Lab 3
Xmgrace, magnitudes, SExtractor, Physical Properties of Stars

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> **Boxes contain questions that you are expected to answer (in the box). You will also be asked to put computer output into special directories, so it can be graded. If you need more room for an answer, put it on the back of a page, with a pointer to it.**

Please read the pages from Nick Strobel's course notes about parallax and distances, about magnitudes, and about temperatures, colors, and luminosities. These three pages are linked from the Phys134 course web page. Please also read through the *xmgrace tutorial*, which you can likewise find on the course web page. We will be using xmgrace a lot, and the tutorial provides a useful overview. Finally, it is not too soon to start looking at Benne Holwerda's excellent *Source Extractor for Dummies*. Don't read it all (it is about 110 pages), but look at Chapter 5, which gives you a general idea of the purpose and methodology behind SExtractor. Finally, we will use two home-grown python scripts to avoid some drudgery in dealing with output files from SExtractor.

Xmgrace is a data-plotting program that we will use a lot. We will not use all of its features, but quite a few. The next few exercises will give you practice with some of the methods you will need.

I have been reminded that each computer has access to a large disk called **backup**, which provides a good central location to store the output from lab exercises. Please create a directory **results_YourName** on this large filesystem via some command such as
mkdir /backup/YourName
and when the exercises ask you to save plots or other results for grading, save them in that directory.

Import the data (3 columns) from **catalogs/lab014.cat** into xmgrace as "block data", and plot the {x,y} pixel coordinates X_IMAGE, Y_IMAGE of all of the stars . Please
- Plot the data points without lines connecting them. Make the data points green upward-pointing triangles, about size = 60, so the data symbols are legible, but small enough that few of them overlap.
- Plot the axes in black. Put an appropriate label on each axis. Put your name as the title of the plot.
- Adjust the axis ranges to be [0-1600] for the x-axis, and [0-1050] for the y-axis.
- Save this plot (and all subsequent ones) as JPEG files (with a .jpg suffix), and name them according to the scheme **Lab*n*plot*xx*.jpg,** where *n* is the number of the lab and *xx* is a sequential plot number for each lab. If *xx* has only one digit, prepend a zero, otherwise the plot names will not sort correctly when we list your directory, and it will be hard to find things. Thus, the first plot stored in your directory should be named **Lab3plot01.jpg**. Let's hope we never need more than 99 plot numbers per lab.

Import the file **lab014.a.cat** into xmgrace using the "block data" option, and make a plot showing MAG_ISOCOR as a function of the index of each star (that is, plot them in the order in which they appear in the data file). Please

- Plot using small circles as the data symbols. Choose a good color.
- Overplot error bars (this is an XYDY plot, in xmgrace parlance). Use MAGERR_ISOCOR for the error bars.
- Label the axes and put your name in the title, and save the plot in your standard place (plot #2).

Now make a more readable version of the same plot, this time with the data sorted into order of ascending MAG_ISOCOR. Save this plot in your standard place (plot #3).
Do the estimated errors vary with magnitude in a systematic way? Explain.

Errors increase with increasing star magnitude, which is to say, with decreasing brightness.

So far we have used SExtractor to obtain only the most minimal information about the objects in the detector field of view -- the positions and fluxes from each detected object. We will now look at SExtractor output files for which we have asked the program to do a more thorough job. Typically we want more kinds of information about each object for one of three reasons: to represent the data in a more convenient way, to display the result of a different way to estimate a number (such as the flux) for which we already have a value, or to give information about the reliability of the results displayed in other columns.

Open the file **lab014.a.cat** using **vi** (or your favorite text editor). Notice there are many more columns (you may need to widen your editor window or shrink the font size to display them all), and each has a header line describing it. Some of these may not make sense to you right away. Don't worry.
Import this file into xmgrace and plot MAG_ISOCOR on the x-axis and FLUX_ISOCOR on the y-axis.

- Make the y-axis logarithmic.
- Plot symbols only (no interconnecting lines). Use symbol types, sizes, and color that look good to you.
- Save the plot, with (as usual) your name in the title. (plot #4)
- Describe the relationship you see. From the graph, estimate the slope d(log flux)/d(magnitude) −0.4, and also the magnitude that would yield flux = 1. Below, write an expression for flux as a function of magnitude. Comment with reference to the definition of *stellar magnitude* (eg from Strobel).

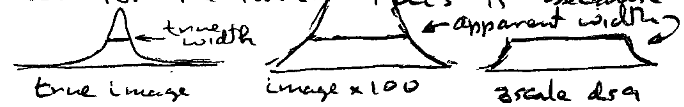
mag = 23 $\quad \log(\text{flux}) = (23.0 - \text{mag}) \times 0.4$ $\quad$ or $\quad \text{mag} = -2.5 \log(\text{flux}) + 23$

This is in line with the standard (Strobel) definition for a stellar magnitude, since $\log(2.512) = 0.4$

$\text{flux} = 10^{0.4(23.0-\text{mag})}$

Column 11 Is labeled "FWHM_IMAGE" (meaning Full Width at Half Maximum of the star image). This parameter is a measure of the width of the star images in units of pixels -- smaller numbers mean sharper images. How do these numbers compare with the widths you estimate using **ds9** with the "scale" option set to "zscale"? Comment on why this ds9 display may be misleading.

The ds9 images appear much larger (~25 pixels wide, vs ~5 pixels for the table). This is because zscaled images show only the very faint wings of bright images. The cores, where all the energy lies, are shown only as a uniform white blob.



Try setting the **ds9** "scale" to "min/max" and "linear" and estimate the sizes of a few of the star images (necessarily the brightest ones, since those are all you can see this way) using the cursor to read the pixel values. Is the comparison better? Set the "Horizontal Graph" option in the "View" tab, and estimate the FWHM of a bright star from this graph. How does this estimate compare with the others? This works better. For a typical bright star, I get a width of 6 pixels, which agrees fairly well with the tabulated (~5.5 pixel) values.

Stars are unresolved on these images, so the measured size of a star image ought not to depend on the brightness of the star. To see if this is true, make a plot of FWHM (y-axis) against stellar magnitude (x-axis). As usual, make sensible axis labels with your name in the title, choose suitable plot symbols and/or lines, and so forth. Save your plot. (plot #5)

From the plot, what do you estimate for a typical FWHM in pixel units? For most stars, FWHM ~ 5.3 ± 0.2

Using the number from above and your image scale/focal length estimate from Lab2, what is the typical FWHM in arcsec?

5.3 pix × 0.574 arcsec/pix = 3.0 arcsec ± 0.1

Do you see evidence for a dependence of FWHM on magnitude? Images get larger at the faint end (mag >14). There are some outliers with very small widths. Otherwise, there is no obvious dependence on magnitude.

Are the star images round, or elliptical? If they are not round, what might be the cause?

They are elliptical, elongated NW-SE. This is probably caused by telescope guiding errors.

The "BACKGROUND" column in **lab014.a.cat** contains estimates of the sky background flux (per pixel) in the neighborhood of each identified object. Make a plot of the sky background as a function of X_IMAGE, using any plot symbols you like, but no lines. Do not bother to save this plot. Instead, answer these questions:

- What happens if you *do* use lines to connect the data points? Explain what the program is doing to generate this unusable plot.

Data points are plotted in no particular order, connected by lines. This results in a tangled mess of randomly-oriented lines.

- What is a typical value for the sky background? What is the approximate scatter in the reported values?

Typical values are ~ 6.2.
The total range containing 95% of the data is about [5.7-7.0] = 1.3, so scatter is ~ $\pm \frac{1.3}{4} = 0.33$

- Within xmgrace, you can find simple statistics (min, max, mean, rms) for data sets by looking at "Edit/Data Sets". Ordinarily, your visual impression of the typical value of a bunch of plotted data points will closely approximate the mean value, and your visual estimate of the peak-to-peak scatter (ignoring rare outliers) will be roughly 4 times the rms. How do xmgrace's mean and rms values compare with the visual ones you just made?

	xmgrace	me
Mean	6.14	6.2
RMS	0.43	0.33

So the comparison is pretty good.

Plot MAGERR_ISOCOR as a function of MAG_ISOCOR. Again, use plot symbols of your choice (no lines). Label your plot, and put your name in the title, since you will eventually save it.
MAGERR_ISOCOR is an estimate of the error in MAG_ISOCOR, based on square-root-rule counting error for the number of detected photons in the object plus the underlying sky background. The total number of sky+object photons is

N_{phot} = GAIN * (FLUX_ISOCOR + BACKGROUND*N_{pix})

Background * Npix = $6.14 \times \pi \cdot \left(\frac{5.3}{2}\right)^2 = 6.14 \times 22.1 = 135$

Where GAIN is the number of detected photo-electrons per signal count (2.36 e-/count for this image, determined from the EGAIN keyword in the FITS header). N_{pix} is the number of pixels occupied by the object image. With ISOCOR photometry this number is hard to know for sure, but a reasonable guess is π (FWHM/2)^2. Use this guess, the GAIN value just given, and your estimate of BACKGROUND to write an expression for N_{phot} as a function of FLUX_ISOCOR:

Nphot = 2.36 × (FLUX_ISOCOR + 135)

Now use the flux-vs-magnitude expression from p. 2 to write an expression for N_{phot} as a function of MAG_ISOCOR.

Nphot = $2.36 \times \left(10^{-0.4(\text{mag\_isocor} - 23.0)} + 135 \right)$

The expected counting error (measured in photo-electrons) is the square root of N_{phot}. To get the noise in units of counts, we must divide by the GAIN. Write an expression for this counting error as a function of MAG_ISOCOR.

$$N_{err} = \left[2.36 \times \left(10^{-0.4(mag\_isocor - 23.0)} + 135\right)\right]^{1/2}$$

Now the tricky part. What error (in magnitudes) is implied by this error in the measured value of N_{phot}? Assume that the error is small compared to N_{phot} itself (ie, that $N_{phot} >> 1$), and show that if

mag = *m1* - 2.5 log(*flux*) (where *m1* is the magnitude that yields *flux* = *1*)

Then

δ *mag* ~= *1.086* δ *(flux)/flux* Derive this expression below.

$$\log_{10}(flux) = \frac{1}{\ln 10} \cdot \ln(flux)$$ where ln = natural logarithm. So

$$mag = m1 - \frac{2.5}{\ln 10} \ln(flux), \quad \frac{d\,mag}{d\,flux} = -\frac{2.5}{\ln 10} \frac{1}{flux}, \quad \delta mag \cong \frac{d\,mag}{d\,flux} \cdot \delta flux = \frac{2.5}{\ln 10} \frac{\delta flux}{flux}$$

$$\ln(10) = 2.3026\ldots \quad \text{so} \quad \delta mag \cong 1.086 \cdot \frac{\delta flux}{flux}$$

Now combine this expression and the one for counting error to write an expression for the expected error in magnitudes as a function of the object magnitude.

$$\delta mag = 1.086 \cdot \left[2.36 \times 10^{-0.4(mag\_isocor - 23.0)} + 135\right]^{1/2} \Big/ \left[2.36 \times 10^{-0.4(mag\_isocor - 23.0)}\right]$$

Finally, evaluate this expression for integer values of the magnitude, in the MAG_ISOCOR range covered by the data in **lab014.a.cat**. Create a text file (using **vi** or some equivalent thing) that contains in two columns the integer magnitude values and their expected errors, as you just calculated them. Call this table "err_vs_mag.txt", and put it in your directory on /backup. Import this data file into xmgrace and overplot the result onto the plot of MAGERR_ISOCOR vs MAG_ISOCOR. Plot just the connecting lines (no plot symbols), and use a thick = 3 red dashed line. Save the plot in the standard place. (plot #6)

Now we know how to use SExtractor output to estimate the fluxes and magnitudes of stars, and also the precision that simple physics says we should be achieving. But how well do we know our errors, really? Might effects other than photon counting statistics be dominant? And what about systematic errors, which give us consistent and repeatable wrong answers? How can we test for these?

SExtractor can estimate source fluxes in several ways – two of these are *isophotal* photometry (which deals well with objects having funny shapes) and *aperture* photometry (which works well for perfectly round objects, as star images are supposed to be). Check section 7.4 of *Source Extractor for Dummies* for an explanation of what these things mean. The picture on p. 41 is particularly helpful. Since there are different ways to estimate what ought to be the same quantities, let's see if we get the same answers with aperture photometry as we did with isophotal photometry. If not, the differences tell us something about our errors.

Make an xmgrace figure with two graphs, one on top of the other. As usual, label your axes and put your name in the title of the figure. For data, import the contents of **lab014.a.cat**. For the upper graph, plot MAG_ISOCOR on the x-axis and MAG_APER on the y-axis. By now you know how to choose plot symbols vs lines to give a sensible plot; do so. You should expect a tight but not perfect correlation between the two measurements, with a few dramatic outliers.

The wide range in plotted magnitudes makes it hard to see the errors. On the lower graph plot MAG_ISOCOR on the x-axis and, on the y-axis, plot (MAG_ISOCOR – MAG_APER). This will require that you do some arithmetic on within xmgrace in order to produce the difference. Try "Data/Transformations/Evaluate Expression". Choose your y-axis plot range carefully, to show the most information. If necessary, sacrifice a few outliers to show the typical scatter better. When both upper and lower graphs are complete, save your plot. (plot #7)

What is the peak-to-peak scatter in the difference (MAG_ISOCOR – MAG_APER), if you ignore extreme outliers? How does this compare with the tabulated uncertainties MAGERR_ISOCOR and MAGERR_APER? What do you conclude from this?

For well-behaved stars, the scatter is ~ ± 0.01 mag. (But note the systematic difference of ~ -0.1 mag, and the upward trend with increasing magnitude.) For most stars this is larger by a factor of a few than the tabulated uncertainties. This means important sources of error are not included in the calculated uncertainties.

Identify the stars corresponding to 3 of the most extreme outliers in your upper plot, and look at them using ds9. Is there a common source for the errors? If so, describe it. I see no common source. One star was a close double. One was a hot pixel (or cosmic ray hit.) One was merely faint and odd-shaped. Many processes may lead to erroneous magnitudes.

The previous exercise explored the systematic differences that result from doing a measurement in two slightly different ways. Next, we will try to measure random errors in the measurement, by analyzing repeated observations of the same stars, taken in the same way.

The program **match_stars** reads two SExtractor catalogs made from images of (almost exactly) the same field of view, taken at different times. In practice, even such nearly-identical images suffer from small displacements, changes in scale, rotations, and stretching with respect to one another. To compare stars between the two images thus requires figuring out the transformation relating star coordinates in one image to those in the other. The purpose of match_stars is to do this, to apply the transformation, and then identify stars that have nearly identical (transformed) coordinates in both images. It writes out a file that looks like an SExtractor catalog, but with twice as many columns, and containing one line for each star that it successfully matched. The column labels have "1" or "2" appended, to indicate whether they came from the first or second input file.

Match the catalogs **lab012.a.cat** and **lab013.a.cat**, putting the results in your backup directory with filename **match012_013.a.cat**. Do it this way: From your catalogs directory, type
match_stars lab012.a.cat lab012.a.cat /backup/results_YourName/match012_013.a.cat

First, it is necessary to see if match_stars derived sensible and consistent position differences between the two images.
Import match012_013.a.cat. Make a plot with 4 graphs in a 2 x 2 grid. The 4 graphs should contain
(1) X_IMAGE2 – X_IMAGE1 vs X_IMAGE1 (ie, X_IMAGE1 is the x-axis)
(2) X_IMAGE2 – X_IMAGE1 vs Y_IMAGE1
(3) Y_IMAGE2 – Y_IMAGE1 vs X_IMAGE1
(4) Y_IMAGE2 – Y_IMAGE1 vs Y_IMAGE1
Choose something sensible for the plot symbols, put your name in the title, and save the plot. (plot #8)

What would you expect to see in these plots if IMAGE2 were identical to IMAGE1, except for small constant (ie, independent of star) displacements in {x,y}? The plotted points would lie along straight horizontal lines at values equal to the x- or y- offsets between images.

What would you expect to see if IMAGE2 were identical to IMAGE1, except for a small rotation?

$x_1 = x_0 \cos\varphi - y_0 \sin\varphi$
$y_1 = y_0 \cos\varphi + x_0 \sin\varphi$

so $x - x_0 \simeq -y_0 \sin\varphi$
$y - y_0 \simeq x_0 \sin\varphi$

You expect sloped lines when plotting X1-X2 vs Y, or Y1-Y2 vs X.

Do you see evidence in the plots for either of these transformations? Explain
There is a clear offset of ~ -1.2 pixels in Y, and perhaps +0.1 pix in X
I see no clear evidence for a rotation.

Accepting that match_stars worked as it was supposed to, how well do the measured star magnitudes in lab012.a.cat agree with those in lab013.a.cat? To see this:
Make a plot of MAG_ISO2 – MAG_ISO_1 as a function of MAG_ISO1, with reasonable choices for symbols, labels, your name, etc. Save this plot. (plot #9)
Can you see any evidence that the magnitudes are systematically different between the two images?

MAG_ISO2 is about 0.025 mag greater (fainter) than MAG_ISO1.

Does the scatter in the magnitude differences depend on the magnitude of the star considered? If so, in what way?

Yes. Fainter stars (with larger magnitudes) show larger scatter.

Compare the scatter that you see in your plot with the theoretical dependence of error as a function of magnitude that you calculated on page 5 of this lab. Is your formula close to correct? Is it better for some magnitudes than others?

The formula is qualitatively correct, with very small (< 0.005 mag) for mag < 10. The quantitative agreement is not very good, however. For example, at mag = 14 the predicted RMS is ~ 0.015 mag, while the observed RMS is about 0.14/4 = 0.035, or about 2.5 times larger.

Make the same plot and do the same analysis for the difference MAG_APER2 – MAG_APER1. Save this plot also. (plot #10)
Can you see a reason (from the point of view of minimum noise) to prefer one or the other of isophotal vs aperture magnitudes? Explain.

There is an intermediate range of magnitudes (roughly 11 – 15) where Mag_Aper2 - Mag_Aper1 scatters a good deal less than Mag_Isocor2 - Mag_Isocor1. This difference can amount to a factor of 1.5 in the RMS. Thus, the Mag_Aper values are preferred.

Leaving aside the issues of error and uncertainty, we still have not put our measured magnitudes on a standard scale, such that the numbers we derive can be directly compared with other work. This comes down to measuring the constant *m1* from the first formula on page 5 of these notes. To choose *m1* so that it is reasonably consistent with other work:

Use **sky-map.net** (from Lab2) to determine the magnitudes of the same 5 stars that you used for the image-scale calculation in Lab2. Make a table below that shows the star number from the Figure in Lab2, its magnitude from sky-map.net, and (by matching {x,y} coordinates) its MAG_APER value from lab014.a.cat.

Star	Sky-Map.net	MAG-APER lab014.a.cat	x, y	Δ (skymap - lab)
1	14.55	12.154	317, 770	2.396
2	14.	11.817	324, 613	2.813
3	13.1	10.803	275, 51	2.297
4	13.7	11.646	1434, 37	2.054
5	13.8	11.503	1407, 840	2.297

Calculate the average difference between the SExtractror magnitudes and those from sky-map.net, and the rms of this difference, and write them here:

Average = 2.371 mag

Rms of individual points = 0.277 mag $= \left[\frac{1}{4}\sum(\text{mag}-2.371)^2\right]^{1/2} = \sigma_i$

Std Dev of mean = 0.139 $= \sigma_i/\sqrt{N} = \sigma_i/2$

Write an expression, including an estimate of the error, for magnitudes on the sky-map.net system in terms of the SExtractor magnitudes.

Sky-map = SExtractor_Aperture_mag + 2.371 mag ± 0.139

Assume the brightest of the stars in your list of 5 has an *absolute magnitude* of 1.50. What is its distance (in parsecs)? What uncertainty do you assign to this distance estimate, given only the uncertainty that you just calculated in estimating sky-map.net magnitudes from SExtractor magnitudes? Justify your answers. Brightest is #3. On sky-map system, mag = 10.803 + 2.371 ± 0.14 = 13.174 ± 0.14

$$\text{mag} = M_{abs} + 2.5\log\left(\frac{\text{dist}^2}{10^2}\right) = 1.5 + 5\log\left(\frac{\text{dist}}{10}\right)$$

$$\frac{11.674}{5} = \log\left(\frac{\text{dist}}{10}\right), \quad \text{or} \quad \frac{\text{dist}}{10} = 10^{2.335} = 216 \quad \text{So dist} = 2160 \text{ pc.}$$

This distance is too large, so we probably assumed too bright an absolute magnitude for star #3.