**PHYS 4270 4.0/5390 4.0 - Astronomical Techniques**

**Fall-Term Project - Part 3/3**

**III. Data Reduction and Analysis**

**Upload (PDF) by 10 pm – Monday 14 December 2020**

1 Introduction

It is presumed that you have acquired the appropriate CCD images using the 1 m PlaneWave telescope, transferred them to an appropriate area on Cosmos (or other machine running IRAF), and have some familiarity with IRAF. (Refer to Part 1/3 for details involving pre-processing, reduction and analysis of CCD data, and Part 2/3 for observing-related details, as well as for astrometric and photometric information for several standard stars in M34, the target open cluster.)

Ideally, you should have taken several exposures of M34 through the *B*, *V* (called *G*) and *R* filters. You should also have acquired calibration exposures including a few flat-field images (courtesy of the on-site staff), dark exposures with a duration equal to those of the light exposures, and a sequence of bias exposures at the beginning and end of the observing session. If your sequence diﬀers from this “standard,” then you will have to modify the instructions accordingly.

2 Data Reductions – In theory:

The process of correcting raw science images for various systematic sources of random and systematic noise present in CCD data is referred to as pre-processing or just processing. The raw images must be corrected for the underlying bias signal and any dark current contribution. The science or target images also require the removal of pixel-to-pixel multiplicative non-uniformities using a normalized flat-field image. The resulting science images are referred to as reduced images on which analysis takes place.

3 Data Reductions – In practice:

The data reduction will be performed in the IRAF environment that is run in command-line mode in an xgterm window, while editing takes place in an xterm window. Images or frames are visualized in a ds9 window, just as for the data in Part 1 of the fall-term project.

1. Renaming data files:

Take care to keep track of your data reduction steps and be sure to take detailed notes: it is important not to omit or duplicate any operations and it makes things a lot easier if you have to redo a particular sequence of operations.

When manipulating or altering FITS files in any way, make sure the output filename is diﬀerent from the input filename. It might be prudent to keep a copy of the raw FITS files in another subdirectory (or on a USB drive), just in case something unforeseen happens. (You have been allocated a generous disk quota, but try not to keep too many extraneous files.)

If the file type of your data is not “FITS” or “fits”, then you will have to rename your raw data files before working in the IRAF environment: that is, you will have to rename the file type from (for example) “FIT” or “’fit” to “fits”. To do this, use the copy command within IRAF. For example,

*copy M34V002.FIT M34\_02\_V.fits*

will rename the file “M34V002.FIT” to “M34\_02\_V.fits” for example. (The IRAF utility RENAME could also be used that does not create another file. Remember to use the DELETE utility within IRAF very carefully!)

1. Inspecting headers and the data:

To inspect the header information of any exposure, type:

*imhead M34\_02\_V.fits*

(for example). You will see a single-line header. To view the entire header on the screen, type:

*imhead M34\_02\_V.fits l+*

or to save it to a file “header.dat”, type:

*imhead M34\_02\_V.fits l+ > header.dat*

Study each of the records; make sure everything looks fine. If there is any header keyword you are unsure of, check with your group members.

Inspect the data using the IRAF utility IMSTATISTICS and redirect the output to a disk file, e.g., “stats.dat” as in Part 1. If the data are zero, negative, or unexpected, seek help. If you reject one or more images (e.g., images are smeared due to temporary tracking problems), you must provide a rationale for their omission in the write-up. Just leaving an image out without a rationale is unacceptable.

It is helpful also to visualize the data to make sure things appear reasonable, e.g.,

*display M34\_02\_V.fits 1*

(Remember to invert the colour map using the “color” tab at the top of the ds9 window for displaying and printing purposes.)

1. Determining the Dark Current and Bias Levels:

The bias level, the “electronic footprint,” must be removed from all images; calibration and science. Whether the dark current is significant enough to have to be removed from your calibration and science exposures is for you to determine. A dark exposure is taken without the shutter being opened, and so it is filter independent. From Part 2, you should have over 100s of dark exposures. Use these data to investigate whether the dark current is insignificant (i.e., much less than the average background level of bias-subtracted science exposures) or significant. If the former, there is no need to deal with dark subtraction. If the latter, then you will have to describe exactly how you plan to deal with dark-current removal and proceed.

Recall, dark current is multiplicative in nature (i.e., is a function of time, *t*, while the bias is additive (i.e., is approximately constant from exposure to exposure). The Flat-Field calibration images and the science images must first have their bias levels removed. If the dark current is significant, it is necessary to build and then remove the average “Dark” image for each sequence (i.e., with the same exposure time).

To build the average Bias, use the IMCOMBINE utility in IRAF with the “average” option; e.g.,

*imcombine @bias\_begin bias\_begin\_avg.fits combine=average*

where “bias\_begin,” for example, is a file containing the names of all the beginning bias exposures. (***Be sure to compare and comment on the beginning and ending biases, both level and structure.***)

Construction of the average Dark exposure follows in the same way (either before or after Bias subtraction): e.g.,

*imcombine @dark10s dark10s\_avg.fits combine=average*

where “dark10s” is a file containing the names of all the darks of (for example) 10-second duration, one per row (see Part 1). You will likely require the IMSTATISTICS utility to decide how to handle these calibration data. Remember to check carefully whether there is an image outlier: remove it before using IMCOMBINE to create a final data set. *Regardless of whether there is a significant dark current,* ***you must list both an average level for the bias and level of the dark current (ADU/s/pixel) and their uncertainty.***

1. Average Flat Field:

You should have been given a series of relevant Flat-Field exposures for each filter taken on the same night as your science exposures. (You may use your own average bias frame to remove the Bias level from the Flats.) Recall, a Flat Field is used to correct the science data for pixel-to-pixel QE non-uniformities, the result of differences in quantum efficiency. To remove the bias levels from a Flat-Field exposure:

imarith Flat\_V\_01.fits – Bias\_Avg.fits BFlat\_V\_01.fits

where the prefix “B” indicates the Bias level has been removed from this flat image in my notation.

Ideally, the Flat Fields should be optimally combined to form a single normalized combined flat; i.e., a combination of flats whose average is 1. It is important to examine each flat using IMSTATISTICS to ensure there are no anomalies (such as saturated pixels). Refer to Part 1 for details on how to combine optimally flat fields and to normalize the final flat, particularly when the mean intensities are significantly different from one another (otherwise, a straight average of the acceptable frames is sufficient).

1. Correcting the Science Images:

The next data reduction step is to subtract the appropriate bias (and dark, if significant) signal from each of the M34 images and to divide these images by the appropriate normalized flat field. It is wise first to display the images to get a sense of the characteristics and quality of the data.

1. Shifting and image combination:

Before combining all the acceptable data exposures (for a given filter), it is necessary to correct for any small shifts in the images that may have been taken place from exposure to exposure, an inevitable consequence of taking a sequence of exposures. (Failure to attend to this step will normally result in inferior quality data, effectively blurring the data.) This is an additional step from the reductions in Part 1. (There will almost certainly be frame-to-frame shifts in these data, so take this step seriously.)

To accomplish this, display each bias-subtracted, flat-field-divided science image in a particular filter to the ds9 window one at a time. Use IMEXAMINE and the “,” key to record the column and row (centroid) position of the same (isolated and unsaturated) star for each exposure. If the column and/or row diﬀer by more than ±1.0 pixels, it will be necessary to use the SHIFT utility in IRAF to shift the frames so that they can be added together without sacrificing image quality.

Suppose you wish to shift image fM34\_02\_V.fits by 1.45 columns (i.e., in *x*) and −2.31 rows or lines (i.e., in *y*) and rename it sfM34\_02\_V.fits. This requires:

*imshift fM34\_02\_V.fits sfM34\_02\_V.fits 1.45 -2.31*

(where I chose the prefix “s” for “shifted”). It does not hurt to display the shifted image and examine it using IMEXAMINE to ensure that the data were shifted correctly. (**It would be most helpful for the next stages of analysis if stars in the *B*, *V* and *R* reduced frames all had the same positions if possible; i.e., shift the *B, V* and *R* data to the same reference or fiducial image.) *Be sure to record and provide the shifts for each of the exposures used to generate the co-added image.***

In the end, use IMCOMBINE (as in Part 1) to combine all the shifted data to yield a single, co-added exposure of the M34 field for each filter. For example, the completely processed (i.e., bias-subtracted, flat-fielded divided, shifted, combined) image for M34 might be named M34\_combined\_V.fits. Do not worry if the very edges of the final image are non-uniform. Shifting and adding will understandably lead to this “picture-frame” eﬀect. (Do not use photometry from any stars in the “picture frame”.)

1. Photometry and Astrometry:

It is now time to get quantitative. First **measure and record the image quality (i.e., FWHM of a few relatively bright and non-blended stars) (as in Part 1) using the interactive IRAF utility IMEXAMINE.** (Recall from Part 1 that one first DISPLAYs the combined image to the ds9 window, then uses IMEXAMINE with the “,” option when the cursor is over a star to determine its FWHM.)

As in Part 1, it is necessary to **perform a curve-of-growth analysis of at least one reasonably bright (though not saturated or nonlinear), isolated star to determine the optimal aperture radius and aperture correction for a “combined” image**. (*Remember to compute your own instrumental magnitudes as in Part 1 and* do not *use IRAF’s instrumental magnitudes.*) Then **use QPHOT to measure/compute the asymptotic instrumental magnitudes for all the standard stars in your image in a given filter, and for at least 60 *other* stars in the field with a variety of apparent brightnesses.** **Be sure to record the parameters used for the QPHOT utility**. (Note: *the optimal aperture radius, the radius and width of the sky annulus may be significantly different for these data than for the data in Part 1*.) **Try to have about one-third of the stars in the brightest two magnitudes, one-third in the middle two magnitudes, and one-third in the faintest two magnitudes.** (Failure to do this will yield an ambiguous and possibly incoherent HR- or colour-colour diagrams.)

**It is also important to measure and record the (sky) background levels in at least four widely separated areas on the image with no apparent stars using the “m” option with the IMEXAMINE utility (as in Part 1).**

Do this for each of the combined *B, V* and *R* frames. You should then **compile a table within a spreadsheet with all the relevant data for each of the stars.**

1. Astrometry

Using the centroids (*x, y*) of two, well separated standard stars and their catalogued positions provided in Appendix A-1 of Part 2/3, **compute and report**:

* **the focal-plane scale or pixel scale; i.e., the number of arcseconds/pixel. With this value, it should be possible to *assign each star an RA and Dec coordinate in the final table*.**
* **the tilt (or position angle) of the CCD columns relative to the RA axis (degrees).**

1. Photometry

It is important to keep track of the eﬀective exposure time of each of the final images. (There can be a quantitative diﬀerence, for example, between averaging images and summing images.)

* Stars: **convert the (measured) total standard star count rates (ADU/s) to instrumental magnitudes for all filters.** (Remember, the apparent magnitude of a star for any filter, m = mINST + *C*, where *C* is a photometric constant which is constant for a given filter and mINST = −2.5 log**10**(total counts/second). This is an exercise in diﬀerential photometry and so a more detailed analysis is not required.) **A separate value for *C* will be computed for each of the standard stars in the field using the standard star photometric data (provided in handout Appendix A-1 in Part 2/3).** The adopted *C* should be an average (or weighted average), with uncertainty, of all available *C*’s (though rejecting a single outlier is within reason). **Use this value for *C* for a given filter to convert the other (60) instrumental magnitudes to apparent magnitudes *with uncertainties* (using IRAF photometric output)**.
* Sky background: **using the information from the analysis of the standard stars above, compute the sky (background) surface brightness (i.e., magnitudes/arcsec*2*) for the *B*, *V* and *R* combined images.** (Hint: Use the pixel scale above to convert from mean background counts per pixel per exposure to mean background counts per square arcsecond per second.)
* Colour-Magnitude Diagrams (CMD): **plot two CMD diagrams; the first plots V *(y* axis) vs. *B-V* (*x* axis), while the second plots *V* vs. *V-R* for all 60 stars (*plus* standards) in your M34 exposures. Plot one colour-colour diagram; i.e., (*V-R*) (*y* axis) vs. (*B-V*) (x axis). Comment on all the diagram(s); e.g., is the Main Sequence visible? What spectral types of stars are represented in the diagram? Estimate the *B-V* and *V-R* colours for the Main Sequence turnoﬀ and therefore the age of the cluster.** Feel free to consult other references if necessary to assist in the interpretation.

1. The write-up:

The (PDF) report for this term assignment need not be overly lengthy, but it must be typed, in sentences, and should proceed clearly and systematically. Begin in a brief introduction with some relevant information about open clusters in general and M34 in particular. Always show representative calculations. There is no need to regurgitate what has already been included in the handouts. Note: **you must include a title, the names of your group members on a cover page**, **and the directory on Cosmos in which your data are stored**.

**Accompanying the write-up should include**:

* an annotated finding chart for the cluster (with inverse colour map)
* an inverse colour map (i.e., negative) combined image for each filter with cardinal directions, scale and title clearly indicated
* an informal observing log (photocopy is fine and don’t worry about neatness here) that summarizes your actual observing session
* the time of your observations in EST, converted to UT. The Modified Julian Date should be provided for local midnight closest to your observations
* the Local Sidereal Time, Hour Angle and Airmass should also be given for all cluster observations (but not calibrations)

The write-up should take the reader briefly through the steps in the reduction and analysis, provide all requested data/information and representative calculations, as well as answer the various questions (especially in Section 3.7) along the way. Anything else you care to mention related to your observations is also welcome.