A Deep Investigation of NGC 1333 in the Near-Infrared

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November 29, 2005
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ABSTRACT

We use the 76.2 cm telescope at Leuschner Observatory to conduct a photometric analysis of NGC 1333 at near-infrared wavelengths (JHK) using magnitudes in all three bands from 87 stars embedded in the cluster. We show the existence of the cluster by comparing the luminosity function in the H band of the cluster and a nearby control field and using the Kolmogorov-Smirnov Test. The construction of the color-color diagram $J - H$ vs. $H - K$ for the cluster yields a estimate for the amount of visual extinction. Using this result, we then estimate the distance to NGC 1333 using the color-magnitude diagram K vs. $J - K$ to first estimate the distance modulus.

1. Introduction

Space is not empty. In fact, much of it is filled with dust and gas. This dust and gas affects the measurement of light from stars here on Earth by decreasing the intensity of light. If the dust and gas occupies an area $dA = n\sigma\, dl$, where n is the number of particles and σ is the cross-sectional area of the dust and gas cloud, then

$$I = I_0 e^{-n\sigma l} = I_0 e^{-\tau} \tag{1}$$

where τ is the optical depth. Extinction is a quantity defined as

$$A = -2.5 \log_{10} \left(\frac{I}{I_0} \right) . \tag{2}$$

From Eq. (1) and Eq. (2), we see that the relationship between extinction and optical depth is

$$A = 1.086\tau. \tag{3}$$

In Table 1 we give the ratio of extinction in a given band to the visual extinction.

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Band	A/A$_V$
U	1.531
B	1.324
V	1.000
J	0.282
H	0.175
K	0.112

Table 1: This table give the ratio of extinction in a given band to the visual extinction.

The magnitude of a star is a measure of the total flux from the star. Since the flux is a function of intensity and intensity is affected by the magnitude of intensity, the magnitude of a star will depends on the magnitude of extinction. To correct for extinction we simply take the difference of the observed magnitude and the extinction.

We have seen that the presence of dust and gas affects the amount of light we receive from stars. Their presence affects physical observations in another equally important way. The mean free path of a particle is the distance it travels on average before colliding with another particle. For a particle in a dust cloud

$$\lambda = \frac{1}{n\sigma} = \frac{l}{\tau}. \tag{4}$$

Using Eqn. 3 and the values from Table. 1, we see that photons in at the infrared wavelengths can travel further than those in the visible range. The important consequence of this result is that we can use infrared photometry to image star formation regions that are obscured at visible wavelengths by dust and gas.

In this laboratory exercise, we image the star cluster NGC 1333 in the infrared bands J,H,and K using the 76.2 cm telescope at Leuschner Observatory. The images are taken using a dither pattern of nine images in five overlapping regions in each filter. A mosaic of the images is created to extract photometry from 87 sources in the cluster. We use these magnitudes to construct a H luminosity function of the cluster and a nearby control field, a K vs. $J - K$ color-magnitude diagram, and a $J - H$ vs. $H - K$ color-color diagram.

The observed magnitude of a star is a function of its distance and the amount of extinction. The color of the star is an intrinsic property and it does not change depending on the distance of the star. Using this, we find that the deviation of our cluster data from a theoretical main sequence in the color-color diagram is due exclusively to extinction. We can use this extinction correction in the color-magnitude diagram to find the distance modulus from the difference in magnitude between our cluster of data and a theoretical main sequence. The distance modulus is the difference between the apparent magnitude and absolute magnitude of a star. The absolute magnitude of the star is a measure of its intensity if it were at 10 pc. Thus the distance modulus is a measure of the correction for the magnitude of the star as a function of distance. With the distance modulus we can solve for the distance to NGC 1333.

2. Observations

Our group observed NGC 1333 starting on Saturday, October 29, 2005 and finishing early the next morning. It was of the utmost to take most or all of the data in a single observation period because of the recent lack of clear skies. Our data acquisition was quite successful.

In this lab exercise, we are interested in observing faint stars in a cluster. In order to receive enough signal from these faint stars, much longer exposure times are required. The nature of the CCD prevents us from taking one 10 minute exposure because it is likely most of the pixels would be saturated after such a long exposure. Moreover, the existence of bad and hot pixels is additional justification for dithering. If we used only one exposure and our object happened to lie on a bad pixel, the scientific analysis of that object would be subject to much skepticism.

To image NGC 1333, we used a dither pattern of nine images offset by 0.01 degrees in either RA or Dec in five larger overlapping regions offset by either 0.03 degrees in either RA or Dec. Each image had an exposure time of 15 sec, 60 sec, and 15 sec in the H, J, and K bands, respectively. The dithering pattern allows use to see more of the cluster and minimizes the systematic error due to bad pixels. We image a control field using the exact same dithering pattern but offset from the cluster by 0.30 degrees in either RA or Dec. We also image the standard star HD201941, which has an H, J, and K magnitude of 6.64,6.63, and 6.70, respectively. We use the standard star for relative photometry. For the standard star, we used the same nine image dithering pattern that we used in each of the 5 larger regions of the cluster. Finally, we took all other necessary calibration frames such as dark frames.

3. Constructing Mosaics

Before we can make a mosaic, all of our data must be corrected for dark current, background sky signal, and differential gain. We construct a pixel by pixel dark frame and use it to construct a flat field in each filter. To create a pixel by pixel sky frame, we use the control field since the cluster may be so dense that there is no sky between the stars. The data for the standard star, control field, and cluster are all corrected by sky subtraction and flat fielding. One last correction to the data is needed. We wish to take out bad pixels and hot pixels. This can be accomplished by search the dark frame for hot pixels and making a mask that has 0's at those pixels and 1's everywhere else. Other bad pixels are found by examining the flat field. We search for pixels that have a value less than 0.75 or greater than 1.25 and make a another mask. We multiply our science frames by these masks and in all the subsequent analysis, these pixel do not enter our calculations since their value is zero.

At this point, we have over 45 processed images of NGC 1333 in three different bands. We would like to sum the images in each band to simulate an exposure time of five to ten minutes depending on the band. However, each image is slightly displaced from the others. If we simply sum each image in IDL, the result will be nonsensical because the stars in each image do not coincide. Our first task is to shift each image such that the stars that are common between the images occupy the same pixel.

First, we find the relative offsets of each of the nine images in one region of one filter. This is accomplished using a center of light program. Each image is displayed and the user is asked to click on the center of a star. We choose a star that is common in all nine images. When we click on the center of the star, the program places a circular mask with a radius of 10 pixels centered at the location of the cursor click. The center of light of the masked image is found using

$$\langle x \rangle = \sum_k \frac{x_k I_k}{I_k} \tag{5}$$

where x_k is the k^{th} pixel and I_k is the signal from the k^{th} pixel. The same formula is used in the y direction. This value is saved in the k^{th} element of a nine element array. Once all of the center of light is located for the common star in each of the nine images, we use the position of the first image as our reference. This amounts to subtracting the position of the star in the reference image from the position of the star each other image.

Armed with the relative offsets, we are ready to shift the images and make a mosaic. The dimension of each image is 256 by 256. Since we are shifting images, the dimensions of the mosaic will be larger. Let x_{max}, x_{min}, y_{max}, and y_{min} be the maximum and minimum offset values in x and y. To find the x dimension of the mosaic, we use

$$x_{mosaic} = 256 + x_{max} - x_{min} \tag{6}$$

where x_{max} will be positive and x_{min} will be negative. The y dimension of the mosaic is found using an analogous equation in y. Since we are accustomed to dealing with square arrays, we take the dimension of the mosaic to be the maximum of x_{mosaic} and y_{mosaic} and set the extra pixels equal to zero. Since each of the extra pixels is equal to zero, it will not affect our photometry.

The trick is now to embed each 256 by 256 science frame into a larger superarray. The hard part is placing the reference image. If we place the reference image in the correct place, the placement of all the other images is simple. The reference image must be placed somewhere in the middle of the superarray so that there is enough room to accommodate the shifted images. But how do we know where to place it exactly? I choose to place the first top left corner pixel of the reference image at $x = x_{max}$ and $y = y_{max}$ where x_{max} is the maximum positive offset in x and y_{max} is the maximum positive offset in y. Now the placement of each subsequent image in a superarray is

$$x = x_{max} - x_k \tag{7}$$

$$y = y_{max} - y_k \tag{8}$$

where x_k and y_k is the offset of the k^{th} from the reference image. This scheme insures that the reference image is placed in the array such that there is enough space to accommodate the images with the maximum offset in x or y.

At this point, we have placed each science frame into a larger array such that each overlapping science pixel coincides. We take a pixel by pixel sum in of the nine superarrays to form a single superarray.

The last step in creating a mosaic is the exposure map. Because the images overlap and we take a pixel by pixel sum of the nine science images, the pixels that overlap correspond to a longer exposure time. The pixel by pixel sum does not reflect this. We use an exposure map to correct for this. The exposure map is an image with the same dimensions as the superarray and each pixels contains the total exposure time of that pixel in the superarray. Thus, if we divide the superarray by the exposure map, we correct for the fact that overlapping regions have more exposure. With this done, we have completed our mosaic, where each pixels contains a measure of counts per second.

We repeat the process for each of the five regions and each of the three filters for both the cluster and the control field and the standard star.

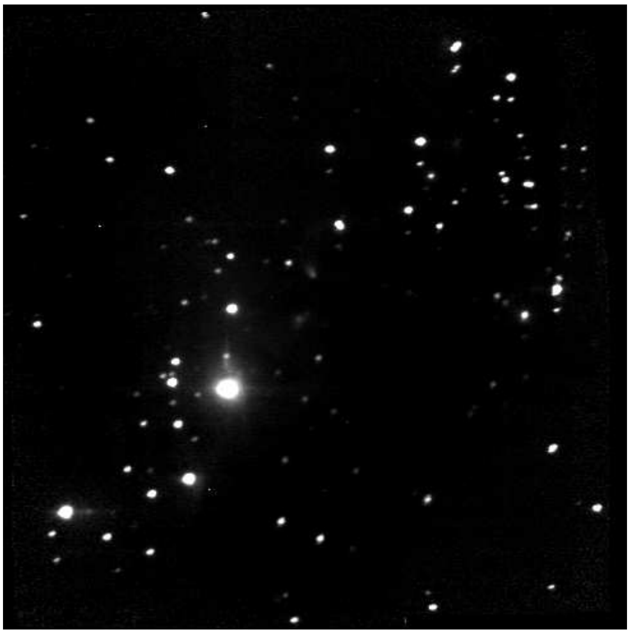

Fig. 1.— A mosaic of NGC 1333 in the H band scaled between 0 and 10 counts per second.

Fig. 2.— A mosaic of NGC 1333 in the J band scaled between 0 and 10 counts per second.

Fig. 3.— A mosaic of NGC 1333 in the K band scaled between 0 and 10 counts per second.

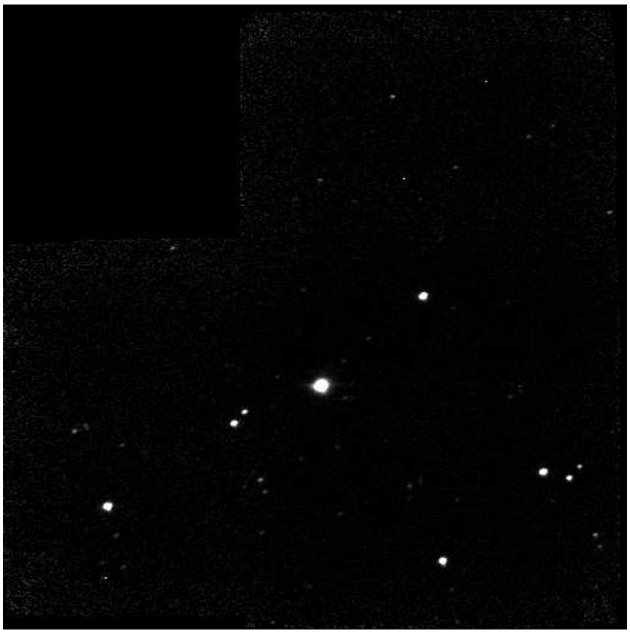

Fig. 4.— A mosaic of the control field in the K band scaled between 0 and 10 counts per second.

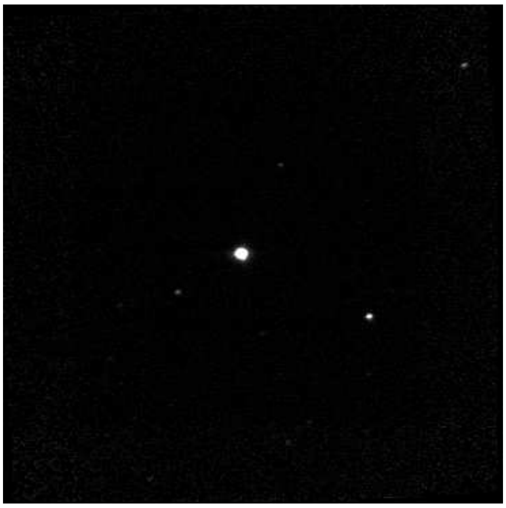

Fig. 5.— A mosaic of HD201941 in the K band scaled between 0 and 10 counts per second.

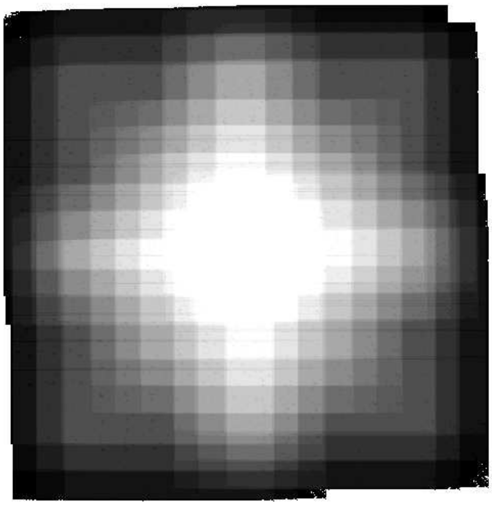

Fig. 6.— The exposure map used to construct the mosaic for NGC 1333. The exposure contains the total exposure time for each pixel. The edges look uneven because we set any pixel with a value of zero to 10^6. This is done so that dividing the raw mosaic by the exposure map does not cause arithmetic error.

4. Quick Photometry Using Convolutions and Correlations

Our goal now is to obtain magnitudes of the same set of stars in all there bands. We could use the aperture photometry techniques used in the previous lab report. This would be extremely time consuming because we would have to repeat the procedure over 100 times. Fortunately, there is a much faster method.

We create an image with the same dimension as the mosaics. This image has a circular aperture at the center with a radius of four, and an annulus with inner radius of 4 and outer radius of 6. The value of each pixel inside the aperture is 1. The value of each pixel in the annulus is such that the sum of the aperture and the annulus is zero. Every other pixel in the image is zero.

We write a program that correlates the two images using the CONVOLVE function in IDL. CONVOLVE returns an array with the same dimensions as the mosaic. Each pixel contains the value of the sum of the product of the two images for a given offset of the two images. This amounts to moving the aperture around the mosaic and summing the values of the mosaic inside the aperture and subtracting the values in the annulus. This is exactly what we did when conducting aperture photometry in the last lab. This when the mask coincides perfectly on a star in the mosaic, we will have a local maximum value in the correlation image. This local maximum value will be the counts per second from that star. We can calculate the magnitude of the star using

$$m_\nu - m_{standard} = -2.5 \log_{10}\left(\frac{N}{t}\right) + 2.5 \log_{10}\left(\frac{N_{standard}}{t_{standard}}\right). \qquad (9)$$

where N is the number of photons and t is the exposure time. Our programs searches the correlation image for local maximums. It will find the largest one first. We save the pixel value and location in an array. The program then sets all pixels out to a radius of four pixels at that location equal to zero and looks for the next largest maximum. Thus, we can specify the number of maximums we want and save each value it finds and this procedure amounts to finding the location and flux of stars in the mosaic. We use this procedure on NGC 1333, the control field, and our standard star to obtain magnitudes in all three bands.

5. The Color-Color Diagram

Now that we have the magnitudes in all three bands for 87 stars in NGC 1333, we can construct a color-color diagram. The procedure is simple. We plot the $J - H$ magnitude of the star on the y-axis and the corresponding $H - K$ value on the x-axis. We include the the values of a theoretical main sequence of stars. The plot is shown in Fig. 7. The stars in our cluster are main sequence stars. Why then is there a spatial displacement of our cluster of data and the main sequence on the color-color diagram? Since the data is photometric, the shift must be due to discrepancies in the measured brightness of the stars.

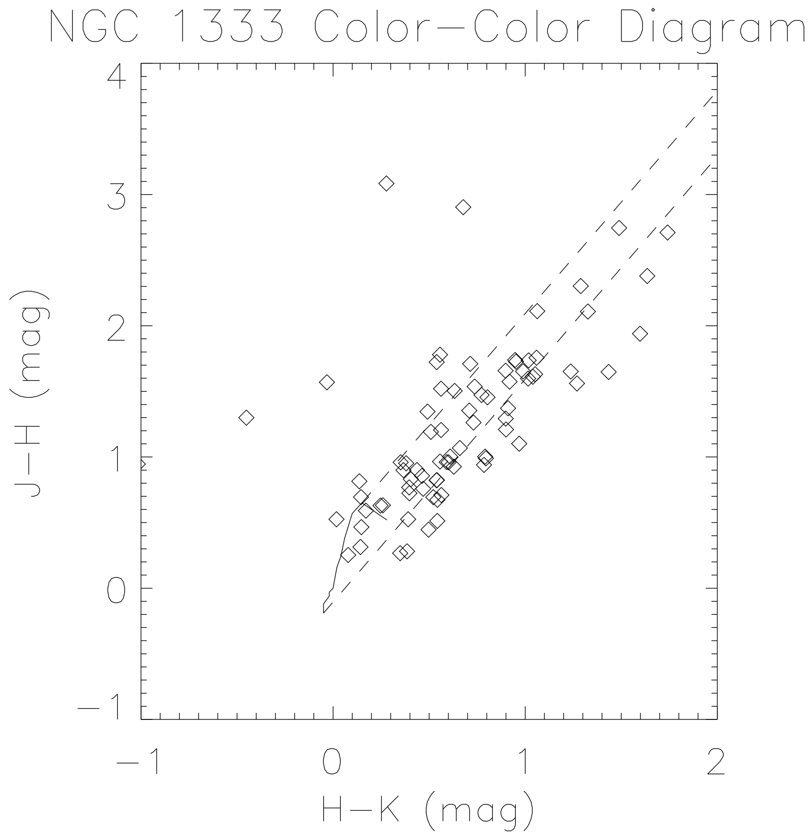

Fig. 7.— A color-color diagram of 87 sources in NGC 1333. The dashed lines represent the reddening of main sequence stars. The distance along the reddening vectors allow us to measure the amount of visual extinction. From our data, the amount of visual extinction for NGC 1333 is approximately 8.

The apparent brightness of a star is a function of distance. This is easily seen in the formula for the flux of a star.

$$F_\nu = \frac{L_\nu}{4\pi d^2} \tag{10}$$

where L_ν is the intrinsic specific luminosity of the star for a given frequency and d is the distance. We also know that the apparent brightness of a star is a function of the extinction. The more extinction the dimmer the magnitude. This is not difficult to comprehend. The more dust present, the less we see of the star.

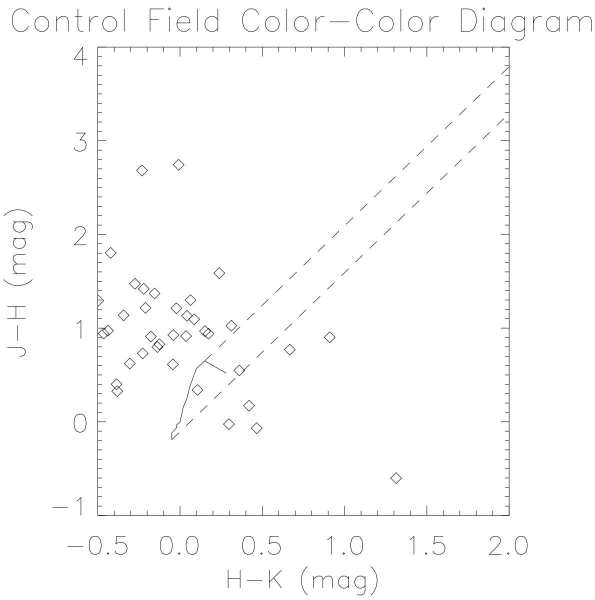

Fig. 8.— A color-color diagram of 87 sources in the control field. The dashed lines represent the reddening of main sequence stars.

The color-color diagram has colors on both axes. The color of a star is not a function of distance. Thus, on the color-color diagram, any aberration between the observation data and the theoretical main sequence is due to the presence of dust and extinction. The lines plotted on Fig. 7 are called reddening lines. Their slope is calculated using the values in Table. 1. Since we have $J-H$ vs. $H-K$ the slope is

$$m = \frac{A_J - A_H}{A_H - A_K} = \frac{0.282 - .175}{.175 - .112} = 1.70. \tag{11}$$

The intercept of the line depends on the spectral type of the star. These lines indicate the shift of a main sequence star as a function of visual extinction. The more visual extinction, the more the star is shifted from the main sequence. If we compute the average value of $J-H$ and $H-K$ for our cluster of data, we find that this point lies on the vertical line through $H-K \approx$0.5. Using the the values from Table. 1, we see that this roughly corresponds to 8 magnitudes of visual extinction.

$$H - K = 0.063 A_V \qquad \Leftrightarrow \qquad A_V \approx \frac{0.5}{0.063} = 7.9 \tag{12}$$

6. The Color-Magnitude Diagram

We make a plot of the magnitude in K vs. $J - K$ as shown in Fig. 9. If we use the estimate of visual extinction that we calculated from the color-color diagram, we can correct each value of the main sequence. The extinction correction of the main sequence will cause the color to redden, i.e increase the value of $J - K$ and the apparent brightness to dim, i.e. cause the magnitude to increase. This is reflected in the shift the dashed line representing the theoretical main sequence. Even though we correct for extinction, there is still a separation between our data and the theoretical main sequence. The cause of the separation now lies in the fact that the magnitude values for the theoretical main sequence are *absolute* magnitudes whereas the values for our cluster are *apparent* magnitudes. Thus the difference in magnitude in K between the cluster of data and the theoretical main sequence gives a value for the distance modulus. Making an estimate for the distance modulus and using

$$m - M = 5 \log_{10} \left(\frac{d}{10 \text{ pc}} \right) \tag{13}$$

where m is the apparent magnitude and M is the absolute magnitude, we estimate that the distance to NGC 1333 is $\approx 400 - 600$ pc.

7. The Luminosity Function

In the last part of the lab, we construct a luminosity function for our cluster in the H band. This is do by making a histogram of the H magnitudes for both NGC 1333 and the control field. These histograms are shown in Fig. 10 and 11. We take the difference of the two histograms and the result is shown in Fig. 12. There remains a peaked distribution of H magnitudes. By the Kolmogorov-Smirnov Test, this indicates that the D statistic is large enough between the two distribution to conclude that the two samples are not drawn from the same parent population. This confirms the existence of the cluster.

The luminosity function can give another important characteristic of the cluster. By looking at the luminosity function, we see that there is a lower limit on the magnitude of stars. This indicates that any star with a smaller magnitude that this has burned out. Our data indicates that the brightest star in NGC 1333 is around 10 magnitudes in the H. This corresponds to a B or A type star. Thus the age of NGC 1333 is approximately $\approx 10^6 - 10^7$.

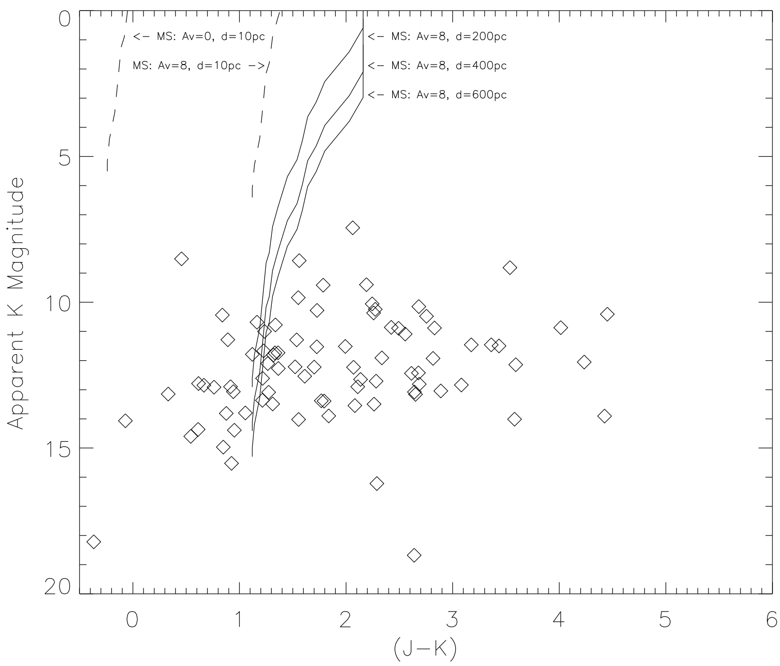

Fig. 9.— A color-magnitude diagram of 87 sources in the control field. From this we estimate the distance modulus and compute the approximate distance to NGC 1333 to be ≈ 400-600 pc.

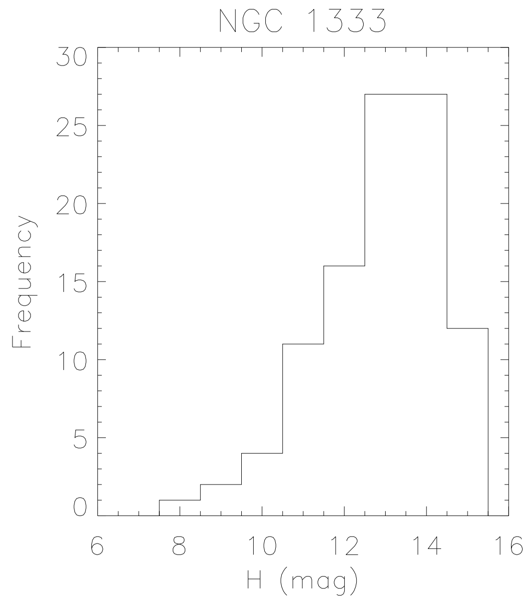

Fig. 10.— The distribution of H magnitudes for NGC 1333.

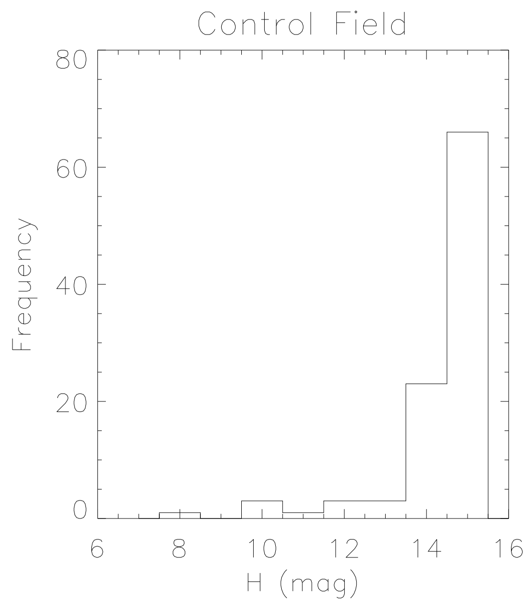

Fig. 11.— The distribution of H magnitudes for the control field.

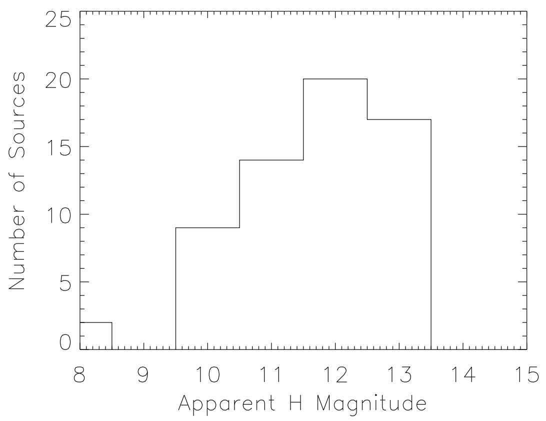

Fig. 12.— The *H* luminosity function for NGC 1333. It is the difference of the histograms of *H* magnitudes of NGC 1333 and the control field. The brightness star in the cluster that is still one the main sequence seems to be of type B or A.

8. Conclusion

The mosaic technique can be used to perform photometry on faint stars. This technique is extremely important in astronomy. We compare the results of our photometry to that of Lada et al (1996). Our values for the age of NGC 1333 and the distance is fairly close to the values 2×10^6 and 320 pc obtained in their paper. Considering their study was probably conducted more thoroughly, I believe this lab exercise to be an overall success.

9. Acknowledgements

I would like to thank Sarah Ballard, and Megan Reiter for taking data into the early morning. I would like to thank Ferah Munshi for teaching me how to perform photometry by convolutions and correlations. I would like to thank Matt Rocklin for explaining the purpose of constructing a color-color and color-magnitude diagram. Finally, I would like to thank Jason Curtis for being such an great IDL programmer and a fantastic lab partner. Finally, I would like to thank Tristan Lewis, for providing entertainment during my long hours in 705 Campbell Hall.