

## Lab 6: Atmospheric Extinction and Color Photometry

(Due: April 30, 2019)

### The Optical Spectrum

Stars can be approximated as a black body radiating at the temperature of the surface of the star. The black body spectrum peaks at a wavelength that depends on the temperature, so that cool objects radiate with a peak in the infrared, while hot objects glow in colors that range from red through yellow to blue as the object's temperature increases. As shown in figure 1, a red star (surface temperature 3000 K) appears red because its black body spectrum peaks in the infrared, and in the visible part of the spectrum the brightness slopes strongly from red to blue. In other words, there is more red light than blue light, and the star has a red hue. A blue star (surface temperature 15000 K) appears blue because its spectrum peaks in the ultraviolet, and in the visible part of the spectrum the brightness slopes in the other direction, from blue to red. For the Sun (surface temperature 5800 K), the spectrum is just about flat, i.e. all colors are equally bright, so that the Sun produces white light.

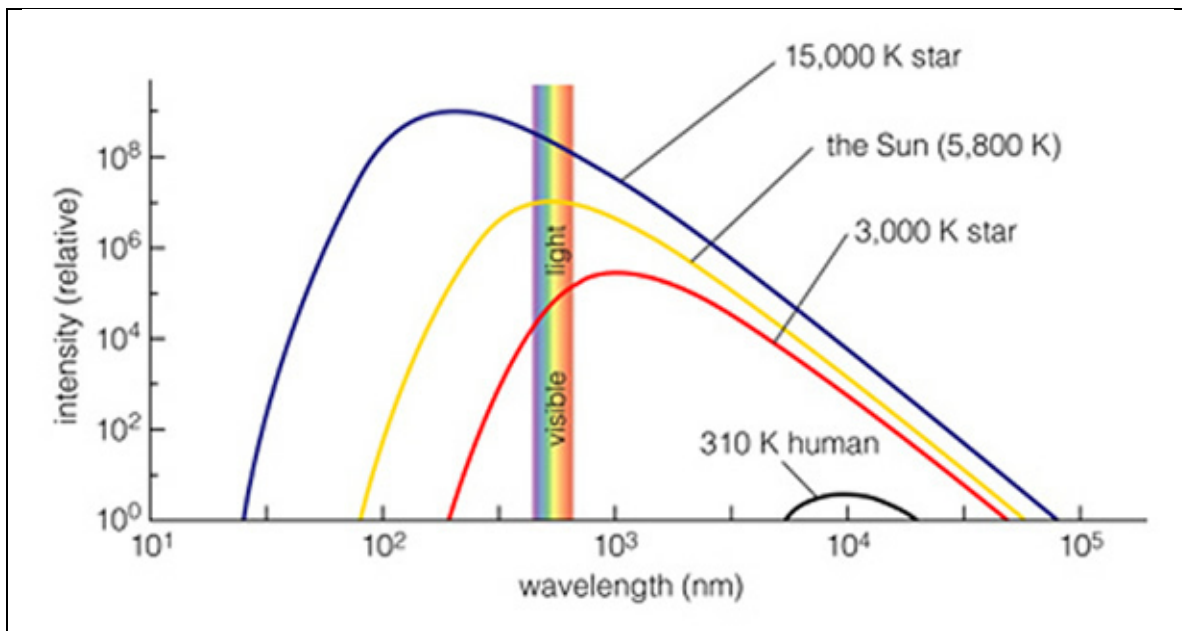


Figure 1: Intensity of radiation emitted by objects of various temperatures. The extent of the visible spectrum is shown by the vertical bar in rainbow colors. The overall shape of the different spectra is the same (the black body spectrum), but is shifted to higher overall emission, and shorter wavelengths as the surface temperature increases.

You may think that it is an amazing coincidence that the Sun peaks exactly in the visible spectrum, but consider that the term “visible” refers to the response of our eyes. Since we evolved in sunlight, it is no accident that our eyes respond best to the peak of the Sun’s radiation spectrum.

Our camera is equipped with three color filters, termed R (red), G (green) and B (blue), as well as a broader filter termed L (luminance) that includes all three colors. The top panel of Figure 2 shows the transmission characteristics of these filters. Astronomers have standardized on other filters, however, designated U, B, V, R and I, with the transmission characteristics shown in the middle panel of Figure 2. Our R, G and B filters correspond roughly to the standard R, V and B that astronomers use.

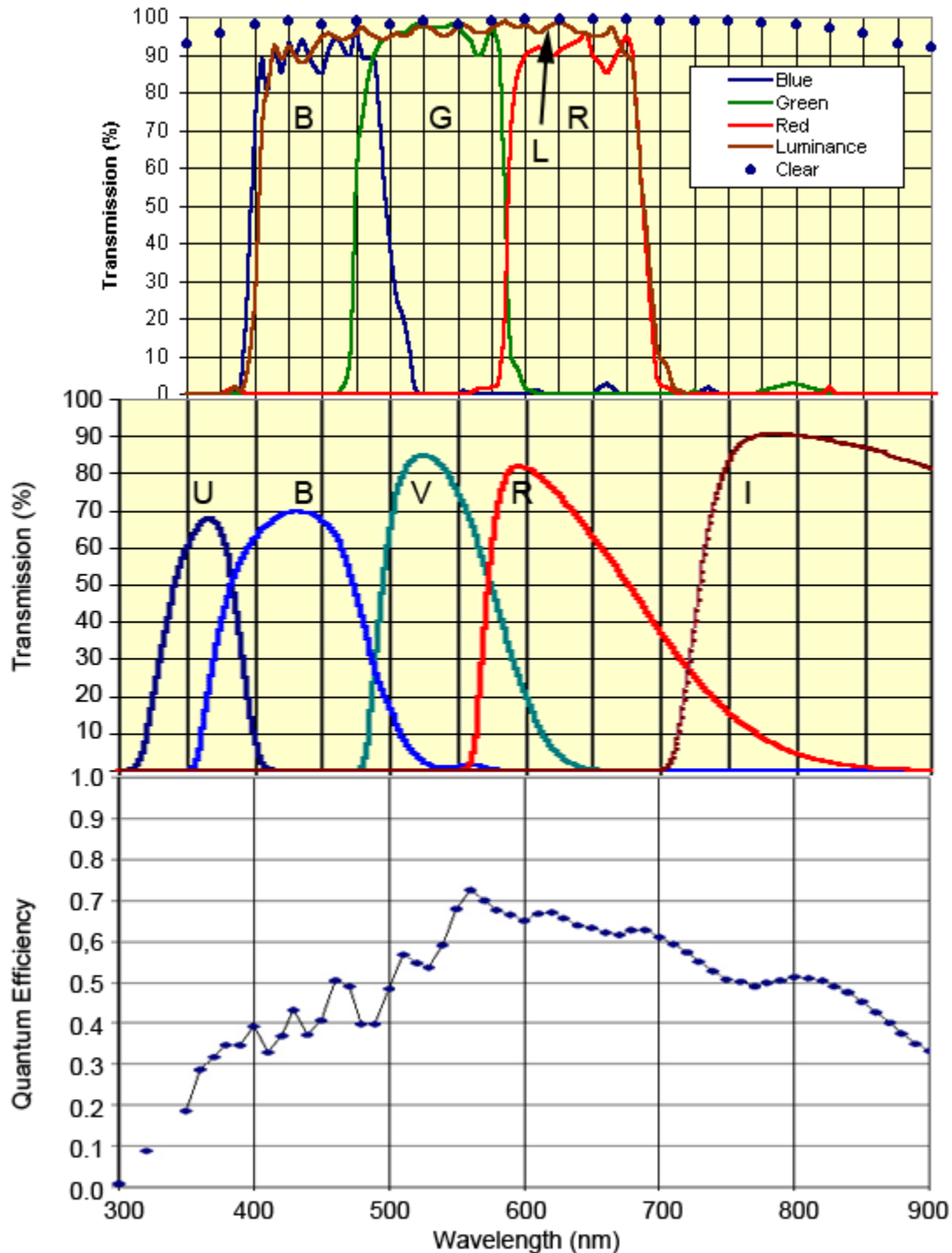


Figure 2: Transmission characteristics of various filters, and the QE of the camera.

When we use our camera to take images of a white object through these filters, the object will appear at different brightness because the filters each have slightly different total transmissions (the integral of the transmission function  $F_\lambda$  times the incoming spectral intensity  $I_\lambda$ ), i.e.  $S_\lambda = \int F_\lambda I_\lambda d\lambda$ . In addition to the filters, the detector (the camera's CCD) has its own response to the incoming light of different colors, which may not be flat. The spectral response, or quantum efficiency, of our CCD camera, based on the Kodak KAF-1301 chip, is shown in the bottom panel of Figure 2. If we write the detector's quantum efficiency as  $Q_\lambda$ , then the measured brightness of the star would be  $S_\lambda = \int Q_\lambda F_\lambda I_\lambda d\lambda$ .

Now let's say that we measure a solar-like star (spectral type G2V), and *assume* that the intensity in the visible part of the spectrum is flat (a reasonably good, though not exact, assumption). Since  $I_\lambda = \text{constant}$ , we can bring it out of the integral and write  $S_\lambda = I \int Q_\lambda F_\lambda d\lambda = \epsilon_\lambda I$ , where  $\epsilon_\lambda$  is a coefficient that depends on wavelength. Thus, the brightness we measure in filter R, for example, will be  $S_R = \epsilon_R I$ , while that in filter G is  $S_G = \epsilon_G I$ , and that in filter B is  $S_B = \epsilon_B I$ .

We have another problem, however. The G2V star has flat intensity only at outside the Earth's atmosphere. When the light travels through the atmosphere, it loses some intensity due to absorption, and some due to scattering, and these effects are wavelength dependent. You know that the Sun appears red at sunset, for example, due mainly to scattering of blue light in the atmosphere. The effect on a star's light due to the combination of these two effects, absorption and scattering, is called extinction, which we will characterize with another coefficient,  $\alpha_\lambda$ .

The goals of this lab are two-fold. The first is to measure the coefficients that are characteristic of our color filters plus detector, i.e. we will measure  $\epsilon_R$ ,  $\epsilon_G$ , and  $\epsilon_B$ . The other goal is to measure the transmission characteristics of Earth's atmosphere (atmospheric extinction), to derive the coefficient  $\alpha_\lambda$ .

## Atmospheric Extinction

The passage of light through a medium (e.g. the atmosphere) is a field of study called *radiative transfer*. We will not go into the specifics, but to motivate the relationships we simply state that in a distance  $dx$ , a fraction  $dI/I$  of the star's intensity is lost. The fraction is characterized by a coefficient  $\alpha'_\lambda$ , i.e.

$$dI/I = -\alpha'_\lambda dx. \quad (1)$$

We are using a prime, here, to indicate that this is related to, but not the same coefficient as  $\alpha_\lambda$  that we introduced above. As you might expect, the coefficient depends on what the atmosphere is made of, especially the water vapor content, its temperature, density, and so forth. To make things simpler, we will introduce the concept of number of air masses,  $X$ , where  $X = 1$  is one air mass, i.e. the total amount of atmospheric material from the ground to the top of the atmosphere. When we look straight up, our line of sight passes through exactly 1 air mass. However, when we look at some angle  $z$  (stands for zenith

angle, and is the complementary angle to the altitude  $a$ ) from the vertical, our line of sight passes through more than 1 air mass (i.e.  $X > 1$ ). This is shown in Figure 3, below. By analogy to equation (1), the fraction of intensity lost when starlight traverses an air mass  $dX$  is

$$dI / I = -\alpha_\lambda dX, \quad (2)$$

where now the prime is removed from the  $\alpha$ , — this is the coefficient  $\alpha_\lambda$  that we mentioned initially, and which we wish to determine. To find out what the intensity is, after the light traverses air mass  $X$ , just integrate equation (2), to get  $\ln I = -\alpha_\lambda X + \text{const}$ , or

$$I_\lambda = I_0 e^{-\alpha_\lambda X}. \quad (3)$$

Thus, if the intensity of a G2V star is a wavelength independent value  $I_0$  at the top of the atmosphere, then it will have the no longer wavelength independent value  $I_\lambda$  given by equation (3) after traversing air mass  $X$ .

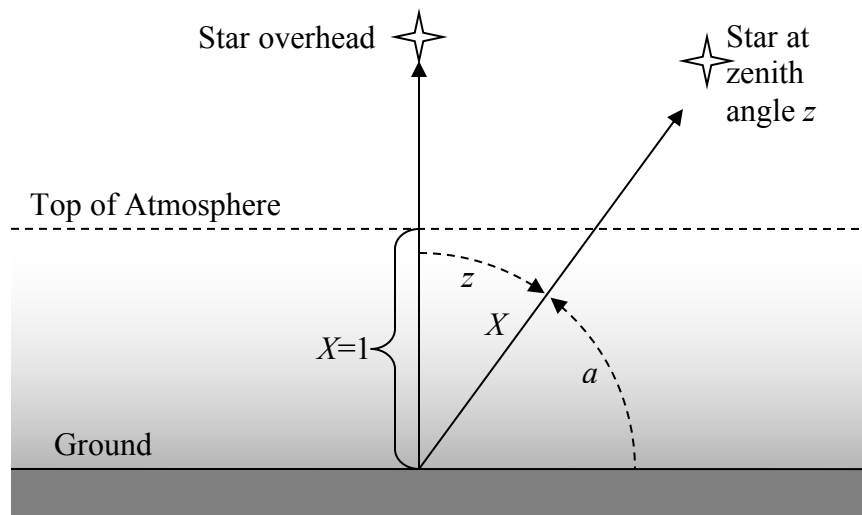


Figure 3: Sketch of the air mass  $X$  traversed by starlight for a star straight overhead, and one at zenith angle  $z = 90 - a$  (where  $a$  is the altitude angle).

## Procedure

The ideal procedure to deduce  $\alpha_\lambda$  would be to observe a star at a wide range of zenith angles as the star rises, and then fit the functional form (3) to the result. However, we only have a limited time to make our observations, of order 2 hours, which means that the star will rise or set less than  $30^\circ$  (remember, the Earth turns  $15^\circ$  per hour) during our observation. We will obtain a wider range of zenith angles by measuring multiple stars in different positions in the sky, and then combining the results into a single curve. Each of you will choose a G2V star from the web page [http://web.njit.edu/~gary/322/G2V\\_stars.html](http://web.njit.edu/~gary/322/G2V_stars.html), and will take two series of images separated by about 2 hours. Each series of images will consist of 5 images each in filters R, G and B, so you will have 15 images in each set, and a total of 30 images for the combined sets.

In order to be able to combine the observations for the whole class, you will have to choose your stars according to several constraints. The stars can be anywhere in azimuth (the angle around the horizon), but must be spread out in altitude (or its complement, zenith angle), so that we get a nice coverage in range of air mass. The stars must also be chosen so as to be fairly isolated from nearby stars, so that we can do photometry, and the stars must not be too bright. **Each of you will be given an altitude angle to shoot for, and you should look over the list from the above web page to find appropriate stars.** The altitude depends on the date and time of observation, and the RA and Dec of the chosen star. We will use Cartes du Ciel to calculate the altitude as follows:

### Set up Cartes du Ciel

Choose “Observatory” from the “Setup” menu and enter the position of the NJIT observatory (latitude  $40^{\circ} 44' 30''$  N, longitude  $74^{\circ} 10' 44''$  W), as in Figure 4a. Enter the name Newark, if you wish. Then enter the date and time of the start of the observations by choosing “Date/Time” from the “Setup” menu.

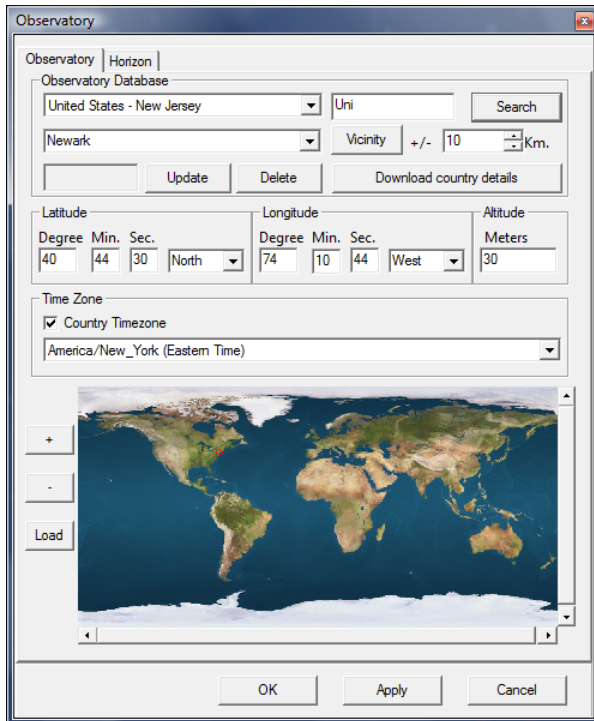


Figure 4a: The Cartes du Ciel Observatory Setup menu dialog, showing the coordinates to enter for the NJIT observatory.

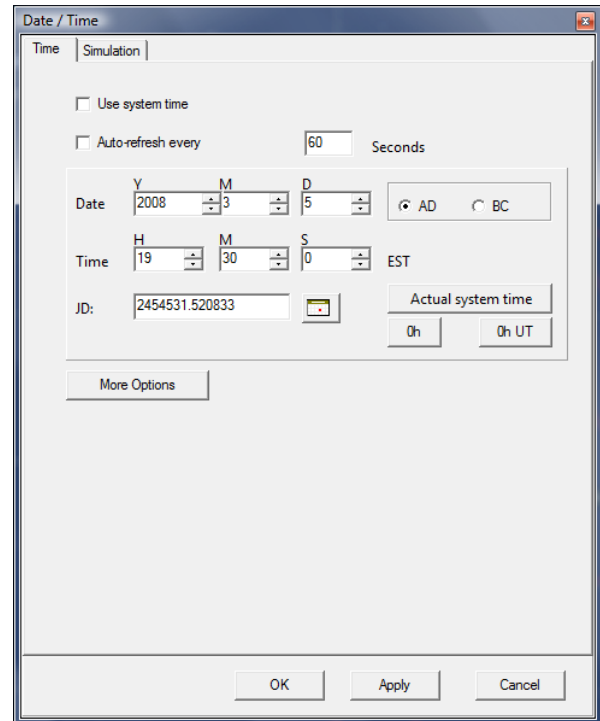


Figure 4b: The Cartes du Ciel Date/Time Setup menu dialog, showing the setting of the date/time for the start of the observations, here assumed to be 2008 Mar 05 at 7:30 pm.

### Choose Your Star

Choose a star from the G2V web page, and enter its coordinates by clicking on the “position” icon on the Cartes du Ciel toolbar, to open the Position dialog box. An example is shown in Figure 5, for the G2V star at RA 05 00 48, Dec +25 09 03.

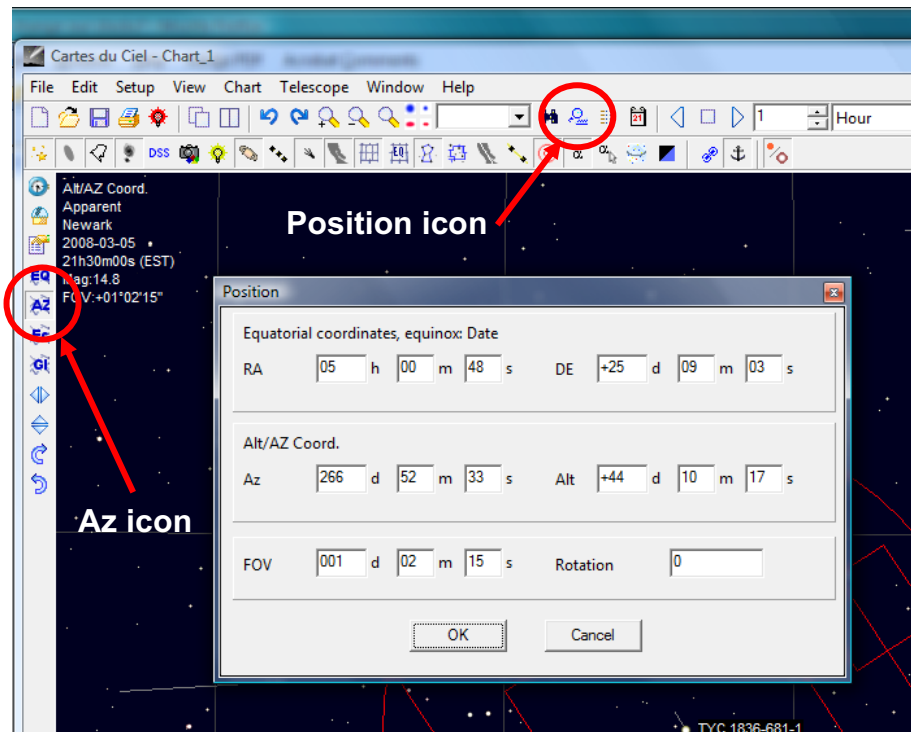


Figure 5: Enter the position (RA and Dec) for your star, and make sure that the Az coordinates icon is selected.

Zoom in on your star (the star may not be exactly in the center, so make sure you select the right one), and write down its designation in your log book (e.g. the star above is TYC 1836-681-1). Right click on it, and select the last item in the pop-up menu, which in this case says “Lock on TYC 1836-681-1”. Make sure that you are in Azimuth coordinates, by selecting the Az icon, as shown in Figure 5.

Click on the star name to bring up the details window. At the very bottom, you will see something like this. Write down the Altitude (+65°49' in this case).

**Visibility for observatory:**  
Newark 2008-03-05 19h30m00s ( EST )  
**Universal Time:** 2008-03-06T00:30:00  
JD=2454531.52083  
**Local Sideral Time:**06h29m45s  
**Hour Angle:** 1h29m  
**Azimuth:**+236°43'  
**Altitude:**+65°49'  
**Rise:** 10h23m Azimuth+55°17'  
**Culmination:** 18h01m +74°25'  
**Set:** 1h43m Azimuth+304°43'

Check whether this is around the altitude range that you have been given. If not, choose a different star. A little trial-and-error should allow you to figure out how to select a star in your designated range. Once you find a suitable star, enter all of its information from the G2V list into your log book, along with its TYC or other designation. Zoom in on the

star in Cartes du Ciel to verify that it is fairly isolated (no other stars nearby within about a 30" radius). If not, pick another star.

Once you have your star, with Cartes du Ciel still locked on the star, open the Date/Time dialog again and advance the time by two hours (i.e. 8:30 pm). Click on the star name, as before, to bring up the details window again, and write down the new altitude. At the end of this process, each of you should have a star selected, with a known altitude range that the star will cover between the hours of 6:30 and 8:30 pm.

### **Observing Your Star**

We will take turns taking the first observation of each star. When it is your turn, you will select your star and slew the telescope, then take a quick 10 s exposure with the L filter to verify that the telescope is centered on the correct field. If the telescope needs focusing, do so, and also make sure the dome is adjusted to where the telescope is pointing. Also check the maximum value in the image to **verify that the star is not saturated. If the star is saturated, reduce the exposure time and take another image.** This is very important. The maximum value in the image should be around 40,000 or less (remember that saturation of a 16-bit camera occurs around the value  $2^{16} = 65536$ ). Once everything is set, use the Sequence tab in the MaxIm DL camera window and set up to take a sequence of 5 images each in filter R, G and B. Set the exposure time according to what you set it to in your final test exposure, but try for 10 s. Set the Autosave Filename to an appropriate name, and set the Start At frame number to 1. When all is ready, start the sequence. The whole sequence should take about 5 minutes.

When everyone has completed their first observation, we will take the calibration frames. This includes bias, darks, and flats, the latter being taking in each of the three filter colors, R, G and B. Once that is done, we will go back to taking a second series of images on each of the stars.

### **Reducing Your Data**

You will follow a typical procedure for reducing your data, consisting of setting up the calibration (Set Calibration from the MaxIm DL Process menu), applying the calibration (Batch Save and Convert from the File menu), and combining the images to improve signal to noise ratio in the images. Just as we did in Lab 2, combining the images means using the Combine tool from the Process menu, flipping through each image to be combined to check that they are okay (reject any bad images), and then doing the combine. Save the combined image in a new directory—I usually call name the directory "Combined". Write down in your log book the time of the third image in each set. Note that you will combine your R, G and B images separately, do not mix them. Also, you will combine the two sets of images separately (early images separate from late images). When done, you will have 6 images, each representing about 50 s of exposure.

Once all of the images have been combined, you will measure your star's magnitude in the images, and then the results will be shared with your classmates to do the final analysis. The determination of magnitude consists of using the MaxIm DL Info tool to measure the "magnitude" of your star in each of your images, as illustrated in Fig. 6,



below. Everyone will set their calibration magnitude to 9.0. You only need to do this once. We will adjust everything for the true magnitudes later. Record the R, G and B magnitudes. In Fig. 6, these are R = 7.945, G = 8.168, and B = 9.073.

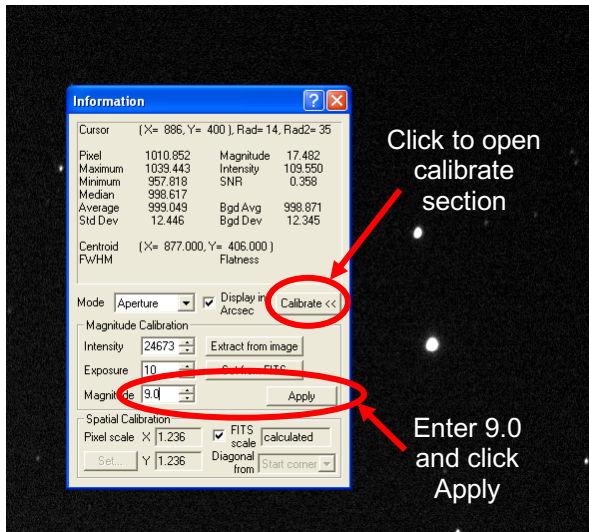


Figure 6a: With R image selected, open the “Information” window, click Calibrate, enter Magnitude 9.0 and Apply.

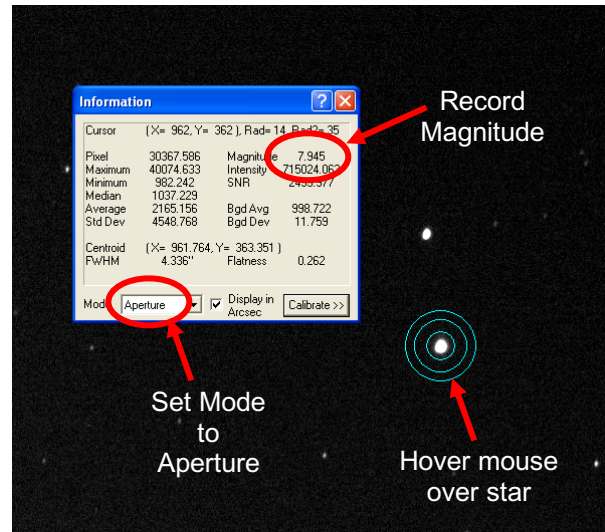


Figure 6b: Click Calibrate to close detail section, select Mode “Aperture”, and hover mouse over your star. Record the Magnitude number for your R image.

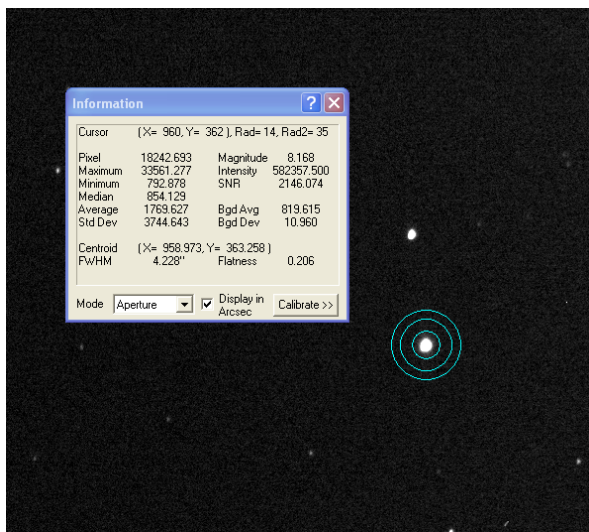


Figure 6c: Repeat previous step on G image, and record the new magnitude.

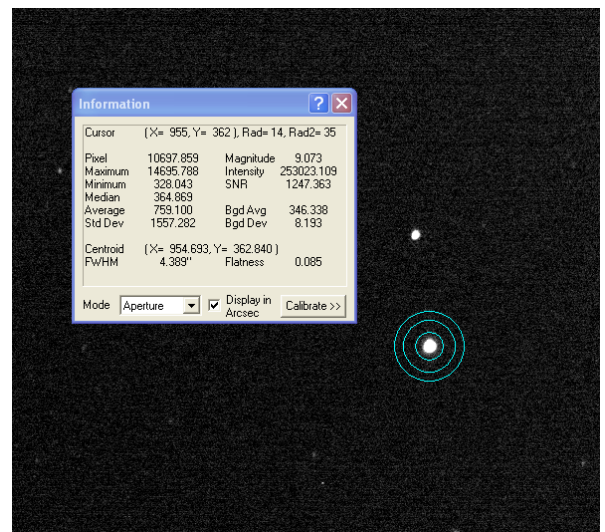


Figure 6d: Repeat previous step on B image, and record the new magnitude.

Repeat the three measurements for your second set of data. Record all of your magnitudes in a neatly arranged table in your log book, along with the magnitude calibration value (9.0) that you used. Include in the table the center times of each combined image that you recorded earlier. Also record the altitude of the star at this center time (you can use *Cartes du Ciel* to help determine this, as before).



## Analysis

You will next combine all of the measurements (yours and those made by your classmates) in an Excel spreadsheet. Here is an example of my spreadsheet for the observations that I did. Columns labeled R Mag, G Mag and B Mag are the measurements, and columns labeled R Adj, etc. are derived from them in a manner that we will discuss as a class. Basically, each star has to be adjusted for its actual magnitude, rather than magnitude 9.0 that we used in the above calibration. Note also the altitude column, which is determined from the Time from *Cartes du Ciel*, while the Zenith Angle (ZA) is the complement of this angle ( $90^\circ - \text{altitude}$ ). The last column is secant of the ZA, which is the same quantity as Air Mass,  $X$ .

	A	B	C	D	E	F	G	H	I	J	K	L
	Name	Number	Time (UT)	R Mag	G Mag	B Mag	R Adj	G Adj	B Adj	Altitude	Zenith Angle	Sec(ZA)
1	Star1	1	233315	9.189	9.337	10.137	9.189	9.337	10.137	65	25	1.103336
2		2	235523	9.184	9.329	10.128	9.184	9.329	10.128	68.7	21.3	1.073288
3		4	244412	9.177	9.316	10.107	9.177	9.316	10.107	75.1	14.9	1.03478
4		5	250611	9.17	9.313	10.103	9.17	9.313	10.103	76.5	13.5	1.028404
5		6	252815	9.174	9.311	10.108	9.174	9.311	10.108	76.4	13.6	1.028837
6	Star3	1	234202	7.848	8.083	8.978	9.198	9.433	10.328	42.3	47.7	1.4856
7		2	240414	7.835	8.065	8.961	9.185	9.415	10.311	45.25	44.75	1.407877
8		3	243048	7.827	8.054	8.946	9.177	9.404	10.296	48.3	41.7	1.339173
9		4	245256	7.82	8.032	8.92	9.17	9.382	10.27	50.3	39.7	1.299574
10		5	251457	7.807	8.037	8.912	9.157	9.387	10.262	51.75	38.25	1.273245
11		6	253702	7.782	8.021	8.909	9.132	9.371	10.259	52.6	37.4	1.25867
12	Star4	1	234627	8.033	8.271	9.193	9.273	9.511	10.433	30.3	59.7	1.981386
13		2	240837	8.03	8.251	9.174	9.27	9.491	10.414	31.9	58.1	1.891787
14		3	243512	8.015	8.238	9.143	9.255	9.478	10.383	33.35	56.65	1.818487
15		4	245715	7.997	8.229	9.127	9.237	9.469	10.367	34	56	1.787803
16		5	251921	8.005	8.228	9.125	9.245	9.468	10.365	34.2	55.8	1.778615
17		6	254126	8.004	8.218	9.136	9.244	9.458	10.376	33.95	56.05	1.790118
18	Star5	1	235051	8.465	8.752	9.782	9.475	9.762	10.792	18.5	71.5	3.14933
19		2	241258	8.432	8.705	9.739	9.442	9.715	10.749	19.5	70.5	2.993782
20		3	243937	8.401	8.691	9.691	9.411	9.701	10.701	20.2	69.8	2.89424
21		4	250139	8.418	8.672	9.69	9.428	9.682	10.7	21.37	68.63	2.742734
22		5	252344	8.408	8.68	9.684	9.418	9.69	10.694	20.18	69.82	2.896986
23		6	254548	8.421	8.692	9.718	9.431	9.702	10.728	19.6	70.4	2.979117

When your spreadsheet is done, you will plot the adjusted magnitudes vs. ZA, to create three curves. You will then plot the adjusted magnitudes vs. Air Mass,  $X$ , to see that the curves become straight lines, as predicted by equation (3). These are called extinction curves. Why do plots of magnitude vs. Air Mass turn out to be straight lines? (Recall that magnitude differences are equivalent to logarithmic ratios of intensities, or fluxes.)

In your report, you will discuss several aspects of your plots. First, apply a linear trend line to each color in Excel, and have Excel print the equation of the trend lines. **Write down your equations for each filter in your log book.** These G2V stars are supposed to be white (equal magnitudes in each color) outside the atmosphere. Determine the

camera response ratio by considering the Air Mass zero values of R, G, and B. Calculate by what intensity factor the G and B images would have to be increased in order to equal R at Air Mass zero (i.e. in order to make the star white). Make a table of G and B factors needed to make the star appear white at various Zenith Angles 0, 10, 20, ..., 80. We will use these factors in the future to scale our G and B images to agree with the R images, when we make color images. Your writeup should include copies of your plots (with trend line and equation, similar to the plot below). Use symbol colors appropriate to the filter! Include 0 Air Mass on your horizontal axis, and plot magnitudes with higher values at the bottom (reverse order), since large magnitudes mean fainter intensities.

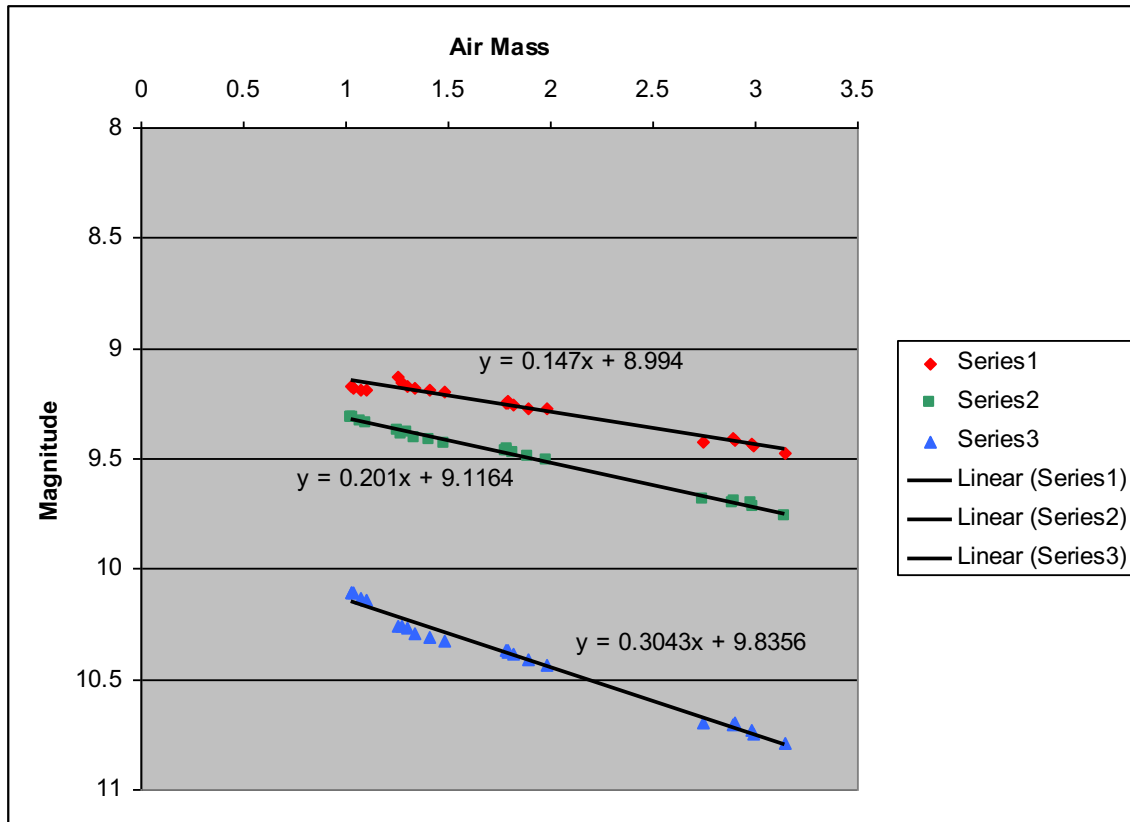


Figure 7: Example plot of magnitude vs. Air Mass, with trend lines and equations added.

## Bulletized Synopsis

### Purpose: Measure atmospheric extinction in R, G and B filters

- Choose a star from the G2V catalog, within a given altitude window.
- Learn how to determine a star's altitude (and Zenith Angle) at different times using *Cartes du Ciel*.
- Take images in each of the R, G and B filters of your star at two times corresponding to a range of ZA.
- Measure the magnitude of your star in each filter for the two times.

- Combine your measurements with those of your classmates in an Excel spreadsheet.
- Use Excel to calculate the corresponding Air Mass for each star at each ZA, and plot the results.
- Fit a linear trend line to each set of points to obtain the “extinction curves,” and obtain the appropriate equations.
- Find the scale factors by which you have to increase the brightness of the G and B images to match R, as a function of ZA.