University of Auckland

Advanced Physics Laboratory

Experiment 225

Photometry of Stellar Clusters

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1 Introduction

Stellar clusters are groups of stars that are bound together by gravity and are also commonly known as stellar nurseries, as the stars within them were born within the cluster(Gohd, May 03, 2023). Inside a stellar cluster are the ideal conditions for star formation, containing large clouds of gas, primarily hydrogen, and dust that can clump together(Gohd, May 03, 2023). After enough material clumps together, gravity causes it to collapse and pressure starts to build, causing the core to heat up. This hot core is called a proto-star and will continue to collect more stellar material, eventually growing into a star. There are two main types of stellar clusters, open clusters and globular clusters. Open clusters have up to a few thousand stars and tend to be located in a galaxies disk. These clusters tend to be relatively young and have stars that are more loosely bound by gravity. Globular clusters are massive and old when compared to open clusters, containing between tens of thousands to millions of stars. These clusters tend to be located in a galaxies halo with its stars held tightly by gravity, causing the cluster to be densely packed and form a spherical shape(Tomaszewski, October 21, 2023).

Being a nursery for stellar formation, stellar clusters offer astronomers essential clues as to how stars evolve over time. According to (Tomaszewski, October 21, 2023) stellar clusters are relatively homogeneous, meaning that the stars within are roughly the same age and composition. This is useful as it allows astronomers to isolate physical properties that are a part of stellar evolution. We can also determine a stellar clusters age from its stars luminosity, composition, and temperature. We can then compare similar clusters of different ages to observe how the stars change over time (Tomaszewski, October 21, 2023).

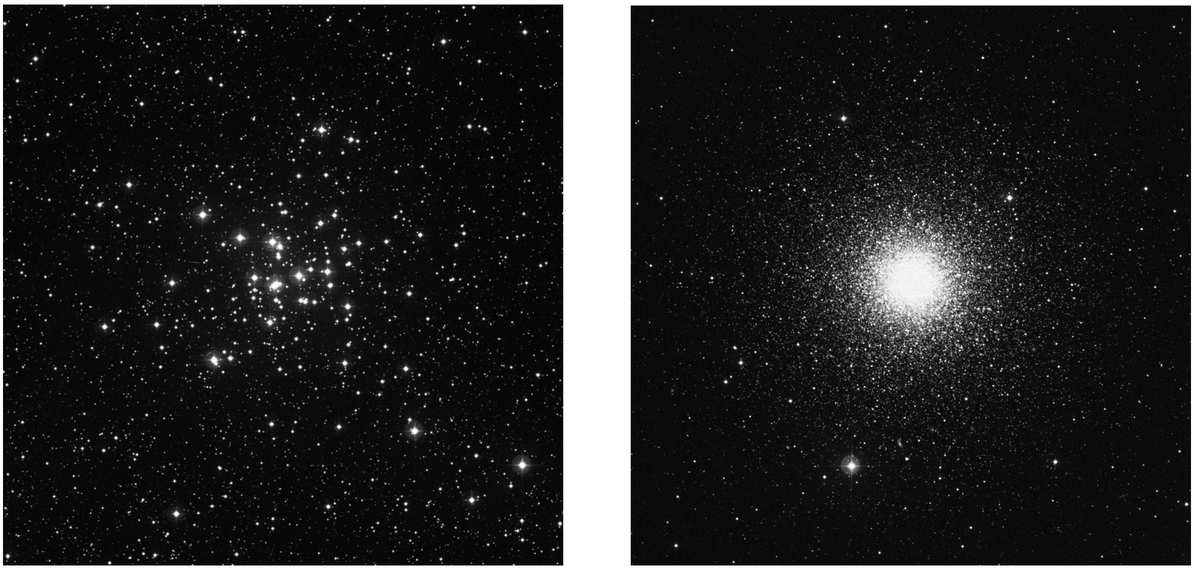


Figure 1: Open cluster M36 on the left and globular cluster M3 on the right. Both images acquired through The STScI Digitized Sky Survey(Association of Universities for Research in Astronomy, 1994)

The purpose of this experiment is to determine the age and distance from Earth of two stellar clusters, one open cluster M36, and one globular cluster M3, using photometry. Remote ground-based telescopes will be operated to take measurements of the apparent magnitude of stars within the cluster in two spectral bands, the visual(V) and blue(B) bands.

2 Methods

2.1 Reference Star Selection

The target visibility of both clusters was checked using STARALT (Peter Sorensen, 2002) where the Teide Observatory and the observing night were selected. The coordinates (R.A., dec) entered for M36 were (05 36 19, +34 08 27) and for M3 were (13 42 12, +28 22 24). The targets were then checked to make sure that they were more than 40°above the horizon and no less than 15°from the moon. Once the target visibility was confirmed finder charts were obtained for both clusters using the DSS query form (Association of Universities for Research in Astronomy, 1994). Here the Messier Catalog ID's for the clusters were entered into the object name field, and the height and width were set to match the field of view of the telescope being used, 32' for PIRATE and 43' for COAST. The finder charts were retrieved using the POSS2/UKSTU Blue catalog and was exported as a .gif file. A reference star of a known apparent magnitude was selected using the VizieR catalog (et. al), a reference star is needed for photometry as it provides a known brightness to compare with a target stars measured brightness, this helps take into account factors that may interfere with a measurement such as atmospheric conditions or equipment variation. To select a reference star, the All Sky Compiled Catalog was used by entering ASCC into the catalog search field and the optical wavelength filter was selected along with stars under the astronomy filter. The target dimension and Messier Catalog ID were entered with target dimension of 10 arcmin for M36 and 16 arcmin for M3. The reference star is then selected from AladinLite, this star should be easily recognizable and distinct in our finder chart and have a similar brightness as the other stars in the cluster. The B and V magnitudes are then recorded along with their error margins.

2.2 Data Acquirement

A control interface named Abot (Open-University) was used to remote control either the PIRATE or COAST telescope to make observations of our chosen star clusters by submitting observation schedules, then observations are then stored in Astrodrive. For the schedule programs, observations were added for both B and V bands for 8, 15, 30 and 60 second exposures all repeated 5 times. The telescope is then operated, provided conditions are safe and suitable for observations, and the scheduled programs are submitted. The observations are then accessed from Astrodrive as FITS files and are assessed to ensure the quality of the image where every star in the cluster should appear circular. Next the images are calibrated, stack aligned and analyzed through multi-aperture photometry using AstroImageJ (kielkopf at louisville dot edu, August 5, 2021). The saturation is checked to be no larger than 65000.0000, any image that is over-saturated is removed from the folder. Science Image Processing is selected in the CCD Data Processor and Filename Number Filtering is disabled, build is then selected for Bias Subtraction, Dark Subtraction and Flat Division, all other calibration settings are left as default. Next the image stack is aligned by importing the calibrated images and selecting Align Stack using WCS or apertures where four or more bright stars are selected in the first image. Multi-Aperture photometry can now be used on the aligned image stack, first we enable toggle display of aperture sky background regions, then open the Aperture Photometry Settings window to set the aperture settings. The Radius of object aperture is set such that the entirety of the reference star fits just within the inner annulus, the inner radius is set to twice this amount and the outer radius is set to three times this amount. Now using the Multiple Aperture tool Auto Fixed Apertures from first image T1 radial profile is selected and Auto comparison stars is deselected. The reference star is selected first in the V band image with the highest exposure, then 80-150 stars from the cluster are selected. After pressing enter the data from the Measurements window is saved as a .csv file.

2.3 Data Processing

The resulting data is imported into Python (Van Rossum u.a., 1995)to analyze. The relative fluxes from the imported table are converted into apparent magnitudes for each filter band following the equation

$$m_1 - m_2 = -2.5log_{10}(\frac{F_1}{F_2}) \tag{1}$$

where $\frac{F_1}{F_2}$ is the relative flux, m_1 is the reference stars apparent magnitude and m_2 is the target stars apparent magnitude we wish to calculate. The error for m_2 was found using

$$\Delta m_2 = \Delta m_1 + \frac{\Delta(\frac{F_1}{F_2})}{(\frac{F_1}{F_2})\ln(10)} \tag{2}$$

where $\Delta(\frac{F_1}{F_2})$ is the error in the relative flux, Δm_2 is the error in the apparent magnitude of the target star and Δm_1 is the error in the apparent magnitude of the reference star. Next the observed colour is calculated by taking the B band apparent magnitude per star and subtracting this by the V band apparent magnitude. The intrinsic colour is then found using the equation

$$E(B-V) = (B-V) - (B-V)_0 \tag{3}$$

where $(B-V)$ is the observed colour, $(B-V)_0$ is the intrinsic colour and $E(B-V)$ is the colour excess, which is 0.22 for M36 and 0.01 for M3. The error for the observed colour is found by subtracting the error of the V band apparent magnitude by the error in the B band apparent magnitude. Due to the multiple exposure times per spectral band, the average of the intrinsic colour is found getting the sum of all 4 exposures and dividing by 4. Now that we have the apparent magnitude and intrinsic colour per star, a colour-magnitude for the star cluster can now be made. The V band apparent magnitude is then found for a A0 star by locating a star with an intrinsic colour of 0, as these stars have a known absolute V band magnitude of 0.7. The distance to the cluster can now be found using the equation

$$\mu_V = 5log_{10}(d/pc) - 5 + A_V \tag{4}$$

where $\mu_V = m - M$ is the distance modulus, d is the distance to the cluster in parsecs and A_V is the interstellar extinction which is 0.66 for M36 and 0.03 for M3. Finally the age of the cluster can be found by plotting the colour-magnitude diagrams against provided isochrones, isochrones are a curve on the colour-magnitude diagram that represents the locations of stars have different masses but have the same age. The isochrone that best fits the colour-magnitude diagram is chosen and the age of the cluster is estimated to the age associated with the isochrone.

3 Results

3.1 M36

From VizieR (et. al) a reference star with record number 567329 was selected with a apparent V band magnitude of 9.885 ste 0.046 and a apparent B band magnitude of 9.932 ste 0.035. Data for M36 was imported into Python (Van Rossum u.a., 1995) where the relative fluxes for the V band and B band were isolated into there own dataframes along with the error data.

```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

filename = 'M36.csv'
M3DataRaw =     pd.read_csv(filename)

relativeFluxesM36 = M3DataRaw.loc[:, "rel_flux_T2": "rel_flux_T84"]
relativeFluxesB_BandM36 = relativeFluxesM36.loc[0:3]
relativeFluxesV_BandM36 = relativeFluxesM36.loc[4:7]

relativeFluxesM36Error = M3DataRaw.loc[:, "rel_flux_err_T2": "rel_flux_err_T84"]
relativeFluxesB_BandM36Error = relativeFluxesM36Error.loc[0:3]
relativeFluxesV_BandM36Error = relativeFluxesM36Error.loc[4:7]
```

Figure 2

The apparent magnitude was calculated per star per exposure time using 1 along with the error data using 2

```
appartentMagB_Band = 9.932 + 2.5 * np.log10(relativeFluxesB_BandM36)
appartentMagV_Band = 9.885 + 2.5 * np.log10(relativeFluxesV_BandM36)

appartentMagB_BandError = relativeFluxesB_BandM36 * np.log(10)
appartentMagB_BandError = 0.035 + relativeFluxesB_BandM36Error.div(np.array(appartentMagB_BandError))

appartentMagV_BandError = relativeFluxesV_BandM36 * np.log(10)
appartentMagV_BandError = 0.046 + relativeFluxesV_BandM36Error.div(np.array(appartentMagV_BandError))
```

Figure 3

Then the observed colour and intrinsic star per star per exposure time was then calculated along with the error propagation by subtracting the error of the V band apparent magnitude from the error in the B band apparent magnitude. The intrinsic colour was then averaged over the 4 different exposure times to give one intrinsic colour value per star.

```
ObservedColour = appartentMagB_Band - np.array(appartentMagV_Band)
intrinsicColour = ObservedColour - 0.22
intrinsicColourAve = intrinsicColour.sum() / 4

ObservedColourError = appartentMagB_BandError - np.array(appartentMagV_BandError)
intrinsicColourAveError = ObservedColourError.sum() / 4
```

Figure 4

Next a colour-magnitude diagram was produced

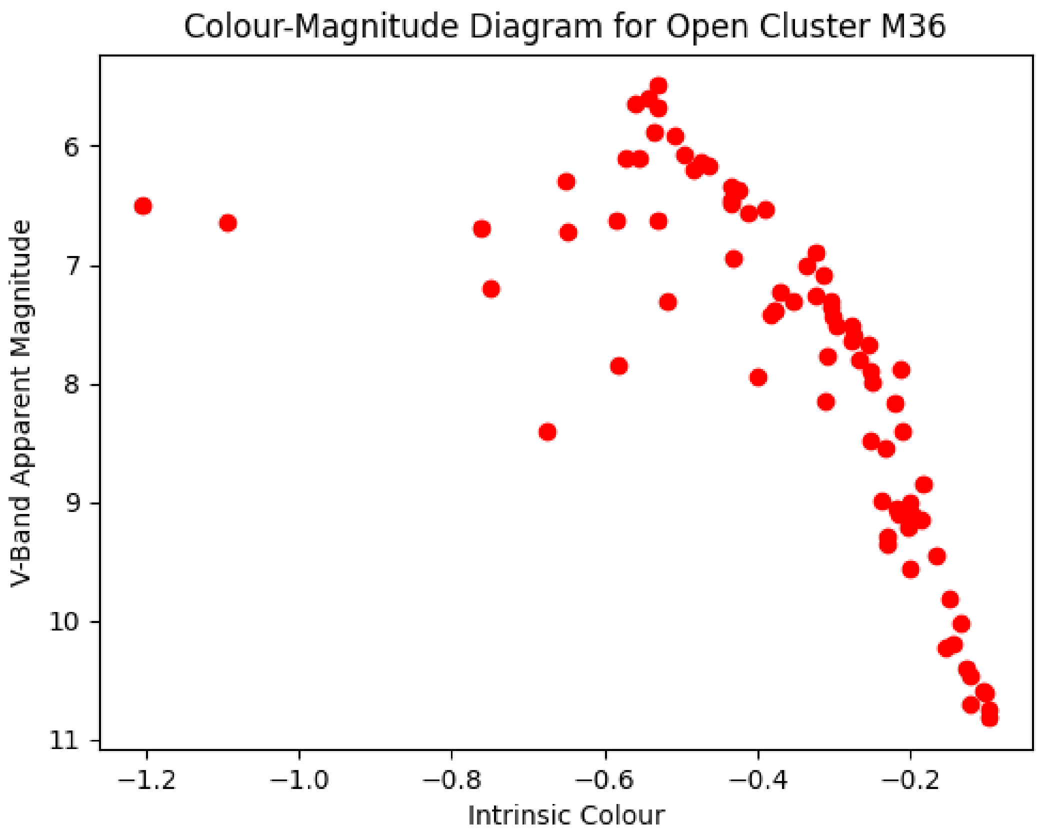


Figure 5

Unfortunately there were no A0 stars in our data, so instead we had to make a guess of where a A0 star would be for this cluster. We see that there is a diagonal trend of stars to the right of the colour-magnitude diagram, a line of best fit using polyfit was used of the data within this trend and the y intercept was taken, as this is when intrinsic colour is 0. To avoid data that strays from the trend skewing our line, data points where the intrinsic colour was less than -0.35 were removed.

```
colToRemove = []
appartentMagV_BandAve = appartentMagV_Band.sum() / 4
for i in range(len(intrinsicColourAve)):
    if intrinsicColourAve[i] < -0.35:
        colToRemove += [i]
intrinsicColourAve_Adjusted = np.array(intrinsicColourAve)
appartentMagV_BandAve_Adjusted = np.array(appartentMagV_BandAve)
intrinsicColourAve_Adjusted = np.delete(intrinsicColourAve_Adjusted, colToRemove)
appartentMagV_BandAve_Adjusted = np.delete(appartentMagV_BandAve_Adjusted, colToRemove)

idx = np.isfinite(np.array(intrinsicColourAve_Adjusted)) & np.isfinite(np.array(appartentMagV_BandAve_Adjusted))
a, b = np.polyfit(np.array(intrinsicColourAve_Adjusted)[idx] , np.array(appartentMagV_BandAve_Adjusted)[idx], 1)
A0_Star = b
```

Figure 6

Now that the A0 star apparent magnitude has been found, we calculate the distance to the cluster using 4. The error propagation for the distance was calculated using the equation

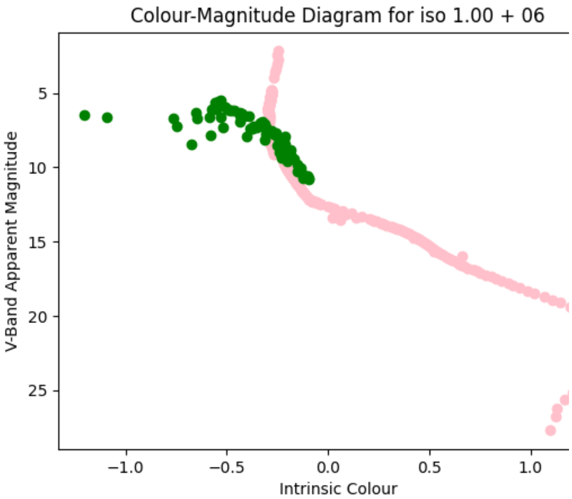
$$\Delta d = d \ln(10) \frac{\Delta m_v}{5} \tag{5}$$

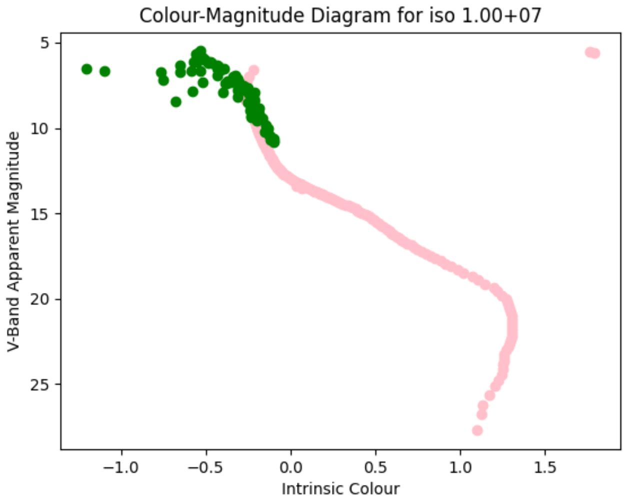
where m_v is the total average of the apparent magnitude in the V band from all stars and exposure times.

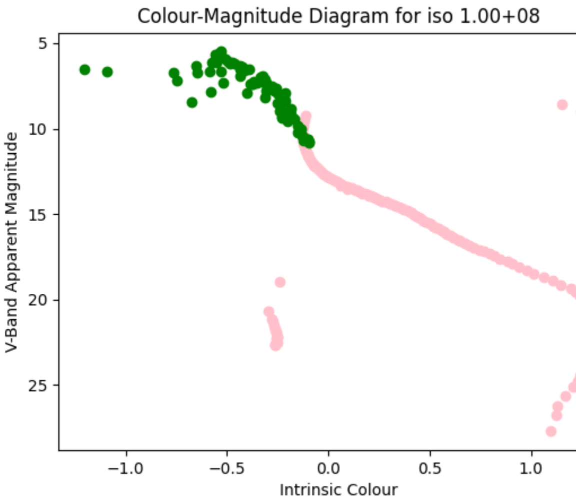
```
Av = 3 * 0.22
distance = (10 ** ((A0_Star - 0.7 + 5 - Av) / 5))

appartentMagV_BandAveError = appartentMagV_BandError.sum() / 4
appartentMagV_BandAveErrorAve = appartentMagV_BandAveError.sum() / 83
distanceError = appartentMagV_BandAveErrorAve / 5
distanceError = distance * np.log(10) * distanceError
```

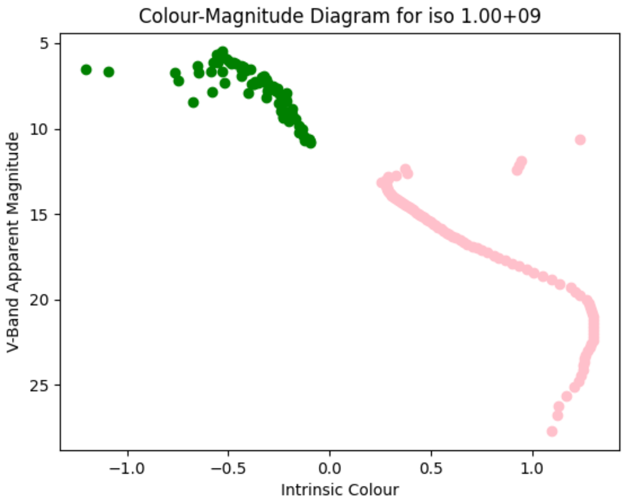
Figure 7

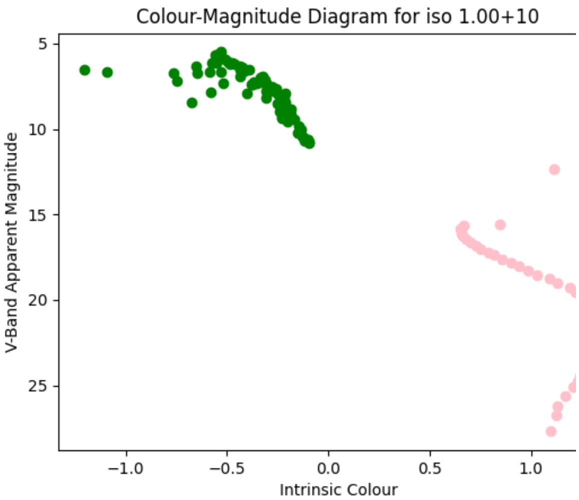
After our analysis we found the distance to the open cluster M36 to be 1553.45 parsecs with a standard error of ±33.88 parsecs. The age of the cluster M 36 is now estimated using isochrones. Looking at which diagram aligns best, i will consider which diagram has the most overlaping points and where the data follows the trend of the isochrone. Considering these two factors isochrone 3.16+07 was chosen, where the age associated with this isochrone being 3.16×10^7 years.

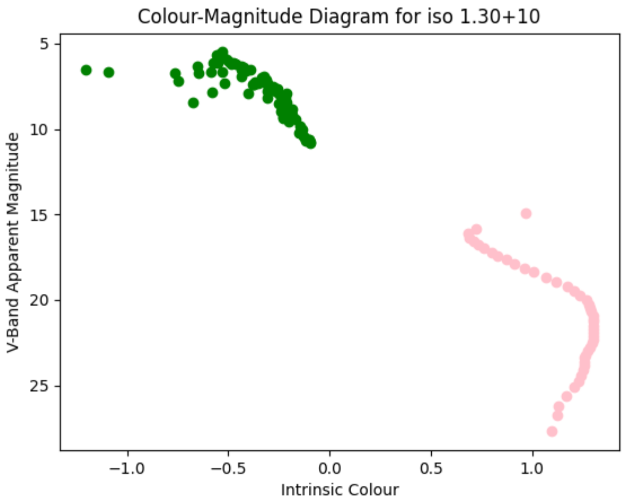

Colour-Magnitude Diagram for iso 1.00 + 06
V-Band Apparent Magnitude
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+07
V-Band Apparent Magnitude
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+08
V-Band Apparent Magnitude
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+09
V-Band Apparent Magnitude
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+10
V-Band Apparent Magnitude
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.30+10
V-Band Apparent Magnitude
Intrinsic Colour

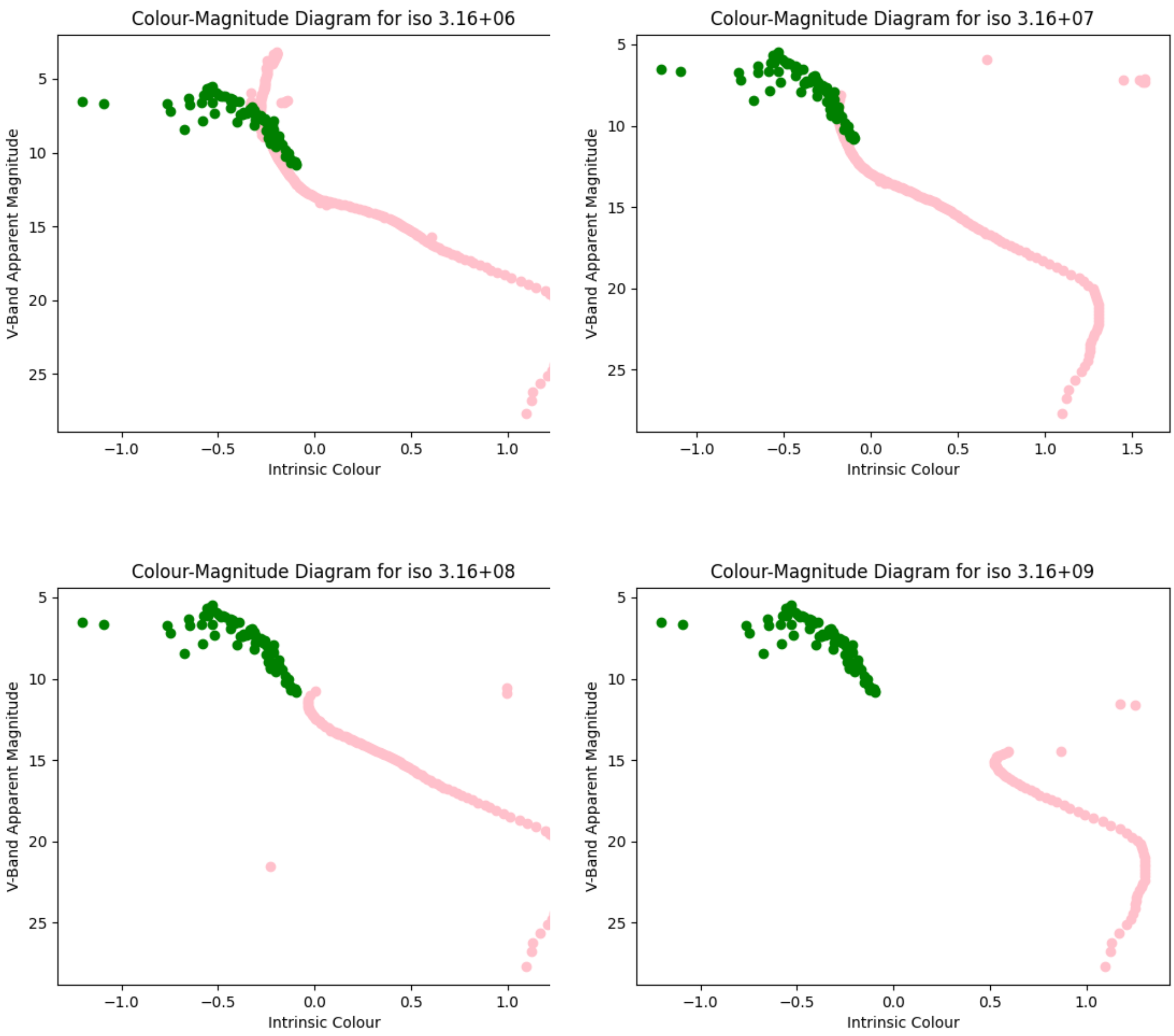


Figure 9: plots of Colour-magnitude diagram for M36 against isochrones

3.2 M3

From VizieR (et. al) a reference star with record number 688050 was selected with a apparent V band magnitude of 12.772 ste 0.201 and a apparent B band magnitude of 12.857 ste 0.201. While attempting to align the image stack for the data the image for V band exposure 60 was quite different from the other images in angle, making the alignment difficult. The decision was made to remove this image and the B band image at exposure 60. As a result we had data for 3 different exposures per band instead of 4. Data for M36 was imported into Python (Van Rossum u.a., 1995) where data processing and code is the same as for our M36 analysis, except when finding averages across exposure times the sums are divided by 3. The resulting colour-magnitude diagram is as follows

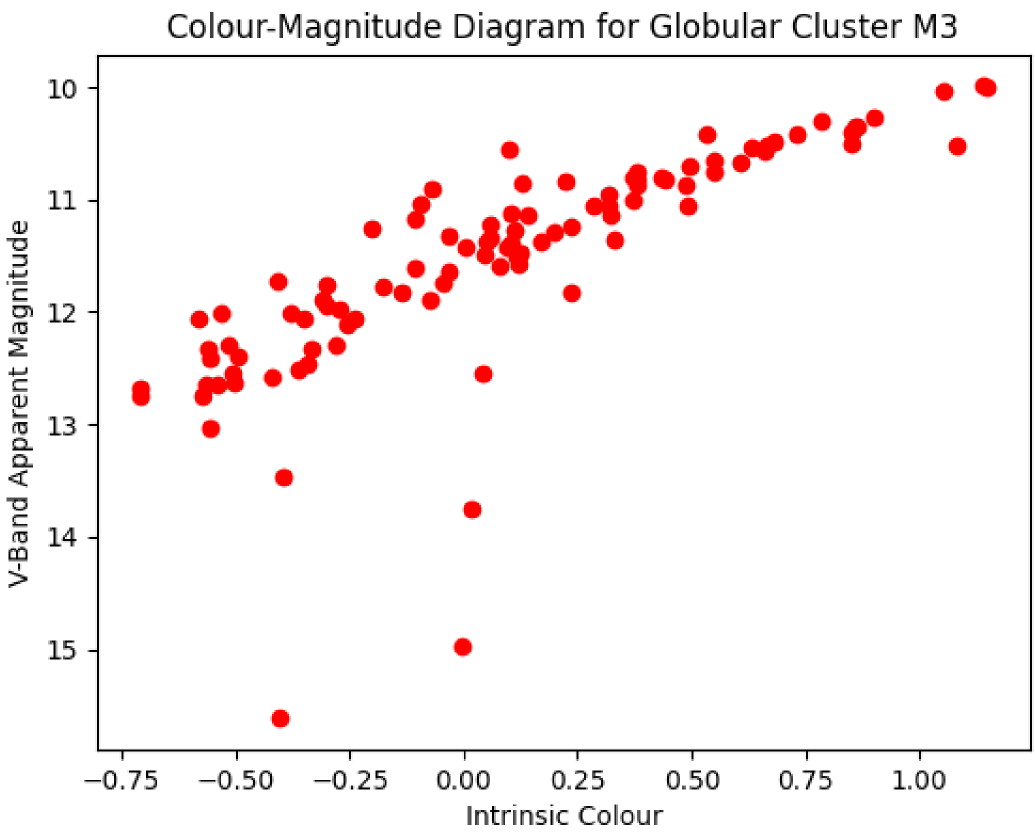


Figure 10

None of the stars had a intrinsic colour of exactly 0, so stars that had a intrinsic colour close to 0, in this case between -0.02 and 0.02, were found

```
A0_Star_col = []
for i in range(len(np.array(intrinsicColourAve))):
    if np.array(intrinsicColourAve)[i] < 0.02 and np.array(intrinsicColourAve)[i] > -0.02:
        A0_Star_col += [i]

A0_ave = (appartentMagV_BandAve)[A0_Star_col].sum() / 3
```

Figure 11

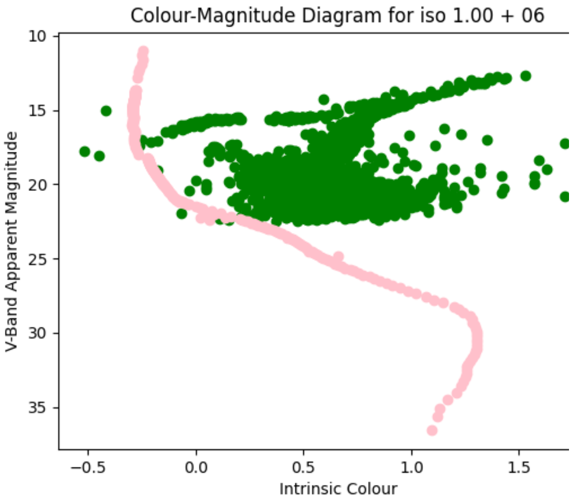
The average apparent magnitude of these stars was then used in equation 4 to find the distance to the cluster, and the error propagation was found using equation 5 where this time Δm_v is the error of the A0 stars, which was found taking using the index found for the A0 stars and taking the elements in the apparentMagV-BandAveError array then taking the average. Finally this gives us a distance of 3389.21 parsecs $\pm$ 6.47 parsecs. This is vastly different than the distance confirmed online. After consulting with our lab demonstrator we were advised that our data most likely consisted mostly of red giants and that it would be better to use data found online that contained a larger variety of stars. This was because due to the age of globular clusters, most of the stars on the main sequence are of relatively low mass, and thus due to the increased distance from Earth globular clusters tend to have these stars are particularly dim, making them unlikely targets to be selected during photometry. This full data set was found through VizieR (et. al) by searching for the J/A+A/290/69 catalog and combining tables 4 and 6. A query was submitted with search preferences "max: unlimited" and ";-Separated-Values" and "All columns". The resultant was data downloaded as a .tsv file, to use the .tsv file, i had to remove all headers and join the tables in the file, it was then imported into Python (Van Rossum u.a., 1995) with ";" as the separator. The data was also imported as strings and so they had to be converted to floats to be able to use it for our analysis. Due to the large amount of data, the range used to search for A0 stars was set much narrower, this time between $-10^{-}15$ and $10^{-}15$. This data was given as apparent magnitudes instead of relative fluxes, so using equation 1 was not needed.

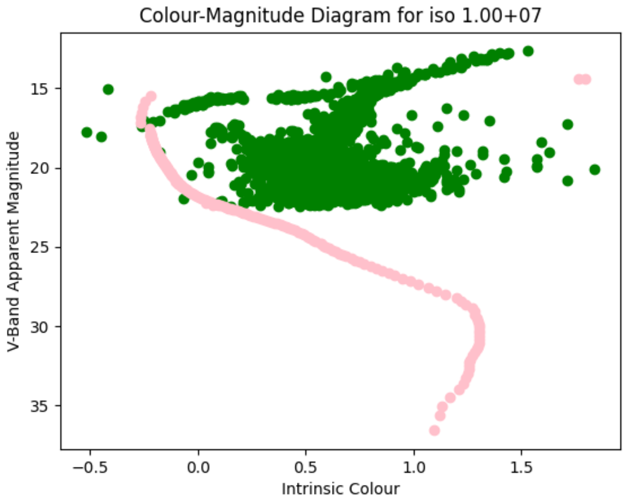
```
import pandas as pd
import numpy as np
import matplotlib.pyplot as plt

filename = 'M3_OnlineEdited.tsv'
DataRaw =    pd.read_csv(filename, sep = ';')

appartentMagB_Band = DataRaw.loc[:, "Bmag"]
appartentMagB_Band = appartentMagB_Band.iloc[2:]
appartentMagB_Band = appartentMagB_Band.astype(float)
appartentMagV_Band = DataRaw.loc[:, "Vmag"]
appartentMagV_Band = appartentMagV_Band.iloc[2:]
appartentMagV_Band = appartentMagV_Band.astype(float)

ObservedColour = appartentMagB_Band - np.array(appartentMagV_Band)
intrinsicColour = ObservedColour - 0.01
A0_Star_col = []
for i in range(len(np.array(intrinsicColour))):
    if np.array(intrinsicColour)[i] < 10**-15 and np.array(intrinsicColour)[i] > -10**-15:
        A0_Star_col += [i]

Av = 3 * 0.01
A0_ave = np.array(appartentMagV_Band)[A0_Star_col].sum() / 3
distance = (10 ** ((A0_ave - 0.7 + 5 - Av) / 5))
```

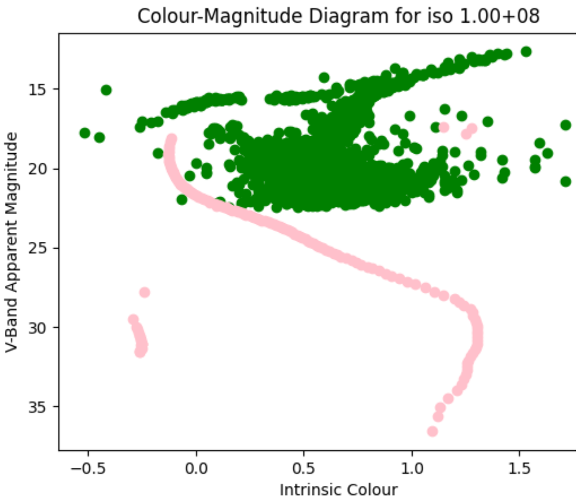
Figure 12

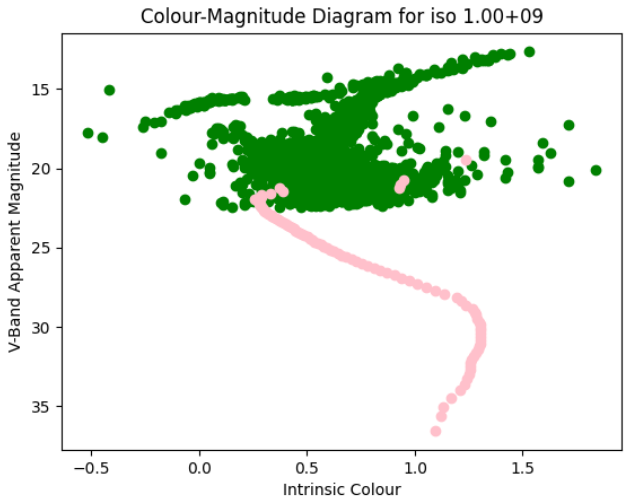
There was no error data provided for this data set and therefore no error propagation was done. Our result for the distance to the globular cluster M3 was 123026.88 parsecs. To estimate the age of M3, its colour-magnitude diagram was plotted against isochrones

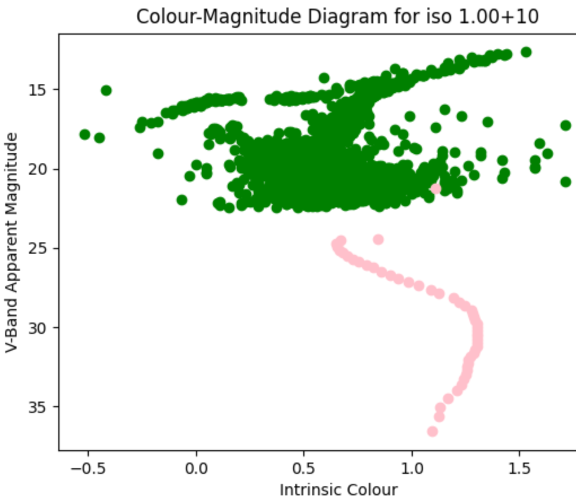
It was difficult to determine which isochrone fit best given the shape of the datas colour-magnitude diagram, it was decided to chose the one that had most overlap with the bottom of the datas graph and which isochrone looked like it would continue the line from the top right corner down. Given these two factors, isochrone 1.00+09 was chosen.


Colour-Magnitude Diagram for iso 1.00 + 06
V-Band Apparent Magnitude
10
15
20
25
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+07
V-Band Apparent Magnitude
15
20
25
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+08
V-Band Apparent Magnitude
15
20
25
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+09
V-Band Apparent Magnitude
15
20
25
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.00+10
V-Band Apparent Magnitude
15
20
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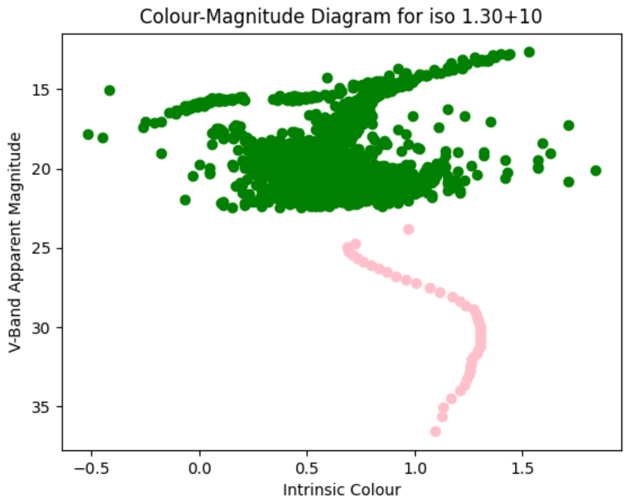
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour


Colour-Magnitude Diagram for iso 1.30+10
V-Band Apparent Magnitude
15
20
25
30
35
−0.5
0.0
0.5
1.0
1.5
Intrinsic Colour

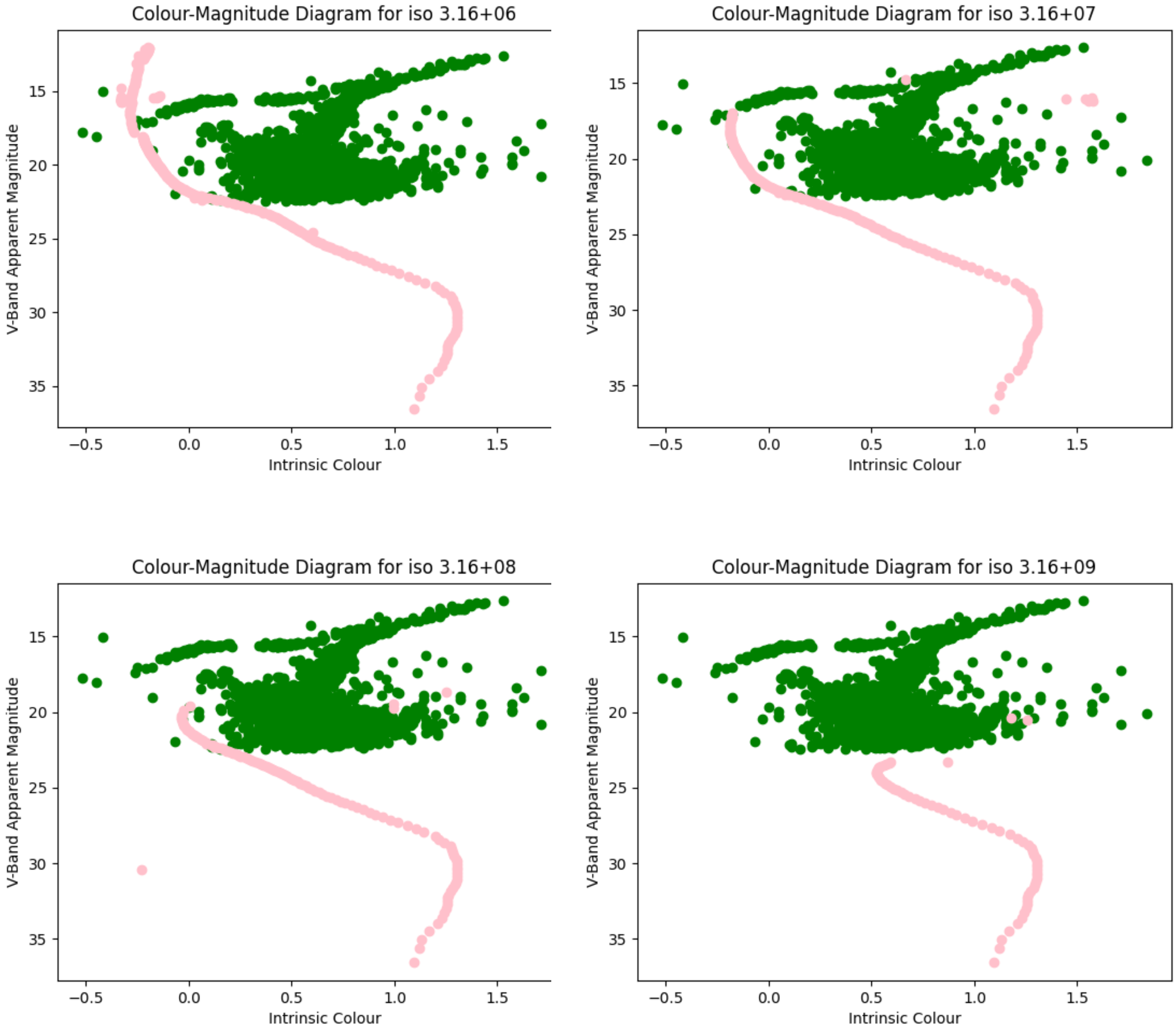


Figure 14: plots of M3 online data against provided isochrones

4 Discussion and Conclusions

Our final results are as follows The distance for M36 is higher than expected as the expected

Table 1: Summary of experimental results

Stellar Cluster	**Distance [parsec]**	**Age [years]**
M36	1553.45± 33.88	3.16×10^7
M3	123026.88	10^9

value is around 1330 parsecs, which is not within the range of our result when taking into account error. Our result for the distance to M3 was also higher than expected, with the expected value being around 10000 parsecs. Some sources of error and variation in this experiment would be star selection during the photometry stage, in particular with the globular cluster. I was more inclined to select distinct and bright stars, ignoring the smaller ones or ones quite close together. With the globular clusters i could only really select stars along the outer area of the cluster as stars more towards the center blurred together, being unsuitable for photometry. It is likely this caused selection bias and is quite likely the reason our data for M3 was not usable. What our data for M3 shows is the horizontal branch where it can also be seen in the colour-magnitude diagram made using online data. Possible ways to improve our distance estimate would be to select more stars during photometry, or use a different method particularly for globular clusters as most stars would not be suitable to be measured using this method.

Our age estimate for M36 was higher than expected, where the expected value was around 2.2×10^7 years. Our age estimate for M3 was lower than expected, where the expected value was around 1.14×10^10, which is a relatively larger error than our other results as this is off by a factor of 10. Main sources of error for age would be in the selection of the isochrones. Since we are given a select amount to pick from, there is a resolution to the result in a sense in terms of how far the isochrone ages are spaced apart. Having more isochrones may help with the resolution problem, however it may get quite difficult to try distinguish them. There is also human error in determining which isochrone to select, as the data does not fit perfectly to any one and choices are to be made and which one to select, particularly with the globular cluster M3 where the shape made it difficult to fit. There is also the nature of colour-magnitude diagrams themselves, as they assumes all the stars to be of the same age, but that is most likely not the case in reality.

References

Astronomy, Inc. Association of Universities for Research in (1994): *The STScI Digitized Sky Survey*
`https://archive.stsci.edu/cgi-bin/dss_form`.

al, Ochsenbein F. et. *The VizieR database of astronomical catalogues*
10.26093/cds/vizier.

Gohd, Chelsea (May 03, 2023): *Star Clusters: Inside the Universe's Stellar Collections*
`https://science.nasa.gov/universe/star-clusters-inside-the-universes-stellar-collections/`

edu kielkopf at louisville dot (August 5, 2021): *AstroImageJ 2.4.1*
`https://www.astro.louisville.edu/software/astroimagej/`.

Open University *Abot UI*
`https://abot-ui-ou.azurewebsites.net/`.

Peter Sorensen, Javier Méndez (2002): *Object Visibility – STARALT*
https://astro.ing.iac.es/staralt/.

Tomaszewski, Paul (October 21, 2023): *Why Are Star Clusters Ideal Laboratories for Stellar Evolution?*
https://astroblog.cosmobc.com/star-clusters-ideal-laboratories-stellar-evolution/.

Van Rossum, Guido / Drake Jr, Fred L (1995): *Python reference manual.* , Centrum voor Wiskunde en Informatica Amsterdam.