

Ay 20 – Robinson Rooftop Observatory Exercise

1. Introduction

Open clusters in the Galaxy are recently-formed. Because individual stars are created from the collapse of gravitationally bound parcels of interstellar gas, the young stellar clusters are located (for the most part) where the gas is – near the Galactic plane. Stars spend almost all of their lives on the “main sequence,” an equilibrium state in which they convert $\text{H} \rightarrow \text{He}$ in their interiors and thus create nuclear energy. This energy gradually makes its way from the stellar interior to the stellar surface and radiates into space according to $L = 4\pi R^2 \sigma T_{eff}^4$ (where R is the star’s radius, T_{eff} its effective temperature, and σT_{eff}^4 the equivalent blackbody emission from a surface of unit area, integrated over all wavelengths).

In the Hertzsprung-Russell (HR, after Hertzsprung 1911 and Russell 1913) diagram of $\log L$ vs $\log T_{eff}$, the main sequence is a well-defined locus. Moving along the sequence from bright blue/hot stars to faint red/cool stars is also moving through mass from high mass stars to low mass stars. The star’s structure does not change appreciably during the main sequence lifetime. But when the hydrogen near the center of the star is used up, the star has to change its structure so that hydrogen-burning can occur further from the center. The structural changes are manifested by changes in the temperature as a function of radius (such that the temperature does not drop off as quickly with distance from the center), and also in the total stellar radius. Physically, the star’s atmosphere gets bigger and cooler (even though its inside gets smaller and hotter). Because $L = 4\pi R^2 \sigma T_{eff}^4$, these changes make the star move off the main sequence. The timescales for evolution *to* the main sequence, equilibrium existence *on* the main sequence, and evolution *away from* the main sequence depend primarily on just one variable: the stellar mass.

Study of HR diagrams for a large sample of clusters has provided the observational basis for our theoretical understanding of both stellar and galactic evolution. In this exercise we will study just one galactic open cluster, NGC 7790. The beauty of clusters is that all stars in them can be presumed – to first order – to have the same distance, the same reddening, the same composition, and the same age. Thus while the luminosity and the effective temperature are fundamental, physical properties of a star, in the case of clusters we can approximate the behavior of stars in the “theoretical HR diagram” of $\log L$ vs $\log T_{eff}$ with an “observational HR diagram” of, for example, V vs $B-V$.

2. Goals of this Exercise

The main goal of this Robinson rooftop observing exercise is to introduce you to the basics of

- obtaining astronomical data;

- performing simple “reduction” of images;
- deriving photometry;
- taking some top-level analysis steps.

We will be observing the Galactic star cluster NGC 7790 through the Robinson Rooftop Observatory 14” telescope. The rooftop is actually a terrible site for astronomy for several reasons, including: substantial light pollution, total occultation of certain parts of the sky by nearby buildings, low altitude (more atmospheric water vapor than at higher sites), and horrendous seeing (especially to the south towards physical plant where there are heat and air currents being generated). So the observing conditions will not be “photometric” by a long shot. But we can still do some observing that is at least instructive and (hopefully) fun.

There are several filters available, approximating the B, V, and R, band passes that we talked about in class. Specifically, we will observe the cluster in Meade’s Pictor 616 Color Filter System with “B” (3900-5050Å), “V” (4950-5800Å), and “R” (6100-6800Å) filters. We will work with the raw image data to extract photometry. With the photometry we can make a color-color diagram (e.g. B-V vs. V-R) and a color-magnitude diagram (e.g. V vs B-V or V vs V-R). Analysis of these diagrams will lead us to the reddening/extinction, cluster distance, and even an estimate of the age. We perform these analysis steps by comparing the observed photometric sequences in various color-color and color-magnitude diagrams with the intrinsic values of the colors and absolute magnitudes that were handed out in class (extra copies available). In other words we are inverting the process of placing our stars on the HR diagram by figuring out how we have to alter the standard HR diagram values to match our distribution of data points. We can compare the numbers derived for the cluster’s extinction, distance, and age extracted from data obtained right here on the Robinson rooftop with those obtained by others at better photometric sites and published in the astronomical literature.

3. Details

3.1. At the telescope

The coordinates of NGC 7790 are 23:58:24 +61:13:00 (J2000.). The cluster is up high in the sky during the early evening hours at this time of year and is therefore amenable to observation. The TAs will guide you through the steps to startup and then point the telescope, which involves setting the telescope to a star of known position and telling the computer where you think you are. The final startup steps are to focus the telescope and initiate the CCD. The TAs will also help you acquire the main object (NGC 7790) in the finder and place it onto the detector for digital data acquisition. Because, as mentioned above, most star clusters are located near the Galactic plane and NGC 7790 is no exception with Galactic longitude 116.6 degrees and latitude -1.0 degrees, you

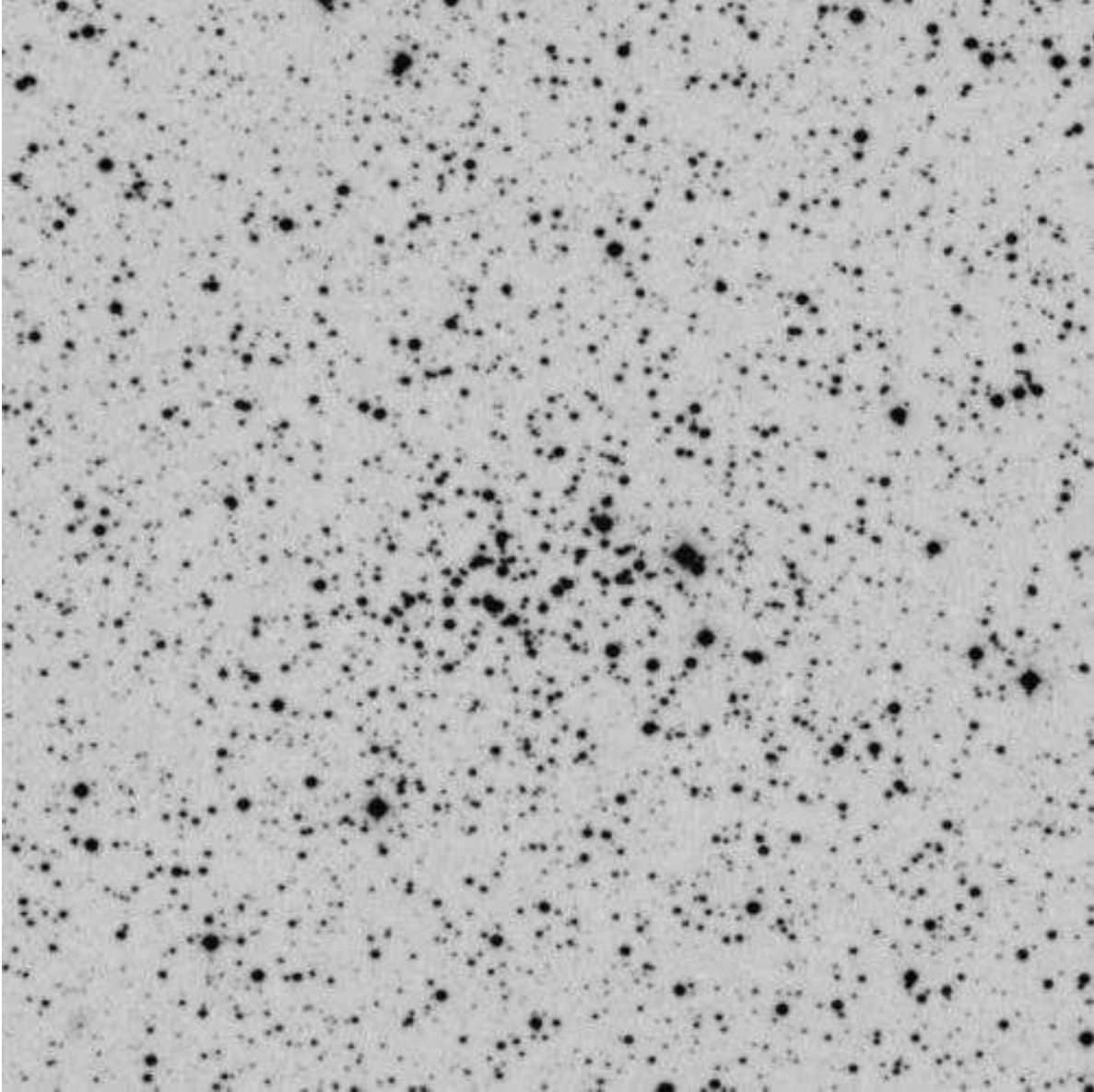


Fig. 1.— NGC 7790 as seen on the Palomar Observatory Sky Survey (POSS) plates. The orientation is up == North and left == East, the proper way of displaying astronomical images. The field shown here is $14 \times 14 \text{ arcmin}^2$ while the field of view of the CCD mounted on the back of the Robson 14" is approximately $9 \times 9 \text{ arcmin}^2$. Both *bona fide* cluster members and unrelated field stars are present in the image.

may notice that the overall surface density (stars / degree²) is higher in this field than in some other areas in the sky you may have looked at with the telescope before arriving at NGC 7790.

Exposures of up to 2-3 minutes are possible and get us down to about 15th magnitude at V-band. We really want to be at a depth of 16th-17th mag for this lab to yield the most easily-interpretable results. (Recall that Vega is 0th magnitude, the Trapezium stars in Orion are 5th magnitude, and the faintest objects seen with Keck are about 28th magnitude.) Longer integration times are not advised due to the relatively poor accuracy of the tracking (constant change of the telescope’s azimuth and altitude/elevation in direct compensation for the earth’s rotation) and the lack of a guider (which would correct for poor tracking by keeping a “guide star” in a fixed position). You can try a long exposure if you want; the effect will be images that are trailed (i.e. smeared) in the east-west direction. In fact, if you were to turn off the tracking you could measure the field of view of the detector if you know the earth’s rotation rate in arcseconds per time second; you would want to point the telescope to declination = 0 degrees to make your life easier. You probably don’t want to engage in such fun at this stage though, as in order to get back to business you would have to re-point the telescope.

Take data of NGC 7790 through the “blue”, “green”, and “red” filters. You will want to check the telescope focus for each filter, preferably by using the computer to examine some test images and minimizing the size of the point sources through focus. To get to the needed depth, you probably want to take at least 10-20 short (30 sec) frames in the blue filter and 5-10 frames in the other filters. The idea is that if they are all suitably good, you can average them together to beat down the background noise and therefore improve the signal-to-noise ratio in your photometry especially at the faint end. You should also take some flat-field frames by holding the white foam dish in front of the telescope and exposing for 5 seconds. It is best to take several of these and average them together.

For calibration, we are lucky in that there are several published papers which have established local photometric standards that are right here in this cluster itself. So you don’t have to go off and measure other more fundamental standards and then correct for the likely substantial differences in zenith distance between the standard and your data (remember that the atmospheric extinction when measured in magnitudes is linearly related to the secant of the zenith distance). Checking Odewahn et al. (1992; PASP 104, 553) or Stetson (2000; PASP 112, 925) shows that many of their brighter stars should be visible in your observations. The figure at the back of this writeup should help you convert the instrumental magnitudes you measure on the computer into real magnitudes.

3.2. Later on with the computer

Reduce the images. The TAs will help you subtract the bias frame (which accounts for electrons trapped in the potential well of the detector pixels in the absence of light incident from

the telescope optical path) and divide by the flat-field (which corrects for differences between the individual pixels in their response to light) right there on the computers at the telescope. If you have taken multiple images through the same filter, go ahead and average the best of these together. For kicks you might make a color image from your three averaged B, V, and R images. Most of the stars in the field are approximately the same color, but there will be a few particularly bright and particularly red ones that are important later on.

Photometry. Extract photometry for as many stars as you can using the “CCDsoft” software which is currently installed on the PC in the dome and on one of the PCs in the Robinson computer room (052). The diameter of this cluster has been determined to be about 5’ and the field of view of your data is about 9’, so you might want to be selective about which stars you choose for photometry so as to maximize the likelihood of your sample being dominated by cluster members. The CCD produces and records as its output “counts” or “ADUs” (analog-to-digital units) which are linearly related to the photons that travelled many many light years from their source in NGC 7790 to hit our detector. There is software available for measuring the integrated intensity of a star over all of the detector pixels that it covers (due to a combination of the instrumental point-spread-function and the atmospheric seeing conditions). Make sure the star is centered in the aperture and that your aperture is big enough; you will underestimate the signal if counts in the wings of the point-spread-function are not included. Part of the photometry process is subtracting from the integrated intensity measurement a “sky” measurement that includes contributions from artificial sources here on the ground (light pollution), moonlight, sunlight scattered from interplanetary dust (zodiacal light), and starlight scattered from interstellar dust. If none of these “sky” terms were present, the image would have very few counts in it other than where the stars were located. Sky subtraction is best done by defining an annulus directly around the photometry aperture for each star; it can also be done by taking a measurement in a beam that is offset from each star and does not include any other stars. If the flat-fielding is very very good, you can also produce just a single sky measurement and apply it to all stars, but this is not recommended. Make sure that you record your output in magnitudes, or $-2.5 \times \lg(\text{counts})$. You will have to convert these “instrumental magnitudes” into calibrated magnitudes by finding the difference between your instrumental magnitudes and the published magnitudes for the same stars, and then applying that difference to all stars. Some of the stars in the images will be cluster members, but many won’t and will instead be unrelated “field stars.” You can’t really tell which is which until you look at the resulting color magnitude diagram, and even then it won’t be totally obvious, especially near the Galactic plane like we are with the NGC 7790 field.

Analysis. Remember that brighter stars have smaller magnitudes and that hotter, bluer stars have smaller colors. All of your plots should have magnitude axes that go from faint to bright, and color axes that go from blue to red.

Reddening/Extinction: Make a diagram of B-V vs V-R. Plot your data compared to the standard color sequence handed out in tabular form in class. The shift between the two color sequences is caused by interstellar reddening. You want to figure out the mean shift, or “color excess”

$E(B-V) = (B-V)_{observed} - (B-V)_{intrinsic}$ or $E(V-R) = (V-R)_{observed} - (V-R)_{intrinsic}$. These do not have the same value due to the differential effect of extinction with wavelength (blue light is absorbed/scattered more readily than red light). The “color excess” is also called the “reddening.” To convert the color excess to a measure of the extinction at V, use $A_V = 3.1 \times E(B - V)$ or $A_V = 3.8 \times E(V - R)$. It really is best to do this exercise using UBV photometry rather than BVR, but good U-band measurements are quite difficult to obtain and in fact are impossible from our meager site atop Robinson.

Distance: Next make a diagram of V vs B-V and V vs V-R. Again plot the standard sequence of M_V vs B-V and M_V vs V-R from the tabular material handed out in class. You will have to correct the observed data points for reddening using the above equations [$V_o = V_{observed} - A_V$; $(B-V)_o = B-V_{observed} - E(B-V)$; and $(V-R)_o = V-R_{observed} - E(V-R)$]. As above, you then want to determine the mean shift between your de-reddened color-magnitude diagram and the standard color-magnitude diagram M_V vs either $(B-V)_o$ or $(V-R)_o$. This shift will be in the vertical direction only, as opposed to the previous shift where both axes were involved. Note that the upper main sequence may not line up exactly with the main sequence you have plotted. This is because this particular cluster is old enough that some of the more massive stars have already begun their evolution away from the hydrogen-burning main sequence. So you should determine the offset between the observations and the Zero-Age Main Sequence (a.k.a the ZAMS) over a range in color where the match-up in slopes looks pretty good. It is possible that this step may not go well if your data do not go deep enough into the main sequence. However, there is still hope. NGC 7790 contains 3 Cepheid variables, a class of pulsating star whose relationship between pulsation period and M_V forms the basis for the extragalactic distance scale. Unfortunately two of these are very close together ($\theta=2.3''$) and likely unresolved in the rooftop images. Check the finding chart on the last page of this writeup to identify the cepheids. Then, using the relationship $M_V = -2.82 \log(\text{period}) - 1.34$, you can use your measured V magnitudes (corrected for extinction!) and the periods for CEa Cas (5.14087 days), CEb Cas (4.47928 days), and CF Cas (4.87522 days) to calculate the average value of $V_o - M_V$ for these 3 cepheids. There is some amount of error associated with this procedure since the cepheids are variable by definition and you are using only 1 measurement as representative of the mean magnitude; nevertheless, your answer for the distance modulus from this method should be right to about 0.5 mag. You should compare the cepheid value to the value you may or may not be able to get from the ZAMS fitting. Recall that the mean value of $V_o - M_V$ is called the distance modulus. Once you know the distance modulus you can convert to a distance in parsecs.

Age: Finally, you can approximate the age of cluster by identifying the luminosity at which the stars begin to deviate from the ZAMS (you will have to convert M_V into L). You then need to use the expression $\tau = \text{energy} / (\text{energy per time})$ or $\tau \approx 0.007 \times 0.1 \times M_* c^2 / L_*$ (where the constants represent the fact that 0.7% of the rest mass is turned into energy during hydrogen fusion and only 10% of the total mass of hydrogen is consumed before other more rapid evolutionary processes begin). You also need to estimate the M_* corresponding to the observed L_* at the main sequence turnoff by employing an appropriate mass-luminosity relationship.

Analysis “how-to’s”: The process of deriving the distance modulus is often described in terms of sliding the measured main sequence up until it matches the ZAMS, with a similar process for reddening. This is okay for amateurs – and even some astronomers do this. It’s also good enough for this Ay20 exercise though you should feel free to do better using least squares fits. If you do, you will need to produce a mathematical function that describes the ZAMS by fitting the sparse tabular data with a polynomial fit. You also need to decide which is the independent variable for your fit, most correctly by considering whether it is the reddening or the apparent magnitude that is determined with less error. You face similar considerations when deriving the extinction from the color-color plot. *It is not required that you use least square fits.* Whatever technique you use, make sure you consider both random and systematic errors! Also note that you are going to have to discard a lot of data points, in particular, all those field stars which are probably clouding up the main sequence! Subjective judgement is best; feel free to ask for help.

There are many published papers on the cluster NGC 7790. You might look up on NASA/ADS (http://adsabs.harvard.edu/abstract_service.html) those by Sandage (1958; ApJ 128, 150) – a classic – Romeo et al. (1989; MNRAS 240, 459), and Gupta et al (2001; AAS 145, 365) – all nice papers with the latter going as faint as $V=21$! These should be used as guides as to what your diagrams should look like and what the approximately correct answers for the reddening, distance modulus, and age are. Note the dispersion in conclusions between these various authors!

4. Assignment

A 2-3 page write-up of your activities at the telescope and your analysis of the data obtained on NGC 7790 is due by 7 December, the last day of classes. It really is best if you don’t procrastinate on this project. We would like to stagger observing sessions through the term to avoid problems with weather (more likely the later it gets in the year). The TAs will arrange the observing sessions and help with the initial data reduction. The analysis can be done either in groups or individually, as you wish. You can probably start on the analysis the same night you take your data. But the full set of steps may require multiple trips to the Robinson PC until you are happy with the results of the photometric extraction. The subsequent analysis can be done using your favorite plotting and analysis software elsewhere on campus.

Be sure to include in your report all relevant plots you have made, and the mean values that you derived for the extinction (A_V) and the distance modulus ($V_0 - M_V$). What is the cluster distance in parsecs? If the sun, a G2/V star, were located in the NGC 7790 cluster, what would its apparent magnitude be? Could you have seen this solar analog in your rooftop data? Also comment on the observed distribution of stars in NGC 7790 compared to the “zero age main sequence” and estimate the cluster age if you think your data are good enough to take this final step. Discuss sources of error at all relevant stages.

Since this is not a lab class I do not have any formal requirements on report format. A

clearly written and detailed summary is all I am looking for. And do tell me who else was in your observing group when you acquired the data. This assignment will carry a weight of several times a single homework set.

