Physics 344 Lab 4

Observing with a CCD: Photometry of the Galaxies M31 and M32

Take Data: October 12 – 17 (weather permitting)
Report Due: Thursday, October 25
Text Reference: Chapters 9 & 10

Purpose: This lab continues the introduction to taking and analyzing data with the direct-imaging CCD system on the 0.5 m telescope. It provides more practice in planning observations so as to use your time at the telescope effectively and in the basic procedures of focusing the camera and setting up the guider, which are necessary for obtaining images of good quality. Analyzing images of the galaxies M31 and M32 will introduce a fundamental astronomical measurement: determining the brightness of an object in the sky using a CCD image. M31 is a spiral galaxy and M32 is a (dwarf) elliptical galaxy that is a satellite of M31. So our data will allow us to compare the two basic kinds of galaxies.

Background: Telescopic observations of galaxies go back hundreds of years, with the earliest predating our understanding of galaxies as gravitationally bound assemblages of stars. Galaxies are extended on the sky, unlike the point-like stars, and early observations focused on morphology – the shape of the light distribution – and on the total brightness. These kinds of observations continued into modern times and were important in determining our ideas about the structure galaxies. A relevant example for this lab is the distortion of the shape of a satellite galaxy by tidal forces. These forces should tend to stretch the satellite along the line connecting its center with the center of the larger galaxy. This could result in the orientation of the major axis of the light distribution of the satellite changing with distance from its center. Because M32 has a projected separation of only 5.5 kpc from the center of M31, it is an interesting candidate to search for such effects.

Measuring the brightness of galaxies in different wavelength passbands yields information about the kinds of stars present, since a young stellar population contains hot, blue stars whereas old stellar populations contain only red main sequence stars and red giants. This same argument is applicable to the stellar populations of clusters of stars that can be detected in galaxies. In some cases the study of the (very brightest) individual stars in nearby galaxies is possible, though this is greatly aided by the high angular resolution possible with the Hubble Space Telescope. We will image both M31 and M32 through the B and V filters and add an R-band image of M31 for the purpose of producing a color picture.

M31 is the nearest large galaxy to our own Milky Way Galaxy, at a distance of about 780 kpc. The Galaxy and M31 are the two most massive members of the gravitationally bound Local Group of galaxies, with the less luminous spiral M33 being the next most massive. Most of the remaining 70 or so members are satellite galaxies of M31 or our Galaxy. New members of the Local Group continue to be discovered today with the number known more than doubling since 2000. We can only discover the faintest galaxies when they are nearby and we can make the most detailed studies of nearby galaxies. For these reasons, studies of the Local Group continue to be important for understanding the properties of galaxies and how they formed.

Galaxies do not have sharp edges and their outer regions are fainter than the night sky. Removing the contribution of the sky is an important step for any measurement of the brightness of an astronomical object and it is particularly important for galaxies. Determining the brightness of the sky is not easy for the largest of the Local Group galaxies because they are larger than the field of view of most telescopes, including our own. Unfortunately, measuring the sky in an image offset far enough away on the sky that M31 does not contribute is problematic because the brightness of the sky can (and often does) change with time. This problem can be overcome using a sequence of overlapping images, but the amount of work involved is beyond the scope of this lab. We will simply make the best estimate of the sky level that we can from each individual image. Even the field centered on M32 will still contain some galaxy light, but it will be a very small contribution to our (rather bright) sky.

As discussed in class and in the last lab, carrying out astronomical observations and their analysis typically involve the following steps.

1. Planning before going to the telescope in order to optimally use the scarce resource of time at the telescope. Determine when your targets are visible, how to find them, and what science and calibration data to take.
2. Taking both science data and calibration data at the telescope. Includes assessing data quality in real time – are you pointed in the right place, are the images focused, are your exposure times too short (not enough signal) or too long (target saturated)?
3. Calibrating the science data. The first step(s) of data analysis.
4. Scientific analysis of the calibrated images.

I. Preparation and Planning:

You will observe the galaxy M31 for this lab and I will supply you with images of M32.. The locations of these objects are shown in *The Sky*.

1. Use *The Sky* running on a computer in the classroom or dome to find where M31 will be in the sky during your observing session. How close is it to the horizon? Will taking your flat-field images at the beginning or end of your session result in the galaxy being higher in the sky when you observe them?
2. Zoom in with *The Sky* at the location of M31 until you can see the red rectangle that is the "footprint" of the CCD camera field of view on the sky. It is helpful to turn off the galaxy picture representation for M31, if it is not already, so that you can identify the stars in its vicinity. Identify a 7th – 8th magnitude star within a few degrees of M31 that can be used to focus the CCD.
3. Click on the red rectangle of the CCD field of view to select it and, if necessary, change the orientation of the autoguider field of view (smaller box) to 90°, since M31 is east of the meridian. Then explore how to place a CCD field approximately centered on M31. The field placement will be constrained by the need to have a sufficiently bright star in the autoguider field of view. Ideally a guide star will be 10th magnitude or brighter. In

this case you will have to use a fainter star, but keep it brighter than 11th magnitude. Once you have selected your guide star, record it and plan how you will point the telescope so as to get your guide stars into the autoguider field.

II. Observations of M31:

If you decided that observing your flat-field images first will result in M31 being higher in the sky, do the first six steps below and then go to part III. Then go back and finish the rest of part II.

1. Ensure that the fold mirror in the red instrument adapter box is in the "CCD" position, that the spectroscopic pick-off mirror is out (rivet in the "direct" location) and make sure that the plastic plug is in the eyepiece tube. Turn on the imaging CCD system with the power strip in the telescope mount base.

2. Start *The Sky*, *IDL*, and the imaging *CCDSoft* program. In *IDL* start RU*PhAst* to view the saved images.
3. In *CCDSoft*, connect to the CCD and set the cooling to a temperature that is 35 to 40 °C below ambient. Allow about 5 minutes for the temperature to stabilize before taking science or flat-field images. If it takes more than about 90% power to maintain the temperature setpoint, raise it a bit.
4. Set up the *AutoSave* tab to save your images in a subdirectory named with the date and your initials in G:/home/ph344/lab4 (e.g., oct10tp). Set the *starting number* to 1.
5. In the *Take Image* tab, set the *Bin* to 2x2.

6. The telescope is focused by moving the secondary mirror using the stepper-motor controller on the observing desk. Turn on the encoder readout above these controls with the green button. Use the focus motion buttons on the panel below to set the encoder to a reasonable first guess at a good focus. Data from from earlier in the semester suggests that this is 2.400 mm at an air temperature of 20 C. Adjust your guess for the your air temperature using the knowledge that the best focus increases by about 0.100 mm for every 5 °C *decrease* in temperature.
7. Open the dome, remove the telescope cover, and initialize the pointing of the telescope starting from the zenith position in the same way as for Lab 3. A brief reminder of the steps is below.

   a. After slewing to the first bright star, take a 1 second exposure.
   b. The bright star should be in the image – shrink the displayed image in the *CCDSOFT* window so that you can see all of it (change the cursor to "zoom out" and click one or more times on the image; then go back to the "select" cursor; click once on the frame of the image to get it to resize).
   c. Display the image in *RUPhast* and note that it is flipped top-to-bottom compared to the *CCDSOFT* display.
   d. Approximately center the bright star in the field using the telescope motion controls, taking an exposure after each move. The long axis of the CCD is north/south and about 32 arcminutes across.

   e. Once the star is centered, sync the telescope coordinates.

8. Slew to a star near M31 that is magnitude 3 or brighter. Take another 1-second exposure to check and, if necessary, refine the pointing.

9. Slew to the focus star you selected. Set *Reduction* to Autodark, *Filter* to *V,* and take a 5-second exposure. Confirm that you are pointed where you expect to be.

10. Focus the camera using the same method as in Lab 3. Remember to use 1×1 binning and select a subframe box to speed up the readout. Use 5-second exposure times. Take a sequence of 7 images stepped by 0.050 mm in telescope focus value that bracket your guess of the best focus. Examine the 7 images in RUPhAst and examine the radial profile of the focus star ("p" key or left mouse button in Imexam mode) to determine the best focus. Set the telescope focus to your optimum value. Include the value of your best focus and the air temperature in your lab report. This same focus value should be OK for images taken through the B, V, and R filters.

11. Take your science images. We will use *Reduction* set to None because the 300-sec autodark exposure would disrupt the autoguiding.
    a. Slew to your M31. Set *Bin to* 2x2, *Subframe* off, and, in the *AutoSave* tab, change the filename to something more reasonable than focus. Take a 300-second dark exposure.
    b. Take a 5-second exposure and examine the image in *RUPhast.* Adjust the pointing to place your guide star in the autoguider field. Set up and start the autoguider.
    c. With the autoguider running and *Reduction* set to None, take 300-sec exposures of your M31 field through the V, R, and B filters.
    d. Stop the autoguider and take **two** 300-sec dark exposures.

III. Acquisition of Flat Field Images:

1. If you have obtained your M31 images, start shutting down the telescope by sending it to the home position. Drop the link with the computer and turn off the black telescope interface box. Point the telescope horizontally by hand and close the dome shutter.

2. Turn on the dome white lights and point the telescope to a region of the inside of the dome that is unshadowed and as free of "structures" as possible.

3. Take seven well-exposed (about 30,000 ADU per pixels in the center) in each of the B, V, and R filters with *Reduction* set to Autodark. Use the *AutoSave* tab to set prefix filenames of flat*B,* flat*V, and* flat*R,* respectively. Good exposure times are about 30, 8, and 7 seconds for B, V, and R, respectively

4. Cover the telescope and point it to the zenith. End the *CCDSoft* program and turn off the power to the CCD at the plug strip in the telescope base (if this is the last data that you are taking in your lab period).

IV. Data Analysis – Data Calibration

Data analysis can be done at any time, using IDL running on the server computer (astrolab). Using VNC, you can connect to astrolab from anywhere and analyze your data.

The first step in measuring the brightness of objects in a CCD image is to remove from the image those features that are solely due to the instrument itself. For the data from this lab, that means subtracting an average dark image and dividing by an average flat-field.

1. Copy all of your Lab 4 CCD images from the folder for your night in /home/ph344/lab4 to a lab4 folder in your home area. Make sure that you always work on these copies, not the original images! Use the file manager tool to copy the images (or the Linux *cp* command on the command line if you are a Linux wizard). Also copy the file /home/ph344/lab4/phast.conf into your lab4 folder. This configuration file initializes certain quantities in *RUPhAst*, most notably the CCD gain and readnoise. Examine the contents of this file.

2. Create a subdirectory in your lab4 folder called calib and move your dome flat-field images and dark images into it. Delete any flat-field images with NOAUTODARK in the name (these are images before the automatic dark subtraction). This step is at least very useful because the IDL routine that combines the darks and flats is not very flexible in the way that it selects multiple files – in a list of files, all of the darks or all of the flats taken through a particular filter need to appear in a block together.
3. Start IDLDE and then change the path to the folder with your calibration files using the IDL *cd* command:

   cd, “/home/yourusername/lab4/calib”

   Recall that the quotes are important, as is the comma. The IDL program *mkflatru* combines your individual flat-field images into an average flat-field image, scaled to be close to one at its center. When combining the images, *mkflatru*, measures the average signal in the central half of each image, divides the image by this number, and then takes the median of all of these normalized images to eliminate cosmic-ray events. Combine your seven dome flats taken through the V-band filter using *mkflatru* and save the resulting image as FlatV.FIT. Similarly, combine your B-band and R-band dome flats.

4. Use the IDL program *mkdarkru* to combine your three (or however many you got) dark exposures and save the resulting average image as Dark.FIT. Note that *mkdarkru* takes a while to complete since it does a somewhat more sophisticated rejection of discrepant pixels – be patient.
5. At the IDL command line, cd back to your lab4 folder (cd, “..” will do this; the .. is a shorthand for the folder above the current one). Start *RUPhAst* and examine your average dark and flat-field images with *RUPhAst* to check that they look reasonable. Briefly describe the appearance of each in your report. If any of your average images do not look OK, return to steps 3 and 4 to determine what you did wrong. For example, display the individual files that went into the average to make sure that they contain what you think they do.

6. Process each of your images of M31 using the *Calibration* (NOT *Batch calibrate*) item in the *Pipeline* menu of *RUPhAst* program. Use the Dark.FIT image as the dark frame for all of your images. Use the FlatV.FIT image as the flat-field image for the V-band images, the FlatB.FIT image for the B-band images, *etc*.. Name your calibrated galaxy

images something reasonable (*i.e.*, shorter than the original names, while preserving the important information about the image).

V. Data Analysis – Photometry

The goal here is to make some simple measurements of the magnitude and colors of the centers of M31 and M32, estimate their shapes on the sky, and to find their surface brightness profiles. We will use stars with known brightness in our images to determine the relation between magnitude and signal levels in the images (in ADU's). Much of the photometry will be done with *RUPhAst*, but measuring the galaxy surface brightness profiles will be done with a separate *IDL* program.

Table 1 below list standard B-, V-, and R-band magnitudes for stars in the direction of M31 and M32. The stars are identified in Figures 1 and 2 below using V-band images taken in 2015 (these finding charts are also available on the class website). These data are taken from the paper "BRVI CCD Photometry of 361,281 Objects in the Field of M31" by E. A. Magnier *et al.* (1992, Astron. Astrophys. Suppl., 96, 379). In practice, I identified bright, unsaturated stars in the M31 and M32 images using *The Sky* and used the resulting right ascension and declination to search an online version of the catalog of photometry. For this search I used the VizieR online compendium of 17,702 (as of October 2018) astronomical catalogs (http://vizier.u-strasbg.fr/viz-bin/VizieR). Magnier *et al.* (1992) estimate that for stars brighter than 19th magnitude their photometric uncertainties are dominated by systematic effects at the level of about 0.02 magnitude for B and V and about 0.05 magnitude for R and I. Larger errors are possible since we must be close the bright saturation limit of the Magnier et al. (1992) photometry.

Also identified in Figure 2 are one open cluster (C203) and two globular clusters (G150 and G205), all members of M31. The open cluster is one of many identified by Hodge (1979, Astronomical Journal, 84, 744). The globular clusters are from the list in Sargent *et al*. (1977, Astronomical Journal, 82, 947). These objects were identified in the 2015 image using Charts 5 and 7 of *The Atlas of the Andromeda Galaxy*, published in 1981 by P. Hodge (available on the class website; the whole atlas is available online at https://ned.ipac.caltech.edu/level5/ANDROMEDA_Atlas/frames.html). Also note the nice image identifying most know M31 globular clusters available at http://www.robgendlerastropics.com/M31NMmosaicglobs.html.

1. If you have not done so previously, copy the file /home/ph344/lab4/phast.conf into your lab4 folder. This configuration file initializes certain quantities in *RUPhAst*, most notably the CCD gain and readnoise. Examine the contents of this file. Start *IDL*, use the "cd" command to navigate to your lab4 folder (similar to the command described in IV.3.). Then start RUPhAst and load in your processed M31 B, V, and R images and the processed M32 B and V images that I will supply. Use the aperture photometry tool to measure (x,y) location of the center of M31 and M32 in the images and report these.

2. In the Scaling menu at the top of the RUPhAst window, select Log. This basically takes the logarithm of the image values before displaying them. Use the t-key to obtain a contour plot of the 100 pixel × 100 pixel region (the default range) centered on M32 in your V-band image. With Log scaling selected, the contours are equally spaced in the logarithm of the pixels values. Because the images of the galaxies extend over a wide

range of surface brightnesses, logarithmic spacing is more useful than linear. Use the outermost and 5th-brightest contours in your contour plot to estimate the ellipticity of M32 ($\varepsilon = 1 - b/a$, where b is the length of the minor axis and a is the length of the major axis). Also estimate the position angle of the major axis, which is the angle between the major axis and the direction north. Position angles are measured increasing from north towards east by convention. Remember that for CCD images taken when the telescope is looking east, the orientation of images in RUPhAst is north to the left and east down. Estimate approximate uncertainties for your ellipticities and position angles. Is there any evidence of either quantity changing with radius?

3. Produce contour plots for 100 pixel $\times$ 100 pixel and 600 pixel $\times$ 600 pixel regions centered on M31 in your V-band image. Measure the ellipticity and position angle for 4th-brightest and outermost complete contours in the 100 pixel $\times$ 100 pixel region and for the outermost complete contour in the 600 pixel $\times$ 600 pixel region. Again estimate approximate uncertainties and comment on any changes with radius.

4. Use the *RUPhAst* aperture photometry tool to measure instrumental magnitudes for at least three stars from Table 1 in each of your M31 B, V, and R and M32 B, V, and R images. For these measurements, in the *Photometry Settings* window select the *IDLPhot* sky algorithm, output units of *Arcsecs Magnitudes*, an *instrumental* magnitude system and *yes* to calculating photometric errors. Also check that RuPhAst has correctly read a CCD gain of 1.8 and a readout noise of 15.5 from the phast.conf file. Use an aperture radius that is twice your typical stellar FWHM (rounded up to the nearest integer) and inner and outer sky radii of 15 and 25 pixels, respectively. Remember that you have to hit carriage return after typing a number into the box. Calculate your best estimate of $\Delta m = m_{std} - m_{inst}$ and its uncertainty for each of the five images. As we will discuss when measuring a color-magnitude diagram, the transformation from instrumental to standard magnitudes can depend on the color of the star (or galaxy) being measured. In this lab we will just use the simple offsets, in part because I am not sure that the Magnier et al. (1992) photometry is accurate enough to determine a more complicated transformation.

Table 1 - Standard Photometry

Name	B	V	R
2801:2073	11.475	11.232	11.056
2805:2142	11.011	10.683	10.442
2805:2145	13.015	12.044	11.495
2805:2181	13.535	12.998	12.686
2805:2213	12.455	12.000	11.644
2801:2055	12.835	11.681	11.047
2801:2061	12.358	12.169	12.087
2801:2030	13.075	12.569	12.319

2801:2046	12.528	11.434	10.822
2801:2082	13.069	12.562	12.347
2801:2085	12.724	12.231	11.911
UCAC	13.651	12.420	11.723
2801:2010	14.004	12.750	12.016

5. Measure instrumental magnitudes in your B and V images centered on M32 for the open cluster C203 and either the globular cluster G150 or G205. Use the same settings as in the previous part. Convert your instrumental magnitudes to standard magnitudes using your Δm values and report the V and B−V and their uncertainties. To get an idea of the typical kind of star contributing to the light in each cluster, use the relation between B−V and main-sequence spectral type given at http://www.stsci.edu/~inr/intrins.html to find spectral type corresponding to your B−V colors. Which cluster do you think formed more recently and why?

6. Obviously, galaxy photometry requires much larger inner and outer sky radii than does photometry of stars. In RUPhAst examine your V-band M32 image and decide what inner sky radius is outside of the visible galaxy. You will want to adjust the brightness and contrast of the display to show a lot of contrast around the background level so you can decide the extent of the faint outer parts of M32. Make the outer sky radius 25 pixels larger than your inner radius. Measure the instrumental B and V magnitudes of M32 with an aperture radius of 11 pixels (about 10 arcseconds) and 100 pixels (about the largest radius that does not have contamination from bright foreground stars). Judge the sensitivity of your measurements to the adopted sky annulus by repeating them after increasing the sky radii by 25 pixels. Convert your instrumental magnitudes to standard magnitudes using your Δm values and report them along with their uncertainties. Also calculate B−V for the two apertures and its uncertainty. To get an idea of the average type of star contributing to the light in the two apertures, use the relation between B−V and main-sequence spectral type given at http://www.stsci.edu/~inr/intrins.html to find spectral type corresponding to your average B−V colors. Is the color of these inner regions of M32 more like that of a globular cluster or an open cluster?

7. Repeat part V.6. for your M31 B and V images with aperture radii of 11 and 50 pixels. Choosing radii for the sky annulus is more problematic in this image since the galaxy really fills the entire field. In this case, just use inner and outer sky radii of (400,425) and (425,450) pixels. These sky annuli clearly still contain galaxy light, but it is much less than the bright inner parts of the galaxy.

8. It is of interest to calculate how bright our sky is in standard magnitudes per square arcsecond. Identify the region of the M32 images that is least contaminated by light from M31 and M32. Use the image statistics tool (i key) in *RUPhAst* to the measure the average pixel value in this region and its uncertainty using a few samples. I recommend a box size of 51 pixels so that each of your samples is itself based on many pixels and using the median instead of the mean to remove the effect of any stars in the box. Stay away from the extreme corners of your images (particularly the lower right corner) since

the flat-field corrections are larger (hence, more uncertain) there. Do this for both filters. RUPhAst calculates instrumental magnitudes using the formula $m = 20.3 - 2.5 * log(c/t)$, where c is the total counts (in ADU) and t is the exposure time (in seconds). Remember that the logarithm in the definition of magnitudes is base 10. Convert your average counts per pixel in the sky into counts per square arcsecond using the image scale of 0.89 arcsec/pixel (remember the square in square arcseconds), calculate the instrumental magnitude per square arcsecond, and convert these to standard magnitudes.

Measuring the surface brightness profile of a galaxy consists of finding the average pixel value in rings centered on the galaxy. This could be done with the aperture photometry tool, but it would be tedious. I have written an IDL program, *galsbmag_ru*, that does this for 21 rings logarithmically spaced from the center out to a specified maximum radius and both prints out and plots the result. Since the rings at large radius will contain foreground stars, the program calculates a "robust" average pixel value that removes (or, at least, greatly reduces) the effect of discrepant pixel values. I could have used the median, but instead used the biweight estimate of the average and the standard deviation around that average. The program divides the standard deviation around the average value by the square root of the number of pixels to estimate the uncertainty in the mean. To ease comparison with published data, the program converts the average pixel value to a standard magnitude per square arcsecond. To do this conversion it needs the offset between instrumental and standard magnitudes for your V-band images of M31 and M32. We will just measure surface brightnesses from the V-band images.

9. The *galsbmag_ru* program is run from the IDL command prompt, so exit from *RUPhAst* and make sure that the current directory is set to your lab 4 folder with the *cd* command (see section IV. of this lab; note that the command *pwd* will print the current directory and *dir* will list the files in it). To run *galsbmag_ru* on the image m31V.0045.FIT, say, the commands are:

   img=readfits('m31V.0045.FIT',h) * 1.0

   galsbmag_ru, img, xcen, ycen, rmax, sky, sky_unc, img_scale, Δm_V, title

   In the above, replace *xcen* and *ycen* with the coordinates for the center of the galaxy from section V.1., *rmax* with the radius to which you want the profile computed, *sky* and *sky_unc* with your estimate of the sky value **(in ADU/pixel)** and its uncertainty, img*_scale* with the arcseconds per pixel in the image (0.89), Δm_V with your value from part V.4, and *title* with a title for your plot (a string enclosed in double quotes). The program plots surface brightness in magnitudes per square arcsecond versus log(radius). The value for every pixel within *rmax* appears as a gray point and the average values for the bins as black triangles with error bars. A horizontal line shows the input sky level. The program prints out for each bin the average log(radius), the average signal per pixel, the corresponding surface brightness, the estimated uncertainty in the surface brightness (including the uncertainty in the sky value), and the number of pixels in the bin. The *galsbmag_ru* program needs the "sky" signal level to subtract from the average pixel values in the rings. Since the galaxy profile rather quickly becomes fainter than the sky, the derived profile depends sensitively on the adopted sky value. We could use the sky values derived in V.8. for this value, but M32 is seen projected against the disk of M31 and so the "local sky" is somewhat brighter. For M31, there is the problem that the sky in the M32 image may not be the same as that in the M31 image. For M32, the most accurate estimate of the sky probably results from using the *galsbmag_ru* program itself with an initial estimate of 0 for the sky and adopting the level that the profile flattens out at at large radii (say with a maximum radius of 700 pixels). Use the scatter between the bins at large radii to estimate the uncertainty in this level rather than the very small estimated uncertainty in the average pixel value. For M31 we don't have a good estimate of the sky since the galaxy fills the field of view. It is probably best to use the approach of section V.8. with the part of the M31 image with the least amount galaxy light in it. Because of the difficulty in estimating the sky and because of the complications introduced by the interaction of the ellipticity of the light distribution with the edges of the field of view, we will confine ourselves to measuring the inner surface brightness profile of M31. Once you have decided on your best values for the sky, generate surface brightness profiles for M31 and M32 with a maximum radius of 500 pixels.

10. Finally, at the IDL command prompt use the command *tctoolru* to make a color image from your B, V, and R images of M31. Also make a color image of M33 using the images in the /home/ph344/lab4/m33 folder. Try different scalings and choose the one that you think produces the best image. In my experience, reducing the Max values for the images to the Min plus the same constant can be useful.

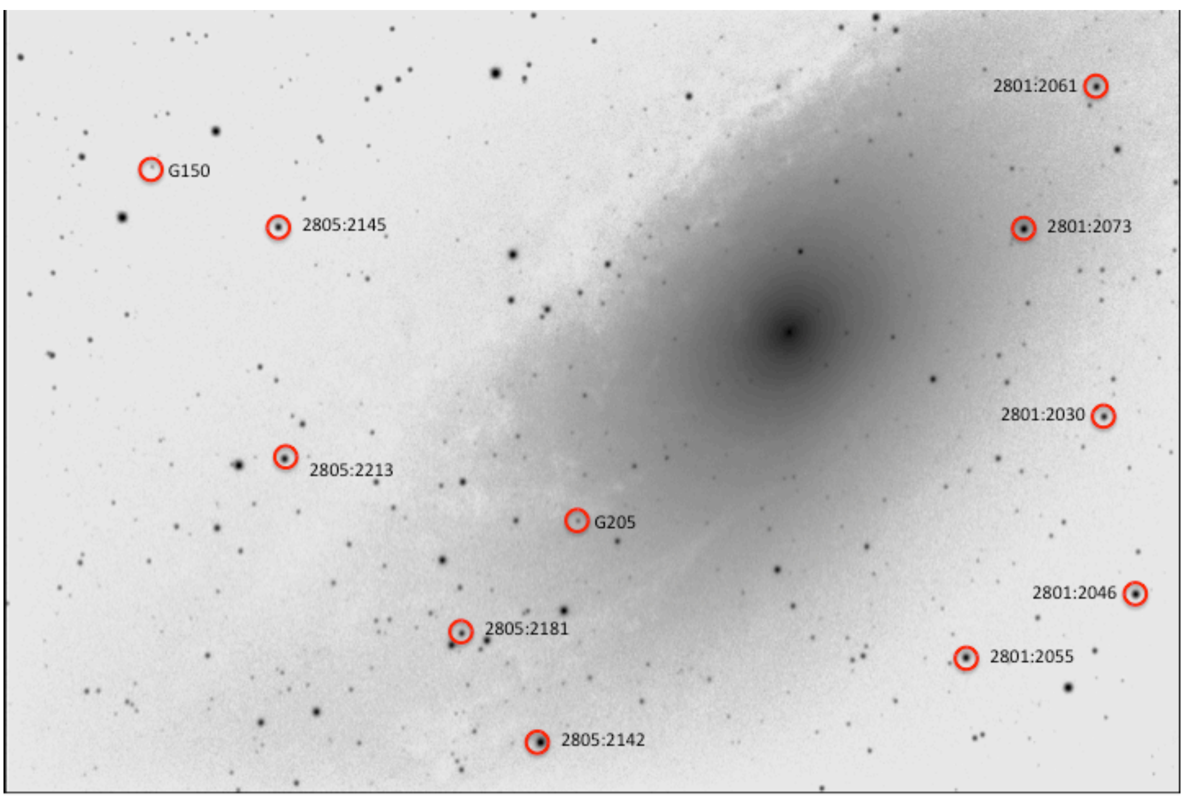

Figure 1: Stars with Standard Magnitudes in the M31 Field

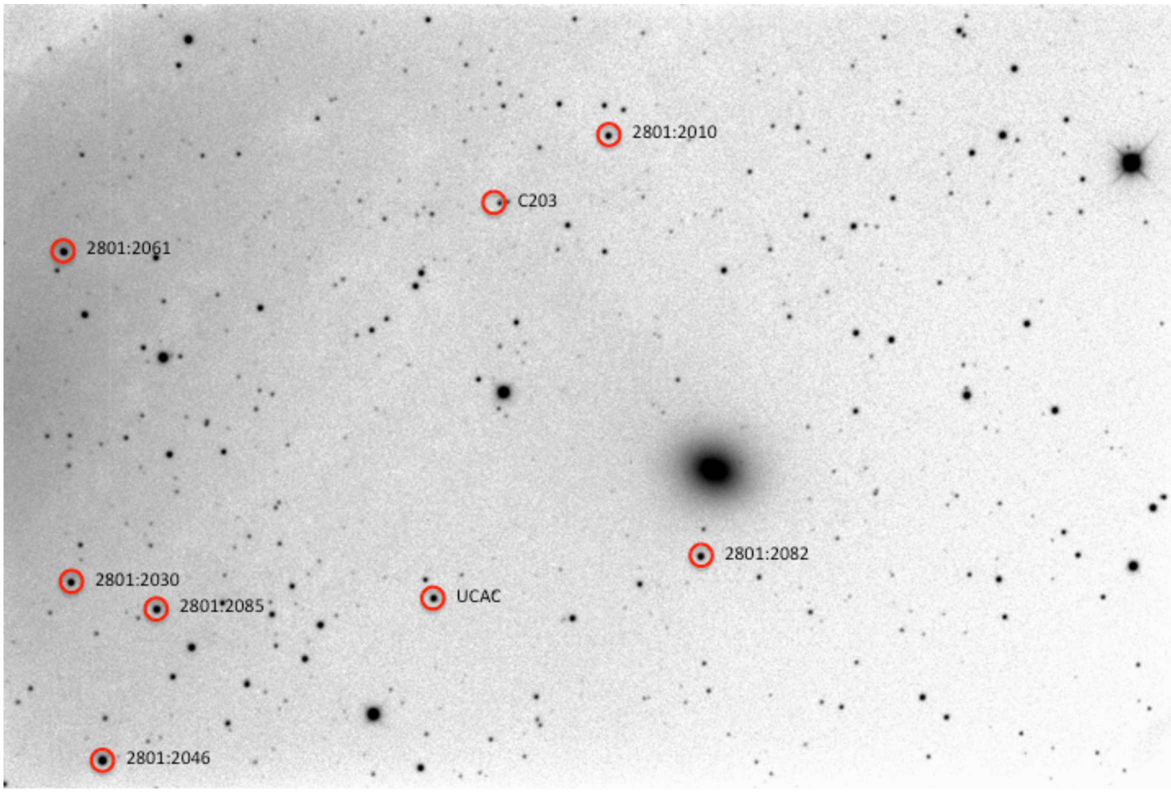

Figure 2: Stars with Standard Magnitudes and Clusters in the M32 Field