors for bands other than V band were not obtained directly, hence there is variability in their values. Similarly the extinction caused by dust in the galaxy NGC-4535 itself was not corrected. In-spite of this, a one-to-one correspondence can be observed between the PHANGS-HST catalog magnitudes and the calculated magnitudes. The correspondence is observed to be lesser for magnitudes $> 25$, due to such limitations.

- Color-color diagrams have enabled us to differentiate between the age distributions in the C1 and the C2 star clusters, with C1 having distinct young clusters (open clusters), middle-aged plume and old globular clusters. In C1 the middle-aged plume is most prominent region. C2 primarily has young clusters and middle-aged clusters with very few old clusters. It does not have any clear separation into the young, middle-aged and old clusters.

- While most of the clusters seem to concentrate along the SSP track, there are some outliers. The track doesn't seem to exactly follow the cluster densities at the turn from the young cluster to middle-aged plume, with significant density having greater values of V-I, and hence lower emission of infrared wavelengths and higher emission of visible-light wavelengths, than what is predicted by the SSP model.

- On overlaying the C1 and C2 star clusters over the HST and ALMA galaxy images, we see that the young clusters align along the gas-dense spiral arms of the galaxy while the middle-aged plume and the old globular clusters are spread out throughout the image (which could be explained by them being situated in the galactic halo). This is further strengthened by the observation that most of the young clusters lie within the ALMA intensity contour plot (corresponding to 50 percentile of intensity data) compared to the middle-aged plume and old globular clusters clump.

# References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