Krittika Computational Astronomy Winter Projects 2024

Pinpricks of the Vortex

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Contents

Chapter 1

Stars

1.1 Stars

Stars are giant balls of hot gas – mostly hydrogen, with some helium and small amounts of other elements. Every star has its own life cycle, ranging from a few million to trillions of years, and its properties change as it ages.

1.2 Classification

Type	Surface Temperature
O	> 30000 K
B	10000 K - 30000 K
A	7500 K - 10000 K
F	6000 K - 7500 K
G	5000 K - 6000 K
K	3500 K - 5000 K
M	< 3500 K

1.3 Star Clusters

A gravitationally bound group of stars formed from the **same molecular cloud** constitutes a star cluster.

They are classified into the following main types :

1.3.1 Open

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

1.3.2 Globular

Globular clusters are ancient, massive stellar systems predominantly **composed of Population II stars** which are metal-poor compared to younger stars. They are densely packed and almost spherical, containing tens of thousands to millions of stars.
Such clusters orbit the galactic core and are **much older than open clusters**, with ages exceeding 10 billion years.

Chapter 2

PHANGS

The Physics at High Angular resolution in Nearby GalaxieS (PHANGS) program is building the first dataset to enable the multi-phase, multi-scale study of star formation across nearby spiral galaxies. The foundation of PHANGS has been built with large surveys with Hubble, JWST, ALMA and VLT/MUSE.
I am using **HST Image products** available on Mikulski Archive for Space Telescopes (MAST) for the galaxy NGC 1365.

2.1 NGC 1365

NGC 1365, also known as the **Fornax Propeller Galaxy** or the **Great Barred Spiral Galaxy** is a double-barred spiral galaxy that lies about 56 million light years away from Earth in the constellation Fornax. It is one of the largest galaxies currently known to astronomers, spanning twice the length of the Milky Way across.

Figure 2.1: NGC 1365

Chapter 3

Aperture Photometry

Link to **Presentation on Photometry**

Photometry is a technique used in astronomy that is concerned with **measuring the flux or intensity of light radiated by astronomical objects.** In aperture photometry, we consider an aperture around a light source, and measure the flux of light falling inside that aperture. But, this flux also contains contribution of the background.
By measuring the median flux of the background in an annulus around the aperture and multiplying it by the area of the aperture, we obtain an estimate of the background flux. Subtracting this from the initially measured flux gives us the luminous flux solely due to the source.

However, aperture photometry works best for **non-crowded images** since the fluxes of nearby objects interfere, making it hard to impose non-intersecting apertures on the light sources.

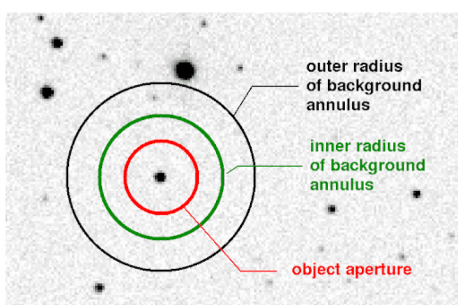

Figure 3.1: Aperture

3.1 Star clusters

First I plotted the image of the galaxy and the location of star clusters present in the galaxy. To do this, I converted the World Coordinate System (WCS) data i.e. the right ascension (RA) and declination (DEC) to pixel coordinates using the WCS module

3.1.1 Code

```
from astropy.io import fits
from astropy.wcs import WCS
import matplotlib.pyplot as plt

# Load galaxy FITS file
galaxy_fits =r"C:\Users\aarus\Downloads\hlsp_phangs-hst_hst_wfc3-uvis_ngc1365_multi_v1_drc-bundle\ng
hdul = fits.open(galaxy_fits)
galaxy_data = hdul[0].data
galaxy_wcs = WCS(hdul[0].header)
hdul.close()

# Load star cluster FITS table
cluster_fits = r"C:\Users\aarus\Downloads\hlsp_phangs-cat_hst_acs-uvis_ngc1365_multi_v1_cats\catalogs\h
hdul = fits.open(cluster_fits)
cluster_data = hdul[1].data
hdul.close()

# Extract RA/DEC from cluster table
ra = cluster_data['PHANGS_RA']
dec = cluster_data['PHANGS_DEC']

# Convert RA/DEC to pixel positions
x_pixel, y_pixel = galaxy_wcs.wcs_world2pix(ra, dec, 0)

plt.figure(figsize=(10, 8))
plt.imshow(galaxy_data, cmap='gray', origin='lower', vmin=0, vmax=np.percentile(galaxy_data,99))
plt.colorbar(label='Flux')
plt.xlabel('X Pixel')
plt.ylabel('Y Pixel')
plt.title('NGC 1365 with Star Clusters')

```

```python
# Overlay star clusters
plt.scatter(x_pixel, y_pixel, c='red', edgecolors='black', s=20,
    alpha=0.6, label='Star Clusters')
plt.legend()
plt.show()
```

3.1.2 Plot

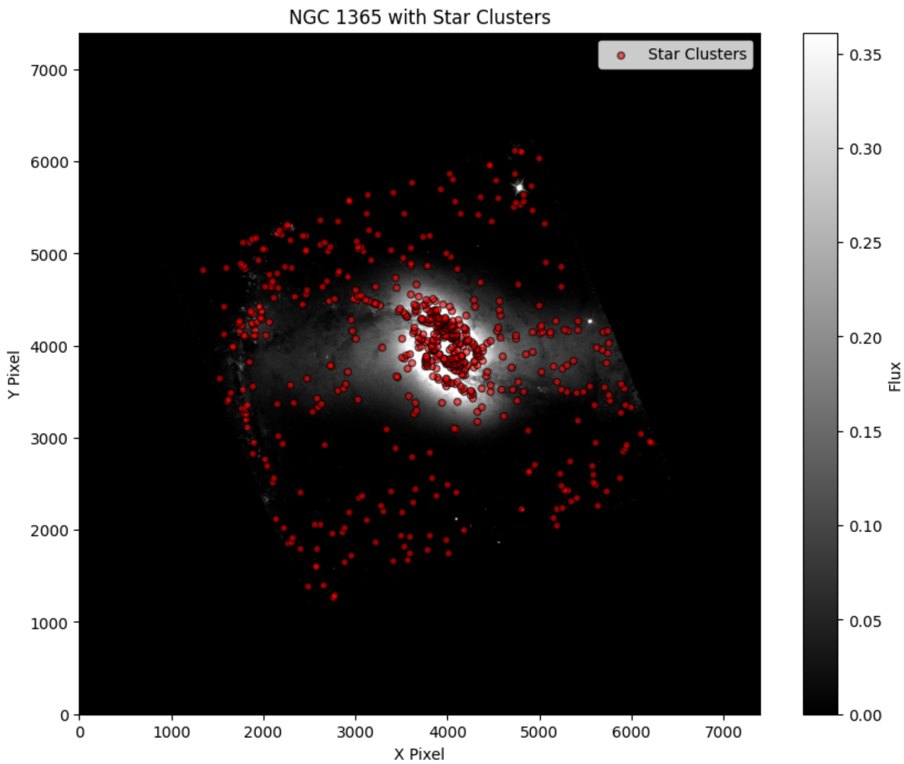

Figure 3.2: NGC 1365 with Star Clusters

3.2 Aperture radius and Flux calculations

I calculated the angular radius using the following formula :

$$Angular\ radius = \frac{206265}{10^6}\left(\frac{R}{D}\right) \tag{3.1}$$

where R and D are the physical radius of the aperture (in pc) and the distance of the galaxy (in Mpc) respectively.
Then we convert this to the aperture radius using the formula :

$$Aperture\ radius = \frac{Angular\ radius}{\theta} \tag{3.2}$$

where θ is the pixel scale of the data in arcsec/pixel.

We would like the physical radius R of the aperture to be of the order of the average size of the star clusters which is about **15 pc.** The distance D of NGC 1365 is about **19.57 Mpc.** The pixel scale for the data is found to be **0.03962 arcsec/pixel.**

Substituting these values gives us **4 pixels** as the aperture radius. For the annulus, I took the inner and outer radii to be **7** and **8 pixels** respectively. To perform photometry, I created aperture objects at the coordinates of the star clusters and implemented the following code to get the flux.

3.2.1 Code

```
# Define the aperture and annulus
aperture_radius = 4  # Aperture radius in pixels
annulus_r_in = 7     # Inner radius of annulus
annulus_r_out = 8    # Outer radius of annulus

apertures = CircularAperture(positions, r=aperture_radius)
annuli = CircularAnnulus(positions, r_in=annulus_r_in,
 ↪  r_out=annulus_r_out)

# Perform aperture photometry
phot_table = aperture_photometry(image_data, apertures)
annulus_masks = annuli.to_mask(method='center')

# Calculate the background level
bkg_median = []
for mask in annulus_masks:
    annulus_data = mask.multiply(image_data)  # Apply the annulus
     ↪  mask to the data
    annulus_data_1d = annulus_data[mask.data > 0]  # Use only
     ↪  non-zero values
    bkg_median.append(np.median(annulus_data_1d))  # Calculate
     ↪  the median

bkg_median = np.array(bkg_median)

```

```python
# Subtract background flux
# (1) Calculate total background flux in the aperture
aperture_area = apertures.area
background_flux = bkg_median * aperture_area

# (2) Subtract background flux from aperture flux
phot_table['residual_flux'] = phot_table['aperture_sum'] -
↪  background_flux

# Print the resulting table
print(phot_table)
```

3.2.2 Output

```
id      xcenter            ycenter          aperture_sum      residual_flux
          pix                pix
--- ------------------ ------------------ ------------------ ------------------
  1 2763.5499999999315 1269.0399999994856  54.15896612288043  38.71695677403113
  2 2758.2999999999465   1271.15999999947 53.169312089444524 29.914215776082166
  3  2755.959999999168  1275.429999997264   52.9721034800611  37.02381605600068
  4  2766.110000000439 1289.3600000002348  6.474920308050069 3.4746471325723536
  5 2485.8399999999237  1392.169999999935 0.5731132178591339 1.4124758778716175
  6  2648.970000000528 1406.6300000004408  5.943232977187514  5.996608678534006
  7 2581.5899999989897 1600.2899999990213  0.911301305390836 1.3448138353392154
  8  2560.229999999939 1606.9299999997934  4.355725132231684 3.7285584353299415
  9  2880.109999999692 1653.4199999994626   2.26656276407615  3.313275828013813
...                ...                ...                ...                ...
620  4523.219999999506  5795.739999999216  4.502414046363487  6.338318749014929
621 4057.3500000001964  5815.470000000065 16.643223843727917  17.14265368341969
622 4013.0899999998855   5864.52999999959 0.6747874195510991  2.309157437919714
623  4733.160000000362  5870.030000001243  6.838230860376732  7.350957384854512
624  4459.350000000088  5960.310000001571 0.6149934194731608 1.6280124137690073
625  4455.949999999712  5970.599999999871  3.270240927764554  3.720709731552657
626  4989.230000000148  6037.010000000038  8.754979720996683  9.409430003923584
627  4785.180000000424  6114.170000001437  4.377980487527742    4.9985637955992
628   4794.67999999997   6116.33999999934 3.3481521652319604  4.060180563089888
629  4732.610000000229  6126.160000000404 10.643563721167737  11.19359723140265
Length = 629 rows
```

3.3 Photometric plots

The FITS file containing the data of the star clusters also contained their Vega magnitudes. I converted the calculated fluxes to magnitude using the following formula and plotted them against the Vega data to check if the photometric analysis produced the correct results.

$$Magnitude = 25 - 2.5\ log_{10}(Flux) \tag{3.3}$$

If the analysis is correct, the line of best fit should be the y=x line. But, the line we actually obtain has an intercept of -1.121.

3.3.1 Code

```
import matplotlib.pyplot as plt
fits_image_filename = r"C:\Users\aarus\Downloads\hlsp_phangs-cat_hst_acs-uvis_ngc1365_multi_v1_cats\catalogs\h
hdul = fits.open(fits_image_filename)
hdrtab = hdul[1].data
vega = hdrtab['PHANGS_F814W_VEGA']

# Collect data using a list comprehension
apertures_array = np.array([25-2.5*np.log10(e[4]) for e in phot_table])

# Example: Clean and prepare data
valid_indices = (~np.isnan(apertures_array)) & (~np.isinf(apertures_array)) & (~np.isnan(vega)) & (~np.isinf(vega))
apertures_array = apertures_array[valid_indices]
vega = vega[valid_indices]

# Plotting array1 vs array2
plt.scatter(apertures_array, vega,s=1, marker='o', color='b')
range = np.linspace(18, 24, 500)  # Generate a range of x values
plt.plot(range, range, color='black', linestyle='-', label='y=x')

# Calculate the best-fit line using numpy polyfit
coeffs = np.polyfit(apertures_array, vega, 1)  # Fit a line y = mx + c
slope, intercept = coeffs

# Generate line points
fit_line_x = np.linspace(17, 25, 100)
fit_line_y = slope * fit_line_x + intercept

# Plot the best-fit line
plt.plot(fit_line_x, fit_line_y, color='red', label=f'Best Fit: y = {slope:.3f}x + {intercept:.3f}')

# Adding labels and title
```

```
plt.xlabel('HST F814W calculated magnitudes')
plt.ylabel('PHANGS F814W Vega magnitudes')
plt.title('HST vs PHANGS F814W magnitudes')

# Ensure 1:1 aspect ratio
plt.gca().set_aspect('equal', adjustable='box')

# Adjust the axis limits to fit the data and maintain aspect ratio
all_data = np.concatenate([apertures_array, vega])
plt.xlim(min(all_data), max(all_data))
plt.ylim(min(all_data), max(all_data))
# Display the plot
plt.legend()
plt.show()
```

3.3.2 Plots

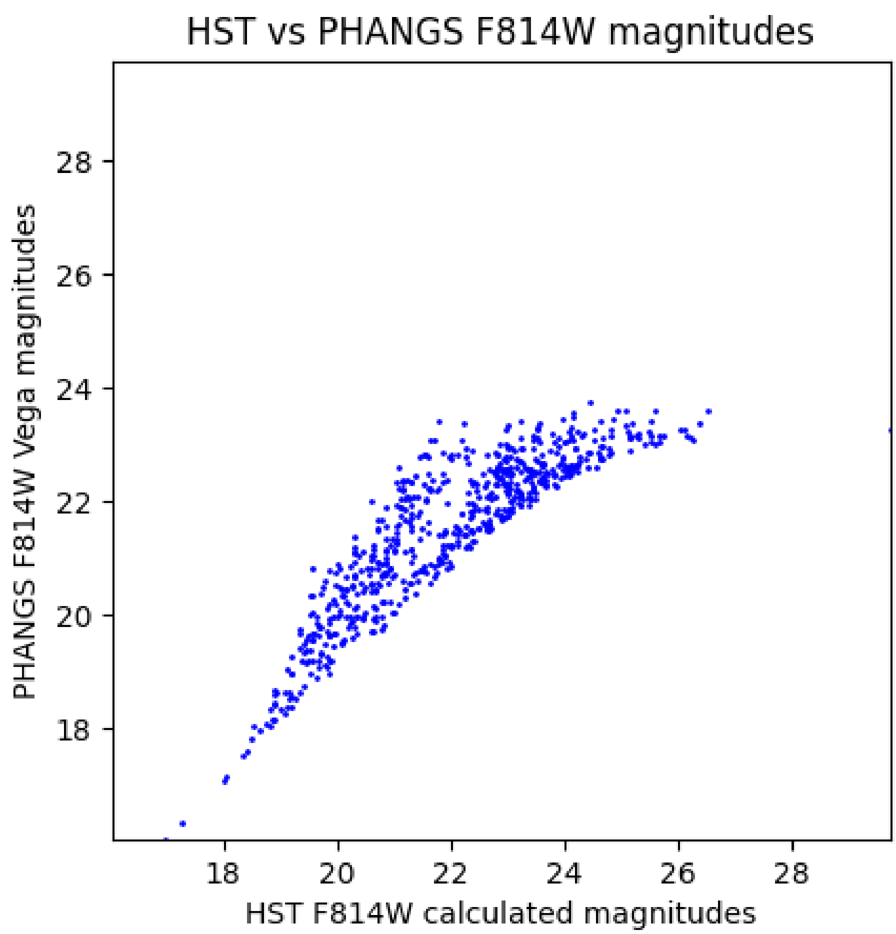

Figure 3.3: Photometric analysis without Background correction

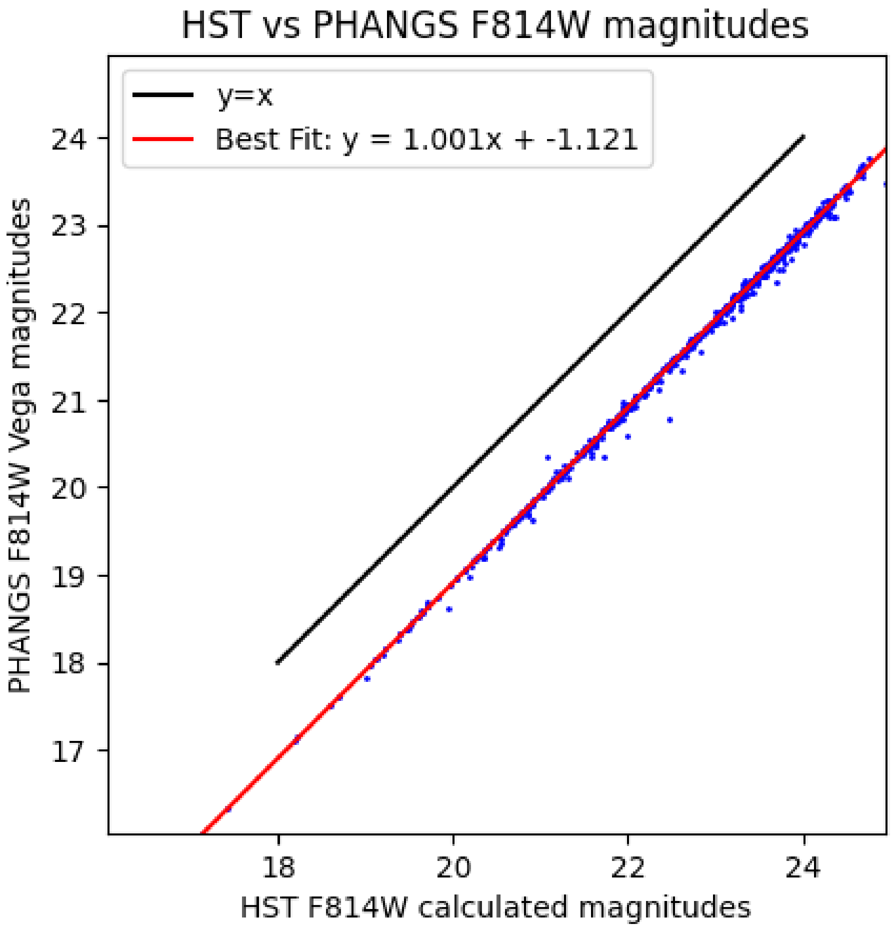

Figure 3.4: F814W

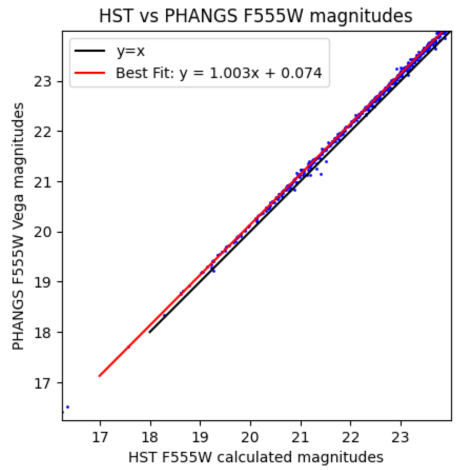

Figure 3.5: F555W

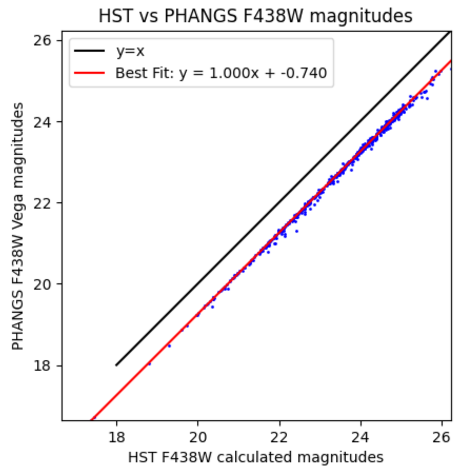

Figure 3.6: F438W

3.4 Corrections

3.4.1 Vega magnitude

The Vega magnitude to be subtracted from the calculated AB magnitude for different bands is as follows :

Wavelength	Correction
F814W	0.395
F555W	-0.048
F438W	-0.178
F336W	1.158

3.4.2 Foreground extinction (for NGC 1365)

Extinction is the absorption and scattering of electromagnetic radiation by dust and gas between an emitting astronomical object and the observer.

Wavelength	Correction
F814W (I)	0.0301
F555W (V)	0.0556
F438W (B)	0.0732
F336W (U)	0.0897

3.4.3 Aperture correction (for NGC1365)

The aperture correction is the difference between the magnitude measured in the our arcsecond aperture and the magnitude that is obtained in the standard photometric aperture.

Wavelength	Correction
F814W (I)	-0.73
F555W (V)	-0.61
F438W (B)	-0.64
F336W (U)	-0.73

3.4.4 Plot

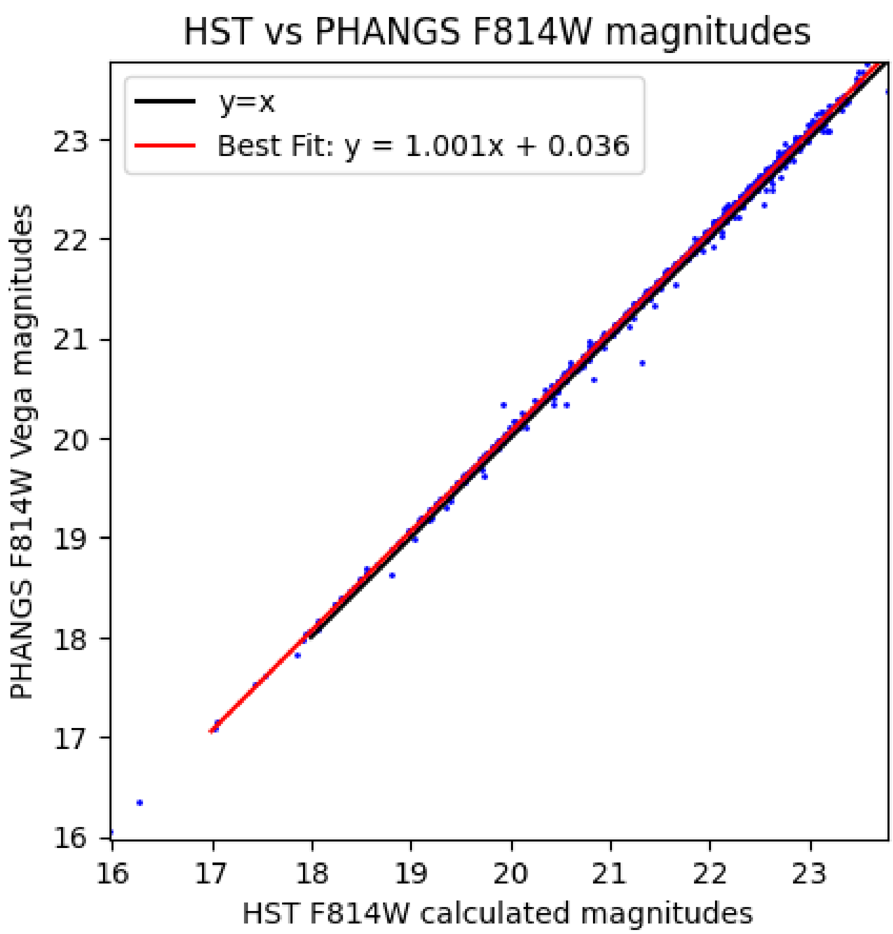

Figure 3.7: F814W corrected plot

Chapter 4

Colour-Colour Diagram

4.1 Colour-Colour Diagram

A colour–colour diagram is a means of **comparing the colours of an astronomical object at different wavelengths.** On colour–colour diagrams, the colour defined by two wavelength bands is plotted on the horizontal axis, and the colour defined by another brightness difference will be plotted on the vertical axis.

Here, I have used the difference of magnitudes in F555W and F814W (I-V) as the x-axis as the difference of magnitudes in F336W and F438W (U-B) as the y-axis.
The stellar evolution model derived theoretical evolution tracks is plotted along with the actual data to estimate the ages of star clusters.

4.1.1 Code

```
# Plot the arrays
plt.scatter(f555w_f814w,f336w_f438w, s=1, marker='o', color='b', label = 'Clusters')

ub_data = np.load('model_ub_sol.npy')
vi_data = np.load('model_vi_sol.npy')
age_model = np.load('age_mod_sol.npy')

# Add labels, title, and legend
plt.xlabel('F555W-F814 magnitudes')
plt.ylabel('F336W-F438W magnitudes')
plt.title('Colour-Colour Diagram')
model_data = plt.scatter(vi_data, ub_data, c=age_model, vmax=2000, cmap= 'inferno', s=10, label='Theoretical track')
cbar = plt.colorbar(model_data, label = 'Age (Myr)')
```

```python

plt.gca().invert_yaxis()
plt.legend()

# Show the plot
plt.grid(True)  # Optional grid
plt.show()
```

4.1.2 Plot

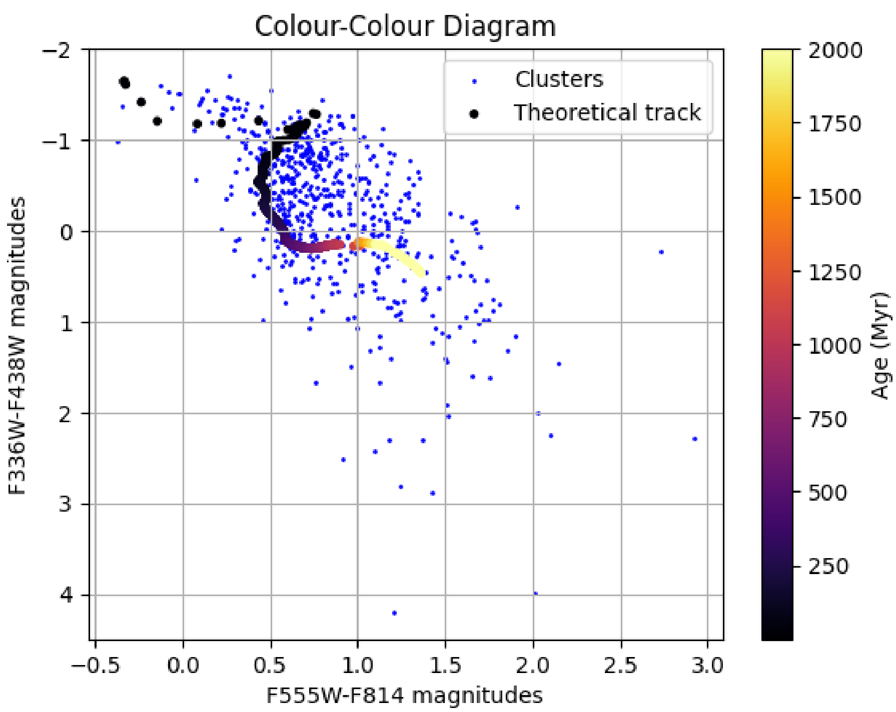

Figure 4.1: Scatter plot for clusters with age track

4.2 Density Contour Plot

To get further insight into the evolutionary stages and the ages of the star clusters, I plotted a density contour plot of the above scatter plot.

Evidently, most of the star clusters in NGC 1365 are **quite young**, with the majority being less than 250 million years old.

4.2.1 Code

```
import seaborn as sns

# Density plot using seaborn
plt.figure(figsize=(8, 6))
sns.kdeplot(x=f555w_f814w, y=f336w_f438w, cmap="inferno", fill=True, thresh=0, levels=100)

# Overlay theoretical track
model_data = plt.scatter(vi_data, ub_data, c=age_model, vmax=2000, cmap= 'grey', s=10, label='Theoretical track')
cbar = plt.colorbar(model_data, label = 'Age (Myr)')

# Overlay actual data
plt.scatter(f555w_f814w,f336w_f438w, s=1, marker='o', color='r', label = 'Clusters')

# Add labels, title, and legend
plt.xlabel('F555W-F814W magnitudes')
plt.ylabel('F336W-F438W magnitudes')
plt.title('Density Contour Plot')
plt.gca().invert_yaxis()
plt.legend()

# Show plot
plt.grid(True)  # Optional grid
plt.show()
```

4.2.2 Plot

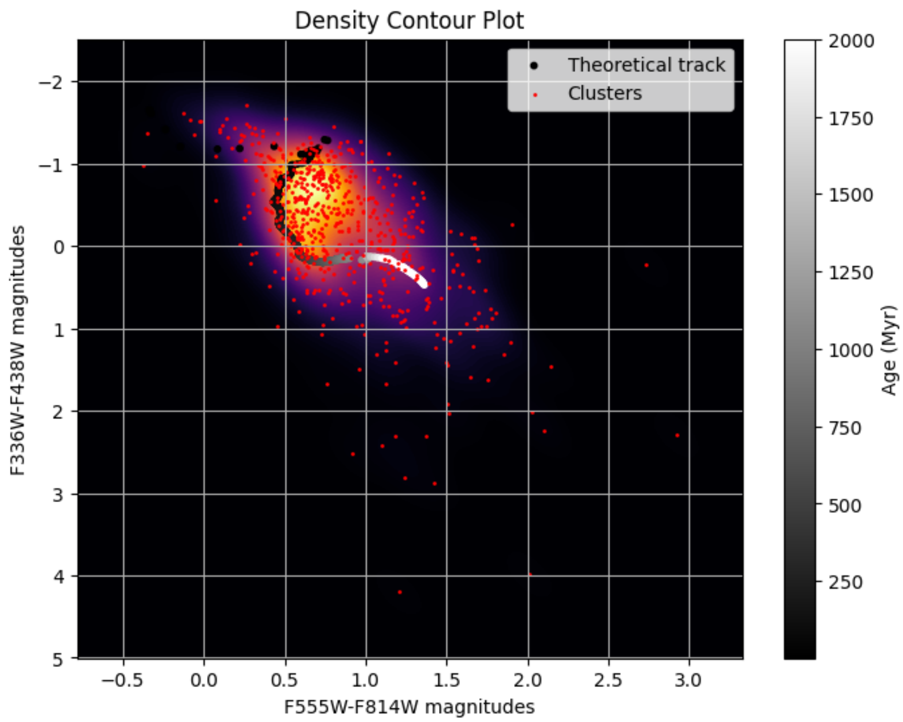

Figure 4.2: Density plot for clusters with age track

Chapter 5

ALMA Gas Distribution

5.1 Relationship between Gas Distribution and Star Formation

The Atacama Large Millimeter/submillimeter Array (ALMA)-the largest astronomical project in existence- is a single telescope of revolutionary design, composed of 66 high precision antennas located on the Chajnantor Plateau, 5000 meters altitude in northern Chile.

It provides **detailed observations of molecular gas in galaxies**, which are crucial for understanding star formation. The data includes measurements of various gas components such as carbon monoxide (CO) and dust emission, which trace the distribution and density of the interstellar medium.

I filtered the star clusters based on their age and superimposed them onto the density plot to gain insight into the relationship between gas density and star formation.
Evidently, young and middle aged clusters are present along the spiral arms of the galaxies which are regions of active star formation whereas older clusters are predominantly located near the galactic center, within the thicker halo region.

5.1.1 Plots

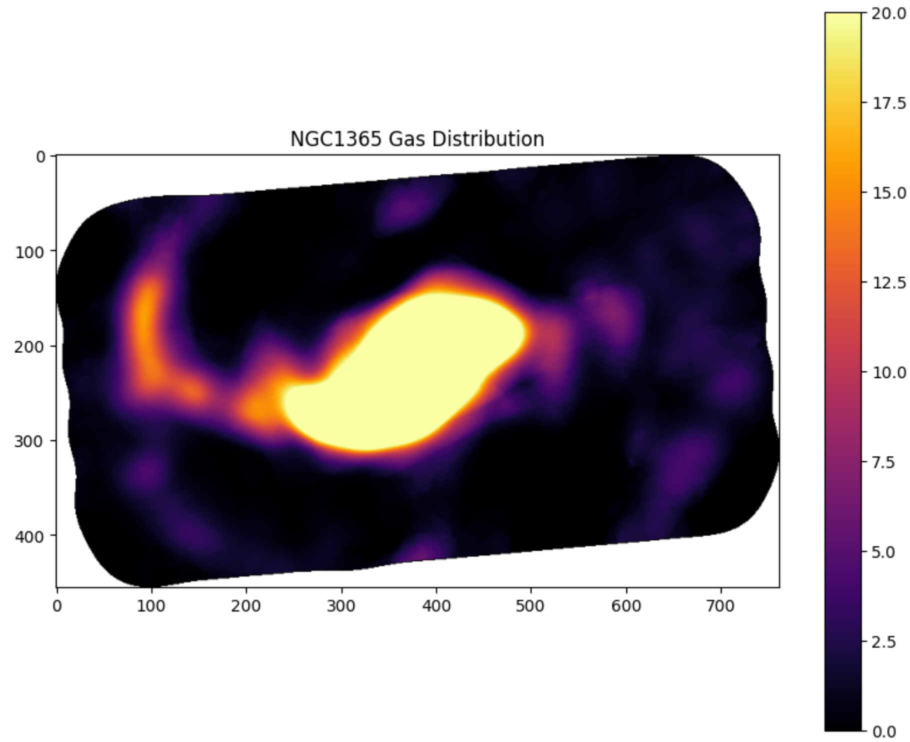

Figure 5.1: Gas density of NGC 1365

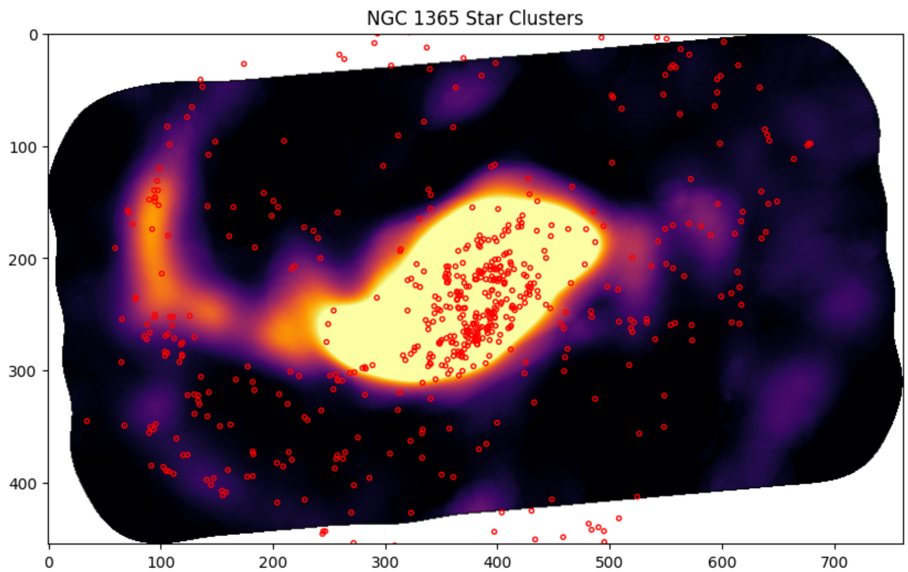

Figure 5.2: Star Clusters of NGC 1365

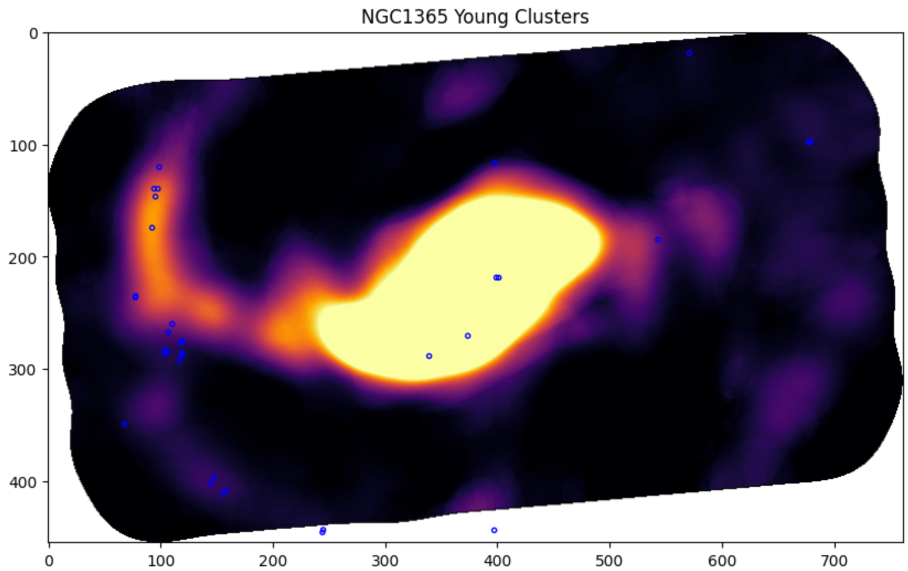

Figure 5.3: Young Star Clusters of NGC 1365

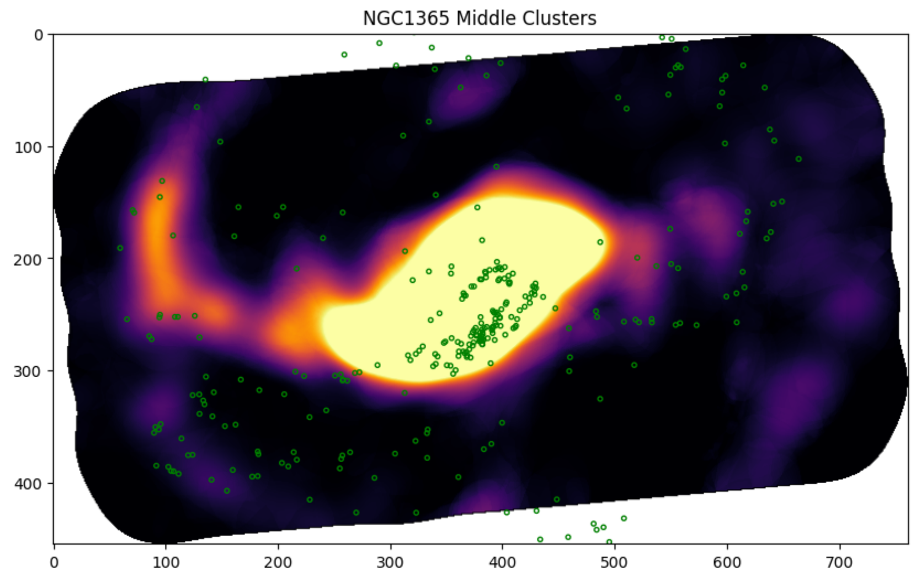

Figure 5.4: Middle Star Clusters of NGC 1365

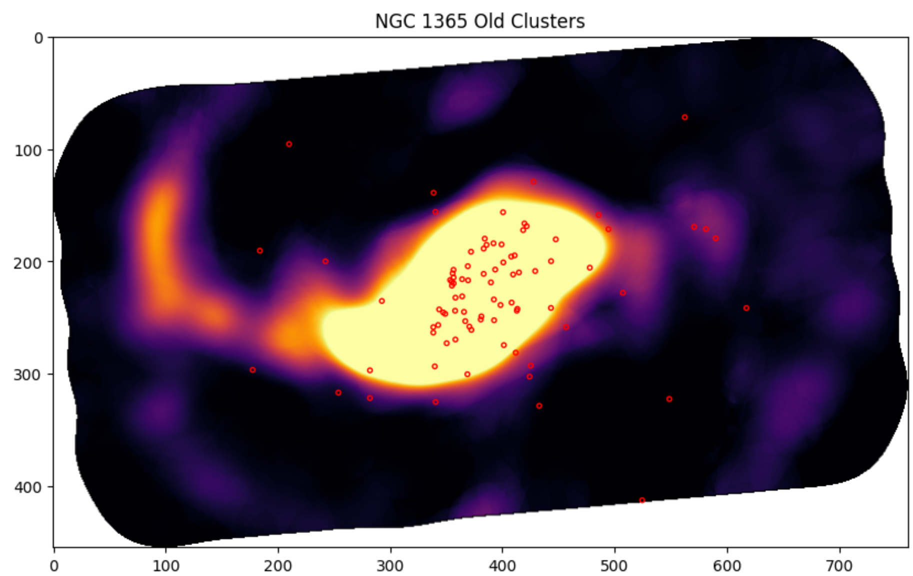

Figure 5.5: Old Star Clusters of NGC 1365