

RR Lyrae Stars and the Distance to Globular Cluster M3

Astronomy 142 — Project Manual

Spring 2024

1 Introduction

In the following, we repeat a classic experiment: detect the periodically-varying stars in a globular cluster and thereby measure its distance, by considering the stars to be **standard candles**. Specifically, we will measure the time-average luminosity of the nearby star RR Lyrae and the time-average flux of stars in M3 that vary with the same period as RR Lyr, combining these measurements to determine M3's distance.

This observing project will involve frequent in-person observation sessions with the telescope over the course of 1–2 weeks, hopefully including a few nights in a row. Everyone who opts for this project will share their data and receive everyone else's in return. Each student will perform his or her own analysis and write an independent report on the results.

Stars in the instability strip of the HR diagram have been fundamental in the determination of the distance scale of the Universe. These stars radially pulsate, often in their fundamental acoustic mode. As we have seen in class, their pulsation periods Π vary inversely with the mass density ρ of the star:

$$\Pi = 4 \int_0^R \frac{dr}{v_s} \cong \sqrt{\frac{6\pi}{\gamma G \rho}} \quad (\text{uniform density star}) \quad (1)$$

Lower average density leads not only to longer periods, but also to larger luminosities L , in part because lower-density stars are much larger than higher-density stars of the same mass. Thus, a given type of pulsating star exhibits a strict relation, often linear, between Π and L . Such relations can be determined by observation of the periods and fluxes for stars whose distances are accurately known, for example, by trig. parallax. Once the Π – L relation is determined, it can be used as a standard candle to measure much greater distances to faint stars of the same type and period. The measured period Π tells us what the star's luminosity is, and the measurement of the star's flux f yields the distance r ,

$$r = \sqrt{\frac{L}{4\pi f}} \quad (2)$$

Henrietta Leavitt invented standard candles in the course of her observations, during 1908–12, of thousands of periodic variables in the Magellanic Clouds. Her variables are classical Cepheids, the highest-luminosity Population I inhabitants of the instability strip; the Π – L relation for classical Cepheids is called **Leavitt's Law** in her honor.

The instability-strip variables in globular clusters include supergiants, giants, and stars close to the Main Sequence: W Vir stars, RR Lyr stars, and SX Phe stars, respectively. RR Lyr stars are by far the most numerous. The *Gaia* mission has measured the parallax and proper motion for about 141,000 RR Lyrs, some of which lie within 87 Galactic globular clusters (Clementini et al., 2019). While the extension of parallax measurements to globular clusters might be expected to automatically make parallax the primary method for determining their distances, there turn out to be significant uncertainties, both random and systematic, in *Gaia* parallaxes. These uncertainties are on the order of only 10 microarcsec (Baumgardt & Vasiliev, 2021), but that is a large fraction of

the parallax of most globular clusters. By contrast, there are many field RR Lyrs much closer to us, for which the uncertainties are dwarfed by the distance modulus of these stars. Thus, the best way to measure the distance to GCs is still to use nearby RR Lyrs as standard candles in comparison to the RR Lyrs in GCs.

In this project, you will identify RR Lyrs in the bright globular cluster M3, in Canes Venatici, through their variability at visible wavelengths. You will also observe a few field RR Lyr stars for which parallax has been accurately measured — RZ Canum Venaticorum (RZ CVn), NR Lyrae (NR Lyr), and RR Lyrae (RR Lyr) itself — to use as standard candles. Then, you will measure the distance to M3 using the nearby RR Lyrs as standard candles, and compare your results with the *Gaia* parallax distance.

2 Experimental procedure

2.1 Planning

1. Find a clear night. Use the Mees ClearDarkSky page frequently throughout the semester to identify one. Once a clear night is available, clear your schedule. Look up or calculate the times of sunset and sunrise, the length of the night, and the times during which M3 and NR Lyr are above 30° altitude.
2. Unlike the observing project in ASTR 111, this one takes all night. Therefore, you will be **required** to sleep at the Gannett House after your observations are complete and before returning to campus. Plan accordingly by packing for an overnight stay, including the all-important requirement of packing sufficient food. (Unfortunately, Mees is beyond the range of pizza delivery.) Familiarize yourself with the rules of the observatory sleeping quarters at the Gannett House.
3. Bring your notebooks, and you would do well to also bring your personal laptop or tablet computer. Paper copies of the telescope checklist and CCD-camera observing guide will also prove useful, though these will also be accessible to you online.
4. Arrive well before sunset.

2.2 At the telescope

One team member should be stationed at the TCS (telescope control system) at all times throughout the night. Be sure to rotate the team members through this position frequently enough so that no one gets bored.

1. Start the telescope and camera by following the steps in Section I of the Mees Observatory in-person observing checklist. This leaves you with both the telescope and the camera ready to observe.
2. On TheSkyX, search for M3 (**Cnt1-F** for the search window), click on it to bring up its information window, and check to see if it is above the telescope's artificial horizon (elevation > 20° for in-person observing). If so, you are ready to start observing!
3. As a guide star, we recommend a 12.5 magnitude star which is known to TheSkyX as GSC 2004:639. Find it by bringing up the search window (**Cnt1-F**) in TheSkyX and entering its name. Follow the steps in Step 19 of Section I in the remote-observing checklist to commence autoguiding.
4. In the Camera tab in TheSkyX, set up for an RGB observation series of M3:

	R	G	B
Exposure length	5 min	5 min	5 min
Binning	2x2	2x2	2x2
Number of exposures	1	1	1

This three-image, approximately 15-minute sequence will be repeated over and over throughout the experiment.

5. Observe M3 for ~ 30 minutes by repeating the above sequence 2 times, and then slew to image the RR Lyr. During this time, watch the imaging results attentively for the first few images to make sure that the autoguiding remains stable. After that, check every several minutes to make sure that the guide star is staying in the middle of the box.
6. When you are ready to slew to RZ CV $_n$, let the current M3 RGB cycle finish. On the **Autoguider** tab, push **Abort** to turn off the autoguider. Then point the telescope at RZ CV $_n$. On **Camera > Take Series**, click the **AutoSave** button and change to the appropriate file name prefix. (Do **not** reset the starting number. TheSkyX does not ask permission before overwriting files!) On **Camera > Take Photo**, take a 2-second image with the L- or G-filter to make sure that the star is reasonably close to the center of the CCD; move it and take another image if necessary.
7. RZ CV $_n$ ($V = 11.6$) is up whenever M3 is up, so it should be observed throughout the night. Use

	R	G	B
Exposure length	30 sec	30 sec	30 sec
Binning	2×2	2×2	2×2
Number of exposures	3	3	3

This sequence will be done in a few minutes; there is no need to autoguide.

NR Lyr (known to TheSkyX as GSC 3120:591) and RR Lyr will not be observable until late in the semester and do not rise until late at night even then. NR Lyr has $V = 12.4$, so the imaging sequence outlined above will suffice. RR Lyr is much brighter ($V = 7.0$), so reduce the per-frame exposure time from 30 sec to 3 sec.

Once these other RR Lyr rise, you should image all three RR Lyr stars.

8. Before returning to M3, we also need to image a calibration star (one with a flux known *a priori*) so that we can convert the data in our images to physical flux units. BD+30 2355 = GSC 1995:133, an A0V star with $V = 10.65$, lies about 8 degrees away from M3, about 3/4 of the way between the cluster and the bright orange star Arcturus. For flux calibration, take a sequence like that for RZ CV $_n$, right after each RZ CV $_n$ observation.
9. From now until dawn, repeat the following series of observations:
 - (a) M3 (2 of the sequences outlined above)
 - (b) RZ CV $_n$
 - (c) Calibration star
 - (d) NR Lyr (once observable)
 - (e) RR Lyr (once observable)

Do not forget to keep changing the file name prefix as you switch targets!

10. When the Sun comes up, shut down the telescope and CCD camera by following the steps in Section II of the in-person observing checklist.
11. Go to the Gannett House and get some sleep. You may not return to campus until at least the driver(s) sleeping for at least four (4) hours. This safety rule will be strictly enforced.

3 Data reduction

Each team will carry out the first stages of processing on their data. These stages will include calibration of your M3 and RR Lyrae data: bias and dark subtraction, and bad-pixel correction. This work breaks into three roughly equal size parts, one for each filter. Make sure your team divides the data reduction workload equally among the members.

Set aside a few hours for your team to meet either in the POA or on Zoom and remotely log into your personal account(s) on the workstation in B&L. Find the directory on this computer's desktop in which the Master Dark and Bias frames are kept. Then:

1. Start CCDStack, using the icon in the Windows taskbar.
2. Open all of the G images of M3, using **File > Open** and navigating to your working directory where all of your files live. This will present you with the full stack of these images, which you can page through and examine with the tools on the left side of the window.
3. Calibrate these images. Choosing **Process > Calibrate** evokes the **Calibration Manager** dialog. Using the two tabs and three buttons, specify the master dark frame and bias frame appropriate to CCD temperature (-20°C) and binning (2×2). Then click **Apply to All**.
4. Next, remove hot pixels: those with (permanently) high and variable dark current that does not subtract out in calibration. Choose **Process > Data Reject > Procedures**. In the resulting dialog choose **reject hot pixels** from the dropdown menu, specify a **strength** of 30, check **clear before apply**, then click **Apply to All**. Then choose **interpolate rejected pixels** from the dropdown menu, use 10 iterations, and again click **Apply to All**.
5. Then cold pixels: also with permanent dark-current problems, if not completely dead. Repeat Step 4, substituting **cold** for **hot** in the first dialog.
6. Align all of these images so the stars are in precisely the same places. First, page through the images until the one taken when M3 was closest to transit is on top. Choose **Stack > Register**, which brings up the **Registration** dialog.
7. On the **Star Snap** tab, click **remove all reference stars**, then **select/remove reference stars**. Double-click to select 6–8 stars which do not have any particularly close neighbors, are not close to the edge of the image, do not include extremely bright looking stars, and are spread uniformly around the cluster.
8. Page through the stack of images to see how close to being in alignment they already are. Drag any misaligned ones into closer alignment. Then click **align all** to shift the frames into rough alignment.
9. Switch to the **Apply** tab, choose **Nearest Neighbor** from the dropdown box, and click **Apply to All** to shift the frames very accurately into alignment. Page through the images to make sure it worked. It should now be difficult to tell when you page from one image to the next.
10. Save these images: Choose **File > Save > All**. In the **File name** box of the resulting dialog, enter a suffix indicating the degree of processing that the images have had, e.g., **CalReg**. Set the file format to **FITS**. Then click **Save**.
11. Adjust all the images to remove atmospheric extinction. Again, page through the images until the one taken when M3 was closest to transit is on top. Choose **Stack > Normalize > Control > Both**. In response to the subsequent instructions, drag a rectangle well off the cluster's center to represent background, and click **OK**. Then drag a rectangle encompassing the densest part of the cluster to represent the highlights, again clicking **OK**.

12. Now that the stack of images is registered and normalized, it can be corrected for cosmic-ray hits and satellite trails. Choose **Stack > Data Reject > Procedures**. In the resulting dialog pick **Poisson sigma reject** from the dropdown box, specify a **sigma multiplier** of 2.2 (sigma), and click **Apply to All**. Then select **interpolate rejected pixels** from the dropdown menu, and again click **Apply to All**.
13. Choose **File > Save > All**. In the **File name** box of the resulting dialog, enter a suffix indicating the degree of processing the images have had, e.g. **NormFix**. Set the file format to **FITS**. Then click **Save**.
14. The Green images are now tidied up; choose **File > Remove all images - Clear**.
15. Repeat Steps 2–13 for the R and B images of M3. Make sure that you do not clear out all of the images after saving the processed B images.
16. Use the stack of B images to search for variable stars. Page to the first M3 image of the night, then use the **Navigate Back** and **Navigate Forward** buttons to toggle between the first and last blue images. How many stars can you find that substantially changed brightness between the beginning and end of the night? You should identify at least a couple dozen; if you try hard and have images throughout a long night, you may find a lot more than that. Keep a list of their pixel coordinates, noting that what is under the cursor is displayed at bottom right of the **CCDStack** window. Repeat this with image pairs separated by different time intervals, such as beginning/halfway and halfway/end. Note that the **Blink** button results in continuously and automatically paging through the contents of the stack with approximately half-second intervals between images.
17. Open one of the B M3 frames in **SAOImageDS9**. Find the best scaling for the image by adjusting the settings in the **Scale** drop-down menu (**ASINH** at 99.5% is a good place to start). Select **Region** from the **Edit** menu and click on the image to draw a circle region around each of your identified variable stars. To change the location and size of the drawn region, double-click on the region. In the resulting pop-up window, specify the center position and radius of the region, and label the star with a number in the **Text** block. Save this annotated image as a **PNG** file (**File > Save Image > PNG**) and save it in the **ASTR 142 M3** folder on the workstation in **203H** for the other M3 groups to reference.

If there are other groups doing this project, compare your list of variable stars with theirs. The more stars that you can identify, the better!

18. Now clear the stack and repeat this procedure for each of the RR Lyrs, with two differences:
 - (a) Do not normalize the images to correct for atmospheric extinction (Step 11), and do not fix cosmic ray hits (Step 12) just yet.
 - (b) Instead, save the stack after aligning all of the images, with file name suffix **CalReg**, and clear the stack. Then open, one at a time, each series of three consecutive 3s/30s exposures. As in Step 12, choose **Stack > Data Reject > Procedures**, pick **Poisson sigma reject** with a factor of 2.2 (sigma) and an **iteration limit** of 10, and click **Apply to All**. Then select **interpolate rejected pixels** from the dropdown menu, and again click **Apply to All**. Save the series with the suffix **Fix**. Choose **Stack > Combine > Mean** to produce an average of these three images in this filter. Save this new image as a **FITS** file, accepting **CCDStack**'s suggested prefix of **Mean**. Then clear the stack and repeat on the next set of images.
 - (c) After processing all the individual series, clear the stack and load all of the **B Mean** images for the **RZ CVn** star. Put them on **Blink**, and note that their brightness changes by quite a bit from the beginning to the end, while the rest of the stars in the field change by much less. Thus, the RR Lyr stars vary like many of the variables in M3. The small changes in the rest of the stars turn out to be the systematic effect of atmospheric transmission; this was taken out of the M3 data in the **Normalize** step, but in the case of the RR Lyrs,

which are the brightest objects in a frame with few stars, normalization has to be done more carefully, in the next set of tasks.

19. Finally, clear the stack and repeat step 18 for your calibration star in each filter.

4 Analysis

Next you will measure the fluxes and magnitudes of the M3 variable stars and the RR Lyrs as functions of time through your observing night. Using these data, you will measure the distance to M3.

1. Run IDL using the icon in the Windows taskbar. Then type `ATV <Enter>` at IDL's command prompt at the bottom of the window. The ATV window will appear. On its `Mouse Mode` dropdown menu, choose `ImExam`.
2. Open the first of your B images of M3 in ATV, using `File > ReadFITS`.
3. Unlike CCDSoft and CCDStack, IDL displays images with the pixel coordinates at lower left instead of upper left, so your images will look inverted top to bottom. (The coordinates of a given star are always the same, though.) If this will be too confusing, choose `Rotate/Zoom > Invert Y` to set it right.
4. Click on any star to bring up ATV's aperture photometry window. In this window, click the `Show Radial Profile` button, which displays the flux per pixel of your star as a function of distance away from its centroid. This window tells you the centroid position and the flux of the star, given by the total flux within the aperture radius minus the flux in the sky annulus between the inner and outer radii. By entering new values in the boxes provided, adjust these parameters so that the star's flux is essentially completely contained in the aperture. `Aperture/Inner/Outer = 8, 10, 16` usually works in the less-crowded regions.
5. In `ImageInfo`, display the current image's `ImageHeader` and copy the UT date and time the image was taken, recorded in the header as `DATE-OBS`.
6. In the aperture photometry window, click `Write results to file...` and enter a file name in which to store star fluxes. It will be useful to have the observation date and time as all or part of the file name. While this file is open, a click on a star will write its centroid position, flux (as "counts"), and FWHM diameter in pixels.
7. Click on each of the variable stars in this image. Note any cases in which the radial profile indicates that nearby stars are influencing the measurement of the variable. Throw the star off the list and choose a different one if there is not a good way to exclude too-bright stars from the sky annulus. When you are finished, click `Close photometry file`.
8. Repeat Steps 2–7 for each of the R and B images of M3 you acquired.
9. Repeat Steps 2–7 for each of the `Mean R`, `G`, and `B` images of each of the RR Lyr stars that you acquired. In this case there is only one variable star in each image, but click the next four brightest stars as well to enable the correction for atmospheric extinction that we postponed from Data Reduction, Step 11.
10. Now, correct your RR Lyr stars' fluxes for atmospheric extinction: For each image, calculate the ratio of fluxes for the non-RR Lyr stars to the fluxes these stars have in the image taken closest to transit. Average these ratios for each image. Correct the stellar fluxes for each of the variable stars by dividing what you measured by the average ratio for that image.
11. Repeat Steps 2–7 for the `Mean R`, `G`, and `B` images of the calibration star. In this case, there is only one star that you need to measure: just the calibration star itself.

12. Convert each measured flux value for every variable star to a magnitude, Using the calibration star’s known apparent magnitude ($V = 10.65$) and flux that you measured in Step 11 for the mean calibration star image closest in time to the variable star’s image:

$$m_{\text{variable}} - m_{\text{calibration}} = 2.5 \log \left(\frac{f_{\text{calibration}}}{f_{\text{variable}}} \right)$$

where the flux is equal to the value that you measured in ATV divided by the exposure time of the corresponding image.

13. Plot the G magnitude vs time — i.e. the **light curve** – and the B–R color vs. time, for each of the variable stars that you identified in M3. Traditionally, these plots use the Day as the unit of time. In good astronomical fashion, make the magnitudes *decrease* up the vertical axis. Have these plots available for use in your lab report.
14. Repeat Step 13 for RZ CVn, NR Lyr, and RR Lyr. Again, have these plots available for use in your lab report.

5 Lab reports

Each student must write their own report, in which they explain the purpose, methods, and outcomes of the observations, and answer all of the questions raised in the sections above. We offer a sample lab report on the course website, to give an idea of the length and level of detail expected. Make sure to address each of the following in your report:

- For how many variables — M3 and nearby ones — do you have good measurements of the maximum magnitude (minimum flux)? What is the range of maximum magnitudes? Do any of them seem anomalously small (i.e. star anomalously bright) compared to the others, and seem to change more slowly than the rest? If so, the anomaly might be M3’s lone Pop II Cepheid; check with Prof. Douglass.
- Discuss the light curves for M3’s variables and the RR Lyrs. Which M3 light curves resemble the RR Lyrs’ most closely? Are there light curves in which you see clear minima and/or maxima? Are there light curves in which you see two maxima or minima, and can thereby measure the pulsation period? Explain the lightcurves’ behavior relative to one another in light of the stellar pulsation model that we discussed in class.
- Are there stars for which you obtained complete periods? Make a table of period, amplitude, and maximum magnitude for those. Is there are trend among the periods and maximum magnitudes?
- Did your observations of RZ CVn, NR Lyr, and/or RR Lyr include a maximum magnitude and/or complete period? If so, add this to the table. If not, borrow another group’s data and determine the maximum magnitude.
- Assume that the RR Lyrs and the M3 variables with similar light curves all have the same luminosity. The distance to each of the RR Lyr stars you observed has been measured by trig parallax (Gaia Collaboration 2020):

Star	Distance [pc]
RR Lyr	250 ± 1.7
RZ CVn	1600 ± 58
NR Lyr	3000 ± 120

Using the maximum stellar magnitudes for each of the variable stars that you measured in M3, compute the distance to each of your M3 RR Lyrs. Average them to obtain the distance to M3; compute their standard deviation to estimate the uncertainty in this distance.

- **(Optional)** From your M3 data, you could make a color image of the cluster and thus a superb ornament for your website or Facebook page. Here is how to make it, back in CCDStack:
 1. For each filter, open all of the `CalRegNormFix` files, as in Data Reduction's Step 2, and create an average of them, with `Stack > Combine > Mean`. Save the `Mean` image and clear the stack before proceeding to the next filter's `CalRegNormFix` files.
 2. Clear the stack if it is not already; then open the three `Mean` images you just created. Choose `Color > Create`. CCDStack will magically identify your R, G and B images and offer the filter scaling factors for adjustment. Enter `Filter Factors` of 1.00, 1.16, and 1.58 for R, G, and B, respectively, which will scale the colors so that an A0V star looks white. Then click `Create`. You will be prompted to drag a rectangle on the image to identify a background area well away from the cluster center; do so, check `Desaturate background`, and click `OK`. Then click `Yes` on the next dialog, and `Apply to this` in the one after that. Save this image under some suitable name, e.g. `M3_RGB.FITS`.
 3. Use `Adjust Display` to tweak the image for display of the faintest stars while keeping from "overexposing" the brightest stars and the cluster center. When you are satisfied, choose `File > Save Scaled Bitmap` to make a JPEG image, or `Save Scaled Data` to make a TIFF image, the better to be imported into Photoshop.