AST 152M: STELLAR ASTRONOMY LAB
FALL 2013
LAB 4: STELLAR PHOTOMETRY
DUE FRIDAY, 30 SEPTEMBER 2013

1. Overview

Now that you have characterized the CCD detector in terms of its response to light and noise properties, you can quantify digital signal (ADU) in terms of brightness (number of photons). In order to establish this relationship, you need to observe a standard star, one where you know the photon flux through different standard filters. Stellar light suffers scattering and absorption as it makes its journey through our atmosphere, the telescope, and the instrument before it gets converted into electrons on the chip. The ratio between photons incident on the telescope and the corresponding numbers of electrons detected on the CCD, converted to flux, is called the system throughput. Once this number has been calibrated, you can then convert ADUs per unit time into a stellar apparent magnitude, allowing you to measure the brightness of any object you image on the CCD.

2. Calibration Standard

In order to obtain a proper photometric calibration of your system in this lab, its very important that you select as a target a known standard star, defined as a star 1) whose output is known to be stable over a period of many years, and 2) for which precise calibrated magnitudes are known. You may want to have several targets ready to go in case there is a problem with one. Some good references for standard stars are the Astronomical Almanac, the SIMBAD website, and the Landolt papers.

The Landolt papers (Landolt, A.U. 1992, AJ 104,340; Landolt,A.U. 1983, AJ 88, 493; Struzubger et al. 2005, PASP 117, 810; Landolt, A.Y. 2009 AJ 137,4186) used a very good calibration in order to measure the flux of a set of stars. These papers establish a very strong reference for doing photometry. You can download these papers from any computer on the UT campus be searching for them using the ADS abstract service (`http://adsabs.harvard,edu/abstract_service.html`).

The Astronomical Almanac combines information from many sources and lists the stars that are reliable standards. The section on "UBVRI Standard Stars" lists these. You can find copies of the Almanac in Pridier Library, and you dont need the current year for these numbers to be accurate; since they are believed to be "standards", they shouldnt change significantly in brightness over the years.

Finally, you can use SIMBAD to search for stars. The challenge with SIMBAD is that for a given star you can't tell only from the SIMBAD information how reliable the star is or the photometric data is as a standard.

When choosing calibration standards, you want to ensure that when you image the star you will not saturate the exposure. Based on the exposure times that you estimated in Lab 3, $m_V \geq 6$ is a guideline for photometric standards using the RLM telescope and camera.

3. Finder charts

You have chosen your stars, and you take an image, and you see an image like fig. 1

FIGURE 1. Exposure of a field after the telescope is set to the chosen coordinates. Note the lack of labels or clearly identifying characteristics. Without a finder chart it is impossible to know if any of the stars in the field are the ones that you are interested in.

It becomes very important to create a finder chart to make sure that a) you are even looking the right place (just because you pointed the telescope somewhere doesn't mean the telescope is actually pointing at the thing you are trying to look at), and b) if you have the right field, you can actually find the star that you are interested in. Some good sources of finder charts are the U.S. Naval Observatory (`www.nofs.navy.mil/data/fchpix`), Stellarium (you can enter data for your telescope and camera and get a pretty good picture of what your image should look like), and SIMBAD (when you select an object you can use the 'Query around with radius X arcmin', then plot the list to get a finder chart). You may also use the Aladdin tool on SIMBAD to get a sample image. Note that the image will probably be deeper than you can get on the RLM telescope.

4. Relative photometry

Relative photometry is the most basic type of photometry that can be done using a CCD. This method compares the measured flux of a standard star with that of a target, then uses the flux ratio to find the magnitude of the target star. Measuring the flux seems relatively straightforward: in labs two (Characterizing the CCD) and three (Creating and Observing List), you found the gain of the CCD (which is how many electrons are required for one 'count' in a pixel), and in lab three you specifically considered the relation between exposure time, gain, system efficiency and flux:

$$S_{ADU} \approx \frac{qlf_{\gamma}tA}{g} \tag{1}$$

where S is the measured count for a pixel in the image, q is quantum efficiency, l is transmission (typically ~ 0.65), f_γ the photon flux, t the exposure time, A the telescope aperature, and g the CCD system gain. The $\approx$ is due to system noise (e.g. dark current, read noise); we will consider these more in depth momentarily.

If we assume for the moment that our measured count is only the signal from the stars, then we could say

$$\frac{S_1}{S_2} = \frac{qlf_1t_1A}{g}\frac{g}{qlf_2t_2A} = \frac{f_1t_1}{f_2t_2} \tag{2}$$

We know the exposure lengths and the counts of each one, and thus can find the ratio of fluxes, which we can then use to find the observed magnitude of the target star

$$m_1 - m_2 = -2.5\log\frac{f_1}{f_2} = -2.5\log\frac{S_1t_2}{S_2t_1} \tag{3}$$

In practice, we need to consider sources of noise. We have previously quantified the sources of noise or signal within the CCD system itself: dark current, bias, and read noise. There is one additional source of signal: spurious light which has been scattering into the telescope. There are three sources of this light: the Sun, artificial light, and other stars. The light of the sun is scattered by dust and gas within our solar system (and the moon, if it is visible) and back toward Earth (then further scattered by the atmosphere. Artificial light from nearby cities or human structures also scatters off of the atmosphere into the telescope. Finally, the light of other stars scatters off of dust and gas in interstellar space then into our detector. The combination of this light from all non-target sources is called the **sky background**. We can't predict how much of this light is actually going to end up in our detector, so we must find a way to remove this light. Fortunately we are looking at stars, which appear (very nearly) as points in our image. Consider the following star image:

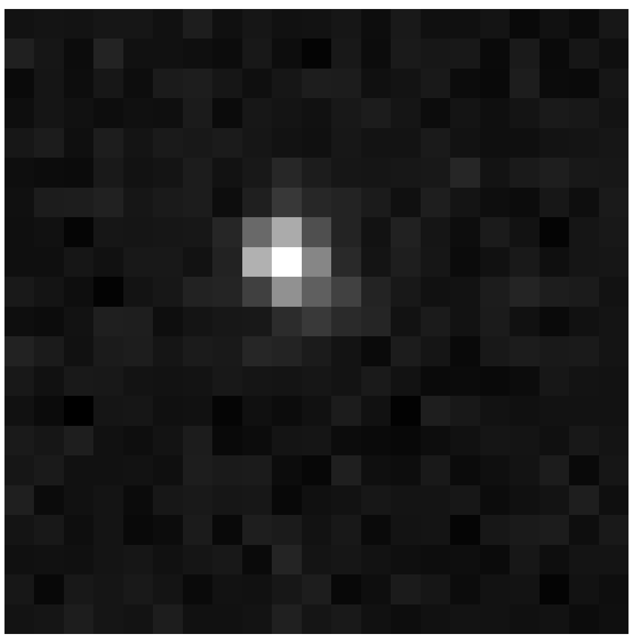

FIGURE 2. An image of a star.

We can first see that the star image has been spread out over several pixels, we also see that the pixels around the star are not black (i.e. their value is non-zero). The latter pixels are mostly sky pixels; there may also be an occasional few photons from the star which was scattered into these pixels.

To find the actual flux from the star, we first need to add together all of the pixels that light from the star lands on. Then, we can use the pixels that are near the star but have no (or very few) star photons in them to find the signal due to the sky itself. If we consider the sky background to have a mean photon flux

f_{Sky}, and a Gaussian distribution ($\sigma_{Sky} = \sqrt{f_{Sky}}$), then we will find the

$$
\begin{aligned}
S_{*,sky} &= \sum_i \frac{q_i l(f_{*,i} + f_{Sky,i})tA}{g_i} + s_{DN,i}t + S_{bias,i} + S_{RN,i} \\
&\approx N_{*,sky} \left\langle \frac{q_i l(f_{*,i} + f_{Sky,i})tA}{g_i} + s_{DN,i}t + S_{bias,i} + S_{RN,i} \right\rangle \\
&\approx N_{*,sky} \left(\left\langle \frac{q_i l(f_{*,i} + f_{Sky,i})tA}{g_i} \right\rangle + \langle s_{DN} t \rangle + \langle S_{bias} \rangle \right)
\end{aligned} \tag{4}
$$

where the sum is over all pixels containing photons from the star and N is the number of pixels sampled; that of the sky area is

$$
\begin{aligned}
S_{Sky} &= \sum_i \frac{q_i l(f_{Sky,i})tA}{g_i} + s_{DN,i}t + S_{bias,i} + S_{RN,i} \\
&\approx N_{sky} \left\langle \frac{q_i l(f_{Sky,i})tA}{g_i} + s_{DN,i}t + S_{bias,i} + S_{RN,i} \right\rangle \\
&\approx N_{sky} \left(\left\langle \frac{q l(f_{Sky})tA}{g} \right\rangle + \langle s_{DN} \rangle t + \langle S_{bias} \rangle + \langle S_{RN} \rangle \right) \\
&\approx N_{sky} \left\langle \frac{q_i l(f_{Sky,i})tA}{g_i} \right\rangle + \langle s_{DN,i} \rangle t + \langle S_{bias,i} \rangle
\end{aligned} \tag{5}
$$

Let us first remove subtract bias and dark current by subtracting the dark frame (or, in the case of our camera, just the bias frame, since dark current is effectively zero for all short exposures)

$$
\begin{aligned}
S_{b,*,sky} &= N_{*,sky} \left(\left\langle \frac{q_i l(f_{*,i} + f_{Sky,i})tA}{g_i} \right\rangle \right) \\
S_{b,Sky} &= N_{sky} \left\langle \frac{q_i l(f_{Sky,i})tA}{g_i} \right\rangle
\end{aligned} \tag{6}
$$

If we normalize using the flats, we also nearly eliminate the q, g, and l factors (reducing them to an averaged gain G):

$$
\begin{aligned}
S_{b,*,sky} &= N_{*,sky} \left(\left\langle \frac{(f_{*,i} + f_{Sky,i})tA}{G} \right\rangle \right) \\
S_{b,Sky} &= N_{sky} \left\langle \frac{(f_{Sky,i})tA}{G} \right\rangle
\end{aligned} \tag{7}
$$

Then, we wish to subtract the sky. The average sky value is

$$
\langle S_{b,Sky} \rangle = \frac{S_{b,Sky}}{N_{sky}} \tag{8}
$$

if we multiply the average by the number of pixels we sampled of star + sky pixels

$$
\begin{aligned}
S_{b,*,sky} &= N_{*,sky} \left(\left\langle \frac{(f_{*,i} + f_{Sky,i})tA}{G} \right\rangle - \langle S_{b,Sky} \rangle \right) \\
&= N_{*,sky} \left(\left\langle \frac{(f_{*,i} + f_{Sky,i})tA}{G} \right\rangle - \frac{1}{N_{sky}} \left\langle \frac{(f_{Sky,i})tA}{G} \right\rangle \right) \\
&= \frac{N_{*,sky}tA}{G} \left(\langle f_{*,i} \rangle + \langle f_{Sky,i} \rangle \right) - N_{*,sky} \left\langle \frac{(f_{Sky,i})tA}{G} \right\rangle \\
&= \frac{N_{*,sky}tA}{G} \langle f_{*,i} \rangle \\
&= \frac{F_* tA}{G}
\end{aligned} \tag{9}
$$

here I use F to designate the total flux of the star over all pixels.

We can now use this method for two stars to find the magnitudes as noted above; however so far we have just measured the magnitude at our telescope. The atmosphere is sitting above us, scatting some of the light of the stars away from us. Thus we still need to account for the atmospheric extinction. The magnitude of a star changes by

$$m_o - m_i = kX \tag{10}$$

where m_o is the observed magnitude, m_i is the 'intinsic' magnitude at the top of the atmosphere, k is the extinction coefficient, defined as the change in magnitude due to an airmass of 1, and X is the airmass. Since the stars that we look at will probably be in slightly different places in the sky, the airmass of each observation will be slightly different. The extinction coefficient is the same[1]. If we look at our reference star twice at different airmasses we can compare the star to itself

$$\begin{aligned} m_1 - m_0 &= kX_1 \\ m_2 - m_0 &= kX_2 \\ m_1 - kX_1 &= m_2 - kX_2 \\ kX_1 - kX_2 &= m_1 - m_2 \\ &= -2.5 \log \frac{S_1 t_2}{S_2 t_1} \end{aligned} \tag{11}$$

If we then apply this to the comparison of target and reference star

$$\begin{aligned} m_* - m_{i,*} &= kX_* \\ m_0 - m_{i,0} &= kX_0 \\ m_{i,*} - m_{i,0} &= k(X_0 - X_*0) + m_* - m_0 \\ &= k(X_0 - X_*0) - 2.5 \log \frac{S_* t_0}{S_0 t_*} \end{aligned} \tag{12}$$

Here I use substrict '*' to represent the target, and subscript '0' to designate the reference star.

5. Absolute photometry

The method above works very well for measuring the relative flux and magnitude between two stars. What if we want to find the actual flux (in erg s^{-1} cm^{-2}). Consider again the measured count in a pixel:

$$S = S_* + S_{sky} + S_{DN} + S_{RN} + S_{bias}. \tag{13}$$

Let's look a little more in depth at the count due to the sky and star

$$S_{*,sky} = \int_{\nu_{min}}^{\nu_{max}} \frac{q_\nu l_\nu f_\nu t A \phi_\nu}{g} d\nu \tag{14}$$

here we recognize that the many of the parameters of the system are dependant upon frequency (or wavelength). The additional ϕ_ν factor that I have added accounts for the filter which we are using. Note that q, l, ϕ are all unique for the instrument, filter, and telescope being used; for a given filter, we can combine these into a single value Φ.

$$S_{*,sky} = \int_{\nu_{min}}^{\nu_{max}} \frac{\Phi_\nu f_\nu t A}{g} d\nu \tag{15}$$

To avoid doing this complete integral, let's take the average Φ and f values across the filter that we are using

$$S_{*,sky} = \frac{\Delta\nu \bar{\Phi} \bar{f} t A}{g} \tag{16}$$

[1]There may be very small differences in the atmospheric extinction coefficient between observations. For most photometry this small variation can be ignored; for very precise photometry, this effect can be reduced by making multiple observations of both the target and reference stars.

If we use the same filter and instrument to measure two stars

$$\frac{S_1}{S_2} = \frac{\Delta\nu\bar{\Phi}\bar{f}_1 t_1 A}{g}\frac{g}{\Delta\nu\bar{\Phi}\bar{f}_2 t_2 A} = \frac{\bar{f}_1 t_1}{\bar{f}_2 t_2} \tag{17}$$

What we measure is below the atmosphere, but we really want the flux above the atmosphere. Let us designate the non-extinced flux by F:

$$f = Fe^{-\tau} = Fe^{-\left(\frac{kX}{1.086}\right)} \tag{18}$$

then

$$\frac{S_1}{S_2} = \frac{\bar{f}_1 t_1}{\bar{f}_2 t_2} = \frac{F_1 t_1}{F_2 t_2}e^{-\left(\frac{k(X_1 - X_2)}{1.086}\right)} \tag{19}$$

We can determine the flux of our reference star using the known magnitude and the following table:

Standard photometric quantities

Filter Band (Johnson)	$\lambda_0[\mu m]$	$\Delta\lambda[\mu m]$	Absolute Spectral Irradiance [$\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{\AA}^{-1}$]
B	0.44	0.098	1462
V	0.55	0.089	1007
R	0.70	0.220	481
I	0.90	0.440	376

Recall that the relation between photon flux and energy flux is

$$f[\,\mathrm{erg}] = \frac{hc}{\lambda}f[\gamma] \tag{20}$$

We now have all of the information we need to find the absolute flux of the target star.

An additional note: here we assume that we can use a reference star. In some cases it is necessary to actually measure the absolute flux from a star without using another star (e.g. initially measuring the standard stars). Doing this is outside the scope of this course. Suffice to say that it requires very good calibration of your instrument, and you basically need to understand the optical characteristics of your telescope, filter, and CCD very well. Standard lab sources (e.g. lamps which have a very well calibrated and known spectrum) are used for this process.

6. Error analysis

We still have one more task, however: we must quantify the uncertainty in the measurement, and account for all sources of error. We also want to quantify the effect of the errors on the measured magnitude. For a system a dependence upon variables $\{x_1, x_2, ..., x_n\}$ as $f = f(x_1, x_2, ..., x_n)$ with uncorrelated errors (that is, uncertainty in variable x_1 does not effect the value or uncertainty in variable x_2) has an uncertainty

$$\sigma_f^2 = \sum_{i=1}^{i=n}\left(\partial_{x_i} f(x_1, x_2, ..., x_n)\sigma_{x_i}\right)^2 \tag{21}$$

If we first consider only the error in magnitudes

$$\begin{aligned} m_1 &= m_2 - 2.5\log\frac{f_1}{f_2} + k(X_1 - X_2) \\ &= m_2 - 2.5\log\frac{S_1 t_2}{S_2 t_1} + k(X_1 - X_2) \end{aligned} \tag{22}$$

$$\sigma_{m_1} = \sqrt{\sigma_{m_2}^2 + 6.25\left(\left(\frac{\sigma_{t_1}}{t_1}\right)^2 + \left(\frac{\sigma_{t_2}}{t_2}\right)^2 + \left(\frac{\sigma_{S_1}}{S_1}\right)^2 + \left(\frac{\sigma_{S_2}}{S_2}\right)^2\right) + 4k^2\sigma_X^2 + \sigma_k^2(X_1 - X_2)^2} \tag{23}$$

The timing uncertainties are typically around a millisecond ($\sigma_t \sim 10^{-3}$ s), and will generally be a negligible contribution to the total uncertainty (except perhaps for short exposures). The uncertainty in airmass is generally relatively small; you can use the approximations that you made in lab one to find the uncertainty; if you use the more complicated estimate for airmass, the uncertainty will still probably be on order $\sigma_X \approx 0.01$. The uncertainty in k is based on measurement (more on this later). The uncertainty in the signal must be determined: first consider that it takes the form σ_S/S; we call the inverse of this quantity (S/σ_S) the **signal-to-noise ratio** or **SNR**; it is a quantification of how many standard deviations the signal is above the mean value. To find the signal to noise ratio, we consider the total signal, S_* to that of the noise within the region in which the signal is measured. We will simplify the equation by using the counts for each component in the pixels rather than the flux, etc, and assume that the timing, aperture, quantum efficiency, and gain uncertainties are negligble

$$(24)\quad S = S_{*,sky} = \sum_i (S_{*,i} + S_{sky,i} + S_{DN,i}t + S_{RN,i} + S_{bias}) = \mathcal{S}_* + N_{pix}(\langle S_{sky}\rangle + \langle S_{DN}\rangle + \langle S_{DN}\rangle + S_{bias})$$

The uncertainty in this total value is

$$\sigma_S^2 = \sigma_*^2 + N_{pix}^2(\sigma_{sky}^2 + \sigma_{DN}^2 + \sigma_{RN}^2) \tag{25}$$

Assuming that the noise is proportional to the signal ($\sigma_S = \sqrt{S}$) for the star, sky, and dark current, then

$$\sigma_S = \sqrt{\mathcal{S}_* + N_{pix}^2(S_{sky} + S_{DN} + \sigma_{RN}^2)} \tag{26}$$

and the signal to noise is then

$$\frac{S}{\sigma_S} = \frac{\mathcal{S}_*}{\sqrt{\mathcal{S}_* + N_{pix}^2(S_{sky} + S_{DN} + \sigma_{RN}^2)}} \tag{27}$$

Once the signal to noise ratio is known, it can be plugged into the above equation to find the uncertainty in your measurement.

To find the uncertainty in the atmospheric extinction requires a similiar analysis. I leave it up to the reader to perform this analysis.

7. Data at the Telescope

In lab 2 you found the bad pixel mask. In general, you should avoid bad pixels when doing photometry, as they can affect the result, so you should try to position the stars which you are measuring off of the bad pixels. Practically speaking, our CCD has few truly bad pixels (the highest count that that occurs in 15 second darks was about 6500; this can be corrected for by using darks, although if the dark count is comparible to the signal this will drive down the signal to noise significantly). Avoid the bad pixels as best as you can, and make sure to take darks of the same exposure time as your images.

One difference in this lab from the previous labs: you will be using the filters. It is important to take your flats *with the filters in place*, so that you have a reference of the system response (all of the $q, l, \Phi,$, etc. factors from above) within the filter. You cannot use unfiltered flats to normalize your image. You only need to take one set of flats in each filter, you do not need flats of different exposure times. You may also take night sky flats, but be aware that the filters may significantly reduce the signal that you get in them. Whichever flats that you take, you will want to take enough to make a median frame.

For this lab, you want to take B, V, and R images of the following target stars:

ID	RA	Dec	Sp Type	Est. V mag
GJ 623	16h 24m 09.32495s	$+48°21'10.4611''$	M3V	10
HD 227858	20h 08m 05.4611s	$+39°26'46.334''$	G5V	11
HD 338931	19h 47m 02.7406s	$+24°50'55.549''$	O6	9

Use the following Landholt standard

ID	RA[2000.0]	Dec[2000.0]	V	
SA 113 475	21h 41m 51.2965s	$+0°39'20.773''$	10.304 ± 0.0004	
B - V	U - B	V - R	R - I	V - I
$+1.058 \pm 0.0005$	$+0.841 \pm 0.0012$	$+0.568 \pm 0.0004$	$+0.528 \pm 0.0006$	$+1.097 \pm 0.0006$

You will need at least two observations of the Landolt star, taken as far apart in time as is pratical (e.g. at the start of the night and at the end of your observing night). You may take multiple observations of your target stars as well. Be aware of the LST and RA of your stars and make sure that they do not get to low in the sky - prioritize your observations with this in mind.

For every exposure time, a set of corresponding dark frames at the same exposure time is needed in order to zero the offset and remove the dark current from the target image. (5-9 darks per exposure time ought to be sufficient; remember, odd numbers!) Make sure you take darks that correspond to the exposure times of the flats as well.

For best results, calibrate the telescope position on a known, easy to identify star as soon as it is dark enough to do so. It will then be easier to point at and find the target stars.

8. Data Reduction and Analysis

8.1. **Dark Subtraction, Bias Removal, & Averaging.** Combine each set of dark frames according to exposure time (`imcombine`) to create a master dark frame. Subtract (`imarith`) from each target frame (object image and flat field) the corresponding master dark frame of the same exposure time. Then median combine together the dark-subtracted frames of the same exposure time and filter setting for each target.

8.2. **Flat fielding and Normalization.** Combine your flat frames of each filter (`imcombine`) into a master flat frame. Normalize each average flat frame by finding the median pixel value with `imstat` (specify the `midpt` field) and dividing all pixels in the flat field by this value using `imarith`. You may also use the `normalize` task to normalize the flats . Divide (`imarith`) each star frame by the normalized flat field to re-scale each pixel value for uniform responsivity. REMEMBER: Divide the images by flats of the appropriate filter: i.e., divide B images by the median B flat, etc.

8.3. **Alternate Reduction Method.** Another way to combine darks and flats is with darkcombine and flatcombine in `noao`→ `imred` → `ccdred`. These were developed by NOAO for IRAF. You can also use `ccdproc` to apply your darks and flats to your target images. Just read the help files.

8.4. **Summing Counts with `phot`.** Now you are ready to sum the counts (ADUs) of your star on the chip. First, display your reduced image in DS9 (`display`).

Next, you need to set some parameters inside `phot` which will sum up all the counts from your standard star on the array. There are several version of `phot`. A standard one is in `noao` → `digiphot` → `apphot`. Use `epar` to edit the parameter list for `phot`. Scroll down to `fitskyp` and type `:e` and return. You will see new list a parameters specific to the topic of background sky counts. IRAF will estimate the background level surrounding your star and remove it. You will need to set `annulus` to a value that is larger than the radius of your star on the array. Set `dannulus` to some nominal width (say 10 pixels) such that there wont be any interference from neighboring stars. Go back to the main parameter list with `:q` and return. Scroll down to `photpar` and get into this sub parameter list like before. Set `apertur` to be the radius of your star (start with 7 pixels).

Now exit back to the main parameter list, and set `radplot` to yes. Execute phot by typing `:go` from within the parameter editor and return. As before, you will see a blinking doughnut in your ds9 window (make sure you first click in the window to activate it). Set the cursor over your star, this hit space bar to get the summed counts of the star with the nearby background level already subtracted out. You will also notice a radial profile plot window will appear showing a cut through the star you selected. Change your parameters if the star aperture and/or sky annulus is not appropriate to what you see in the profile.

You will see numbers output to the xterm window after you hit the space bar. These numbers are x and y coordinates, summed counts (ADU) and arbitrary magnitude. This information is saved to a file with a `.mag` file extension and the original image name. Repeat this procedure for the other exposure times and filter settings. Look in the file and you will see the following near the end:

```
#N IMAGE                  XINIT     YINIT     ID    COORDS                  LID    \
#U imagename              pixels    pixels    ##    filename                ##     \
#F %-23s                  %-10.3f   %-10.3f   %-6d  %-23s                   %-6d
#
```

```
#N XCENTER    YCENTER    XSHIFT  YSHIFT  XERR    YERR            CIER CERROR   \
#U pixels     pixels     pixels  pixels  pixels  pixels          ##   cerrors  \
#F %-14.3f    %-11.3f    %-8.3f  %-8.3f  %-8.3f  %-15.3f         %-5d %-9s
#
#N MSKY           STDEV          SSKEW          NSKY   NSREJ     SIER SERROR   \
#U counts         counts         counts         npix   npix      ##   serrors  \
#F %-18.7g        %-15.7g        %-15.7g        %-7d   %-9d      %-5d %-9s
#
#N ITIME          XAIRMASS       IFILTER                OTIME                   \
#U timeunit       number         name                   timeunit                \
#F %-18.7g        %-15.7g        %-23s                  %-23s
#
#N RAPERT   SUM           AREA       FLUX          MAG    MERR   PIER PERROR   \
#U scale    counts        pixels     counts        mag    mag    ##   perrors  \
#F %-12.2f  %-14.7g       %-11.7g    %-14.7g       %-7.3f %-6.3f %-5d %-9s
#
nccd137                395.000   382.000   1     nullfile              0      \
   397.163    380.896    2.163   -1.104  0.091   0.049          107  BigShift \
   20.79403       9.689811       3.271409       941    2        0    NoError  \
   1.             INDEF          INDEF                  INDEF                   \
   5.00     1629.08       78.84825   -10.49313     INDEF  INDEF 0    NoError
```

The bottom several lines are the actual data, the top lines describe the order of the data. The fields which are important are the mean sky value (MSKY), the number of sky pixels (NSKY), and the total count (SUM). In reference to the quantities discussed above,

$$S_{*,sky} = \text{SUM} \quad S_{sky} = \text{MSKY} \cdot \text{NSKY} \tag{28}$$

8.5. **Atmospheric extinction and relative magnitude.** Once you have the flux (counts) for the target stars and standard star, use these to find the relative magnitude of the target stars. Use the multiple observations of the standard star to find the extinction coefficient k in each filter.

8.6. **System response.** Once you have found the extinction coefficient, you can use the standard star and the known flux in each filter to find the system response for each filter. For each filter, using the standard star, find the system response in counts per photon. Using a gain of $3.0e^{-}/ADU$, state what the total light losses are in the telescope / camera system.

8.7. **Intrinsic flux of target stars.** Using the system response you find from the standard star, and the measured flux for your target stars, find the observed flux at the top of the telescope. Correct this value for atmospheric extinction and report the flux of the star at the top of the atmosphere.

8.8. **Error analysis.** Include an error analysis as described above to find the uncertainty in the target star magnitudes and fluxes, the atmospheric extinction coefficient, and the system response.