Physics 344 Lab 6
Stellar Photometry and the Color-Magnitude Diagram

Observing: November 9 - 14
Due: Instrumental CMD on Wednesday, November 21; whole lab on Thursday, November 29
Text Reference: Chapters 7 & 10

Purpose: The color-magnitude (or Hertzsprung-Russell) diagram is the observational tool that leads to understanding stellar properties, structure, and evolution. In this lab we will determine the B and V magnitudes for stars in the open star cluster M34. We will use these data to construct a color magnitude diagram, determine the cluster's distance, and estimate its age.

Completely clear nights are rare in New Jersey. This introduces the problem that the images taken with the same exposure time and filter differ in their sky levels and in how bright the stars are. This makes combining these images somewhat tricky since they should be adjusted to have equal sky values and star brightnesses before being averaged. Instead, we will take the approach of photometering each image individually and then adjusting and averaging the measured instrumental magnitudes.

To reduce the amount of manual labor involved in measuring several images, you will use the software package *DAOPHOT*, which is able to identify all of the stars in an image, perform aperture photometry on them, and then measure the average shape of a star in the image (the *point-spread function* or psf). The program *allstar* will then estimate magnitudes for all the stars by performing a fit of the psf to the image of each star.

I. Preparation and Planning:

We will observe the open cluster M34. We will take images in two, overlapping fields to increase the number of stars measured.

1. Use *The Sky* running on a computer in the classroom or dome to determine whether M34 will be east or west of the meridian during your observing session. Zoom in on M34 and identify a 7^{th} – 8^{th} magnitude star within a few degrees of the cluster that you can use to focus with. Actually, you can find a star within the cluster that satisfies this requirement.
2. Zoom in further with *The Sky* at the location of M34 until you can see the red rectangle that is the "footprint" of the CCD camera field of view on the sky. Click on the rectangle to select it and adjust its position angle to 90 degrees if you will be observing east of the meridian and 270 degrees if you will observing west. Identify two 10^{th} magnitude or brighter stars that you can place in the guide CCD and so that the field of view of the main CCD will cover most of the cluster with 30-50% overlap between the two fields. Plan how you will get your "guide star" into the field of view of the guide CCD. For example, identify a star that placing near the center of the main field will place the guide star in the guide CCD.

3. With the positions of your two fields of view with the main CCD determined, find the brightest star in each field. When taking your shortest-length exposures, you will want to check this star to be sure that it is not saturated.

II. Observations:

1. Initialization

a. Cool the CCD to the lowest practicable temperature (−20°C or cooler, if possible), and allow the temperature to stabilize for at least 10 minutes. In the meantime, open the telescope and dome, home the telescope and initialize the pointing using a bright star in the eastern sky. Set the telescope focus to a value calculated by increasing the focus value from 2.350 mm by 0.100 mm for every 5°C *decrease* in the temperature from 20 C.

b. Set up autosave to save your images in a subdirectory named with the date and your initials in /home/ph344/lab6.

2. Focus

a. Point to the star which you want near the center of the field of view. Position the star so that it is near the center if it is not there already and sync the telescope again.

b. Set the binning to 1×1 and take a 5 second test exposure using the V filter. Find your focus star in this image and ensure that it is NOT SATURATED (peak intensity less than about 50,000). Select a box around that star and use this "subfield" to take the usual sequence of 7 focus exposures, all of 5 second exposure time, centered on the estimated best focus and using steps of 0.050 mm between exposures.

c. Examine these 7 images with the IDL program *RUPhAst*, measuring the FWHM of the star in each using the radial profile routine (left mouse-button in the *ImExam* mouse mode). There should be a clear minimum, and the best value may be between two of the sampled positions. Set the telescope focus to this optimum value.

d. The focus should be the same in the B filter. If the temperature changes significantly, you may need to adjust the focus using the prescription in part 1a. If the telescope crosses the meridian to the other half of the sky, you may need to refocus.

3. Cluster Observing

a. Adjust the pointing of the telescope until your first guide star is visible in the guide CCD. Set up and start the autoguider. Use autoguiding for all of the exposures on the star cluster.

b. Set the filter to V, and select full frame readout with 2x2 binning, and reduction mode to *Autodark*. Make sure that you have set the telescope focus to the best focus value that you determined in step 2 above. Take a test exposure of 7 seconds and check that the brightest star in your field is not saturated. Decide if you need a slightly shorter exposure or if you can use a longer exposure and still keep the brightest stars with a peak signal below 50,000 ADU.

c. Set up a delay between exposures that is long enough for at least two autoguider cycles. Take one exposure with a 7-second exposure time (or whatever you chose) in both the V and B filters. Then take one of 45 seconds in both V and B and one each of 300 seconds.

You will probably lose the guide star during the first 300-second autodark exposure. Abort the guiding and restart it. If you want, you can use motion controls to move the guide star back close to its original (x,y) location in the guide image (I found that the telescope needed to be moved 15 arcseconds east).

d. Move to your second field and start auto-guiding. Repeat part 3.c in this new field.

4. Dome Flat Fields
   We will obtain flat-field images as before, except in two filters.

a. Once you are done taking data of M34, home the telescope and then manually point it at the inside of the dome. Using the procedure from Lab 4, take 7 well-exposed flat-field images of the inside of the dome with the white lights on with the V filter and another 7 with the B filter. Use 2×2 binning and Auto-dark subtraction.

b. Finally, cover the telescope and shut everything down. Remember to fill out the log.

III. Data Analysis − Photometry:

1. Copy your data to a working directory in your home area, and only work on the copies, not the original images.
2. Combine your 7 V-band dome flats, using the IDL program *mkflatru*, and save the image as FlatV.FIT. Similarly, combine the B-band dome flats and save the image as FlatB.FIT.
3. Process each of your images of the cluster using the *Calibration* (NOT *Batch calibrate*) item in the *Pipeline* menu of *RUPhAst* program. Use the FlatV.FIT image as the flat-field image for each of the V images, and the FlatB.FIT image for each of the B images. You will save much typing later if you give your output files simple names like M34v7-010.fits. Note the dash between the base name and the sequence number and also the change in the file extension from .FIT to .fits – these changes are necessary to get later programs to recognize these files.
4. Use *RUPhAst* to examine the processed images and compare them to the raw images to see what the effects of the processing were. Use the aperture photometry tool to measure the FWHM of a few unsaturated stars in each image. Record these values.
5. It will make your life easier to create another subdirectory and move your calibrated files into it. Also copy the files daophot.opt, photo.opt, and allstar.opt from /home/ph344/lab6 into this subdirectory. These contain default values for various parameters used by the *daophot* and *allstar* programs.
6. If the worst (i.e. largest) FWHM for the stars in your images differs by more than a few pixels from the value of 4.0 in the daophot.opt file, you can edit in your value. But the default value should generally be OK. This value is used only in finding the stars in the images.
7. Open a terminal window and change the default to the directory with your calibrated images (i.e., something like: cd lab6/proc). Then type the command *daophot*. The program will begin by showing the values it is using for various parameters and then give

the prompt “Command:”. At this prompt issue the following sequence of commands for one of your calibrated images with your shortest exposure time. You will eventually do this same sequence for each of your calibrated images.

a. attach M34v7-010.fits (use the name of one of your images)
b. find
    i. the number of frames averaged, summed is 1,1
    ii. use the default file name for positions (just hit the return key)
    iii. a long list of stars found is typed out; answer “y” to “Are you happy with this?”
c. phot (does aperture photometry)
    i. hit return to accept the default photo.opt file
    ii. You could edit the aperture radius and the inner and outer sky annulus radii at this point. Use the default values read from photo.opt by just hitting return again.
    iii. Hit return again to accept the default input file of star positions.
    iv. And again to accept the default ouput file name. Instrumental magnitudes for many stars will appear on the screen (and be saved in the output file).
d. pick (picks stars used to generate the psf)
    i. Hit return to accept the default input file.
    ii. Use 30, 99 for the desired number of stars and faintest magnitude.
    iii. Hit return to use the default output file.
e. psf (actually generates the psf)
    i. Hit return three times to accept the default names for the files with aperture photometry, the list of psf stars, and the ouput psf.
    ii. The program types out simple representations of the brightness distribution around the stars. Answer “y” to use each isolated star in the psf and “n” for any stars that have companions. (You may need to increase the vertical extent of the terminal window to see the entire plot for each star.)
    iii. After accepting or rejecting the 30 stars, the program tries fitting six different functional forms for the psf and uses the one that gives the best fit. It then types out a measure of how well each star matches the adopted psf and flags those with larger errors. Usually the stars with larger errors reflect the actual variation of the psf across the image (we are using a constant psf for the whole image) and so we want to include these stars in the generation of the psf to get a representative average.
f. exit (returns to the unix prompt)

8. Issue the command *allstar* at the unix prompt.

   a. Hit return to accept the default parameters (read from allstar.opt).
   b. Type the name of your image, i.e., M34v7-010.fits.
   c. Hit return four times to accept the default names for the files containing the psf, the aperture photometry, the output psf-fitting photometry, and the file containing the "subtracted" image. This last is the input image with the psf fitted to each star subtracted.
   d. The program prints out its progress and finally exits, leaving the output psf-fitting photometry in an "als" file, i.e., M34v7-010.als

9. Load the image and its "subtracted" counterpart (i.e., M34v7-010.fits and M34v7-010s.fits) into ruphast. Comment on how well the stars have been subtracted by allstar.
10. Repeat steps 7 – 9 for each of your calibrated images.
11. At the unix prompt, type the command *daomatch*. This program begins the process of matching stars in the different images by looking for congruent triangles among the 30 brightest stars in each of two files of photometry. The cross-identifications are used to estimate the transformation that predicts the coordinates at which a star should appear in the first image from its coordinates in the second and later images. You will run this program to match first your V-band images with different exposure times and then your B-band images.
    a. Enter the filename of the "als" output of one of your V-band images as the "master input file" (i.e., M34v45-010.als). It is best to use an image with the intermediate exposure time since that will maximize the number of stars in common with both the shorter and longer exposures.
    b. Choose a name for the output file that will contain the approximate coordinate transformation between the different frames based on the matched stars. Something like M34v.mch is a reasonable choice.
    c. Continue entering the names of the "als" output files of the rest of your V-band images in both fields. When done, hit return to exit.
12. The program *daomaster* finishes the matching by using the initial coordinate transformations to calculate the positions of the stars in all of the images in the coordinate system of the first image and then matching stars in the different images whose predicted coordinates in the first image agree within a specified tolerance. These new matches are used to refine the coordinate transformations between images. Start the program by typing daomaster at the unix prompt.
    a. Input the name of the output file produced by *daomatch*, i.e., M34v.mch.
    b. The program then asks how many images a star must appear in in order to make it into the final matched list. Requiring a star to be present in more than one image eliminates spurious detections caused, for example, by charged particles (cosmic rays) passing through the CCD. However, the faintest stars may only be detectable in the images with the longest exposure time. In line with these points, require that stars be detected in at least one images and so respond to the query "Minimum number, minimum fraction, enough frames" with: 1, 0.16, 1.

c. The program allows the imposition of an upper limit on the uncertainty of the average magnitude of a star. Use a "maximum sigma" of 0.2, which will reject stars whose brightness is uncertain by more than about 20%. Such stars contain little information in the color-magnitude diagram.

d. The next choice is the form of the transformation between the coordinates in different images. Because our telescope and camera do not introduce much distortion, use a choice of 2, which allows just simple Δx and Δy offsets between the frames. I have experimented with the different choices and concluded that a more complex linear transformation is unnecessary.

e. The "critical match-up radius" is how well the coordinates from different images must agree to accept two stars in different images as being the same star. Use a value of 3 (the value is in pixels). The program then prints a line for each image that gives the root-mean-square scatter around the average position in x and y for the matched stars in that image, the nearest integer to the Δx and Δy (I don't know why the nearest integer), the median difference between the magnitude system of that frame and that of the first frame, the uncertainty in that difference, the number of matched stars in that image, the number of coefficients in the coordinate transformation (2), and the name of the "als" file.

f. Keep inputting a "critical match-up radius" of 3 until the number of matched stars stops changing. Then enter 0. The final rms coordinate difference should be less than or equal to about 0.5 pixel – I chose the match-up radius of 3 to be around 5 times the rms in order to account for the presumably approximately Gaussian distribution of position errors and for the fainter stars having less accurate positions than the average star. The DAOPHOT/ALLSTAR magnitudes do not take the different exposure times into account (unlike the magnitudes produced by *RUPhAst*), so the typical magnitude difference between 7-second and 45-second images will be $2.5\log(45/7) = 2.02$ and between the 45-second and 300-second images will be $2.5\log(300/45) = 2.06$. (These magnitude differences will depend on your shortest exposure time, of course.)

g. Say "n" to assigning new star IDs. The program then asks whether to create a series of files. Say "y" to creating a file with mean magnitudes and scatter (placed in a file with a .mag extension – M34v.mag or M34b.mag is a reasonable choice, depending on which filter you are working on), "y" to saving the new transformations (overwrites your original .mch file), and "n" to the rest. The file of mean magnitudes contains two header lines followed by one line per matched star that contains: ID number, x and y position in the coordinate system of the first image, the average magnitude and its uncertainty, the uncertainty in the magnitude in a single frame based on the scatter of the measurements around their mean, the number of images in which the star appeared, the average chi-square per degree of freedom of the fit to the psf, a measure of whether the star is more or less peaked than the psf (an index called "sharp"), the ratio of the "external" uncertainty of the magnitude (based on the scatter around the mean magnitude) to the "internal" uncertainty (based on the uncertainties calculated by ALLSTAR for the individual measurements), and a "blunder index" that is the fraction of the magnitude residuals that are positive (should be about 0.5). For this lab we will just use the average magnitude and its uncertainty.

13. Repeat steps 11 and 12 for your B-band images.

14. The final step in producing instrumental magnitudes is to match the B- and V-band photometry. Again run *daomatch* using your V-band "mag" file as the first file and the B-band "mag" file as the second file. Call the "mch" file something like M34bv.mch to avoid overwriting the file produced by matching all of your V-band images. Then run daomaster with the M34bv.mch file as input. We now want only stars with photometry in both bands, so "minimum number, minimum fraction, enough frames" should be 2, 1.0, 2. Again use a maximum sigma of 0.2 and translations only. Input a matching radius of 3 until the number of matched stars stops changing. Assign new star IDs (renumbers the stars in order of increasing x-coordinate) and answer "n" to the creation of all files except for a file with the raw magnitudes (which will have a .raw extension; since the B and V magnitudes are different there is no reason to try to correct them to be the same) and overwriting the file with the new transformations. The "raw" file has for each matched star: ID, x and y position in the V-band image, the average V-band magnitude and its uncertainty, the average B-band magnitude and its uncertainty, the average chi-square, and the average sharp. Read this "raw" file into Excel or Calc, discarding the three header lines at the beginning of the file.

IV. Data Analysis – Transformation from Instrumental to Standard Magnitudes

To measure the distance and age of M34, the instrumental magnitudes and colors must be transformed onto the standard system. This accounts for the efficiency of our telescope, the sensitivity of the CCD camera, and the local atmospheric transmission at the time of observation. See chapter 10 of the *Observational Astronomy* text for a full discussion of this procedure. The relevant transformation equations are:

$$B - V = \phi_{bv} + \mu_{bv}(b - v)$$
$$V - v = \phi_v + \varepsilon(B - V)$$

Here lowercase v and b are the measured instrumental magnitudes, uppercase V and B are the transformed standard magnitudes, ϕ_{bv} and ϕ_v are the zero-points, and μ_{bv} and ε are the transformation coefficients.

1. As discussed in lecture, we are using stars in the M34 field with known standard magnitudes to determine the coefficients in the transformations. This greatly simplifies the procedure. Identify the stars listed in the table below that are in your medium-exposure V-band images using the attached finding charts and use the (x,y) positions to find these stars in your photometry. Some of the stars may fall outside of both of your fields. Stars that are outside of the first field used in the *daomatch*-ing, but in the second field, will have (x,y) positions in your spreadsheet that are in the coordinate system of the first field. In this case you need to find the coordinate offset, (Δx,Δy), for the other field using your M34v.mch file and add these offsets to the coordinates obtained by displaying the image of the second field. Copy the lines for the stars from Table 1 to elsewhere in

the spreadsheet and add the standard V and B−V from the table. The B and V magnitudes are drawn from the photoelectric aperture photometry of Johnson (1954, ApJ, 119, 185) and Cester *et. al.* (1977, A&A Suppl., 30, 227). When both studies measured the same star I generally used the weighted means from *Catalogue of Homogenous Means in the UBV System* (Mermilliod, 1991, Institute d'Astronomie, Universite de Lausanne). The uncertainty in the V magnitudes of the brighter stars is typically about ±0.01 and for B−V about ±0.005. The uncertainties for the fainter stars may well be ×2 − ×3 larger. Johnson estimated that his photometry was tied to the standard system with an accuracy of ±0.01 magnitude in V and ±0.005 magnitude in B−V. It is very difficult to establish this tie more accurately than that. Cester *et. al.* tied the zero point of their photometry to that of Johnson, rather than independently determining it.

Table 1. Standard B and V Photometry

Star	V	B	B − V
SAO 38219	9.656	9.687	0.031
SAO 38221	9.466	10.014	0.548
GSC 2853:852	10.090	11.150	1.060
SAO 38229	8.472	8.532	0.060
GSC 2853:61	11.210	12.298	1.088
GSC 2853:1140	11.210	11.551	0.350
SAO 38237	8.980	8.982	0.002
GSC 2853:460	11.130	12.176	1.046
SAO 38243	8.520	8.521	0.001
SAO 38244	8.460	8.468	0.008
SAO 38248	8.330	8.324	-0.006
SAO 38254	7.920	7.932	0.012
SAO 38255	8.800	8.860	0.060
SAO 38256	9.300	9.353	0.053
GSC 2853:1178	10.960	11.914	0.954
GSC 2853:1628	10.970	11.982	1.012
SAO 38268	7.330	8.274	0.944
SAO 38271	8.260	8.270	0.010
GSC 2853:1141	10.598	11.144	0.546
SAO38284	8.899	8.888	-0.011

2. Make plots of V – v vs. B – V and B – V vs. b – v for these stars. Fit a straight line to each plot using least-squares in order to determine the four coefficients. The star SAO 38254 is a known binary with a separation of 1.4 arcseconds and a position angle of 55°. This separation is so small that *daophot* only finds the pair as a single star – though the subtracted image shows that the fit to a single psf leaves large residuals. The two stars have V = 8.5 and 9.2 and the B and V magnitudes listed above are for the combined light

of the two stars. Aperture photometry would yield a magnitude for the combined light of the two stars, but the psf-fitting photometry of *allstar* may not. If the photometry for SAO 38254 seems discrepant in your estimate of the transformation, you can exclude it from the determination of the coefficients.

3. Use your values for the four coefficients and the above equations to correct ***all*** of your instrumental magnitudes to standard V and B – V.

4. A further correction is needed to account for the interstellar absorption, called "extinction" by astronomers, along the line of sight to this cluster. The amount of this absorption is traditionally expressed with a single number: the color excess (or "reddening"), $E(B-V) \equiv (B-V) - (B-V)_0$. Here the quantities with a subscript 0 are the extinction-corrected magnitudes. Describing the extinction with a single number implicitly assumes that the dependence on wavelength is the same for all lines of sight. This is not true, but is nearly so when the extinction is small and when considering optical and longer wavelengths. Then the extinction-corrected magnitudes are:

$$V_0 = V - 3.1\,E(B-V)$$

$$(B-V)_0 = (B-V) - E(B-V).$$

The factor 3.1 is an empirical quantity that characterizes the average absorbing properties of dust in our Galaxy. There is some uncertainty in the color excess towards M34, with values of $E(B-V)$ ranging from 0.07 to 0.10. The most recent determinations use the value of 0.10, so use that value and correct your data for interstellar absorption.

V. Data Analysis – the H-R Diagram:

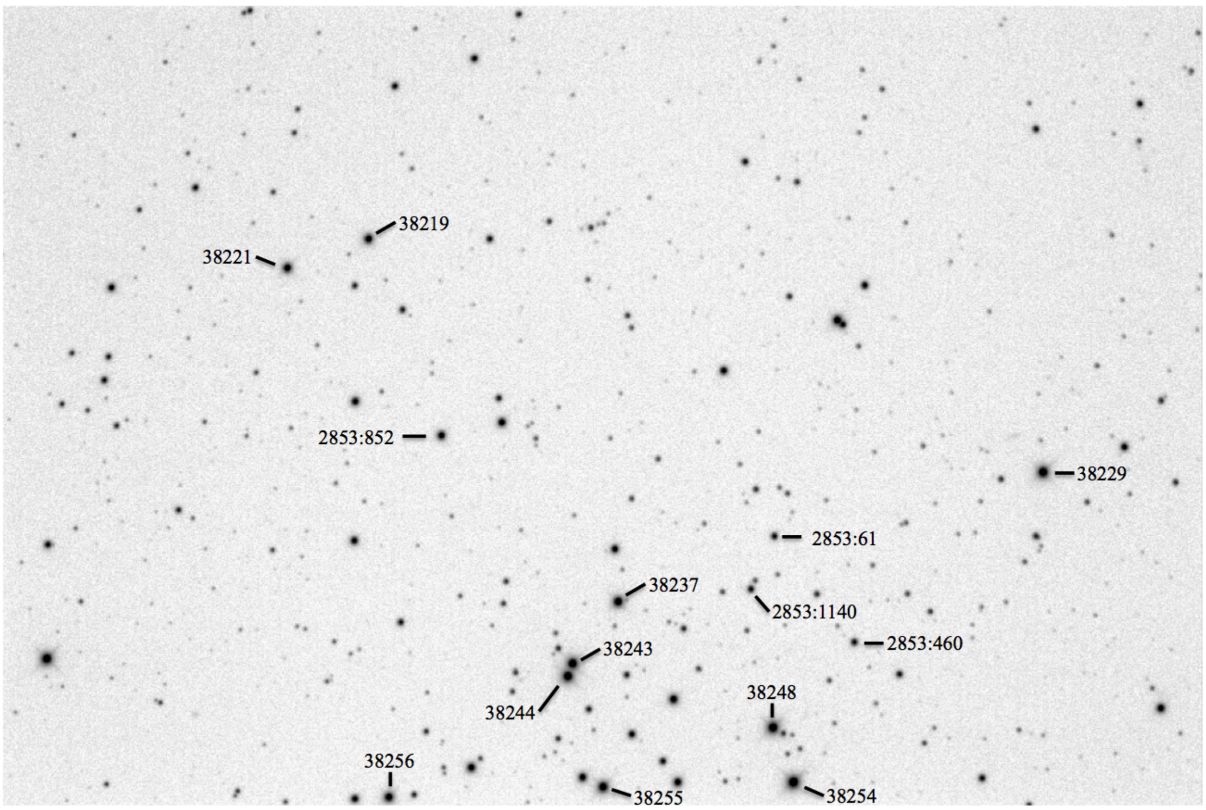
1. Plot your V_0 magnitudes versus the $(B-V)_0$ color for each of your stars, with the associated error bars. Be sure to arrange the axes in the style of a standard H-R diagram (bright, blue stars in the top left corner). Describe the features of the diagram that you see.

2. Import the data from /home/ph344/lab6/isochrones.xls to your spreadsheet. These data are the absolute V magnitudes (M_V) and $B-V$ colors for stellar models of various masses at fixed ages, with ages ranging from $10^{6.6}$ to 10^{10} years in steps of 0.2 in *log(age)*. These isochrones are derived from stellar models calculated with PARSEC (PAdova and Trieste Stellar Evolution Code). The models include many bells and whistles including mass loss due to stellar winds on the giant branch. The latter is the reason that the upper end of the very young isochrones does odd things. See Bressan et al. 2012, Monthly Notices of the Royal Astronomical Society, 427, p. 127 for a detailed description of the models. The isochrones (and many other things) can be downloaded from http://stev.oapd.inaf.it/cgi-bin/cmd. Once you have the isochrones in a spreadsheet, add a column that is the M_V column of the $10^{7.8}$ year old isochrone plus the contents of a particular cell, which will contain the distance modulus (use the cr notation to specify the cell at fixed column c and fixed row r). Plot this column and its associated B−V on your H-R diagram. Then vary the contents of the distance modulus cell until the shifted isochrone fits your data well over the main sequence bluer than B−V = 0.0, i.e., ignoring possible deviations at the top of the main sequence caused by the age of the cluster.

Calculate the distance (in parsecs) to the cluster, and estimate its approximate uncertainty from the range of distances that produce acceptable agreement with the data.

3. Modify your spreadsheet to plot isochrones of different ages, offset by your distance modulus from step 2, and determine which isochrone fits the data best. What is the age of the cluster and its approximate uncertainty?

M34 west   45 sec V-band image   North is to the left and east is down.



M34 east 45 sec V-band image North is to the left and east is down.