Presentation – Script

**Slide 1**

Hello and welcome to my talk on measuring distances to globular clusters using RR Lyrae variable stars.

**Slide 2**

Measuring distances to objects within the universe is very difficult, mostly because we don’t have all the information directly available and to us on Earth, space looks as though it is a 2-D plane.

The image slideshow in the bottom right demonstrates this issue, as the perspective changes it becomes clear all the individual balls are at greatly different distances from the original observation point.

This presentation will hopefully give some insight into how we can measure cosmological distances and why we might measure them.

**Slide 3**

Observations taken as part of two key programs: SMHASH, the spitzer merger and shape of the galactic halo and CRRP, the Carnegie RR lyrae program, were used in for this project.

SMHASH’s main aims are to investigate the Milky Way’s merger history and to construct a 3D map of the Milky Way, mainly it’s halo, by using mid-infrared wavelength observations of RR Lyrae stars.

SMHASH uses observations as part of its complementary program, CRRP, which primarily studies RR Lyrae stars in the Milky Way.

These programs are reliant on accurate distance measurements and are within the research interests of this project, and the supervisor as part of the Astrophysics research group here at Bath.

**Slide 4**

A few brief facts about the Spitzer space telescope:

The telescope was in operation for just under 17 years, far outliving it’s planned mission duration of 2.5 to 5 years.

The main instrument of interest is the Infrared Array Camera, IRAC. This camera contains an array of 4 detectors, each most sensitive to slightly different wavelengths of light: 3.6 microns up to 8 microns as shown.

The two larger waveband camera required cooling, supplied by a cryogen, which ran out in 2009 resulting in just the 3.6 and 4.5 micron cameras operational; signalling the start of the Warm Mission.

**Slide 5**

RR Lyrae variable stars are a type of variable star whose luminosity varies with periods of around a few hours up to a day. These stars belong to Population II which means they’re relatively old, greater than 10 billion years, slightly less massive than our Sun, about 0.5 to 0.8 solar masses and have low overall metallicities.

The Hertzsprung-Russell diagram shows where these stars reside, on the instability strip, which is home to several other types of pulsating variables, such as Cepheids.

RR Lyrae are particularly abundant residents within globular clusters in the Milky Way galaxy, making these stars particularly useful for study – especially as they’re what are known as standard candles. Standard candles are essentially markers to calibrate distances to cosmological objects!

**Slide 6**

There are three main types of RR Lyrae:  
RRab types, which pulsate in the fundamental mode and characterised by larger amplitudes and longer pulsation periods: a typical RRab light curve is shown at the top.

RRc types, which pulsate in the first overtone and typically have smaller amplitudes and shorter periods – the bottom light curve shows a typical RRc type star, which is more symmetrical and sinusoidal than RRab types.

A final type, RRd, pulsates in both the fundamental and first overtone modes simultaneously.

**Slide 7**

Previous work on pulsating variables has often focused on Cepheid variables. These are similar to RR Lyraes but are younger, brighter and have longer pulsation periods, on the order of weeks. In 1908, Henrietta Swan Leavitt discovered the Leavitt law, which is the relationship between a Cepheid’s absolute magnitude and its period of pulsation.

These are known as period-luminosity relations or PL relations.

The PL relation shown is the original Cepheid PL relation published in 1912, to give an idea on what a PL relation is, how they look and their history because they’re integral to finding distances to objects!

Cepheids, being brighter have been used in the past to calculate distances on cosmological scales but RR Lyraes could provide some advantages over Cepheids, mainly due to RR Lyrae PL relations having less dispersion (or scatter) about them.

**Slide 8**

This leads us to the cosmic distance ladder, which is a process of using cosmological distances at different scales in order to calibrate distances of cosmological objects. The ultimate aim of the cosmic distance ladder is to determine a value for the Hubble constant.

There are two main routes in the diagram: the previously well climbed Cepheid route, following the green boxes on the right and an independent route on the left hand side, using RR Lyraes. The general hope in the field is that this RR Lyrae route will obtain more accurate values.

We’re starting around the bottom rung of the ladder: globular cluster RR lyraes and each rung provides more information for progression onto the next one, gradually increasing in distance.

**Slide 9**

Determinations for the Hubble constant appear to be inconsistent depending on the approach used to obtain it. Values of around 73.5 kilometres per second per mega parsec have been found using the Cepheid distance ladder, where as values of 70.5 kilometres per second per mega parsec have been found using the cosmic microwave background, as shown in the diagram.

The good news is that even in the past 15 years uncertainties are gradually decreasing but the hope remains that using a completely independent route using RRLs could resolve this disagreement and provide accuracies down to 2 or 3%.

This has exciting implications on our understanding of the Universe, particularly in confirming details regarding its age, size and evolution.

[10 mins]

**Slide 10**

We now move onto the methodology section!

The data from IRAC was pre-processed into what is known as basic calibrated data (BCD) by image reduction: such as corrections for pixel sensitivity and any biases, this was all done prior to receipt of the data.

The observations of the globular clusters involved 12 epochs in series, spread over a duration of the RR Lyrae with the longest period in the cluster and covered a region around 6by15 arcminutes around the centres.

Mosaic frames, which are a stitching together of BCDs, were created for each epoch by the project’s supervisor, resulting in the final data to be analysed.

Master mosaic frames were also created…

**Slide 11**

Here’s the master mosaic frame for Palomar 5, indicating the channel 1 and 2 regions, with channel 1 overlaying channel 2. These are basically a median image using data from across all 12 epochs, which is particularly useful as it gives them a higher signal to noise ratio.

A quick note on SNR: for the SMHASH program, the data were optimised for channel 1, which resulted in channel 2 having lower SNRs than channel 1, particularly noticed in the epoch frames

**Slide 12**

This is the master mosaic frame for Palomar 13, the other globular cluster analysed. It is of note this bright star on the right, which is just over an order of magnitude closer to us than the cluster. When analysing the data for channel 2, which is of particular note perhaps in the discussion.

Both Pal 5 and Pal 13 exhibit long tidal streams as they are undergoing disruption by and accretion to the Milky way.

These master frames, owing to their higher SNR, were used to generate master source lists for use in the photometry…

**Slide 13**

Photometry is the measurement of the amount of light, or flux, from an image produced by a camera or detector. There are two main methods of photometry considered:

Aperture photometry: which is measuring the total amount of flux or data counts through an aperture drawn around the star: as shown by this inner radius in red here. The total amount of flux is also measured through an annulus region around the star, represented by this region bounded by the inner and outer radii: this value is the background flux and is subtracted from the total flux measured through the inner radius.

The second method, PSF, involves building a model based on the image profiles of the point sources produced by the detector in order to determine their flux. The graph shows the idea of a PSF, depicting a point source in light blue and a Gaussian PSF model in maroon.

PSF was chosen due to its ability to handle lower SNR fields and especially crowded fields!

**Slide 14**

Before obtaining flux values, the PSF model had to be built first, which follows this process:

A source detection algorithm with a high detection threshold value is used to detect candidate stars for the PSF model. The PSF is then built and the candidate stars examined for defects such as nearby neighbours, blending (two unresolved stars or galaxies), or artifacts such as cosmic rays. These stars are removed and then the model rebuilt – if the model looks like a fair representation of a well-sampled Spitzer star: the model is used, an example of which shown for Pal 5 channel 2.

**Slide 15**

With the PSF model in hand, it’s time to do some photometry: this starts with the first epoch frame, and running the source detection algorithm with a threshold of around 6 standard deviations above the median value. The PSF model derived is then fit to the detected stars in order to obtain flux values. The detected stars are then subtracted from the image, leaving a residual image. Arriving at the junction there is a choice: to perform another iteration on the remaining stars in the residual image or to progress onto calculating apparent magnitudes. As Pal 5 and Pal 13 are relatively diffuse for globular clusters, only 2 iterations of photometry was required. Apparent magnitudes are then calculated from the flux values and the detected stars matched by their coordinates to the stars in the master source list mentioned before; the apparent magnitude data is then added to this list. Once complete, we advance to the next epoch frame and repeat the process until all 12 frames are analysed.

**Slide 16**

Apparent magnitudes are calculated using the equation shown, covered back in 1st or 2nd year. The logarithm can be split up and a conversion factor put in place because IRAC measures surface brightness, not flux, to give a zero-point reference magnitude is required, which is given by ZP, the details of which were provided in the cameras handbook.

**Slide 17**

The known RR Lyraes in each channel for each cluster were extracted using catalogues of variable stars [1][2]. Light curves were plotted for each of these RR Lyrae stars. Light curves are useful for examining how a star’s magnitude varies with time and provides a visual check that the analysed RR Lyraes from our data do vary.

The time for each data point was converted into a phase to align each epoch and to make it easier to check that the periods join together smoothly as only 1 period of data was taken.

A light curve for an RRab star in Pal 13 is provided.

In order to calculate distances, an average apparent magnitude is required for each RR Lyrae. This was obtained using an algorithm called GLOESS, which calculates the time-averaged apparent magnitude, alongside it’s uncertainty by considering the photometric uncertainty, the uncertainty in the fit and the uncertainty for the dust extinction, which was corrected for by subtracted the extinction magnitude from a dust map from the average apparent magnitude.

**Slide 18**

A PL relation must be fit to the data in order to obtain distances. Calibrated PL relations for each IRAC channel were obtained from Neeley et al in 2019, as they contain the most recent RR Lyrae PL relations. These calibrated PL relations, which are in ABSOLUTE magnitudes, take the form shown. So the PL relations fit to the data must follow the same mathematic form. The exact forms are shown below, and the values for the y-intercepts and gradients of the calibrated PL relations can now be unveiled, so we now know part of the puzzle. The next stage is to obtain the y-intercept values for the data, which is in APPARENT magnitudes.

**Slide 19**

Before we fit the PL relations, the periods of the RRc type stars must be fundamentalised by using the equation given where Pfo is the first overtone period – this is done to enable comparisons between RRab and RRc stars using the same PL relation.

The equations of these fitted PL relations, the maroon lines on these graphs shown above, which are the PL relations for Pal 13 in both channels, are shown below. The gradient of the calibrated PL relation is held fixed, but the intercept is left to vary – a naught.

**Slide 20**

The y-intercepts of the fitted PL relations are obtained using a least-squares fit, but are illustrated by the blue dashed lines for the Pal 5 PL relations as shown in the figures. So consider again the distance modulus equation. By subtracting absolute magnitude from apparent magnitude, it is possible to find the distance in parsecs to the globular cluster. Substituting in the calibrated PL relations, big M, and the fitted PL relations, small m, the distance can be obtained from the difference between the y-intercepts, as shown.

**Slide 21**

These are the distance results obtained for both Pal 5 and Pal 13 in kiloparsecs.

The important results, the mean distance to each cluster is highlighted in bold: a distance of 20.37 kiloparsecs was obtained for Pal 5 and 24.23 kiloparsecs for Pal 13.

The uncertainties have been split into two categories, random and systematic, due to the disparity between the two types of uncertainty, as seen in the table.

The average distance was calculated as simply the mean between the two channels, and the average uncertainties were calculated in quadrature with respect to each channel.

**Slide 22**

The table here represents the comparison between my results, shaded in light grey, and literature results shown in either blue or red. The main important information has been emboldened.

So for Pal 5: In the first paper, by Price-Whelan et al in 2019, obtained a value of 20.60 kiloparsecs for their distance to Pal 5. This agrees very well with all three values obtained in this project. However, the second paper, which has been highlighted red, by Kupper, is on the surface inconsistent with the results. As discussed by Price-Whelan et al in their paper, this result of 23.60 kiloparsecs was not accompanied by a correction for dust extinction. This makes sense, because the dust causes a reddening effect, which essentially shifts the PL relation down, giving a larger distance. According to Price-Whelan et al in their paper, once they considered extinction themselves, Kupper’s results became more consistent.

And for Pal 13: There is good agreement for both literature values here, given by Cote and Shipp in 2002 and 2020 respectively.

Now an extra note on the Pal 13 values: there is a large difference between the channel 1 and channel 2 values, almost 1 kiloparsec difference – this is most likely due to the lower SNR in channel 2 but not only that there were only 3 RR Lyraes in channel 1 and 4 in channel 2, which is a very small sample.

**Slide 23**

The uncertainties in the distance values obtained have been split into two main categories: random error, which accounted for around 25% of the overall uncertainty for both clusters and systematic error, which accounted for around 75% of the overall uncertainty.

Random sources of error came from: the least squares fitting for the y intercept of the PL fit, the uncertainty in the calibrated PL relation’s y intercept and, by extension, photometric uncertainties in the apparent magnitudes caused by background noise, blending of the RR Lyraes (which was observed in one case) and crowding. These uncertainties are absorbed into the random error.

Systematic sources, by far the main contributor of uncertainty, came from: the uncertainty in the gradient of the PL relation, as given in the Neeley et al 2019 paper, as well as the uncertainty in the y intercept of the calibrated PL relation

**Slide 24**

The overall uncertainties in the mean distances to both Pal 5 and Pal 13 were around 10%, which is much higher than the anticipated 2% for the SMHASH program. So, why is this? The bulk of the uncertainty is caused by the uncertainty of the gradients, contributing to around 75% of the overall uncertainty. The uncertainties in the gradients themselves were around 14% of the values for bath channels. The PL relations in Neeley et al 2019 were based on Gaia parallax values, which came with large uncertainties themselves, and so improvements in these values which will come with future Gaia data releases could significantly improve the uncertainty in these distances.

Other improvements can also be made by considering the metallicity of the RR Lyraes in the clusters using a period-luminosity-metallicity, PLZ, relation when that data becomes available in Gaia. Another improvement could perhaps come by including the RR Lyraes in the tidal streams of the clusters to increase the sample sizes.

**Slide 25**

This work could be extended by applying the work to other globular clusters, such as the crowded IC4499 and also considering the metallicities of the samples if the data is available for that cluster.

In terms of the field, improvements in Gaia parallax values could reduce the uncertainties in the PL relations, or just general improvements in PL relations for RR Lyraes would significantly decrease say, the error budget for determining the Hubble constant.

It will hopefully be possible for uncertainties in the region of 2-3% or less to be achieved for the Hubble constant - as the cosmic distance ladder is climbed – and so more and more precise values could be obtained to resolve this inconsistency in values for the Hubble constant and in turn, significantly improve our understanding of the age, size and evolution of the universe!