**Measuring distances to the Palomar 5 and Palomar 13 globular clusters using RR Lyrae variable stars**

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**Abstract.** RR Lyrae stars resident in two globular clusters in proximity to the Milky Way Galaxy, Palomar 5 and Palomar 13 are analysed to calculate the distances to the globular clusters. PSF photometry was performed on a series of 12 epochs using data taken from the *Spitzer* IRAC in the mid-infrared bands, 3.6 µm (channel 1) and 4.5 µm (channel 2). Apparent magnitudes of detected stars were calculated and averaged using a Gaussian local estimation algorithm (GLOESS) which were corrected for extinction effects. PL relations were fit to the data in both clusters and distance moduli were obtained from the intercepts of the PL fit and subsequently their distances. Distances of *d* = 20.37 ± 0.36 (random) ± 1.13 (systematic) kpc for Pal 5 and *d* = 24.25 ± 0.44 (random) ± 1.35 (systematic) kpc for Pal 13 were found to be consistent with previous work.

**1. Introduction**

*1.1. SMHASH program and Spitzer*

The measurement of distances to objects throughout the universe is notoriously difficult due to the lack of information available and remains an active area of research within astrophysics. Observations made using the *Spitzer* Space Telescope as part of the *Spitzer* Merger History and Shape of the Galactic Halo program (SMHASH) alongside the Carnegie RR Lyrae Problem (CRRP) can be used to help measure distances in the universe to a higher accuracy that before. The SMHASH program primarily aims to construct a three-dimensional map of the Milky Way Galaxy [1] by using mid-infrared observations of RR Lyrae (RRL) variable stars in globular clusters and dwarf spheroidal satellite galaxies (dSphs) of the Milky Way (MW) and so these programs are contingent on accurate calculation of distances to these globular clusters and dSphs.

In this paper, distances to the Palomar 5 (Pal 5) and Palomar 13 (Pal 13) globular clusters are calculated using observations from the Infrared Array Camera (IRAC) on board the *Spitzer* Space Telescope following the process outlined in sections 2 and 3. Observations were made during the Warm Mission of IRAC in 2013, with data collected using the 3.6 µm and 4.5 µm bands, after the telescope’s ability to maintain cryogenic cooling to sustain its larger two waveband cameras as part of its array of four wavebands.

*1.2. RR Lyrae variables*

RR Lyrae stars are Population II variable stars, meaning they are relatively old and metal-poor stars that vary with regular periods of around a few hours to a day [ref]. RRLs are frequently found in globular clusters in large quantities which reside in the galactic halo of the MW galaxy [ref]. Starting life on the main sequence with masses typically less than that of the Sun, RRLs have evolved past their red-giant stage to lie on the instability strip of the Hertzsprung-Russell diagram [ref]. There are tree main types of RRL: (i) RRab types typically pulsate with a larger period and amplitude and in the fundamental frequency, (ii) RRc types pulsate in the first overtone, typically with smaller amplitudes but in a more sinusoidal fashion and (iii) RRd types which pulsate simultaneously in the fundamental frequency and first overtone.

Due to their varying brightness with regular periods, RRL stars are used as standard candles for measuring distances within the galactic neighbourhood. Standard candles are useful as they provide markers to calibrate distances to cosmological objects, which gradually builds into the cosmic distance ladder. Previous work has typically focussed on Cepheid variable stars, discovered by Henrietta Swan Leavitt in 1908, which pulsate with a longer period than RRLs, on the order of weeks compared to hours. Cepheids are brighter than RRLs and so have typically be used as standard candles however, due to numerous advantages, such as their abundance in globular clusters in the MW galaxy and their lifespan, RRLs are particularly suited to use for accurate measurements of distance and as standard candles [ref]. Period-luminosity (PL) relations show the relationship between a star’s period to its magnitude and is the key to calculating distances. The cosmic distance ladder details a process of using various cosmological objects, such as Cepheids and RRLs, to calibrate different scales of distances ranging from the galactic neighbour of around 10 kpc all the way scales of 100 Mpc in an aim to yield accurate measurement of the Hubble constant, *H0*. There appears to be a fundamental disagreement on the value for *H0* between different methods of calculation, such as using the cosmic microwave background radiation (CMB), or indeed Cepheid variables [ref]. It is noted that calculations involving Cepheids carry a larger uncertainty compared to CMB calculations, potentially due to the reliance of the optical wavebands for measuring distances to Cepheids. In contrast to this, distances to RRLs are calculated using data collected in the mid-infrared bands, and so PL relations for RRLs provide a number of advantages over Cepheids due a number of reasons, namely (i) dust extinction effects are weaker, (ii) effects of metallicity are damped, (iii) more sinusoidal and symmetrical light curves and smaller amplitudes improve the precision of average apparent magnitudes, and (iv) a narrower PL dispersion [ref]. Therefore, RRLs are particularly suited to high accuracy distance measurements and improve the accuracy to around 1%, the necessary first step on the cosmic distance ladder to calculating a value for *H0* to an accuracy of 2.4% [ref]. The ability to solve the disagreement on the value of *H0* and obtain an accurate value is an area of active research with implications affecting the current understanding of the scale, expansion, and evolution of the universe [ref].

**2. Data selection and photometry**

*2.1. Data selection*

The IRAC on board *Spitzer* observed a region around the centres of the Pal 5 and Pal 13 clusters, however both Pal 5 [Erkal 2017] and Pal 13 [Bradford 2011] exhibit long tidal streams extending beyond their centres due to interaction with and accretion to the MW galaxy, and so RRLs within these parts of the clusters were not observed. Each cluster was observed in each waveband of 3.6µm and 4.5µm corresponding to IRAC channels 1 and 2 respectively and over a duration of 12 epochs, with a frame in each channel per epoch, which was calibrated such that at least one full cycle for each RRL in the frame was observed. Prior to use, the raw data was pre-processed to basic calibrated data (BCD) by *Spitzer* Science Centre using an established pipeline to reduce the images into a useable state. This process includes flat fielding of the images and the removal of biases [Reach 05]. Mosaic frames of each epoch in each channel were created, which is a stitching together of the individual BCDs, a task completed prior to usage by the supervisor of this project, Dr Victoria Scowcroft resulting in Flexible Image Transport System (FITS) files used. A pixel phase effect can be exhibited on individual BCDs due to differences in flux depending on the location within the pixel a point source falls because of quantum efficient variations [Handbook], however correction of this effect is neglected because the combination of BCDs smooths out this pixel phase effect.

The positions for right ascension (RA) and declination (dec), periods in days and RRL type of previously known RRLs was obtained from the *Catalogue of Variable Stars in Galactic Globular Clusters* (CVS) maintained by Christine Clement [ref]. Further data was gathered from the *Gaia* Data Release 2 (*Gaia* DR2) by considering a region of 10’ radius around the centre of the cluster and searching for stars marked *variable*. This was then checked against the CVS to identify any stars missing from the CVS, as well as information of their periods obtained by scanning the *gaiadr2.vari\_rrlyrae* list containing information on the type and periods of 140784 RRLs. If a match was found between the region search and DR2 RRL lists in *Gaia* by matching *source­­\_id*s, then the periods in *Gaia* were used instead of those in the CVS as these periods were obtained in 1962 [ref] due to the fact RRL periods can shift over the course of human lifespans [ref??].

Master mosaic images were also created for each IRAC channel to create FITS files of a median image using data from across all 12 epochs. These master mosaics are particularly useful due to their higher signal-to-noise ratio as a result of this combination of data. The data for the SMHASH and CRRP projects were optimised for IRAC channel 1 in the 3.6 µm band and so the channel 2 data, in the 4.5 µm has a lower signa-to-noise ratio which presented issues, particularly regarding the individual epoch data which is explained more in section 2.4 [1].

The individual FITS files contained the flux data in MJysr-1, and header information regarding the exposure time, observation date and time and a flux conversion time. This information, minus the observation date and time, was also present for the master mosaic. This information was used to covert the data into data number counts, DN, using equation 1,

(1)

where flux is measured in MJysr-1, exposure time in seconds and the provided conversion factor in MJysr-1 · DN-1 · s.

*2.2. Photometry*

Photometry was then performed on the data to obtain the apparent magnitudes of point sources detected in the frames. Photometry involves measuring the amount of light that falls within a desired aperture radius, in this case in data number counts. There are two main methods for performing photometry that were considered in this project, aperture photometry and point-spread function (PSF) photometry. Aperture photometry involves considering the flux of light measured through an aperture centred on the star, alongside a second aperture of larger radius drawn to create an annulus around the star. The average background flux measured in the annulus region is then subtracted from the inner aperture to obtain the flux of the star. A problem of optimisation is present here, particularly regarding the radii of the inner and outer apertures, as such a radius that is just large enough to capture light from the star but not too large such as to include nearby stars but a radius that is not too small such as to omit light from the star. The second method, PSF photometry, involves using a model to measure the flux of the stars under an iterative process whereby the measured stars are essentially removed from the image to create a residual image which may show yet more stars that were not found in the previous iteration, particularly noticeable in crowded fields. PSF photometry was chosen over aperture photometry due to the crowded nature of globular clusters and so PSF photometry was far more effective than aperture photometry.

*2.2.1 PSF model.* A point-spread function was built from the master mosaic frame such that it can be used to identify point sources within the master frame, as well as the epoch frames, with profiles that are expected to be stars. A star detection algorithm, *DAOStarFinder*, [ref, also adnerson & king somewhere] was used to identify these initial point sources and requires several parameters to aid with its identification of stars. The first of which is the full width at half maximum (FWHM) value of the typical star in the sample. The radial profiles of several uncrowded stars were identified using a program called *Imexam* [ref] to gain an appreciation for the range of values for the FWHM, and a value of 5.0 was deemed acceptable. Another parameter is the threshold value, which determines which count values are deemed high enough to be a star. There is an efficiency problem here as there is a compromise between selecting a value too high such that actual stars are not detected but also if a value too low is chosen such that random noise is being detected as stars and the process becoming computationally time expensive. The threshold value was determined using the standard deviation of the image data and a sigma level of how many standard deviations should the data be clipped from, a sigma value of 6.0 was chosen for this data [EXPLAIN BETTER!!]. The next parameter is the *round* parameter which considers the profiles of the point sources and aims to discard elongated sources or sources where the light has a directional bias. This is important to ensure that, for example, galaxies are not counted as stars. The final main parameter is the *sharp* parameter which in some respects is the opposite of the *round* parameter and considers how fast the profile drops off, as opposed to any directional bias as in *round*, and aims to eliminate cosmic ray hits or bad pixels which may otherwise be counted as stars. These values were manually determined by inspection of the data and resultant PSF models and suitable values were found to avoid a trade-off between detecting stars erroneously or missing out sources that are valid stars. Once these values were determined, the PSF model was built, however using a high threshold value to select only uncrowded stars, typically around 100 stars per channel in the master frame. These stars were then individually checked and individual star frames with contamination from other stars, bad-pixels, or edge-of frame stars were removed and then the final PSF model built.

*2.2.2 PSF photometry.* A master source list was created from the master mosaic frame by using the star detection algorithm and performing a PSF routine based on the PSF model built previously, however, in this case neglecting the photometry as it was not required for this frame. This list serves as a reference for the photometry performed on the stars in the 12 individual epochs and enable them to be matched to consistent star ID numbers between epochs because each run through the detection algorithm in different epochs frequently returns the stars in different orders. Coordinates in *x* and *y* for the stars detected were converted into right ascension and declination coordinates using the International Celestial Reference System (ICRS) based on information provided in the *Spitzer* image headers. The use of right ascension (RA) and declination (dec) is particularly useful as it allows direct comparisons between stars in the master frame and the epoch frames as well as objects identified in *Gaia* data release 2 (DR2) because the cartesian coordinates in each frame is unique to that frame and does not necessarily translate between the frames and the channels.

Once the master frame was created and saved, the PSF routine was performed on each epoch in turn. The process followed that described previously, following Stetson’s process [ref] whereby the stars were identified in the first epoch and photometry performed on the sources to obtain values for their flux at that moment in time and an error value provided [how? why?]. The coordinates of the stars were converted into RA and dec values and these were checked against the master source list and then joined as columns to the master table, forming the main table. This process was repeated in sequence up until the 12th and final epoch obtaining a final table with each source identified in the master table matched with up to count values for each star. If no match was found in a particular epoch, then no entry was made for that epoch when joined to the growing master table. This process was completed on both the 3.6 µm band (channel 1) and the 4.5 µm band (channel 2) giving two lists of sources identified, with a unique master ID, coordinates in RA and dec and values for apparent magnitude [insert ap. mag calculations before here!] and their corresponding uncertainties.

*2.3. Apparent magnitudes*

Apparent magnitudes *m*, were calculated using equation 2,

(2)

where *ZP* is the zero-point magnitude for each IRAC channel, which is 18.80 for channel 1 and 18.32 for channel 2 (in the IRAC Handbook [ref]) and an aperture correction applied as a result of difference between the apertures used to calibrate IRAC and the aperture size of 6 used to perform photometry, also in the IRAC Handbook [ref], *counts* is the measured counts from photometry and the flux conversion factor and exposure time used to convert counts in data numbers back into flux. next phase was identifying the RR Lyrae variables in each list. This was achieved by consulting a catalogue of variable stars created by Christine Clement for each globular cluster of interest [ref] as well as identifying stars classed as variable in a region of radius 10 arcmins around the centre of the cluster in *Gaia* DR2 [ref]. The coordinates of the stars in both the *Gaia* list and the catalogue of variable stars were matched to the main photometry tables created in both *Spitzer* channels to identify which table entries in the main tables corresponds to an RR Lyrae star. For the Pal 5 globular cluster, seven RRLs were identified in channel 2, five of which were also visible in channel 1 and for the Pal 13 globular cluster, **x** RRLs were identified in channel 2, **y** of which were also visible in channel 1.

The periods of the RRLs were obtained from the *Gaia* DR2 RR Lyrae list containing around 140000 RR Lyrae stars, if the star was not identified in this list by matching their *Gaia* source\_id value then the periods provided in the catalogue of variable stars was used. The period is important as in order to construct light curves for the stars and, to find the distance to a globular cluster, a period-luminosity (PL) relation must be fit.

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Description automatically generated*2.4. Light curves*

Light curves of the identified RRLs were constructed by plotting the apparent magnitude for each epoch against phase. The phase is calculated by taking the date and time the epoch frame was taken, converting this into a modified Julian date, using software within the AstroPy module and then dividing this by the period of the star and subtracting the floor value. The light curves contain several cycles by simply adding an integer value to the phase to create three periods as shown in figure **x**. By concatenating the phases in this way, it was easier to identify whether the end of the one period followed nicely into the start of the second period as the data collected only contained around one full period for each star. A fit was produced for each light curve using a Gaussian local estimation algorithm (GLOESS) [Persson 2004]. The GLOESS algorithm calculates the mean apparent magnitude of the RRL in its corresponding channels and this was then appended to arrays containing the period of the star.

**3. Period-Luminosity relations and distance measurements**

*3.1. Building PL relations for Pal 5 and Pal 13*

A PL relation shows the relationship between the magnitude of a variable star with its period [ref]. Only the apparent magnitude has been considered up until now and in order to calculate the distance to the globular clusters, the absolute magnitude must be known. This is achieved by comparing the data obtained for both Pal 5 and Pal 13 to a PL relation for RRL stars. The PL relations have been fit using the information provided for IRAC channels 3.6 µm and 4.5 µm in the Neeley et al. 2019 paper, hereby referred to as the Neeley paper [Neeley 2019].

Prior to applying the PL fit, the average apparent magnitudes, and uncertainties for each RRL in both channels were extracted from the GLOESS analysis described previously. The average magnitudes were corrected to account for extinction effects, which are caused by dust in the MWG resulting in a reddening of the apparent magnitudes which would influence the calculated distances. The corrections for dust extinction were obtained, for both clusters, from the IRSA Dust Extinction Service Queries built Chart

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The periods of each RRL were also extracted from either *Gaia* DR2 or the catalogue of variable stars and if necessary, they were fundamentalised [ref]. This applies to RRc stars which pulsate in the first overtone and to enable comparisons of RRc stars to RRab stars in the PL relation, their periods were fundamentalised using the following equation,

(2)

where *P* is the fundamentalised period and *PFO* is the first overtone period; the logarithms have been taken in preparation for the plot of the PL relation [ref].

The PL relation from the Neeley paper takes the form,

(3)

where *M* is the absolute or apparent magnitude of an RRL in the sample, *a* is the intercept of the PL fit, *b* is the gradient of the PL fit and *P* is the period of the RRLs. The specific format of the PL fits can be found from the coefficients given in *Table 3* of the Neeley paper. For the two IRAC channels, the PL fits are,

(4)

(5)

and so, it is now possible to fit the PL relations to our data. This was done by holding the gradient *b* as constant and fixing it to the data but allowing the intercept *a* to vary. This means that the PL fits shown in figure x and figure y follow the form,

(6)

(7)

where *m* is the average apparent magnitude and is the intercept to be found by fixing the PL fit equations 6 and 7 to the corresponding IRAC channel. The intercept was found by using a least-squares fit and intercepts were found for Pal 5 in channel 1 as *a0* = 16.10 ± 0.03 mag and in channel 2 as *a0* = Chart, line chart

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Description automatically generated16.16 ± 0.03 mag and for Pal 13 in channel 1 as *a0* = 16.47 ± 0.02 mag and in channel 2 as *a0* = 16.55 ± 0.03 mag.

**Figure 2**. Diagram of the LIGO interferometer. A simplified laser interferometer showing perpendicular arms, Lx and Ly, of 4km in length and a schematic diagram of distance between the observatories across the continental United States measured in light travel time[15].

*3.2. Calculating distances to Pal 5 and Pal 13*

The distance to a globular cluster can be calculated using a distance modulus [ref], which is the difference between the apparent magnitude and the absolute magnitude,

(8)

where *µ* is the distance modulus, *m* is apparent magnitude and *M* is absolute magnitude. Consider the PL relations in equations 4 to 7, for IRAC channel 1 the distance modulus can be calculated by subtracting equation 4 from equation 6, and likewise for IRAC channel 2 by subtracting equation 5 from equation 7, giving a general distance modulus, and substituting the relevant IRAC channel data of,

(9)

where *a0* is the calculated intercept from fitting the PL relation for each IRAC channel and *a* is the intercept given in the Neeley paper for the calibrated PL relation for each IRAC channel. Therefore, distance moduli values were calculated for Pal 5 to be *µ* = 16.51 ± 0.04 (± 0.12) mag in channel 1 and *µ* = 16.57 ± 0.04 (± 0.12) mag in channel 2, where the first uncertainty is the random uncertainty, defined as… , and the uncertainty in brackets is the systematic uncertainty, defined as… . Distance moduli were also calculated to Pal 13, giving *µ* = 16.88 ± 0.04 (± 0.12) mag in channel 1 and *µ* = 16.96 ± 0.04 (± 0.12) mag in channel 2.

The distance *d,* in parsecs (pc) can be calculated from the distance modulus by,

(10)

which can be rearranged to solve for *d* resulting in a final equation for the distance to be,

(11)

and so, distances to Pal 5 were calculated to be *d* = 20.04 ± 0.37 (± 1.11) kpc in channel 1 and *d* = 20.69 ± 0.35 (± 1.15) kpc in channel 2, as well as in Pal 13 to be *d* = 23.80 ± 0.38 (± 1.32) kpc in channel 1 and *d* = 24.69 ± 0.49 (± 1.37) kpc in channel 2. A summary of the results from this project is provided in table 1.

**Table 1.** Summary of the results and uncertainties for the intercept *m*, distance modulus *µ* and distance *d* obtained for Pal 5 (top) and Pal 13 (bottom).

|  |  |  |  |
| --- | --- | --- | --- |
| Pal 5 | | | |
| IRAC Channel | *m* [mag] | *µ* [mag] | *d* [kpc] |
| [3.6]  ± σrand (± σsys) | 16.10  ± 0.03 | 16.51  ± 0.04 (± 0.12) | 20.04  ± 0.37 (± 1.11) |
| [4.5]  ± σrand (± σsys) | 16.16  ± 0.03 | 16.57  ± 0.04 (± 0.12) | 20.69  ± 0.35 (± 1.15) |
| Pal 13 | | | |
| IRAC Channel | *m* [mag] | *µ* [mag] | *d* [kpc] |
| [3.6]  ± σrand (± σsys) | 16.47  ± 0.02 | 16.88  ± 0.04 (± 0.12) | 23.80  ± 0.38 (± 1.32) |
| [4.5]  ± σrand (± σsys) | 16.55  ± 0.03 | 16.96  ± 0.04 (± 0.12) | 24.69  ± 0.49 (± 1.37) |

**4. Discussion**

The distances to Pal 5 for both IRAC channels are within the bounds of the uncertainties when the random and systematic uncertainties are considered and so a mean distance to the Pal 5 globular cluster is calculated to be *dPal5* = 20.37 ± 0.36 (± 1.13) kpc. This value can be compared to previous efforts to calculate the distance to Pal 5, such as in the Price-Whelan *et al*. paper in 2019 which found a distance to Pal 5 to be 20.6 ± 0.2 kpc [ref]. The distance to Pal 5 calculated in this project is therefore consistent with the results obtained in [ref]. The differences in values for the distance to Pal 5 could be explained by the method used in [ref] considering the metallicity of the globular cluster. Other measurements of the distance to Pal 5 has been undertaken by K[ü](https://en.wiktionary.org/wiki/%C3%BC)pper *et al.* and found a distance of  kpc [ref] which does not agree with the value obtained in this report which could be because it appears extinction effects have not been considered.

The distances to Pal 13 in IRAC channel 1 and 2 are also in agreement and so an average distance to the cluster is *dPal13* = 24.25 ± 0.44 (± 1.35) kpc. A value of 24.3 ± 1.1 kpc was obtained by Cotê *et al*. [ref] which is consistent with the value obtained in this paper. Another distance of 23.6 ± 0.2 kpc was obtained by Shipp *et al*. [ref] which is again consistent with the distance to Pal 13 obtained. Therefore *dPal13 =* 24.25 ± 0.44 (± 1.35) kpc is consistent with recent efforts to calculate the distance to Pal 13.

There are a number of sources of uncertainty in the distance measurements obtained for both Pal 5 and Pal 13 which quote the random and systematic uncertainties separately. The random uncertainty in the distance modulus arises from the least-squares model used to calculate the intercept point of the PL fit and has been calculated by adding this in quadrature with the uncertainty in the calibrated absolute magnitude PL relation in the Neeley paper. This is influenced by photometric uncertainties in the apparent magnitudes of the RRLs which come from the background noise in the epoch images, as well blurring or smearing of stars, bad pixels and the potential for nearby bright sources to contaminate the field in the vicinity of the RRLs in the sample. Uncertainty in the dust extinction correction is also considered in the random uncertainty as it is primarily realised in the apparent magnitudes as opposed to the uncertainties of the PL fit itself.

Systematic uncertainties have been considered, which is the largest uncertainty as seen in the distance measurements. This arises from the calibration of the PL relations provided in the Neeley paper, where it is discussed that this is likely to do with the accuracy of the parallax values from *Gaia*.[REFINE EXPLAIN also NEELEY 2015].

The distance measurements obtained for both Pal 5 and Pal 13 have a total uncertainty of around 7% when propagated through to kpc. The large uncertainties obtained could be explained by the largest drawback of the analysis which is the small sample size. The channel 1 PL relations were fit four and three RRLs for Pal 5 and Pal 13 respectively and for channel 2 the PL relations were fit using seven and four RRLs respectively. It is remarkable that the resultant distance measurements are consistent with previous work completed which may owe to the relatively uncrowded clusters that Pal 5 and Pal13 are, but agreement is still observed for both globular clusters. Future work should focus on ways to perhaps mitigate some uncertainties, an example of this would be by considering the metallicities of the RRLs in the samples, in which case it is possible that the uncertainty could be reduced by up to 1% [Neeley 2019]. Further improvements could be made by refining the photometry.

Variability indices were also calculated for the entire sample of detected stars in both Pal 5 and Pal 13 [ref]. Analysis of standard deviation, IQR, and Welch-Stetson variability were considered in an attempt to identify and quantify statistically whether a star varies which would be useful to identify new variable stars in the cluster and confirm that the known RRLs do, indeed vary. Unfortunately, no progress was made here which may be due to the small amplitudes involved, particularly in the case of Pal 5 where most of the known RRLs are of type c.

**5. Future work**

The globular clusters analysed in this project contain a relatively small sample of RR Lyrae stars and attempts to avoid crowded fields has been made. The next step would be to apply this process to a more crowded globular cluster, such as IC4499, work has already started on this but is not yet complete. The IC4499 cluster contains at least 97 known RRLs from initial investigation of the catalogue of variable stars [ref] and so this may require adjusting the PSF photometry code to further optimise it for crowded fields.

A further development on this work would include considering the metallicities of the RRLs in the cluster which could improve the precision of the distance measurements, as was touched upon in the discussion and so this would be considered going forwards.

In terms of the wider field, looking to the future, improvements in uncertainties would be a main consideration, particularly concerning systematic uncertainties brought about from the calibrated PL relations. Improvements in parallax measurements could significantly reduce the uncertainties in distance measurements [ref]. This would be particularly exciting as this could help work towards refining the value and uncertainty in Hubble’s constant, as described in the introductory sections of this report, which would help improve the field’s understanding of the scale and evolution of the universe [ref].

**6. Conclusion**

Distances to the Pal 5 and Pal 13 globular clusters have been calculated using data collected from the *Spitzer* IRAC in the mid-infrared spectrum. An average distance of *dPal5* = 20.37 ± 0.36 (± 1.13) kpc to the Pal 5 globular cluster was obtained and found to be in agreement with the most recent measurement using a similar method when the random and systematic uncertainties are considered. An average distance of *dPal13* = 24.25 ± 0.44 (± 1.35) kpc to the Pal 13 globular cluster was calculated and in agreement with previous measurements undertaken.

These distance measurements were obtained by performing PSF photometry on mosaic images of individual epochs across a duration of at least one period for the largest RRL period in the frame using software coded in python. Apparent magnitudes of the detected sources were calculated and the RRLs within the frames identified and their data extracted and mean apparent magnitudes calculated by way of a gaussian local estimation algorithm. Extinction effects caused by dust in the MWG was corrected for and the apparent magnitudes adjusted as a result. PL relations were then fit to the data for each IRAC channel for both clusters using a calibrated PL relation from Neeley *et al.* [ref] to yield the intercept point of the fit using a least-squares model. All data points were within one standard deviation of the fit for both channels in Pal 5 and Pal 13 when considering uncertainty in the average apparent magnitude. The intercept was then used to calculate the distance moduli for each channel for both Pal 5 and Pal 13 and converted into distances in kpc.

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