

# PHYSICS 157 Observing Guide

## Spring Quarter 2022

### TEAMWORK

Working in pairs or groups is quite common in science labs and in astronomical observing, and this lab is no exception. Teamwork can be quite effective; it's often possible to figure things out faster if you work with another person, and some experiments are much easier with two pairs of hands. Everybody on the team should be involved and contribute to the group effort. You are encouraged to compare your pre-lab exercises and observing timeline schedule (see below **Pre-Lab**) with other members of your team in advance. You should divide up the nighttime observing tasks as evenly as possible. While you will work with the same data, your data processing and analysis will be done individually. To ensure that everybody is involved, we require you to *use your own words* in writing up your results.

### OBSERVING

Your group will be assigned a number of observing nights [just like professional astronomy]. We will try to observe every night the weather seems reasonably good, and meet indoors only when bad weather rules out any kind of observation. This means that your group may have multiple attempts at an observing session. Do not be discouraged – this is the life of an astronomer!

Observing is like working on any experiment in physics – you must come with a plan, you must carefully manage your time, you must understand all your equipment before observing begins, and you must continuously check for systematic error while taking data. Come to the telescope with your observing plan for the night fully laid out. Allot needed time for each step: bias frames, flat field frames, zeroing the telescope coordinate system, calibration stars, object exposures. Check your images to see if they have the expected number of counts in the pixels that matter to you. When doing observational astronomy, patience is necessary. For example, the weather may be bad when we go out to observe. The best course of action may be to wait until conditions improve, or to try again another night.

### Safety

Astronomy is generally a safe activity. Unlike some science labs, we have little need for hazardous materials or equipment. We will be working outdoors at night, mostly in the dark (see note below re flashlights). You will be up on the roof of Hutchison Hall in the dark. Do not walk outside the catwalk and pathway guard rails. There is no guard railing at the edge. Follow your instructor's directions at all times. Stay inside the dome. There is enough room in the dome for up to 6 people, and chairs.

It is likely that you will be at the observatory during daylight, to test your equipment and familiarize yourself with its operation. There is one safety rule which must be emphasized, even though it may not seem all that relevant to this class: **never look at the sun through any telescope** unless you are using a professionally-designed solar filter! It's important that the filter

cover the **entire** aperture of the telescope and that it is securely attached and **can't** fall off by accident.

## Comfort

We will be observing outside at night for several hours at a time, and you should plan to dress appropriately. It can get cold in the evenings, and clothes which were comfortable in mid-afternoon will not keep you warm enough at night. Wear loose-fitting warm clothes you can move around in easily, and bring a sweater or jacket. Other than a light snack such as trail mix and water, do not bring food to the dome.

## EQUIPMENT

Below is a summary of the equipment you will be using. However, before going to the observatory you should read carefully the descriptions of each component of the instrumentation which have been uploaded to the 157 webpage for this observing project. Be particularly familiar with the CCD Camera, the filters, and the software.

1. **14-inch Celestron Reflecting Telescope.** This is robust and simple to operate. It is controlled by *TheSkyX Pro* software from Software Bisque.
2. **Apogee U-6 1024x1024 pixel CCD camera.** This is a research grade CCD camera with a filter wheel attached with 7 filters, 4 broadband and 3 narrowband. The broadband filters cover the spectral range 4000 – 9000 Angstrom in four filters B, V, R, I. The three narrowband filters are used for emission line imaging: H-alpha, Oxygen-III, Sulfur-II. The camera images an area of approximately 24x24 arcminutes.
3. **Precision fork mount, computer controlled.** This is a professional observatory fork mount, drive, and controller. It is interfaced with the telescope software package.
4. **Observing Flashlights.** Ordinary flashlights are too bright to use while observing, and white light temporarily impairs your ability to see faint stars. We will use special red LED flashlights when observing.
5. **Observing software.** *TheSkyX Pro* by Software Bisque, which controls the CCD camera as well as the telescope.
6. **Dome.** The telescope dome is atop Hutchison Hall and is accessed via the east elevator to the 5<sup>th</sup> floor, then up to the roof, and special keys that the instructor will have.

You will need to bring a few things:

1. Your lab book.
2. Pen.
3. Warm clothing. It gets cold at night.
4. A scientific calculator.
5. A small flashlight for getting around outside the dome.

## PRE-LAB ASSIGNMENTS [Warning: this will take you at least a day]

**Part 1.** Read and understand Chromey chapters 5, 6.1-6.2, 8, 9, and 10. **Do exercises 6, 7, and 8 at the end of chapter 9** (first edition; = exercises 5, 6, 7 in second edition). These exercises are transcribed below for convenience.

9.6. On a 20-second exposure, a star with magnitude  $B=15$  produces an  $\text{SNR}=100$  signal with a small telescope/CCD combination. Assuming this is a photon-noise limited case, how long of an exposure should be required to produce the same  $\text{SNR}$  for a star with  $B=13.6$ ?

9.7. A star with  $V=21.0$  is known to produce a count rate of 10 electrons per second for a certain telescope/detector combination. The detector read noise is 4 electrons per pixel, and the dark rate is zero. Compute the exposure time needed to reach a  $\text{SNR}=10$  under the following conditions:

(a) dark sky and good seeing: aperture radius = 3.5 pixels, sky brightness = 1.4 electrons per pixel per second;

(b) moonlit sky and poor seeing: aperture radius = 5.0 pixels, sky brightness = 4 electrons per pixel per second.

9.8. A certain CCD has a gain of 2.4 electrons per ADU, a read noise of 7 electrons per pixel, and a dark current of 2.5 ADU per pixel per second. In the V filter, the sky brightness averages 8 ADU per second. An astronomer wishes to observe a nebula whose average brightness is expected to be 7 ADU per pixel per second over a digital aperture area of 100 pixels. Compute the expected  $\text{SNR}$  for measurements of the nebula's brightness on exposures of (a) 1 second, (b) 10 seconds, and (c) 100 seconds.

**Part 2.** Sketch a color-magnitude diagram of an old globular star cluster. Label the following features on the diagram: (i) main sequence, (ii) red giant branch, (iii) horizontal branch, (iv) white dwarfs, (v) main sequence turnoff point.

Explain how you can determine (a) the distance to the cluster, and (b) the age of the cluster, using features in the diagram.

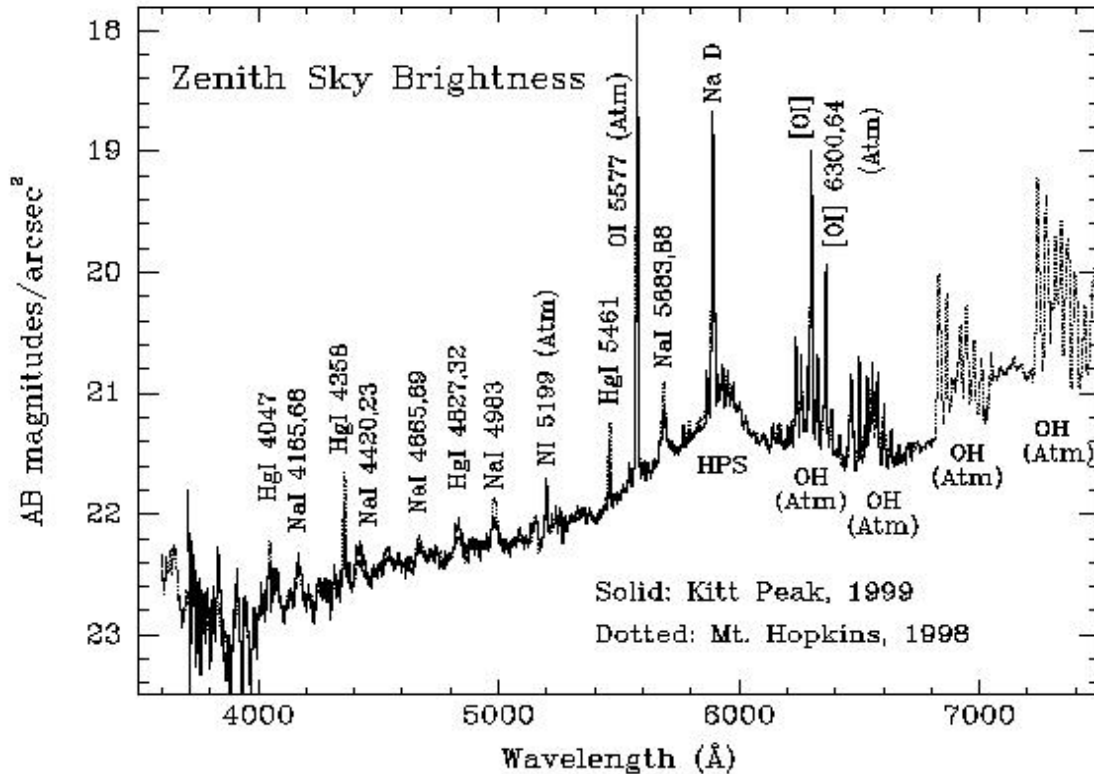
**Part 3.** Develop a *schedule of observations* for CCD exposures needed to determine the distance and age of the globular star cluster Messier 13 (object and calibration exposures, when to take them, what filters to use). Estimate the required exposure time so that you obtain sufficient signal-to-noise (S/N) in each filter. In a long exposure, most of your noise will come from the variance of your night sky photon flux. You must also flux-calibrate your observations: do not forget to include exposures of photometric calibration stars in all filters which you are using. To estimate the required exposure, you need to know the flux of photons per pixel from your object, the flux from the background sky, and the read noise of the CCD. This estimate of the required total integration time, given your estimated S/N, is critical. This is always part of an observing proposal to an observatory; you must show that you can achieve your science goals with the instrumentation available and the background noise (discussed below). Put all of this in your lab

book, and when you write your report, describe this planning and show the calculations. *Print a copy of your observing timeline, discuss it with your team, and bring it with you to the telescope!*

For a rough estimate of the photon flux from an object of apparent magnitude  $m_V$  in the V band, you can use the approximation that a 6<sup>th</sup> magnitude star produces about  $10^6$  photons per second at the focal plane of a 6-inch diameter telescope. Scale to your 14-inch telescope. Divide by 2 for a rough correction due to the ~50% quantum efficiency of your detector. If you are imaging a diffuse source such as a galaxy or nebula, or a star whose image will typically span multiple pixels, then you need to estimate the effective number of pixels this flux will be spread over, and correct the photon flux per pixel for this dilution. This should yield an estimate of the number of photo-electrons per pixel per second. You then must convert to ADUs (analog-to-digital units) because the output of the camera is digital data. For this, you need to know the so-called *gain* of the camera electronics. For our Apogee U-6 CCD camera this is 1.4 electrons/ADU. Dividing by this gives you an estimate of the *signal* in ADU counts per pixel per second.

You must also estimate the *noise* per pixel, in order to calculate your S/N. The noise will likely be dominated by the relatively bright night sky, even if the moon is down. (Note that you may wish to avoid observing in broadband filters in bright moon.) Night sky brightness is normally expressed in units of magnitudes per square arcsecond (a measure of surface brightness). So you will have to convert to magnitudes per pixel, and then to electrons and ADU per pixel per second as above. This is your sky background level per second in that filter (the sky brightness varies with wavelength; see below). Then multiply by the integration time in your individual exposures. Since these photons are arriving randomly (i.e., they should obey Poisson statistics), your noise per exposure is then the square root of this sky count (in units of electrons). Finally, then you can estimate the total integration time to reach a desired S/N using the knowledge you gained in your photon counting statistics lab. Signal increases in proportion to integration time, and of course the noise increases as the square root of integration time since it is a random process. All the above is described in Chromey.

Below is a dark night sky spectrum. Beware that your sky can be brighter due to campus lighting and moonlight. 19<sup>th</sup> V magnitude per square arcsecond sky surface brightness is typical at the UC Davis site. There is a portable meter in the dome.



*Knowing what to expect.* Finally, before heading to the telescope, you must prepare an observing chart showing what objects are in and around your selected field in the sky. To do this you can enter the name or coordinates of your object and the size of your field of view (about 24 arcminutes) into the astronomical database GUI: <http://ned.ipac.caltech.edu/forms/byname.html>

You can view an image or -- better -- download a FITS format image which you can display and manipulate using (for example) ds9 (free download from <http://hea-www.harvard.edu/RD/ds9/>) as well as your own python image processing code. Become completely familiar with this image processing well in advance of your data run.

## **OBSERVING PROJECT: analysis of the globular cluster M13**

Your observing project is to study the globular star cluster Messier 13 (or M13 for short, also known as NGC 6205 or the Hercules cluster). The science you will pursue is to study the stellar population of this globular cluster with photometric analysis of many individual stars, examining features such as the red giant branch and horizontal branch to determine the distance to the cluster and its age. See the color-magnitude diagram examples below. You will construct color-magnitude diagrams for this cluster with multiple broadband filters (B, V, R, I) and use them to eliminate non-cluster members which fall off the expected evolutionary tracks, as well as make an estimate of the overall age of the star cluster by comparison to theoretical models.

**M13** coordinates and V magnitude: 16h 41.7m +36° 28' V = 5.7 16.6' Diameter

Stellar magnitude at the horizontal branch:  $V \approx 15$

Stellar magnitude at the main sequence turnoff:  $V \approx 18 - 19$

For purposes of pre-lab planning, required exposure times will likely sum to ~20 minutes or more per broadband filter. It is recommended that you take a number of 300-second exposures to reach the necessary total integration time.

You will need a variety of calibration exposures in addition to the M13 science exposures. Calibrations can be taken at any time in the night. Plan your observing session so that M13 is high enough in the sky when taking science exposures. Be alert for clouds; do not take data through clouds. After your eyes adapt to darkness you will be able to detect clouds by how they obscure the stars, and you can see them by reflected moonlight.

### **Instrument Signature Removal Calibration**

You will need to use CCD camera calibration images. On an observing night, you can do much of this system sensitivity calibration and systematics data collection while you are waiting for the sky to get dark:

1. Take at least ten “bias” frames [zero second exposure with shutter closed]. Some CCD cameras exhibit a low level repeatable systematic pattern due to the electronics clocking signals and electrical pickup. You will take the median average of these images during image reduction.
2. Take at least five “dark” frames [with shutter closed and telescope cover on]. You will use the median average of these to correct for the thermal current in your exposures. A good strategy is to take dark frames with the same exposure time as your science frames.
3. Take at least five “dome flats” with the telescope pointed at the dome screen – illuminated by the special projector. You will use the median average of these to correct for the pixel-to-pixel sensitivity variations. Check that your counts per pixel are not too high (else the CCD becomes non-linear), or too low (which would give you poor statistics). Exposure times can be adjusted to give about 5-10 times the night sky background counts that you have on your sky exposures (to get good statistics per pixel). You don’t want to divide your nice science data by a noisy flat field image!

### **Science Data Presentation**

Once you have preprocessed your images as discussed in class by subtracting a median bias and dark current from all the other images (including all your calibration and science exposures), and then dividing by your normalized flat field image, your data are ready for scientific analysis. You may have many exposures in a given color filter, and they may be dithered in position. First register and then co-add your good exposures into a final deep exposure, one for each band. Register by tagging a number of bright isolated stars in ds9 (or python) and using their x,y positions to measure offsets and shift each frame to the same position. Co-add these registered images by median filtering (average via median) to eliminate outlier pixel values (caused by cosmic rays, for example).

Include the following in your lab report:

- One or two color images of your processed M13 observations. For this you need three input “RGB” images of M13 (i.e., some combination of B, V, R, and I).
- Discuss the physics of your detector, S/N considerations including the effect of sky background, a table of data used (including both object and calibration exposures), and your data reduction process (instrument signature removal). Scientific writing style is very important. See examples in the “Observing Data and Info” folder on the experiment page:

[http://157.physics.ucdavis.edu/sites/157.physics.ucdavis.edu/files/files/Observing/file\\_folder.html](http://157.physics.ucdavis.edu/sites/157.physics.ucdavis.edu/files/files/Observing/file_folder.html)

## Measuring Star Fluxes

Read chapter 10 in Chromey on photometry. In this case you are performing photometry on stars (measuring flux in a small number of pixels). What you actually measure is the integrated flux in some (usually circular) aperture from your object, plus the underlying flux from sky emission, and possibly also underlying flux from other nearby objects (such as faint stars). You must subtract any such background within your photometric aperture. To measure the sky level you need to estimate its value in an area outside the region of your object. For isolated star photometry, it is best to use an annular region around the star (inner radius sufficiently beyond the tail of the stellar point spread function). Devote some thought to your choice of object and sky apertures. Be sure to correct for the different area of your sky annulus and star region.

For large numbers of stars you will want to use an automated routine. One widely used tool is called SExtractor (Source Extractor; Bertin & Arnouts 1996, A&AS, 117, 393). This has been implemented in python via the SEP package (Source Extraction and Photometry; Barbary 2016, JOSS, DOI: 10.21105/joss.00058), available here:

<https://sep.readthedocs.io/en/v1.1.x/>

As always when using automated software, you will need to do careful tests to ensure that your results and derived uncertainties are reliable.

## Photometric Calibration

To calibrate your broadband filter observations, you will need shorter exposures of “standard stars” (of known and nearly unvarying magnitude) taken before and after your science exposures. *Be sure to include this in your timeline plan.* The Landolt catalog can be found on-line, and there is a list of Landolt UBVRI calibration stars in the 3-ring binder in the dome. Another excellent option is Oke’s (1990) list of spectrophotometric standards:

[https://www2.keck.hawaii.edu/inst/common/oke\\_stds.html](https://www2.keck.hawaii.edu/inst/common/oke_stds.html)

See also the link to “Spectroscopic Calibration” on the Observing web page. For spring observing (April/May), you may want to use Feige 66 or perhaps the fainter Feige 67.

The goal of photometric calibration is to convert from instrument units (such as ADU or electrons/second) to physical units, such as erg/s/cm<sup>2</sup>/Hz or magnitudes. Note that there are many magnitude systems such as Vega and AB – be sure to specify which system you are using! You will need to do this for *each filter you are using*. In addition to standard stars, there are often a number of stars within the field of view for which magnitudes have been measured by other well-calibrated surveys such as SDSS (the Sloan Digital Sky Survey). You can use these to verify your calibration by identifying stars of known magnitude. The general approach of this calibration is to find the appropriate photometric zeropoint **Z** such that:

$$m = -2.5 \log_{10}(\text{Flux}) + Z$$

where **m** is the known magnitude of a standard star and **Flux** is the star flux measured from your data. By examining several such stars, you can determine the appropriate zeropoint and its uncertainty, and additionally check the uncertainty of your Flux (and magnitude) measurements.

One trick to identify stars of known photometry in your field is to open an image using ds9 and use the “Catalog Tool” (under the Analysis menu), although this requires astrometric calibration of your image. You can also identify stars and find their magnitudes interactively using online tools such as the SDSS Sky Server or the Legacy Survey Sky Browser.

## Extinction Corrections for Color and Magnitude:

There are a few points to consider when measuring intrinsic object magnitudes, as opposed to magnitude differences.

Recall that magnitude differences are given by:

$$m_1 - m_2 = -2.5 \log_{10}(F_1 / F_2)$$

where **F<sub>1</sub>**, **F<sub>2</sub>** are fluxes in the same filter. The *color* (or *color index*) of an object is defined as the difference in magnitude at different wavelengths (i.e., measured with different filters):



$$m_1 - m_2 = -2.5 \log_{10}(F_1 / F_2) + (Z_1 - Z_2)$$

where here we must also include the appropriate zeropoints for the two filters.

Points to consider:

(1) The atmospheric extinction changes as a function of airmass and wavelength. We generally try to observe close to the zenith, where extinction is minimized. Typical zenith atmospheric extinction values from Kitt Peak are B  $\sim$  0.3 mag, V  $\sim$  0.2 mag, R  $\sim$  0.15 mag, I  $\sim$  0.1 mag. The correct values for our UCD site can be found by observing a standard star at several zenith angles in all of the filters. However this is quite time consuming, and an alternative approach is to use the values for extinction coefficients in your filters from Palomar or Lick Observatory.

(2) There is interstellar extinction and reddening caused by dust grains within the Milky Way. This is described in terms of an overall extinction curve as a function of wavelength (see Carroll and Ostlie pages 402-403). Total extinction in the V filter is expressed as  $A_V$  (and similarly for other filters, e.g.  $A_B$  for the B filter), in units of magnitudes. The *color excess* is defined as the difference in extinction between two filters at different wavelength, often expressed as  $E(B-V)$ :

$$E(B-V) = A_B - A_V = (B-V)_{\text{observed}} - (B-V)_{\text{intrinsic}}$$

The ratio of total to selective (wavelength-dependent) extinction is expressed as  $R$ :

$$R = A_V / E(B-V)$$

and has a value of approximately  $R = 3.1$  within the Milky Way.

To determine intrinsic magnitudes of astronomical objects, you must correct for total interstellar extinction ( $A$ ) in each filter and color. Note that this cannot be determined from standard star calibrations (which are used to correct for atmospheric extinction only). Fortunately there has been careful work to map the extinction caused by Milky Way interstellar medium, and you can look up extinction data in NED (NASA Extragalactic Database): <http://ned.ipac.caltech.edu>

For M13, the color excess  $E(B-V) = 0.015$  magnitudes. (You should look up this value in NED or elsewhere, and cite the *original source*! Note that NED aggregates data from many different sources and includes links to the original papers.)

## Science Data Analysis

Your objective is to study the evolved stellar population of M13 by plotting color-magnitude diagrams, and identifying the different components of the diagrams. See the examples below. From this you can in principle determine the distance to the cluster and the age of the stars. Be sure to avoid the crowding in the cluster center where stars are not resolved. Your diagram will also contain some foreground field stars, so there will be scatter due to sample pollution.

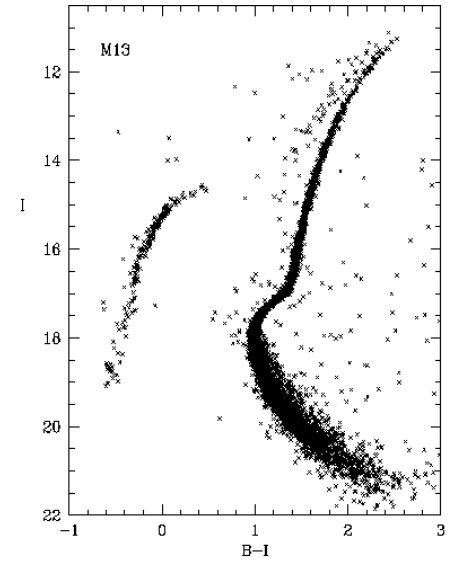
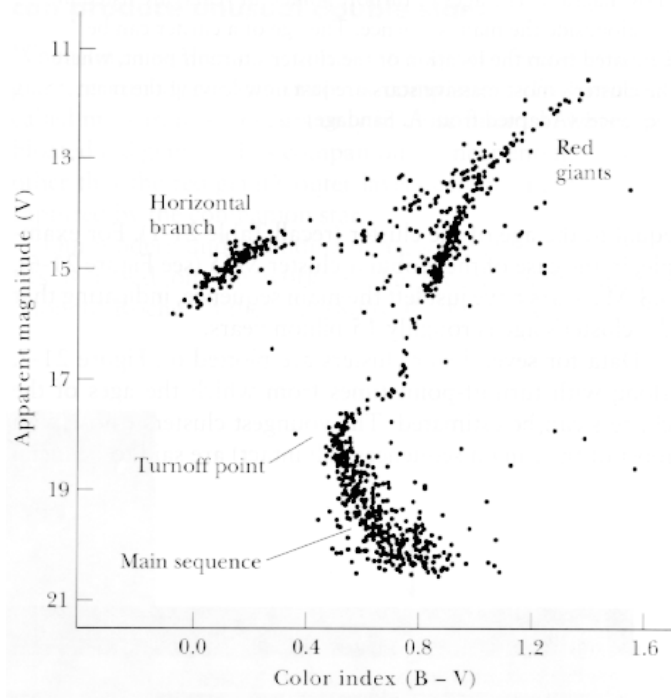
## Color-Magnitude Diagrams

(1) Plot both  $V$  vs  $B-V$  and  $I$  vs  $B-I$  color-magnitude diagrams. Can you identify the Tip of the Red Giant Branch, the Asymptotic Giant Branch, and the Horizontal Giant Branch? Is the exposure long enough to identify the Subgiant Branch and the Main Sequence Turnoff? How much longer would you have had to expose to clearly identify the main sequence? (Remember here that integrated flux is proportional to exposure time, while magnitude is proportional to log of the flux.) Try plotting diagrams with other filters as well, and identify which filter combination gives the clearest results.

(2) Look up the absolute  $V$  magnitude (or other filter) of a particular group of stars in the cluster that you can identify, and use this information to find the distance to the cluster M13. How does your value compare to the actual value (i.e., reported by other work)? Discuss possible sources of systematic error and how they might affect your distance value – making it larger or smaller.

(3) To the extent possible, estimate the age of the stars in M13. Explain the stellar evolution theory which allows you to determine the age of the cluster. Discuss possible sources of systematic error in determining the age, and any limitations in the data. Note that the position of stars in the color-magnitude diagram is dependent on their metallicity, in addition to their mass and age.

Various research groups have calculated theoretical stellar isochrones with which to compare your measurements. The Dartmouth stellar isochrone website is a good example where you can download these theoretical models: [http://stellar.dartmouth.edu/models/isolf\\_new.html](http://stellar.dartmouth.edu/models/isolf_new.html)



*Color-magnitude diagram for 6,624 minimally crowded stars in the field of M13.*

Color-magnitude diagrams for M13 using different filters. The Asymptotic Giant Branch (AGB) can be seen as the giants descend from the Giant tip but before the RR Lyrae gap. The Red Giant tip occurs at  $V \sim 12$ , the Horizontal Branch at  $V \sim 15$  and the main sequence turn-off at  $V \sim 18-19$  mag.

## References

As with all lab reports, you should include appropriate references to previous scientific papers. These can be found using the NASA ADS query form (*as you have done in Phy 151 and/or Phy 152!*): <https://ui.adsabs.harvard.edu/>

Classic paper: Baum et al. (1959) ApJ, 130, 749. "The Main Sequence of the Globular Cluster M13"

Images with different filters and instruments: [www.princeton.edu/~rvdb/images/NJP/m13.html](http://www.princeton.edu/~rvdb/images/NJP/m13.html)

Other papers on Photometry of M13:

Paltriniei, B. et al. (1998) MNRAS 239, 434. "CCD Photometry of the Globular Cluster M13"

Rey, So-Chang et al. (2001) AJ 122, 321. "CCD Photometry of the Classic Second-Parameter Globular Clusters M3 and M13"

Spectrophotometric standard stars:

Oke, J. B. (1990) AJ, 99, 1621

Data on Milky Way globular clusters:

<https://www.physics.mcmaster.ca/~harris/Databases.html>