Senior Honours Project

Globular Clusters in the Era of Gaia and WEAVE

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Abstract

This report presents the results of examining the outer envelopes of 13 globular clusters out to 3 tidal radii using the Pan-STARRS survey and Gaia Data Release 1. It was found that many clusters displayed signs of containing stellar envelopes out to at least 2 tidal radii and some clusters contained traces of envelopes out to 3 tidal radii. These results were significantly hampered by contaminant stars but this problem will be largely resolved upon the release of Gaia Data release 2 which will allow cluster stars to be more easily identified. It was found that NGC 6341, NGC 5904 and NGC 6205 were all promising candidates for further study but NGC 6341 was the most suitable. Further study would help to clearly identify the properties of the extended stellar envelopes and their origins.

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1 Theory

1.1 Research Context

The aim of this project was to examine the outer envelopes of globular clusters using the first data release of the Gaia observatory. This would be done for a series of globular clusters which would show how far the stellar envelopes extended. Additionally, the clusters were examined to determine which would be most suitable for further study using the second Gaia data release which was not available at the time of this project.

Globular clusters are a dense collection of stars formed from a gas cloud. Another type of star cluster are open clusters which consist of young stars and are loosely bound by gravity so are easily disrupted by clouds or other clusters[1]. In contrast, globular clusters are a very dense collection of stars which are tightly bound by gravity, giving them a spherical shape. Additionally, open clusters are found in the disc of a galaxy whereas globular clusters are located in the halo.

Globular clusters are important as they are among the oldest objects in the universe that can be observed. As such, they are often used to estimate the age of the universe and are also an important way of calibrating the cosmic distance ladder[2] but their origins are still largely unknown.

It has recently been found that the outer envelopes of some globular clusters are far more extended than previously thought. An example of this is that a research team led by P.B. Kuzma found the globular cluster NGC 7089 to have an envelope which extends to at least 5 tidal radii[3].

Other globular clusters where the outer regions have been studied include NGC 1851, NGC 5824 and NGC 1261[4]. It was found that the outer envelope for NGC 1851 was similar to NGC 7089 but the outer regions for the other clusters differed. NGC 1261 contained a stellar envelope but it was far smaller than the envelopes for either of the other two globular clusters. On the other hand, NGC 5824 contained no strong evidence of a diffuse stellar envelope but is extremely extended in size.

The reasons for the diversity of outer regions of globular clusters is not yet known but two leading possibilities are currently being examined: it could be due to dynamical evolution of the cluster or due to accretion of a dwarf galaxy.

Dynamical evolution consists of many processes but the primary one involved in the formation of outer envelopes for globular clusters is tidal shocking. This is when a cluster moves near a large mass and the gravity from this mass adds energy to the cluster, creating a tidal force. This disrupts the cluster, causing it to expand and lose stars in the outer regions. This also creates tidal tails which are thin regions of stars which have been thrown off during the shock[5].

It can be seen from simulations that diffuse stellar envelopes can form during tidal shocking. Further evidence for this theory is that some existing globular clusters are similar to what was predicted in simulations[4]. However it would be expected that a cluster undergoing tidal shocking would contain tidal tails which have not been found in the clusters examined so far. Globular clusters with profiles similar to the clusters in the Kuzma et al paper have been seen without tidal tails but never with envelopes this extended or diffuse.

Another possible explanation for these extended, diffuse envelopes is that these clusters were formed in a dwarf galaxy which were then accreted into the Milky Way halo. The dwarf galaxy would then be destroyed but the structure surrounding the core could remain which would form an extended diffuse envelope[6]. There is evidence for this theory in that simulations show that it is possible for the envelope of the dwarf galaxy to remain even after most of the mass of the cluster has been lost to tidal shocking. Additionally the globular clusters studied by Kuzma contain properties such as iron and neutron capture elements which are indicative of dwarf galaxies.

It is suggested by Kuzma that the stellar envelopes of NGC 7089, NGC 1851 and NGC 5824 are all likely to be due to accreted dwarf galaxies because their size and properties are similar to dwarf galaxies. It is therefore possible that the clusters themselves are the cores of the accreted dwarf galaxies. It is also suggested in the paper that NGC 1261 is more likely to be due to dynamical evolution such as tidal shocking due to its smaller stellar envelope. However the nature and origin of these extended stellar envelopes is still not known. As such, a primary aim of this project is to study the outer envelopes of globular clusters to provide further evidence for how these clusters formed and whether or not they were part of dwarf galaxies.

1.2 Uses of Gaia

The dense inner regions of globular clusters have been studied extensively but these less dense outer envelopes have gone relatively undocumented. This is because there are lots of non-cluster stars which lie on the plane of any cluster, so whenever the outer regions are viewed there is no way to differentiate between cluster stars and non-cluster stars which lie on the same plane. This is not a problem for the inner regions of clusters as they are so dense that any detected star is highly likely to be a cluster star.

However the second data release from the Gaia observatory would allow for the outer envelopes of globular clusters to be studied in far greater detail. This is because Gaia focusses on astrometry which is measuring the positions and motions of stars in the sky. In particular Gaia tracks the proper motion of stars, which is the angular velocity of stars in the sky relative to background stars. Knowing the proper motions of stars allows the user to distinguish between cluster and non-cluster stars which would allow the outer envelopes of globular clusters to be examined in far greater detail.

This is because globular clusters are found in the galaxy halo whereas stars in the disc rotate around the galactic centre as can be seen in figure 1. Due to this, stars in the disc will show a Gaussian distribution on a proper motion graph when seen from the Earth, whereas all stars in

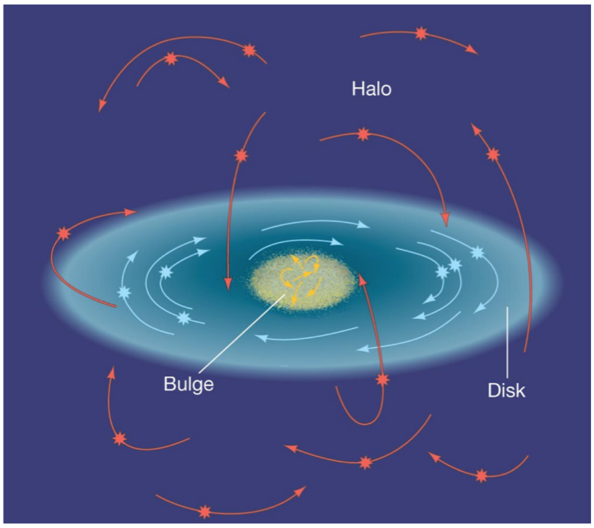


Figure 1: Galaxy diagram showing globular clusters in the halo (red) and open cluster in the disc (blue)[7].

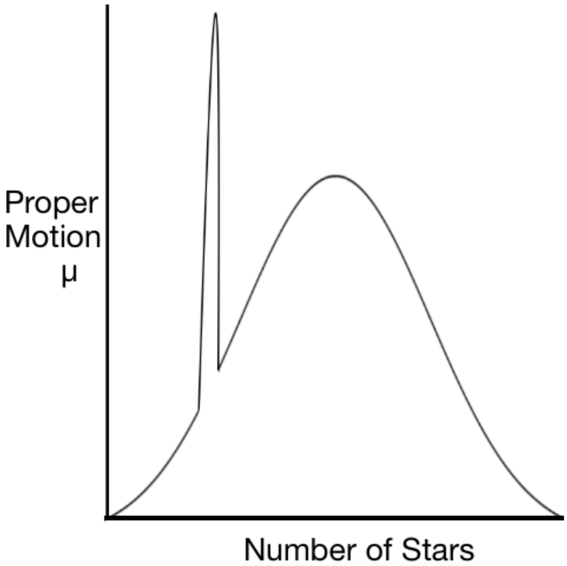


Figure 2: Proper motion graph found when observing globular clusters.

a given globular cluster will have roughly the same proper motion. This results in a spike on a proper motion graph (as can be seen in figure 2) which allows globular cluster stars to be separated from non-cluster stars. As a result, this would allow for the outer envelopes of globular clusters to be studied in far greater detail[8].

However at the time of this project, only the first Gaia data release (Gaia DR1)[9] was available which only includes proper motions for nearby stars. Therefore the outer envelopes for globular clusters cannot be properly examined until the release of the second Gaia data release (Gaia DR2) in April of 2018. As a result, a primary aim of this project was to inspect the outer envelopes of globular clusters with Gaia DR1 to determine which clusters contained the most prominent outer envelopes and determine how far they extend. These results could then be used to determine which clusters would be most promising to examine with Gaia DR2.

1.3 Gaia and Pan-STARRS

In order to study the stars in these globular clusters, the survey from the Pan-STARRS1 telescope (PS1)[10] was used in conjunction with Gaia DR1. This was necessary because, although the astrometry from Gaia DR1 is extremely precise, it only measures light from stars in one waveband. In order to study globular clusters, Hertzsprung-Russell (HR) diagrams have to be plotted which requires photometry in at least two different wavebands. This is because HR diagrams plot magnitude (brightness) against colour, and plotting colour requires magnitudes in two wavebands.

	# sources in Gaia DR2	# sources in Gaia DR1
Total number of sources	**> 1,500,000,000**	**1,142,679,769**
Number of 5-parameter sources	> 1,300,000,000	2,057,050
Number of 2-parameter sources	> 200,000,000	1,140,622,719
Sources with mean G magnitude	> 1,500,000,000	1,142,679,769
Sources with three-band photometry (G, G_{BP}, G_{RP})	> 1,100,000,000	-
Sources with radial velocities	> 6,000,000	-
Lightcurves for variable sources	> 500,000	3,194
Known asteroids with epoch data	> 13,000	-
Additional astrophysical parameters	> 150,000,000	-

Figure 3: Comparison of Gaia DR1 and DR2[11].

Therefore the PS1 catalogue was used as it contained photometry for stars in five band filters (g, r, i, z, y) so it could be used in conjunction with Gaia DR1 to create a catalogue which contained both very precise astrometry and photometry in multiple wavebands. PS1 was a ground based telescope with a very wide field of view and had the largest digital camera ever built. It was used to provide astrometry and photometry for objects which had already been imaged by detecting differences from previous observations.

Gaia DR1 was obtained from the Gaia space observatory which was designed for astrometry. The aim of the Gaia observatory was to create an extremely large and precise three-dimensional map of the Milky Way[12] which could then be used to study the composition of the galaxy as well as its origin and how it evolved over time.

The Gaia survey was expected to last 5 years during which time Gaia would monitor over a billion stars, taking measurements of each star roughly 70 times. However Gaia DR1 is only based on data collected in the first 14 months of observations and is also not fully calibrated so the data from Gaia DR1 is limited. This will be corrected for in Gaia DR2 which will be far more comprehensive, both in terms of data collected and in terms of calibration.

The data collected by Gaia DR2 is superior to Gaia DR2 in multiple areas but the most important difference for this project is the number of 5-parameter sources. A 5-parameter astrometric solution is when Gaia captured a star's parallax, proper motion and position in terms of right ascension (RA) and declination (Dec). In contrast, a 2-parameter solution contains only the position in the sky. It can be seen from figure 3 that Gaia DR2 contains far more sources with 5-parameter solutions than DR1 meaning that it is far more useful for examining the outer envelopes of globular clusters as described previously.

2 Methodology

2.1 Manual And Pipeline Photometry

In order to use the PS1 survey in conjunction with Gaia DR1, it was first necessary to determine which photometry and image compiling methods were most effective to use with the PS1 survey. Compiling images was necessary because PS1 took images of objects multiple times over a given period so to perform photometry on objects, all images of that object had to be compiled together.

There were two different procedures for photometry that could be used for the PS1 survey: manual and pipeline photometry. Manual photometry is when the procedure for each object is carried out on each object individually to maximise the amount of light captured whereas pipeline photometry uses a standard procedure for all stars. As such, manual photometry is far more time consuming than pipeline photometry but was expected to be more precise.

As such, manual and pipeline photometry had to be compared to determine if manual photometry was more precise and to what extent. This will also be useful for future research as comparing manual and pipeline photometry allows other researchers to determine if it is worth the time investment to perform manual photometry or whether it is sufficient to use the more time efficient pipeline photometry.

Once these photometry procedures have been compared, the method which is most effective will be used in conjunction with Gaia DR1. However before manual and pipeline photometry can be compared, it had to be established which is the most effective pipeline procedure. This project examined three pipeline photometry procedures and three image compiling methods which were crossed to produce nine possible combination of methods.

2.2 Pipeline Methods

The three pipeline photometry procedures examined were aperture, PSF and Kron photometry. Aperture photometry is when an aperture is placed around an object and the flux inside it is summed as seen in figure 4. However the background flux must also be removed by using an annulus. This annulus is placed further from the object to find the sky background which is then removed from the aperture flux.

Another method was PSF photometry. PSF stands for point spread function which is the shape light from an astronomical source takes when it is observed through a telescope as can be seen in figure 5. Since it is known that an observed star will take the form of a PSF, an aperture can be used to capture a portion of light from a star which can then be scaled up to a PSF shape to find the total flux from the star.

The final photometric measurement used by the Pan-STARRS database was Kron photometry. This method is similar to aperture photometry but it uses a standardised aperture size which is twice the radius of the first image moment radius[13].

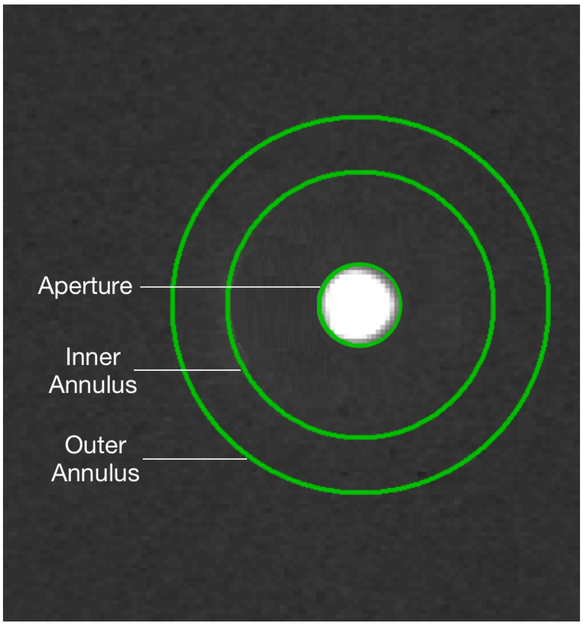


Figure 4: Aperture photometry diagram[14].

Figure 5: Diagram showing how an imaging system captures images as point spread functions[16].

In dense regions such as clusters, apertures can overlap which skews the resultant flux obtained. Therefore in globular clusters it is expected that PSF photometry would obtain more accurate results than the aperture procedure. Kron photometry was developed for galaxies rather than stars and contained many of the same problems as aperture photometry so was not expected to be optimal for this project.

Also as previously described, it was necessary to use image compiling methods as the PS1 telescope takes images of objects multiple times which have to be compiled into a single image before scientific analysis could be carried out. The three image compiling methods examined in this project were mean, stacked and forced mean compiling[15].

Mean compiling is when the flux for an object is taken in all images and then averaged whereas stacked compiling is when all the images are layered on top of each other. Forced mean compiling is an amalgamation of the two previous techniques where the positions of each object are found by stacking the images together. Then the mean of each object is taken using these positions.

Stacking creates an image with a greater signal-to-noise ratio than mean compiling so it would be expected that the positions of objects obtained from stacking would be very precise. Having accurate values for the positions of objects was very important in compiling because if the position was not correct, the aperture would be off centre resulting in noisy measurements. As a result, it was expected that forced mean com-

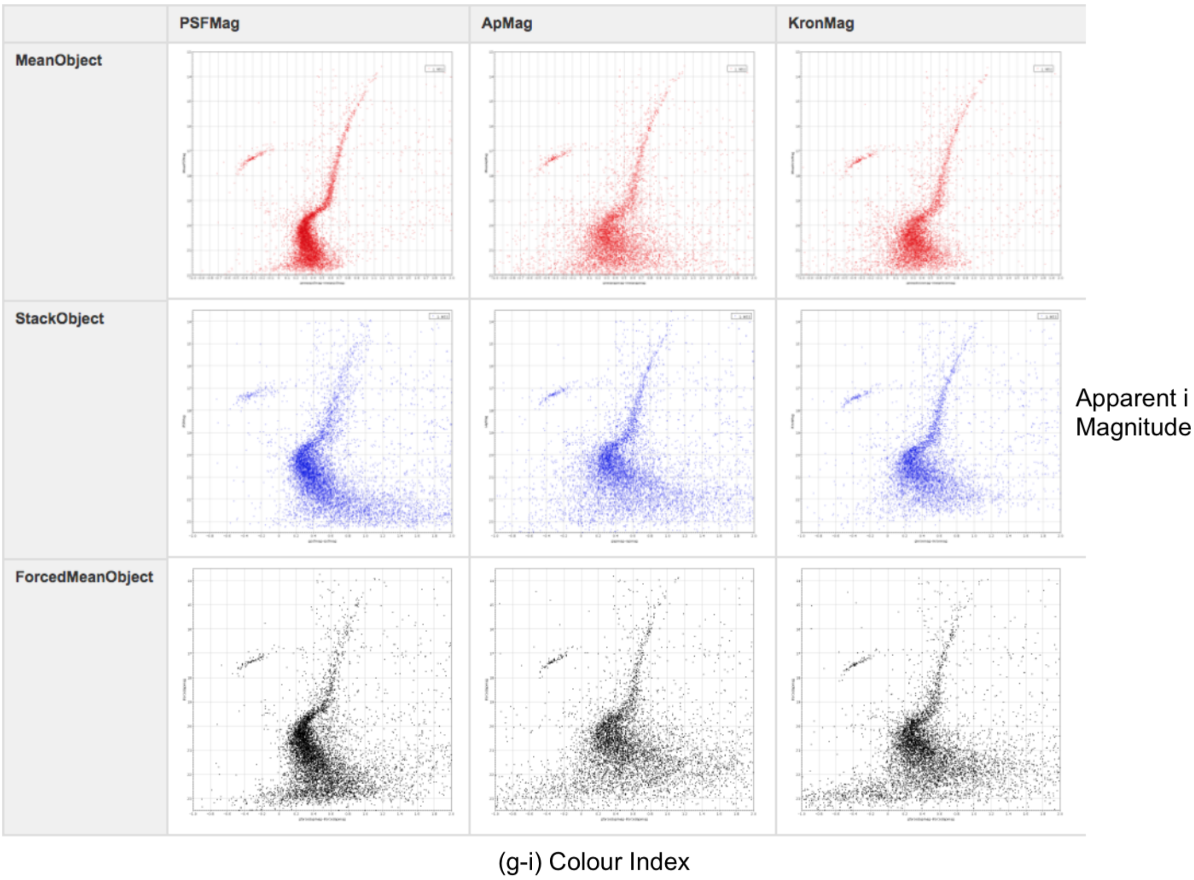
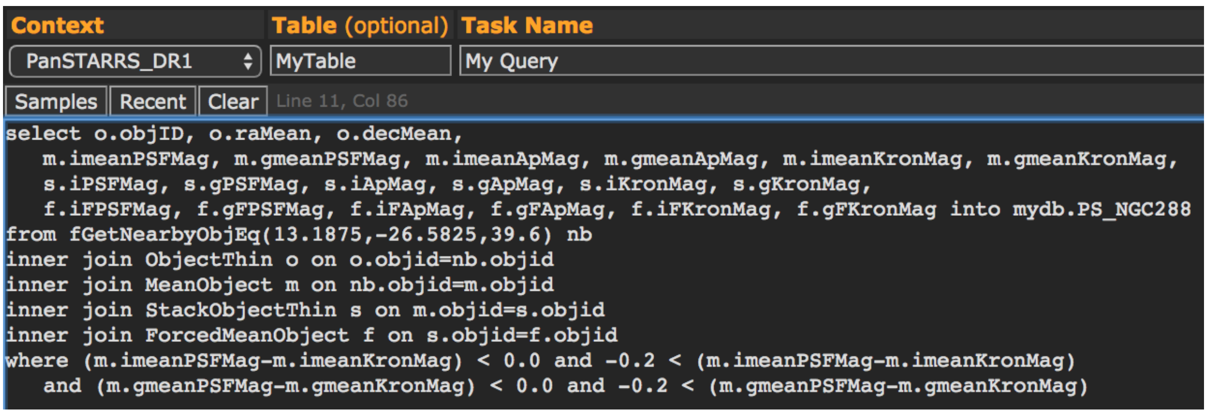


Figure 6: Graphs resulting from different combinations of photometry and image compiling methods for the Messier 53 cluster[10].

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select o.objID, o.raMean, o.decMean,
   m.imeanPSFMag, m.gmeanPSFMag, m.imeanApMag, m.gmeanApMag, m.imeanKronMag, m.gmeanKronMag,
   s.iPSFMag, s.gPSFMag, s.iApMag, s.gApMag, s.iKronMag, s.gKronMag,
   f.iFPSFMag, f.gFPSFMag, f.iFApMag, f.gFApMag, f.iFKronMag, f.gFKronMag into mydb.PS_NGC288
from fGetNearbyObjEq(13.1875,-26.5825,39.6) nb
inner join ObjectThin o on o.objid=nb.objid
inner join MeanObject m on nb.objid=m.objid
inner join StackObjectThin s on m.objid=s.objid
inner join ForcedMeanObject f on s.objid=f.objid
where (m.imeanPSFMag-m.imeanKronMag) < 0.0 and -0.2 < (m.imeanPSFMag-m.imeanKronMag)
   and (m.gmeanPSFMag-m.gmeanKronMag) < 0.0 and -0.2 < (m.gmeanPSFMag-m.gmeanKronMag)
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Figure 7: Example query used to find the data for all methods of photometry and image compiling for a globular cluster (in this case NGC 288).

piling would be the most effective method as it used the precise position from stacking in conjunction with the mean compiling method.

2.3 Plotting Pipeline Graphs

In order to determine which of the pipeline photometry and image compiling methods were optimal, a series of Hertzsprung Russell (HR) diagrams were plotted which are graphs of magnitude against colour. A HR diagram would be plotted for each possible combination of methods for pipeline photometry and image compiling, resulting in nine graphs in total. An example of these graphs can be seen in figure 6 which is from the Pan-STARRS website and plots i band magnitude against g-i colour for the Messier 53 cluster.

The best combinations of methods were the ones which produced the tightest fit to the expected globular cluster curve. For example in figure 6 the best combination of methods was using PSF photometry with mean image compiling as almost all the points in this graph lie on the globular cluster line with very little scatter. Any stars which lay significantly off the globular cluster line were not taken into account when assessing the quality of the fit as they were stars which were not part of the cluster. Therefore they do not represent a lack of precision because even if the positions of these stars were known precisely, they would still not lie on the cluster line.

It had been expected that a combination of PSF photometry and forced mean image compiling would be the most effective method but this seems not to be the case for the Messier 53 cluster. As such, one aim of this stage of the project was to determine whether the PSF photometry and mean compiling combination was optimal or whether the result obtained from the Messier 53 cluster was an outlier.

In order for the outer envelopes to be examined, a series of globular clusters had to be chosen to study. It was decided that the manual photometry would be taken from the 2014 Bernard et al paper on the Galactic Globular Cluster Fiducial Sequences in the PS1 Photometric System[17]. The objective of the Bernard paper was to obtain well-defined cluster fiducials which could be used as a reference for future research. As such, the globular clusters chosen were highly populated, nearby clusters with little foreground reddening. Therefore the clusters chosen for the Bernard paper would also be useful clusters for this project. These clusters were selected by Bernard from the Harris paper[16] using the criteria $(m-M) < 16$, $E(B-V) \leq 0.1$ and $M_V < 6$.

However because the Bernard paper was intended to be used as a reference for future research, it had to cover a wide range of metallicities and ages. To accomplish this, three open clusters and two globular clusters (NGC 6838, Pal12) were also included despite not achieving the criteria described above. In this project the three open clusters were discarded but the globular clusters were included in the research. However it should be noted that it was highly likely that the photometry for NGC 6838 and Pal12 would be of significantly lower quality than the other globular clusters.

The manual photometry for the clusters in the Bernard paper was carried out manually using a series of programs (DAOPHOT, ALLSTAR and ALLFRAME) which were created for photometry in crowded regions. Two cuts were used on the data to remove contaminant stars which were $|sharp| \leq 1.5$ and $sep \geq 3.5$.

The list of thirteen globular clusters chosen for this project can be seen in the Bernard paper[17]. To obtain the pipeline photometry for these clusters, the Pan-STARRS archive was queried using CasJobs[18] which is an interface that allows users to find and store data from astronomical surveys. This was done by querying CasJobs for the PS1 survey using SQL (structured query language) an example of which can be seen in figure 7.

In order to separate stars from galaxies, a cut had to be used. The cut chosen for this project was $-0.2 < (PSF - Kron) < 0$ was used. This was done in both the i and g magnitude bands to improve precision. The PSF-Kron cut separates galaxies from stars because Kron aperture photometry was developed for galaxies whereas PSF photometry was developed for stars. As a result, when photometry is performed on galaxies Kron will be lower than PSF so PSF-Kron will be positive and the opposite is true when performing photometry on stars. Therefore by dismissing all objects with a positive PSF-Kron value, galaxies can be removed from the data.

The query used in Casjobs had to be able to produce nine HR diagrams, displaying all possible combinations of photometry and compiling methods. Therefore the query had to sort for all these combinations in both the g and i band because producing colour for a HR diagram requires photometry in two bands. Additionally the right ascension and declination for each star was obtained. Finding these coordinates would allow for the distance of each star from the centre of the cluster to be determined. An example of the cuts and how the parameters were obtained can be seen in figure 7.

This query was carried out using a cone search which detects all objects within a certain distance of the origin and returns the desired parameters for these stars. In this case the cone search was used to find all stars within 3 tidal radii of the centre of the cluster in order to include stars in the outer envelope. This querying process was carried out for all the clusters which produced tables containing all the parameters necessary to produce the graphs.

Using python code, stars which lay at a distance greater than 1 tidal radius were then removed. Then HR diagrams were plotted for each combination of photometry and image compilation methods for all thirteen globular clusters in the Bernard paper. From these images, it could be determined which combination of photometry and compilation was most effective.

3 Results

3.1 Pipeline Graphs Comparison

It was found in all clusters that the PSF photometry procedure gave the most precise results. In most clusters it was found that there was very little difference between results obtained using the mean or forced mean compilation methods. However in some clusters it was found that mean compilation performed significantly better than forced mean. Additionally, in almost all clusters the mean compilation method performed better low magnitudes. Therefore the combination of PSF photometry with mean compilation was deemed to be the most effective method.

One of the resulting graphs is shown in figure 8 where it can be seen that the PSF photometry with mean image compiling produce a much tighter globular cluster curve than any other combination of methods. The effectiveness of the mean PSF method disproves the hypothesis that the optimal combination of methods would be PSF photometry with forced mean compilation and further reinforces the results from Messier 53 (figure 6).

The HR diagrams for the vast majority of clusters showed clear globular cluster lines but a cluster line could not be identified for the clusters NGC6838 and Pal12. However this is not unexpected as these two clusters were added to the Bernard paper in order to provide a wide range of metallicities as previously described so did not meet the normal criteria in the Bernard paper. As such it was expected that it would be more difficult to establish precise globular cluster lines for these clusters.

3.2 Pipeline And Manual Comparison

Now that it had been determined that the mean PSF combination of methods was most effective, this could be compared to the photometry from the Bernard paper which was determined manually. This was done by removing all stars lying at a radius greater than 0.75 tidal radii from both the pipeline and manual photometry data. Then the mean PSF (pipeline) and manual photometry graphs were plotted and compared as can be seen in figure 9. 0.75 tidal radii was chosen as the radius because it would minimise the number of foreground contaminants.

It can be seen in figure 9 that the pipeline photometry detects fewer objects than the manual photometry which suggests that it might not be effective at detecting objects in high density regions. Also it can be seen that the manual photometry is far deeper than the pipeline as it detects far more objects at faint magnitudes. Furthermore, at bright magnitudes the pipeline photometry fails to detect many stars so it does not show the full giant branch. Due to these factors, it can be seen that the manual photometry is significantly better than the pipeline photometry.

It could be suggested from these HR diagrams that the pipeline photometry has a tighter globular cluster line but this is most likely just because it contains less data points than the manual photometry. Additionally the manual photometry detects more stars which are not part of the cluster but this is also because it contains

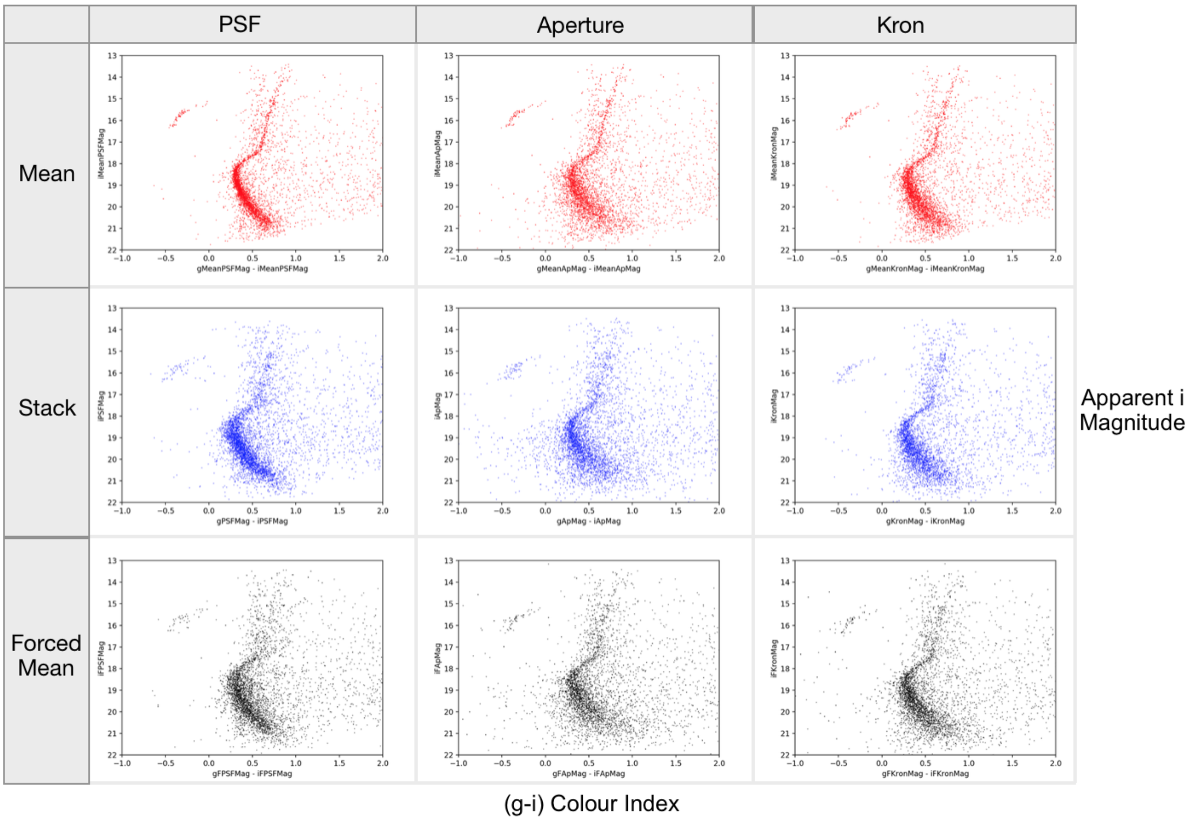

Figure 8: HR diagrams resulting from different combinations of photometry and image compiling methods for NGC 7099.

more stars. These stars lie off the globular cluster line but this does not suggest photometric uncertainty because these stars would always lie outside of the cluster, even with perfectly precise photometry.

Both the pipeline and manual diagrams were plotted using the data from Pan-STARRS within 0.75 tidal radii of each cluster so it would be expected that both methods would produce the same number of data points. There were two likely reasons that the manual photometry picked up more stars than the pipeline photometry. Either the manual photometry had a lower threshold brightness for detecting stars, or the pipeline photometry failed to work in crowded regions such as the centre of the cluster. Whether or not the manual photometry worked better in crowded regions could be tested by plotting the right ascension against declination for clusters, the results of which can be seen in figure 10.

It would be expected that the pipeline photometry would not pick up stars in the densest regions of the clusters so there would be a hole in the middle of the cluster which can be seen in the results. It would

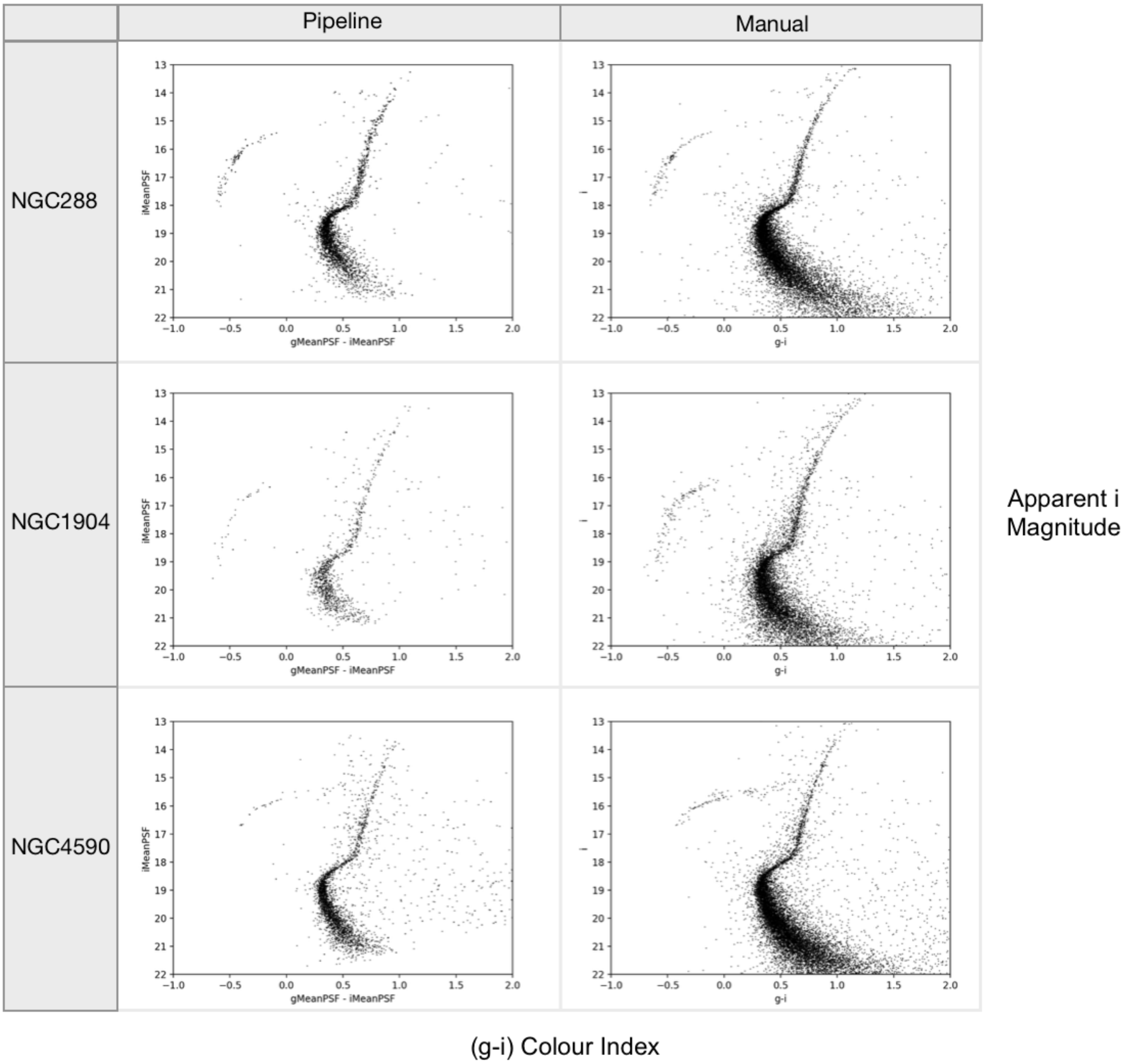

Figure 9: HR diagrams for globular clusters comparing pipeline (mean PSF) and manual (DAOPHOT) photometry.

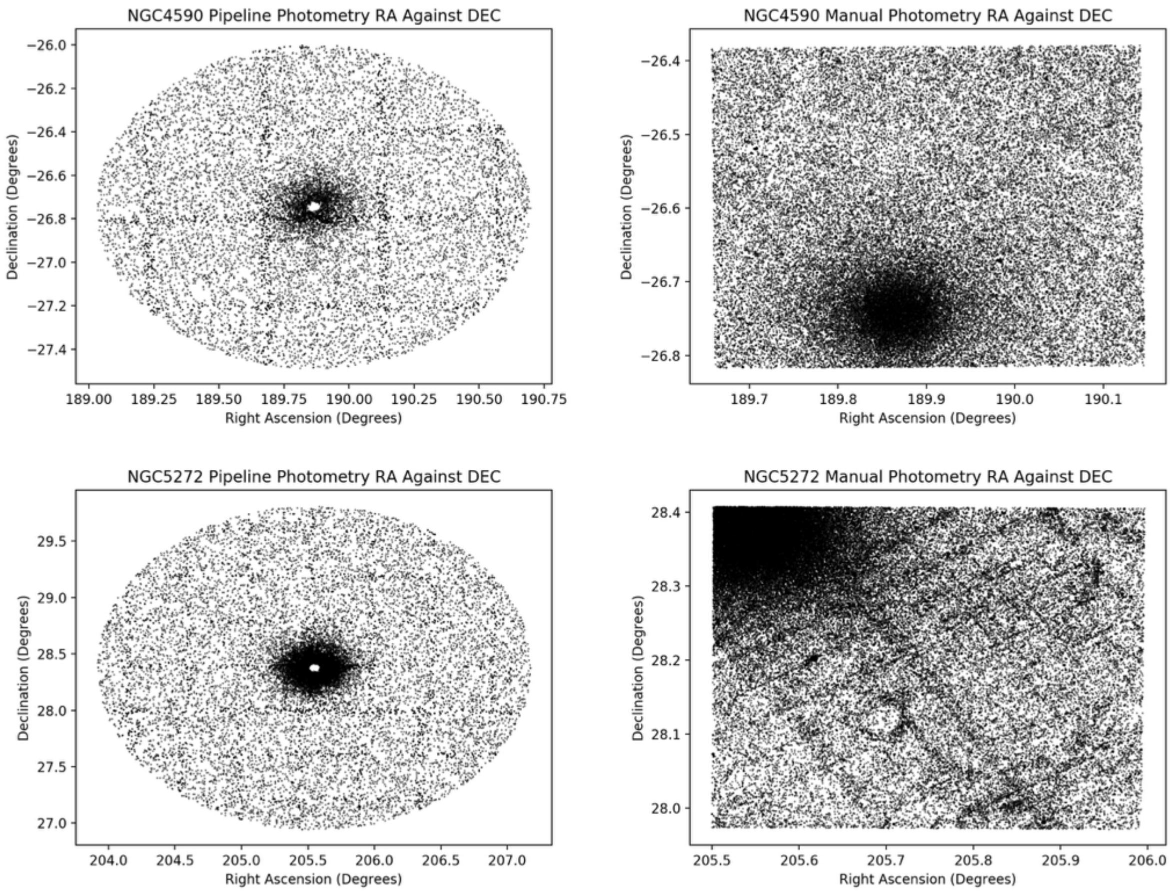

Figure 10: Diagrams showing the difference between manual and pipeline photometry in clusters.

also be expected to see a sparse region in the centre of the cluster for the manual photometry because the manual photometry should have been better in dense regions but would still fail to detect some stars. However what was found was that there was no apparent drop in the number of stars detected in the centre of the cluster for manual photometry which suggests that the manual photometry works better than expected in crowded regions.

However it was also seen that the pipeline photometry was centred whereas the manual photometry was significantly off centre for many clusters. This was because the pipeline data comes from a survey catalogue which has amalgamated all images together. Therefore the survey can be queried for any coordinates and can give all stars in a radius around that point. However the manual photometry was carried out before this survey was completed meaning that the images had not been joined together so only individual images could be used for each cluster. The

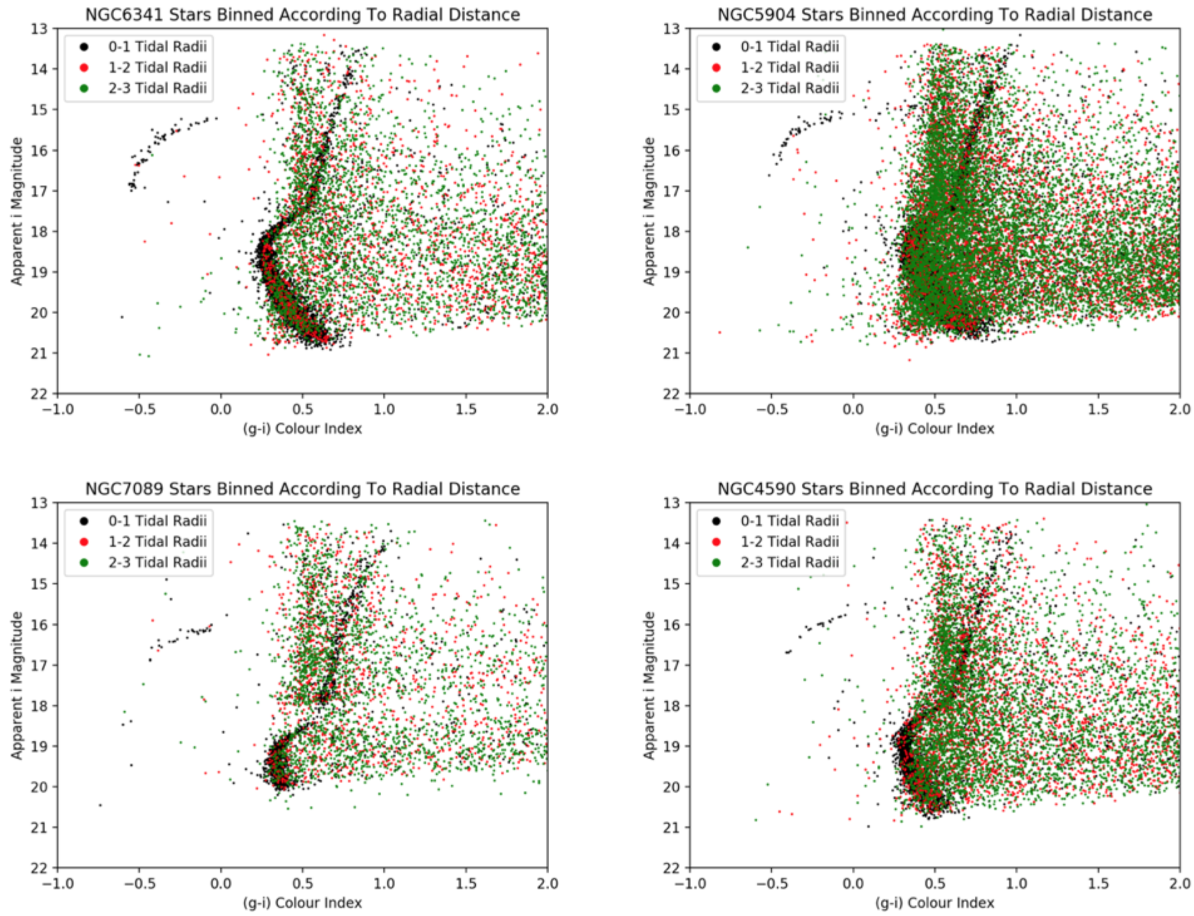

Figure 11: Stars in globular clusters shown with different colours according to their where they lie in the cluster. Black: 0-1 tidal radii. Red: 1-2 tidal radii. Green: 2-3 tidal radii.

PS1 telescope was not focussing on specific objects. Instead it surveyed the sky indiscriminately so images were not taken specifically of the clusters. Therefore the images of clusters taken for manual photometry were very unlikely to be centred.

This would not particularly affect the photometry graphs for central regions of the cluster since the manual photometry is very effective as can be seen in figure 9. However it does mean that for many of the clusters, parts of the outer envelope were cut off. For example in figure 10 it can be seen that the majority of the outer envelope is not contained in the image for NGC 5272 due to the cluster not being in the centre of the image. The result of this was that the manual photometry was not suitable for studying the outer envelopes of clusters despite being a more effective method of photometry.

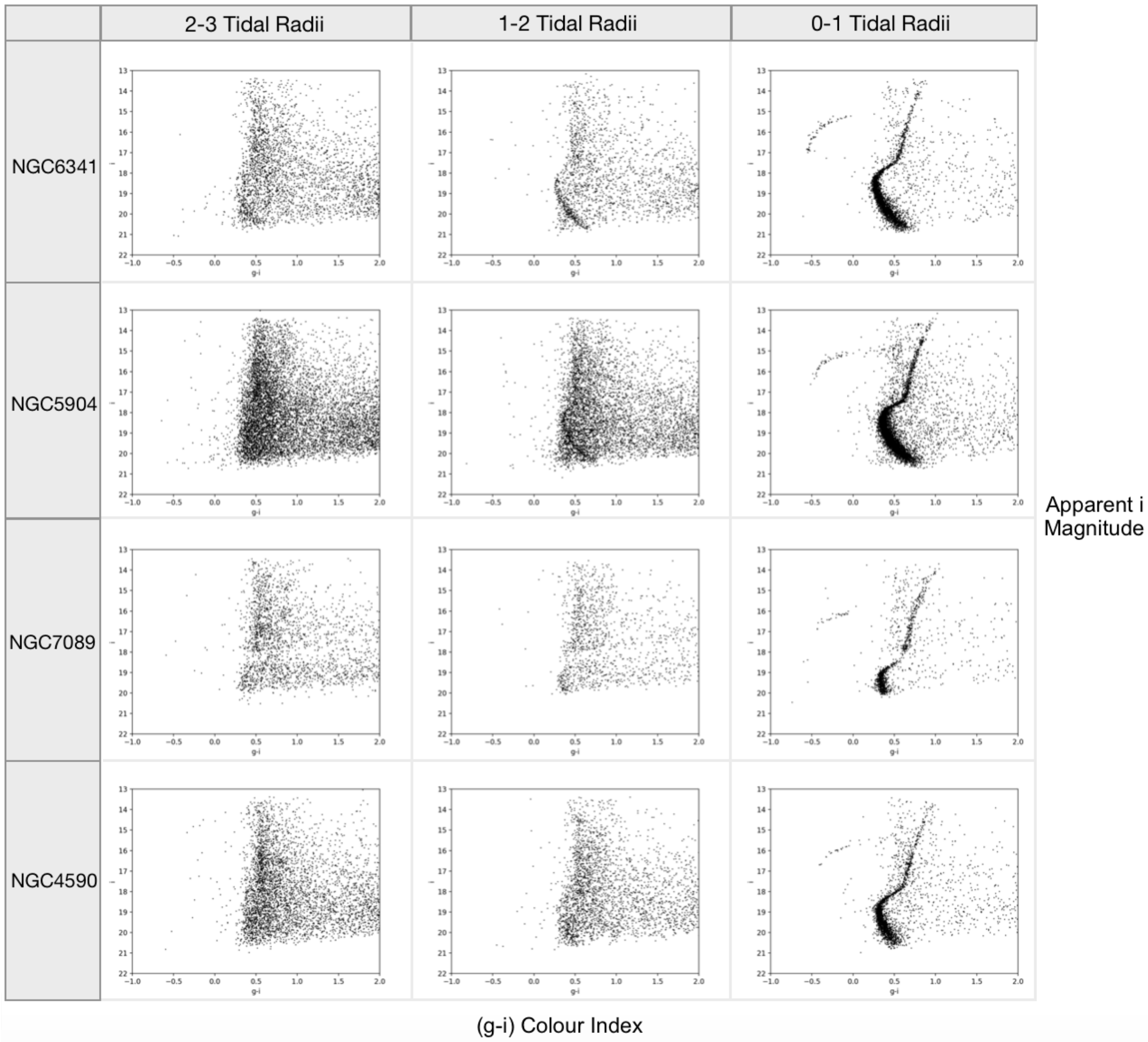

Figure 12: Stars in globular clusters binned according to where they lie in the cluster. From left to right: all stars that lie between 2-3 tidal radii, 1-2 tidal radii, 0-1 tidal radii.

3.3 Gaia Matching

As a result the pipeline photometry was then matched with the Gaia DR1 data. This was done by querying the Gaia archive for the cluster stars within a 3 tidal radii of the cluster. Then TOPCAT[19] could be used to match the Gaia table to the manual photometry table for each cluster using its pair matching function. TOPCAT is a graphical viewer which is used to edit data tables. From there, graphs for each cluster could be plotted which used the right ascensions and declinations from the Gaia.

Then the stars in the cluster were sorted according to their radii, the results of which can be seen in figures 11 and 12. It can be seen from these diagrams that many stars are detected between 1-3 tidal radii from the centre of the cluster but they are not focussed on the cluster line which suggests a large amount of contamination. However it can be seen that some of the clusters definitely show signs of having an extended envelope beyond 1 tidal radius. NGC 4590 was presented in the results as it was representative of most clusters.

Most clusters contain a tight globular cluster line between 0-1 tidal radii then a roughly random distribution of points between 2-3 tidal radii. There may well be an extended envelope in these clusters but there were too many contaminant stars to be able to verify that. In NGC 4590 it could be seen that there was a possibility of a cluster line between 1-2 tidal radii but this disappears entirely at 2-3 tidal radii as can be seen in figure 12.

NGC 7089 was included in these results as it was a cluster that was previously studied in the Kuzma paper[3] so it could be compared to previous results. Due to this previous research, it is known that this cluster has an extended envelope out to at least 5 tidal radii. It can be seen in figure 12 that there is a possible globular cluster line in both 1-2 tidal radii and 2-3 tidal radii. However there was too much contamination to verify this conclusively. Another problem with this cluster was that a large number of 18-19 and 20-21 magnitude stars were removed from this data set. The reason for this was unknown but it is known that it was due to a problem with matching the pipeline to Gaia DR1 using TOPCAT and was not a problem with the pipeline photometry itself. Usually this data would have been excluded from the results but it was left in as it was used to compare with the results from the Kuzma et al paper.

NGC 6341 and NGC 5904 were included in the results for this paper as they were two clusters which were concluded that would be useful to study upon the release of Gaia DR2. There were were two criteria that were used to determine if a cluster would be used for further study: the globular cluster line and horizontal branch at 1-3 tidal radii. This was because the outer envelopes of globular clusters were to be studied so clusters showing signs of an envelope at distant radii would be more likely to produce interesting results.

Most clusters showed either very faint signs of a globular cluster line at 1-2 radii or none at all and very few clusters showed signs of a line at 2-3 tidal radii. It can be seen in both NGC 6341 and NGC 5904 that they showed a clear globular cluster line at 1-2 tidal radii suggesting that both would be good to study further. However it was decided that NGC 6341 was likely to produce better results as it contained a trace of a globular cluster line at 2-3 tidal radii and was the only cluster to do so. Another cluster that showed a clear sign of a globular cluster line between 1-2 tidal radii was NGC 6205 but this was not of the same quality as the other two clusters.

The second criteria was to examine the horizontal branch between 1-3 tidal radii. The stars in the horizontal branch are hot blue stars which are rare so any blue stars observed near the cluster are very likely to be in the horizontal branch of the cluster and not contaminants. As such any blue stars observed at distant radii near the horizontal branch is a sign of an extended envelope. In all clusters there were very few blue stars between 1-3 tidal radii as expected. NGC 6341 contained four stars which lay directly on top of the horizontal branch between 1-3 tidal radii and so are very likely to be a part of the cluster. NGC 5904 contained two stars which lay directly on top of the horizontal branch at far distances. However it did contain multiple stars at distant radii which were near the horizontal branch of the cluster but did not lie on top of it.

To conclude, by using the criteria of how many stars lay near the horizontal branch and whether there was a globular cluster line present between 1-3 tidal radii, it was concluded that NGC 6341, NGC 5904 and NGC 6205 were all candidates for further study. However the cluster most likely to have an identifiable extended envelope was NGC 6341 which suggests this cluster would be best to study further using Gaia DR2.

4 Discussion and Conclusions

Since this project contained no calculations and consisted entirely of collated information from different databases, there were few major sources of error. The primary source of error in the manual photometry was that most of the clusters were off centre. This made it unsuitable for studying outer envelopes but did not largely affect the photometry of the inner regions of the clusters. The main source of error in the pipeline photometry was that it failed to detect stars in the densest regions of the cluster. As a result, the pipeline photometry was generally inferior to the manual photometry but it was still suitable for examining the outer envelopes of globular clusters as was required in this project. It also was lower quality as it used a standardised procedure for each star as previously discussed but this did not appear to seriously affect the quality of the photometry.

The project could have also been improved by using more sophisticated cuts to separate galaxies from stars instead of using a PSF-Kron cut. Additionally the comparisons between all methods were carried out by eye but could have been improved by using more quantitative methods. However both of these improvements were discarded as they would not have increased the quality of results enough to warrant the time required to carry them out.

The results of this project can now be used with the release of the second Gaia data release in order to study the outer envelopes of globular clusters. With the release of the new data fundamental questions about globular clusters could finally be answered such as questions of their origin, their evolution and the nature of the diffuse stellar envelopes.

One of the main questions to be answered, which was discussed in the Kuzma papers, was how many clusters have an extended envelope and whether they were created by dynamic evolution of the cluster or by accretion of a dwarf galaxy. If the extended envelope was created by dynamic evolution, it would be expected that tidal tails would be found which are caused by tidal shocking. The tidal tails are thin lines of stars coming off of the cluster. These could be detected using Gaia DR2 by looking at whether the distribution of stars in the cluster was spherical or asymmetric. If tidal shocking has occurred, there should be evidence of tidal tails and an asymmetric distribution of stars. If this has not occurred, the envelope would be expected to be spherical.

Tests could also be carried out using Gaia DR2 for whether the cluster was due to a dwarf galaxy. This could be done by using metallicity as it would be expected that the cluster would have a higher metallicity if it was previously part of a dwarf galaxy. If the metallicity was higher than expected, the globular cluster line on a HR diagram would be shifted right further than would be expected. This would also help get a sense of how many globular clusters have higher metallicities than would be traditionally expected and whether they can be separated into two groups (metal rich and metal poor) or whether it forms a spectrum of metallicities[3].

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