Presentation – Script

**Slide 1**

This project was 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 of the information directly available and to us on Earth, space looks as though it’s a 2D plane

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

**Slide 3**

This project used 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.

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 observations of RR Lyrae variable stars in both globular clusters and dwarf Spheroidal galaxies, though this project focuses only on globular clusters

SMHASH uses observations of RR Lyraes taken by its complementary program CRRP, which primarily studies RR Lyrae in the Milky Way

So these programs are reliant on accurate determinations of distances

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Some information on the Spitzer Space Telescope:

The telescope was in operation for just under 17 years and one of its main instruments of interest is the Infrared Array Camera (IRAC). This camera contains an array of 4 detectors, each most sensitive to slightly different infrared wavebands: 3.6 microns, 4.5 microns, 5.8 microns and 8 microns.

The two larger waveband cameras required cooling, supplied by a cryogen, however this ran out in 2009, leaving on the 3.6- and 4.5-micron waveband cameras operational, which signalled the beginning of Spitzer’s Warm Mission

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We’ll now move onto some background science

RR Lyrae variables are a type of variable star whose luminosity varies with periods of only around a few hours up to a day. These stars belong to Population II and so are relatively old stars, (MASS) and have low overall metallicities and have typically less mass than the Sun, around 0.8 solar masses.

The Hertzsprung-Russell diagram shows where roughly these stars reside, on the instability strip, which is home to several pulsating variable stars

RR Lyrae are particularly abundant residents within globular clusters in the MW galaxy, making these stars particularly useful for study, especially as they can be used as standard candles. Standard candles are essentially markers used to calibrate distances to cosmological objects

There are 3 main types of RR Lyrae:

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RRab types, which pulsate in the fundamental mode and usually have larger amplitudes and longer periods – a characteristic 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 much more symmetrical than the RRab types

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

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Now, 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, of several days to weeks. In 1908, Henrietta Swan Leavitt discovered the Leavitt law, which is the relationship between a Cepheid’s apparent magnitude and it’s period of pulsation. These are known a period-luminosity relations or PL relations.

The image shows the original Cepheid PL relation published in Leavitt’s 1912 paper, just to give you an idea on the what a PL relation is and their history as they’re integral to finding distances to objects!

Now, 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) around them, weaker effects due to dust extinction; particularly owing to their well defined PL relations in mid-infrared bands versus optical wavelengths and reduced metallicity effects in the mid-IR.

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This leads us onto the cosmic distance ladder, which is a process of using cosmological distances at different scales in order to calibrate distances. The diagram shows an example of the scales, so 1 kpc up to 100 Mpc. The cosmic distance ladder’s ultimate aim is to determine a value for the Hubble constant!

Previously the Cepheid route, which follows the green boxes on the right-hand side, has been used to climb the ladder, however a second route, on the left-hand side, using RR Lyraes can be climbed to potentially obtain even more accurate values for the Hubble constant

We’re starting around the bottom rung of the ladder, globular cluster RR Lyraes and each rung will provide information for progression onto the next rung – which would involve Local Group RR Lyraes.

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Determinations for the Hubble constant appear to be inconsistent depending on the approach used. Values of around 73.5 kilometres per second per mega parsec have been found using the Cepheid distance ladder but values of around 70.5 kilometres per second per mega parsec have been found using cosmic microwave background models, as shown in the diagram from Beaton et al in 2016.

Analysis of RR Lyraes could resolve this fundamental disagreement by providing accurate values for the Hubble constant, with accuracies down to 1 or 2%

This has exciting implications on our understand of the Universe, particularly relating to its age, size and evolution.

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Where does this fit into our research at the University?

This research comes under the astrophysics research group, predominately under time-domain astrophysics as shown in the flow chart. This project is at the end of the chart, labelled SMHASH

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This ties into the supervisor for this project, Dr Victoria Scowcroft, research interests which surrounds the SMHASH program and scaling the cosmic distance ladder to obtain precise values for the Hubble constant. This work has involved both Cepheids and RR Lyraes.

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So the brief aims of this project are: to measure distances to globular clusters in the Milky Way galaxy, by using observations taken by the IRAC on board Spitzer. This will be done by performing photometry on these observations in the two mid-infrared bands available, and fitting PL relations to the average apparent magnitudes of RR Lyrae stars with in these clusters. We’ve managed to analyse two globular clusters: Pal 5 and Pal 13

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We’ll now move onto the methodology, which follows this brief overview.

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The observations from IRAC involved an area of around 6by15 arcminutes around the centres of globular clusters.

As before, Pal 5 and Pal 13 were analysed only, using data in both the 3.6um and 4.5um wavebands, corresponding to Channels 1 and 2 respectively.

A series of 12 epochs of data was analysed, taken over at least one full cycle for the longest period RRL in that particular cluster.

The raw data from the camera was pre-processed into what is called basic calibrated data, or BCD, frames in order to reduce the images: this involves correcting for pixel sensitivity variations and removing biases in the images

Mosaic frames, which are a stitching together of individual BCDs, were created for each epoch in each channel by our supervisor, creating the final data to be analysed

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RR Lyrae catalogues were also consulted to obtain positions in right ascension and declination and periods of known RR Lyraes in the clusters.

This catalogue, an example for Pal 5 shown in the bottom corner, by Christine Clement was used as well as region searches of stars flagged as variable in Gaia to identify any other potential RR lyraes within the epoch frames

The RR Lyrae stars from the Gaia region search were matched against the Gaia RR Lyrae list, containing 140thousand RR Lyraes, by using their unique Gaia source\_ids to obtain more information such as their more up to date periods and their types as well

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Master mosaic frames were also used. These are basically a median image using the data from across all 12 epochs, one for each channel. This gives them a higher signal-to-noise ratio than the individual epoch frames, so they could be used as a sort of frame to reference to

A quick note on the signal-to-noise ratios of the data: for the SMHASH and CRRP programs, the data was optimised for channel 1, which resulted in channel 2 having a lower signal-to-noise ratio, especially in the individual epoch frames

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Photometry is the measurement of the amount of light, or flux, from an image produced by a detector or camera. This process was completed by converting the data into data number counts from Mega Janskies per steradian using the equation shown. The exposure time and flux conversion factor constants were provided in the header information of the data files

Photometry was then performed to measure these count values for point sources in the frames, ultimately to find the apparent magnitudes for each star

There are two main methods:

aperture – which is drawing an aperture of radius just larger than the stars, measure the flux through the radius then subtract the background flux values which were calculated from an annulus around the star

PSF – this involves building a model of the point sources in the frames and then fitting this model to all detected point sources in order the measure the flux of them. This process was chosen as it is better handled to crowded fields

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A PSF model was built for each channel for both globular clusters. A PSF is the image profile produced by a particular instrument when a point source is incident on it, these are unique to the frames because they are constructed based on a selected of well-sampled high SNR stars in the frames. These created what are called effective PSF models, which is a net PSF describing the amount of light falling on an individual pixel.

The master mosaic frames for each channel were used to build these ePSF models due to the frames higher SNR, as we touched on earlier, which improved the quality and accuracy of these models – an example is shown which is the PSF model for channel 1 in Pal 5.

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In order to construct the ePSF models and indeed to perform photometry, the point sources must be detected. This was done using an algorithm called DAOStarFinder which follows a version of the DAOPHOT routine developed by Peter Stetson – essentially a process of performing photometry

To refine your detections to reduce false positives and also false negatives if too conservative, parameters must be determined

This present a sort of optimisation problem, where values too relaxed could result in false positives, like galaxies, bad pixels or noise being detected as stars or too conservative such that actual stars, which could be RR Lyraes, aren’t being detected.

The full width at half maximum of the stars is a parameter required: this was found by manually examining the radial profiles of stars in the sample.

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A list of sources using the master mosaic frames was generated, detailing their locations, which was achieved by running a source detection algorithm on the frames, and fitting the PSF model to improve precision of the locations

The DAOPHOT routine, which was followed (though not explicitly used) involves detecting the sources on a given frame, performing the photometry on the sources, subtracting those sources from the frame and then re-run the process again to pick up any stars that may not have been detected the first time round, or were cloaked by nearby brighter stars

The PSF models are fit to the frames, and a fixed centroids process was used, where the initial positions of the sources are fixed in the process to improve the precision of the detected sources.

This was performed on all 12 epochs in series and these were then matched, using their sky locations, to the master source list

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Apparent magnitudes were calculated using the standard equation shown, where an aperture correction, which accounts for the difference in aperture used to calibrate IRAC, the telescopes camera, and the aperture we used in the PSF photometry as well as a location correction, which corrects for distortion and scattering caused by IRAC. The zeropoint of the image was given in the IRAC handbook and used for each channel.

We now have a final list containing all detected stars in the master frame, alongside apparent magnitudes and uncertainties for those stars in all 12 epochs. These epoch apparent magnitudes were matched back to the master list using the star’s unique location

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The known RR Lyraes were extracted from the final lists using the catalogues discussed before. Light curves are useful for examining how exactly a star’s brightness varies as a function of time.

The time of each data point was converted into a phase to check if each period joins together nicely, as shown in the light curve provided.

The curve was fit using a Gaussian local estimation algorithm, GLOESS, which calculated the time-averaged apparent magnitude of each detected RR lyrae in the globular clusters

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In order to calculate distances, a PL relation must be fit to the data for each channel and globular cluster. Calibrated PL relations for each IRAC channel from the Neeley et al paper in 2019 was used as it contains the most recent RR Lyrae PL relations. These take the mathematical form shown:

So the PL relations fit to our data must take the exact same form, which is shown for each channel from the paper.

The PL relations were fit by fixing the gradient of the PL relation to the values shownL -2.78 for channel 1 and -2.83 for channel 2 and allowing the intercept to vary, as this will be compared to these intercept values given in the paper. Note that the PL relations here are in absolute magnitudes.

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So, here are our PL relations for Pal 5 in channel 1, left, and channel 2, right. These equations take the form shown, where the intercept value, a nought has been left to vary. It is from these intercept values that distances can eventually be found. These intercept values were calculated using a least-square fit to the data in each channel, resulting in the lines shown in the figures. The dashed lines show a dispersion about the PL relation, as it has it’s own uncertainty and is given as 1 standard deviation of the points about the PL relation.

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Now, distances can be calculated from the distance modulus, which is apparent magnitude minus absolute magnitude and so we can substitute the equations for small m and big M into the distance modulus, and this gives the difference between the intercept calculated for our data in the previous slide, from the intercept in the given, calibrated PL relation from the paper!

Using the relationship between distance modulus and distance in parsecs as shown, we can now obtain the distance to the globular cluster in question.

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Here are the results, using the equations in the previous few slides

The main take-away results are the distance to Pal 5 was calculated to be 20.37 kpc, with a random uncertainty of 0.51 and a systematic uncertainty of 1.6 kpc

And for Pal 13, the distance obtained was 24.23 kpc, with uncertainties of 0.62 and 1.9 kpc

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Let’s compare the values obtained to the literature:

A value obtained by Price-Whelan in 2019 was 20.6 … kpc, which is consistent with our values, shown in the red boxes.

However a value by Kupper was not found to be consistent – however further analysis of that result showed that dust extinction was not corrected for, and dust, which blocks light, would result in a shifting down of the PL relation by a constant factor, giving a distances further away than the object actually is, due to the larger y intercept

Comparisons were also made to Cote and Shipp for Pal 13, both being consistent with our determinations!

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The uncertainties in the calculated distances had 2 quoted uncertainties: random and systematic.

Random sources of uncertainty include: the least squares fitting for the y intercept of the PL fit, uncertainty in the calibrated PL relation’s intercept as well and by extension the photometric uncertainties in the apparent magnitudes caused by background noise, SNR, blending of the RRLs (observed in one case) and crowding, obersved in a number, all contributing to the error bars seen in those PL relations

However, systematic uncertainties dominate the overall uncertainty and these are primarily caused by the uncertainty in the gradient of the PL relations

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The overall uncertainties for both Pal 5 and Pal 13 are around 7%, which is higher than anticipated for the SMHASH program, however, 75% of the uncertainty is caused by systematic uncertainties

This is because the PL relations in the paper were based upon Gaia parallax values for RR Lyrae stars, and so improvements in these values, which will come with future data releases, could significantly improve the uncertainty in these measurements

In the mean time, consideration of the metallicities of the RR lyraes in the cluster can be done by using a Period luminosity metallicity relation, which could reduce uncertainties by a further 1%

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This work could be extended by applying the process to more globular clusters, such as IC4499 and by considering metallicity information if it is available for these other clusters.

In terms of the wider 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 increase the error budget available for determining the Hubble constant.

It will be possible for uncertainties in the region of 2% to be achieved for the Hubble constant and so in the coming years more and more precise values will be obtained and could resolve this inconsistency in values for the constant. And in turn, this could significantly improve our understanding of the age, size and expansion of the Universe!