Astronomy 337
Fall 2014
Final Project: Open Cluster Photometry and HR Diagram
Final report due Tuesday, Dec. 09

We now have in hand imaging data of a target open star cluster, NGC 7092 = M39, taken with the SBIG STXL6303 CCD on the Meade 16-inch telescope in V, R, and I filters on the night of 2 November 2014. We may add to this dataset with observations of a second cluster, weather permitting.

In this project you will:

1. Reduce the data;

   Reduced and stacked VRI FITS images due on 18 Nov.

2. Create a multiple-filter photometry catalog from those observations;

   Calibrated photometry catalog in IDL 'save' format due on 25 Nov.

3. Analyze these measurements using the famous Hertzprung-Russell (color-magnitude) diagram and find its age using the best-fitting isochrone for the target cluster.

4. Finally, present your results in a coherent, detailed writeup.

   Project report is due 9 Dec. We will also present the project results to each other in teams using Powerpoint slides.

You'll be using all the tools you've developed to reduce and analyze this original dataset. You should expect there to be more than a few challenges, hurdles, complications, and deviations from the roadmap given below. Work together (of course the work you hand in should be your own), consult with me or any other available resources as need be, and be creative in your approach to solving problems. And enjoy the privilege of having your very own data!

1. **Data Reduction**

   (a) Start by downloading all the data from the class Moodle webpage. A scanned version of the observing log is also posted on the Moodle page.

   (b) Note the binning (1×1 or 2×2) used for each dataset. Calibration files **with the same binning** must be used to reduce each dataset.

   (c) Reduce the V, R, I images in IDL starting with the CCD Data Reduction Guide and **keep a notebook** (paper or electronic) with a detailed record of every step, measurement, and conclusion you make in the process of reducing and analyzing your images. For median combination, try the ASTROLIB *medarr.pro* routine. As much as possible, make your IDL scripts and procedures fully automated so that they are easy to adapt, revise, and rerun on this or different datasets with minimal intervention by hand.

i. Make a master bias frame (use median combination, not average).

ii. Make a master dark frame (use median combination, not average).

iii. Make master flat fields for each filter used (use median combination, not average). Be sure to normalize (divide by its own median value) each flat before combining.

iv. Process all your data files with the master bias, dark, flat calibration frames that you made.

Examine the output of each step carefully and quantitatively, making sure the flux, noise, and appearance of the images make sense.

Of course we will make an HR diagram with just TWO filters (one color and one magnitude, e.g. $V - R$ *vs.* R or $V - I$ *vs.* I), but if we want to make a nice RGB picture too, we'll need three.

(d) Make stacked images in each filter of your science target (M39) and standard star field (NGC 7790) frames:

i. Move the images for your science target and your standard star field into separate directories (optional, probably makes book-keeping easier).

ii. The images are not aligned, so measure the shifts between them using the function `xyoff.pro` (posted on moodle page):

```
IDL> shifts = xyoff ( imgA, imgB, 500, 500)
IDL> xshift_out = shifts[0] & yshift_out = shifts[1]
```

... put all individual $xshift\_out$ and $yshift\_out$ values into two arrays $xshift$ and $yshift$...

(e) ...and then combine the separate images for each cluster (science field and standard star field) and each filter (V, R, I) together to make six stacked images (use average combination, not median). Use Marc Buie's stacker.pro:

```
IDL> stacker, file_list, xshift, yshift, my_combined_image, /robust
```

(read source code for more options)

(f) Run `xyoff.pro` on the V, R, I stacked images to measure their offsets and then shift two of them to align with the other one (to within < 1 pixel offset). We'll use all three to make an RGB image, but only two for the rest of the project.

(g) Optional: Combine the V, R, I images into a pretty RGB (red/green/blue) JPG or TIFF format image. Try the ASTROLIB routine `FITSRGB_to_TIFF`. There are also several routines available online to do this; some of them are linked on the class Moodle page. Alternatively, run each FITS file through the application "FITS Liberator", save as a .TIFF file, then combine to RGB using Photoshop.

2. **Source Detection and Photometry**

   Now we need to measure the position and brightness of each star in the images in two filters. You will measure the star positions in one image (we'll assume the V band image in the following examples), and then use those positions to measure fluxes of the same stars in the other image(s) (remember: the images must be co-aligned for this to work!).

   Explore the section on DAOPHOT-type Photometry Procedures in the ASTROLIB code folder for these tasks.

   (a) Use ASTROLIB's `find.pro` in IDL to make a list of positions (and fluxes) of all the stars in one filter's image.

   (b) Use the X, Y arrays output from `find.pro` as input to `aper.pro` to measure aperture fluxes and uncertainties (in ADU) in several concentric apertures around each star in both the V and I images.

   (c) Save your work in an IDL "save set" to "restore" later, e.g.:
   `IDL> save, id, x, y, magv, errv, magi, erri, file='VIstack_phot.sav'`

3. **Calibrate the Photometry**

   Next we use the NGC 7790 images to obtain an absolute calibration for our M39 photometry, turning fluxes in ADUs into magnitudes. *Be sure to keep track of possible differences in exposure time and binning between the science target images and the standard star images.*

   (a) We obtained VRI images of the open cluster NGC 7790 to use for photometric standard stars. Identify in your images at least three stars in NGC 7790 and find from the literature their V, I magnitudes.

   (b) Use `aper.pro` (or the photometry mode in *atv*) with the same aperture and sky parameters as you used in `aper` above for M39 to measure the total background-subtracted signal S_* in ADU and count rate $c_* = S_*/t$ from for each standard star in each filter, where t is the exposure time of the image.

   (c) From these measurements, calculate the instrumental (uncalibrated) magnitude for each standard star, $m_{\rm inst} = -2.5\log(c_*)$. E.g., if Star A has a flux $S_* = 3000$ ADU in a 30-sec V band image, then $c_* = 100$ ADU/sec and $m_{\rm inst} = -5$ mag. These instrumental magnitudes may be very different from the actual published magnitudes. What *should* be the same is the stars' *relative* magnitude values, i.e. the positive and negative offsets of one star's magnitude with respect to other stars'.

   (d) Using the published magnitudes and your measured instrumental (uncalibrated) magnitudes, calculate the (true, not instrumental) apparent magnitude zeropoint for each filter, i.e. the magnitude of a star that provides a signal count rate of 1 ADU/sec in your images. (In the example above, suppose that Star A with $m_{\rm inst} = -5$ has $V = 10$. What would be the V magnitude of a star that delivered only 1 ADU/sec instead of 100 ADU/sec?)

(e) Apply the magnitude zero point offsets to your M39 photometry values to obtain the true V and I magnitudes of each target star. Be sure to account for possible differences in exposure time. Make a table of all the flux data in magnitudes, and be sure to include error estimates.

(f) Save the calibrated photometry in a new IDL "save set".

(g) TBD: We may be able to apply corrections for atmospheric extinction to improve our photometry. The basic steps would be:

  i. Reduce all standard star images in the same way as you did science target images

  ii. Use RA, Dec, and time of obs to calculate *airmass = sec(zenith distance)* for all images (science and calibration)

  iii. Do aperture photometry on all the standard star images

  iv. For each science filter (V, I), use the standard star images at different airmasses to measure the extinction curve, i.e. how many magnitudes of extinction each unit airmass causes in that filter.

  v. Apply your extinction curve to the science data to derive final magnitudes for each star as they would be observed above the earth's atmosphere, i.e. airmass = 0.

4. **Analyze the Photometry**

(a) Make a plot of σ_V, the standard deviation in V magnitudes, as a function of V. What does it show? Does it makes sense?

(b) Make a Hertzprung-Russell diagram! Plot V on the y-axis (with bright up!) and $V - I$ on the x-axis for all stars in the target cluster. Include a display of the typical (median) error bar on the plot but offset from your data points, for clarity.

(c) Use the isochrones supplied (arrays of color and magnitude for a range of masses at a fixed age) and "χ by eye" to find the best-fit isochrone for the M39 data.

(d) Assuming you see a Main Sequence, try to derive the distance modulus to the cluster using Main Sequence fitting: given the known $V - I$ colors and absolute magnitudes of Main Sequence stars of different spectral types, how much would you have to shift your HRD up or down to make absolute magnitudes match apparent magnitudes? That's the distance modulus $m_V - M_V$!

(e) Optional: you can also make a "2-color" diagram showing $B - V$ on the x-axis and $V - R$ on the y-axis. This plot reveals additional information about age and metallicity.

5. **Final report**

Write a final report describing your project and summarizing your findings in a way that another astronomers could follow to reproduce your process and results. Include the following:

(a) An abstract summarizing your project motivation, technique, and results.

(b) Brief description of scientific motivation for making an HR diagram, brief description of what you did to make this one.

(c) Printouts of your final images.

(d) Table of observing run details (date, location, equipment, field of view, pixel scale, seeing FWHM, exposure times, number of exposures, sensitivity reached).

(e) Table of results: magnitude zero points, sample magnitudes and S/N of stars used in each filter, number of stars used, etc.. How did you choose your aperture size?

(f) Any figures you've made including at least your HR Diagram.

(g) Comment on the appearance of the HRD. Identify any patterns you recognize. What sorts of stars have you detected in the star cluster? According to your HRD, how massive are the most massive stars left on the main sequence? Are all the stars in the image (and your HRD) members of the cluster? How did you choose a metallicity for your isochrones?

(h) Discussion of the isochrone fitting. How old is the cluster? Find at least one reference in the literature against which to compare your results.

(i) Summarize any conclusions you reached about the nature of the cluster.

(j) Make suggestions for how you might improve on your measurements. Discuss sources of error (systematic and random) in your data.

(k) Compare your results to at least one published HRD of the same cluster from the literature.

(l) List any references you've used in your project.

(m) Turn in all IDL code used, with your name and comments.