Photometry with an Infrared Camera

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November 1, 2005
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ABSTRACT

The main goal of this experiment is to provide an introduction to one of the basic tools of observational astronomy, photometry. Images of HD 201916, HD 201941, HD 203856, and HD 3029 are taken using the K short filter, which has a central wavelength of 2.2 μm and bandwidth of 0.39 μm, of the infrared camera mounted on the 76.2 cm telescope at Leuschner Observatory. In order to perform reliable photometry, these images must be corrected for dark current, sky brightness, and non-uniformity in individual pixel gain. In addition, we must choose our exposure time carefully in order not to saturate the CCD. We find that each pixel saturates in the K short filter at around 20,600 data numbers (DN). At a temperature of 72.7 K, the mean dark current is 76.0 $\pm$ 0.1 DN/s, the bias is 0.7 $\pm$ 0.1 DN, the average gain is 36.850 $\pm$ 0.001 electrons/DN, and the read noise is 7 $\pm$ 5 DN. Once the images are corrected, we use HD 3029 as a standard star and calculate the magnitude of HD 201916, HD 201941, and HD 203856 to be 7.81, 6.53, and 6.99, respectively. These experimentally measured magnitudes are compared to the accepted magnitudes and correspond to a percent error of 0.26%, 1.43%, and 1.90%, respectively. Finally, we use the known magnitudes of each star and Vega in the K short filter in order to calculate the flux of each star. We plot these values against photoelectrons/sec. and that that the conversation between the two is $(1.6 \pm 0.3) \times 10^{-6}$ Jy $(e^{-}/\text{sec})^{-1}$.

1. Introduction

Photometry is a technique for measuring the brightness of a celestial object. We are interested in measuring the brightness of stars in the infrared region of the electromagnetic spectrum. Brightness is really a measure of flux, which is the energy per unit time that is

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detected in an area A at some distance d way. If the star is at a distance d from the observer then the specific flux for a given frequency is

$$F_\nu = \frac{L_\nu}{4\pi d^2} \tag{1}$$

where L_ν is the intrinsic specific luminosity of the star for a given frequency.

Since the brightness of stars varies over a large range, it is more convenient to use a logarithmic scale. The magnitude of a star (m_ν) is

$$m_\nu = -2.5\log_{10}\left(\frac{F_\nu}{F_{\nu 0}}\right) \tag{2}$$

where $F_{\nu 0}$ reference flux that defines the magnitude system.

Under the assumption that L_ν and the quantum efficiency of the detector (η_ν) change slowly over small frequency ranges, then

$$F_\nu = \frac{N\,h\nu}{At\,\Delta\nu\,\eta_\nu} \tag{3}$$

where N is the number of photons, h is Planck's original constant, ν is the frequency, and A is the area of the detector.

The quantity N/t can be measured directly with great precision. However, the quantities A, η_ν, and $\Delta\nu$ are more difficult to measure. Relative photometry can be used to by bypass the need to measure these quantities directly. In relative photometry, the absolute flux is calculated using Eq.3 for a few stars, which are then called standard stars. Then the magnitude of other stars are calculated by

$$m_\nu - m_{standard} = -2.5\log_{10}\left(\frac{N}{t}\right) + 2.5\log_{10}\left(\frac{N_{standard}}{t_{standard}}\right). \tag{4}$$

We can compute N/t by taking images with the infrared camera mounted on the 76.2 cm telescope at Leuschner Observatory and totaling the signal produced by the star for a given exposure time. Corrections must be made to the raw images before photometry can be performed. We make a saturation plot by taking images of the night sky at different exposure times to determine the appropriate exposure time for the science frames. The CCD is not perfect and each pixel has a slightly different gain. We use a flat field to correct for this. The sky brightness is calculated by doing a pixel by pixel median and subtracted off so that the majority of the signal in the image is from the star.

Once the values for N/t have been obtained from the corrected images, we pick one of the stars to serve as our "standard star" and use Eq.4 to compute the magnitude of the other three stars. These values are compared to the known magnitudes to check the accuracy of our photometry. We then construct a plot of F_ν versus N/t to examine the relationship between the two quantities and determine a conversion factor between the two.

2. Saturation

The first step in photometry is to obtain images of a star. In order to determine the appropriate exposure time in the K short filter for science frame, we begin by examining the saturation level of the infrared camera. We point the telescope at a relatively empty region of the sky and take images with exposure times from 1 sec to 35 sec. The mean DN value of each image is computed using

$$\bar{x} = \frac{1}{N} \sum x_i \tag{5}$$

where N is the total number of data elements. However, the mean is not necessarily the statistic we want. Even though the saturation images are taken in a region of relatively empty sky, there may still be a few stars in the image. The presence of the star in will certain affect the mean since each pixel is weighted by its DN value. Since the median will just take the middle value, it will be unaffected by the presence of a star. Thus, the median DN value is plotted against the exposure time as shown in Fig.1. From plot we see that the infrared camera saturates at around 20,600 data numbers and that the onset of saturation begins at around 17 seconds. Hence, for science frames that contain a bright star, it is best to keep the exposure length to less than 10 seconds.

3. Dark Frames

In performing photometry, we sum all the signal produced by the star in our science image. In order for this measurement to be accurate, it is important that we only count the signal that is produced by the star itself. As a result, we must subtract off a dark frame.

A dark frame is an exposure where the filter is set to blank and the shutter does not open. The dark frame represents all the signal that is produced by the thermal agitation of valence electrons. A dark pixel by pixel median dark frame is shown in Fig.2 The mean dark current per second is directly proportional to the temperature of the CCD. During the course of the three weeks in which the experiment was conducted, the temperature slowly rose from around 70 K to over 100 K. As a result, it became increasingly important to take dark frames for specific science frames during the same observation period in order to minimize the systemic error that a arises from the changing temperature of the CCD.

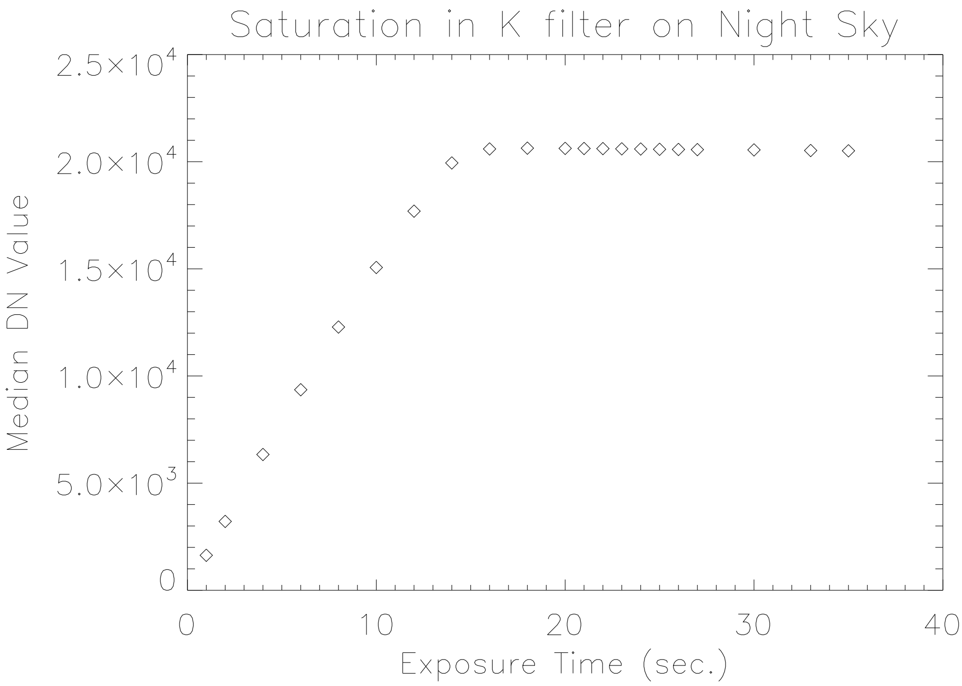

Fig. 1.— The median DN value versus exposure time in the K short filter of the infrared camera on a relatively empty region of the night sky to explore the onset of saturation. It appears that each pixel saturates at approximately 20,600 data numbers and the CCD saturates in the K filter on the night sky after approximately 17 sec.

For a science frame of given exposure time, we subtract off the mean dark current from each pixel by averaging several dark frames with the same exposure time. Subtracting the dark frame will add noise to the science frame. We can minimize the additional noise from the subtracting off the dark frame by increasing the number of dark frames averaged. The number of dark frames (N) needed to insure that the additional noise is no more than 10% of the original noise in the science can be found by

$$\frac{s_{dark}}{\sqrt{N}} \leq \frac{1}{10} s_{science} \tag{6}$$

where s is the standard deviation of either the dark frame or the science frame.

To get an idea of the mean dark current per second, we take dark five dark images at each of six exposure times. The results are plotted in Fig.3. From the least squares line, we find that the mean dark current per second at a temperature 72.7 K is 76.0 ± 0.1 DN per second. The intercept of the least squares line yields a bias of 0.7 ± 0.1 data numbers.

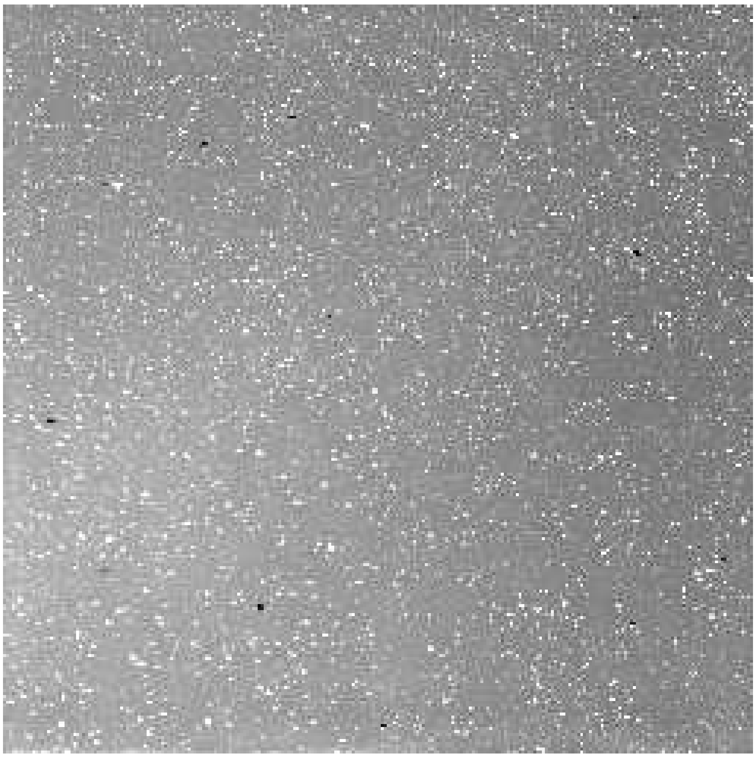

Fig. 2.— A dark frame that is calculated using a pixel by pixel median of 100 dark frames of exposure length of 6 seconds.

4. Pixel Gains

4.1. Relative Gain: Using the Sky as a Flat Field

Another correction to the image must be applied beyond subtracting off the dark frame in order for accurate photometry. The CCD converts photoelectrons to data numbers. The conversion factor between the two is called the gain of the CCD. The CCD is not perfect and each pixel has a slightly different gain. As a result, if we compute the photometry of the star when it is located at a different location in our image, we would get different results!

To correct for this, we create a flat field. A flat field is an image with a median value of 1. It gives the relative gain of each pixel. To compute the flat field, four six second exposures are taken in the K short filter starting around 45 minutes before sunrise. Since the sun is rising, the sky brightness (B_i), where i denotes the image number, is different in each of the four images. The signal (z) in the pixel (x, y) of the i^{th} image is

$$z_i(x, y) = f(x, y)B_i + c(x, y) \quad (7)$$

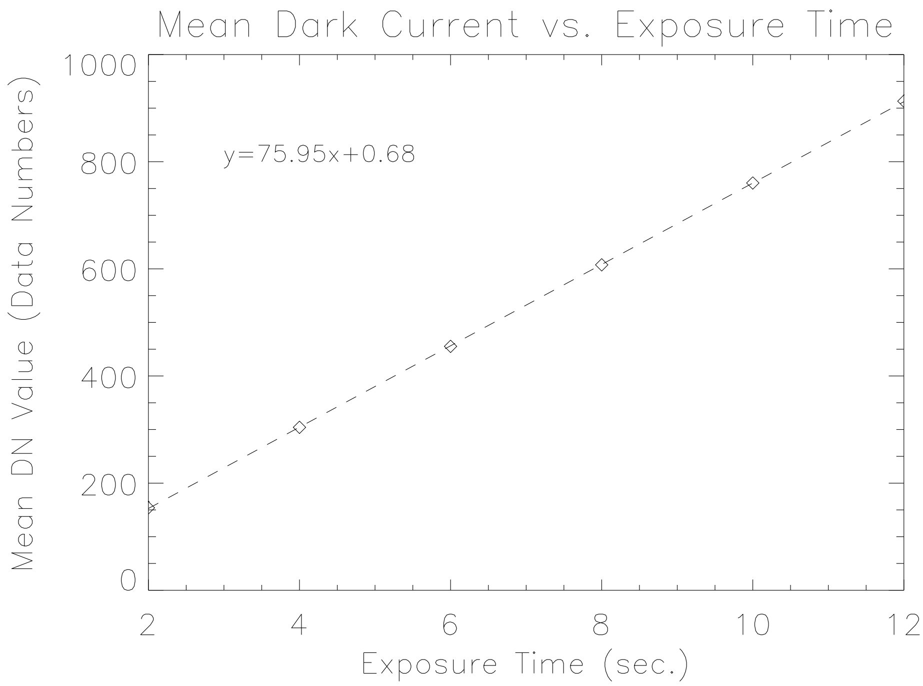

Fig. 3.— The mean DN value versus exposure time for dark 5 dark exposures at six different exposure times at 72.7 K. The slope gives the mean dark current/sec of 76.0 ± 0.1 DN/s and the intercept gives a bias of 0.7 ± 0.1 DN.

where c is just a constant term due to the dark current. Thus, we compute a pixel by pixel median dark frame and subtract it off. We can then compute the sky level in the i^{th} frame by

$$B_i = \text{median}[z_i(x,y) - c(x,y)]. \tag{8}$$

Now that we have B_i we can calculate $f(x,y)$ by the average

$$f(x,y) = \langle \frac{z_i(x,y) - c(x,y)}{B_i} \rangle \tag{9}$$

since $f(x,y)$ is the is the same in each frame. The flat field for the K short filter is shown in Fig.4. We can divide a science frame in the K short filter by this flat field to correct for the different individual gain of each pixel.

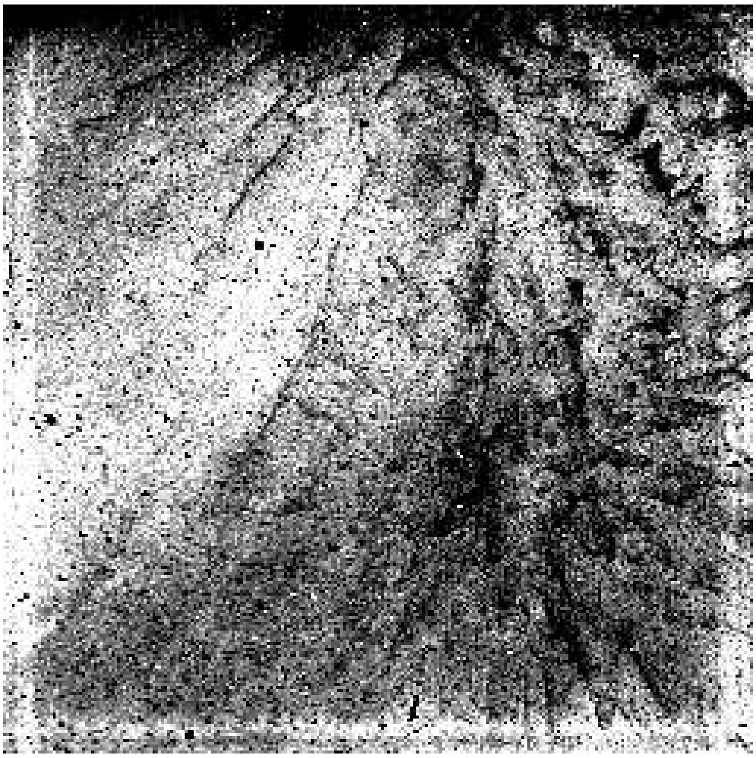

Fig. 4.— A flat field image in the K short filter. The pattern is due to imperfections in the manufacturing of the CCD. The flat field gives the relative gain of each pixel and is used to correct the stellar images before photometric analysis. The flat field is calculated by taking empty sky images during a time interval when the sky brightness is changing noticeably.

4.2. Average Pixel Gain

We also compute the average gain of each pixel by taking two images at each of 6 exposure times in the K short filter while the dome slit is closed. We take the difference of the two images in order to produce an image of pure Poisson noise that is centered around zero. We compute the variance of this image and plot it against the mean of each image to determine the gain and read noise. The variance of the difference image is just twice the variance one of the images by Poisson statistics so we must divide the variance of the differance image by two. The plot is shown in Fig.5 and the inverse of the slope of the least squares line gives an average gain of 36.850 $\pm$ 0.001 electrons/DN and the square root of the intercept gives a read noise of 7 $\pm$ 5 DN.

For those who are skeptical that the inverse of the slope gives the gain (g), let x^i_{DN} be the observed data number of the ith pixel. Let $x^i_{e^-}$ be the number of electrons detected by

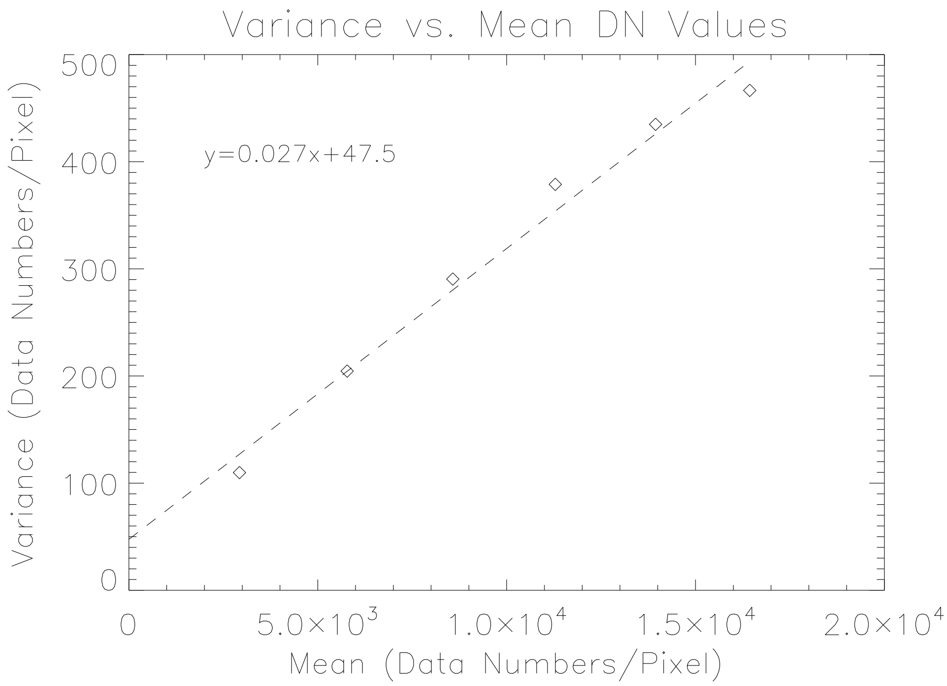

Fig. 5.— A plot of the variance versus mean in DN. Using our knowledge of Poisson statistics, we can show that the inverse of the slope gives the gain for the CCD in electrons/DN. The average gain for the infrared camera is 36.850 ± 0.001 electrons/DN and the camera has a read noise of 7 ± 5 DN.

the ith pixel of the CCD. Then the two quantities are related by $x^i_{DN} = \frac{1}{g}\, x^i_{e^-}$. Using Eq. 5

$$\bar{x}_{DN} = \frac{1}{N}\sum_i^N x^i_{DN} = \frac{1}{g}\frac{1}{N}\sum x^i_{e^-} = \frac{1}{g}\bar{x}_{e^-} \tag{10}$$

Now if we calculate the variance in data numbers we have

$$s^2_{DN} = \frac{1}{N-1}\sum_i^N (x^i_{DN} - \bar{x}_{DN})^2 \tag{11}$$

$$= \frac{1}{N-1}\sum(\frac{1}{g}x^i_{e^-} - \frac{1}{g}\bar{x}_{e^-})^2 \tag{12}$$

$$= \frac{1}{g^2}\frac{1}{N-1}\sum(x^i_{e^-} - \bar{x}_{e^-})^2 = \frac{1}{g^2}s^2_{e^-} \tag{13}$$

Hence

$$\frac{s^2_{DN}}{\bar{x}_{DN}} = \frac{1}{g}\frac{s^2_{e^-}}{\bar{x}_{e^-}} = \frac{1}{g} \tag{14}$$

since in Poisson statistics $s_{e^-}^2 = \bar{x}_{e^-}$.

5. Sky Subtraction

Only one more correction to the stellar images is needed before we can begin our photometric analysis. The stellar image contains signal from other celestial objects in the sky in addition to the star. We wish to eliminate these sources to improve the accuracy of our measurement. We begin by locating a star of known magnitude. The first star we choose is HD 201916 of magnitude 7.79 with an exposure time of 10 seconds. Nine images are taken at a given exposure time, in which the star occupies a different pixel in each one. A pixel by pixel median is taken since the median is unaffected by the presence of the star. Each of the nine images is divided by the flat field and the pixel by pixel median of the sky level is subtracted off. Note that the sky level subtraction takes care of the dark subtraction. This is because dark current is present in both the science frame and the sky level frame. Hence, when you subtract the two, the dark current cancels. We now have a relatively clean and clear image of the star as shown in Fig.6. The process is repeated for HD 201941 (mag=6.625, t=5 sec), HD 203856 (mag=6.860, t=7 sec), and HD3029 (mag=7.09, t=10 sec). Once these stellar images are corrected using the the flat field and sky level subtraction, we are ready to begin our photometric analysis.

6. Photometry

To measure the brightness of a star, we sum the data numbers in an aperture of radius R centered on the star. Each stellar image is taken with the same exposure time. Using the gain, we can calculate N/t for each star. Since there are nine stellar images for each star, this procedure is carried out on each one and the nine values of N/t are averaged.

To facilitate the summing of the data numbers in each pixel occupied by the star, we create a mask. The mask is a circle of radius R where each pixel that lies inside the circle has a value of 1 and every pixel outside the circle has value zero. If we center the mask at the center of the star and multiply the mask by the stellar image, we obtain an image that is zero everywhere except in the region immediately around the star. If we choose the radius of the mask carefully, we can be virtually certain that we are only counting the signal produced by the star. A plot of mask radius versus total DN is plotted in Fig.7.

We see that as the mask (aperture) radius increases, the total DN value increases until a critical radius is reached at which the total DN value levels off. It is possible for this plot

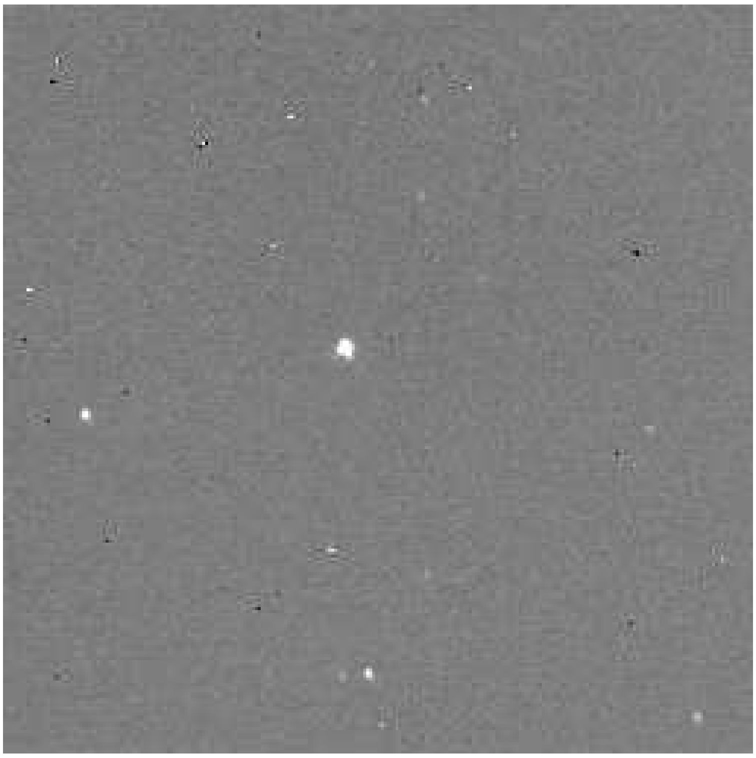

Fig. 6.— The flat fielded, sky level subtracted image of HD 201916. The background is fairly uniform with most only Poisson noise present.

not to asymptotically approach some limit. If the flat field and sky level subtraction are not perfect (highly likely), the background surrounding the star may not be uniformly zero. This problem can be correct by subtracting the averaged local sky brightness in an annulus with inner radius equal to the mask radius and outer radius chosen so that the annulus contains enough pixels to minimize the additional noise upon subtraction from the masked stellar image. An image of a mask applied to a star is shown in Fig.8.

The question now becomes how do we choose a radius for the mask such that nearly all of the signal produced by the star is counted. The procedure is described as follows. First, a mask of fairly large radius approximately centered at the star is applied to the stellar image. This is done to insure that the highest signal remaining is coming from the star. We then apply a 2D Gaussian fit to the masked stellar image. The 2D Gaussian image returns the center of the Gaussian and the standard deviation in the x direction (s_x) and y direction (s_y), respectively. We let $s = (s_x + s_y)/2$. We then create a new mask centered at the 2D Gaussian of radius $3s$, since for a 2D Gaussian, 99% of the data lies within 3 standard deviations.

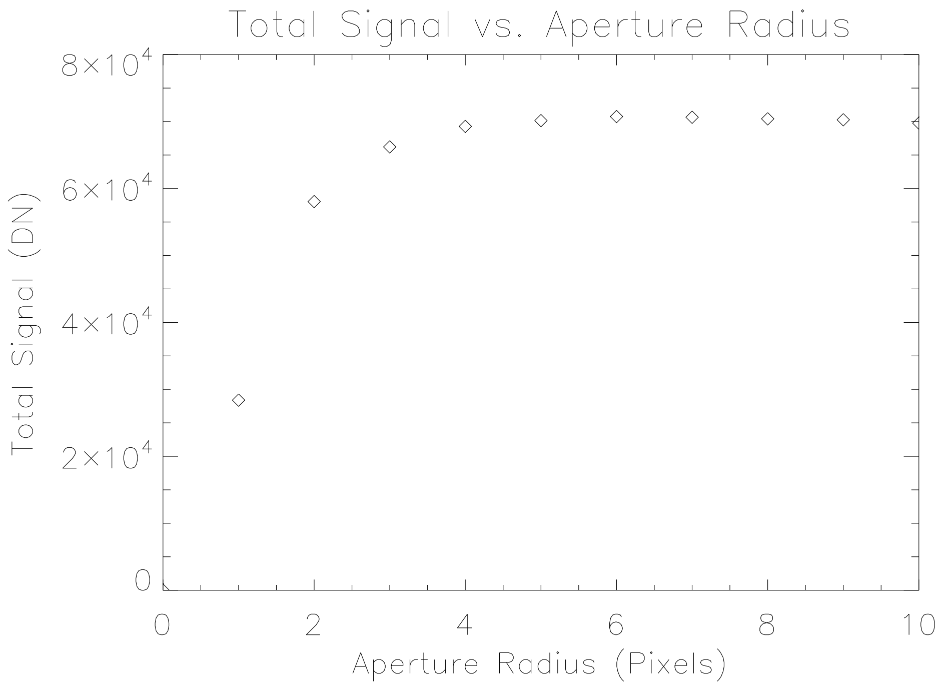

Fig. 7.— A plot of the total signal versus aperture radius centered on the star HD 201916. The relationship between the two quantities is is fairly linear until a critical radius is reach and the signal drops off. The radius at which this occurs gives a rough approximation of the size of the star.

Using this algorithm for each of the 9 stellar images for each of the 4 star, we obtains values for the DN values per second. We can use the gain to compute N/t. Armed with N/t for each of the four stars, we pick HD 3029 to be our standard star and use Eq.4 to compute the magnitudes of the other three stars. For HD 201916 we get 7.81, HD 201941 we get 6.53, and for HD 203856 we get 6.99. The results are summarized in Table.1

We can use the known magnitude of the four stars, the flux of Vega in the K short filter (636 Jy), and Eq.2 to compute the flux of each star in Janskys (Jy). We make a plot of flux versus photoelectrons/second and use the slope to obtain a conversion of $(1.6 \pm 0.3) \times 10^{-6}$ Jy $(e^{-}/\text{sec.})^{-1}$. This is shown in Fig.9

7. Conclusion

The properties of the infrared camera are summarized in the Table.2.

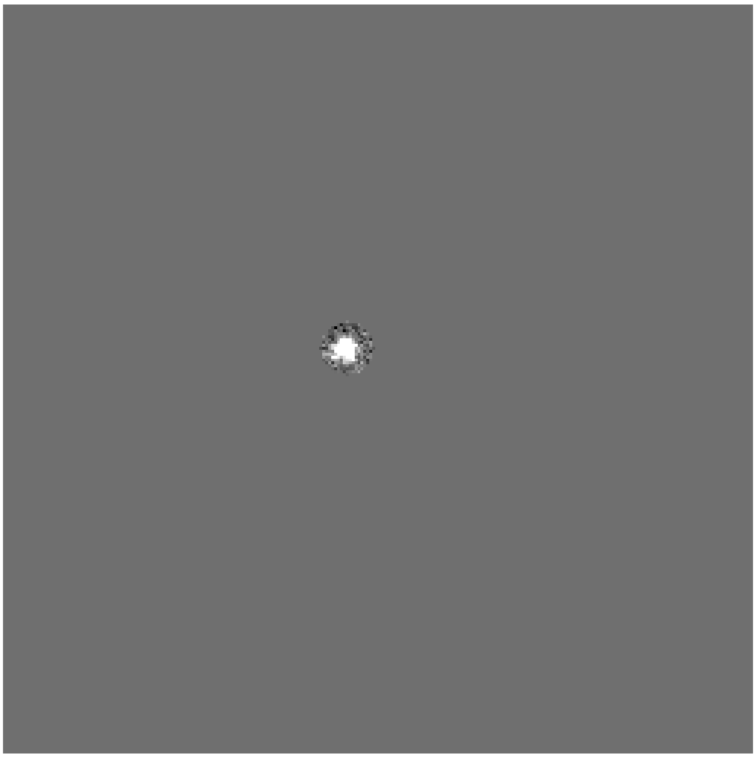

Fig. 8.— The image of HD 201916 after a mask of radius of 9 pixels is applied to it. Every pixel outside of the mask zero and we are mainly left with the strong signal from the star and a small amount of sky background.

If we calculate the percent error of our known magnitudes and the experimentally measured magnitudes for HD 201916, HD 201941, and HD 203856, using

$$\%\text{error} = \frac{|m_{known} - m_{measured}|}{m_{known}} \times 100\% \tag{15}$$

we get errors all within two percent. It has been said that more accurate results than this can be obtained. However, the error is low and we concluded that reliable photometry can be conducted using the infrared camera and 76.2 cm telescope at Leuschner Observatory.

8. Acknowledgement

I would like to thank the members of Group 1 (Ashley Bacon, Hung Ha, and Ferah Munshi) for allowing me to take data with their group and to use their flat images to create an amazing flat field. I also like to thank the members of Group -1 (Jo Daniels, Pinal Patel,

Star	Known Mag.	Mag.	N/(gt)(DN/s)	s(± DN)	t(sec)
HD 201916	7.79	7.81	7200	4000	10
HD 201941	6.625	6.53	23000	2000	5
HD 203856	6.860	6.99	15300	400	10
HD 3029	7.09		13900	700	7

Table 1: The results of photometry using HD 3029 as out standard star and measuring the flux the other three stars using Eqn.4.

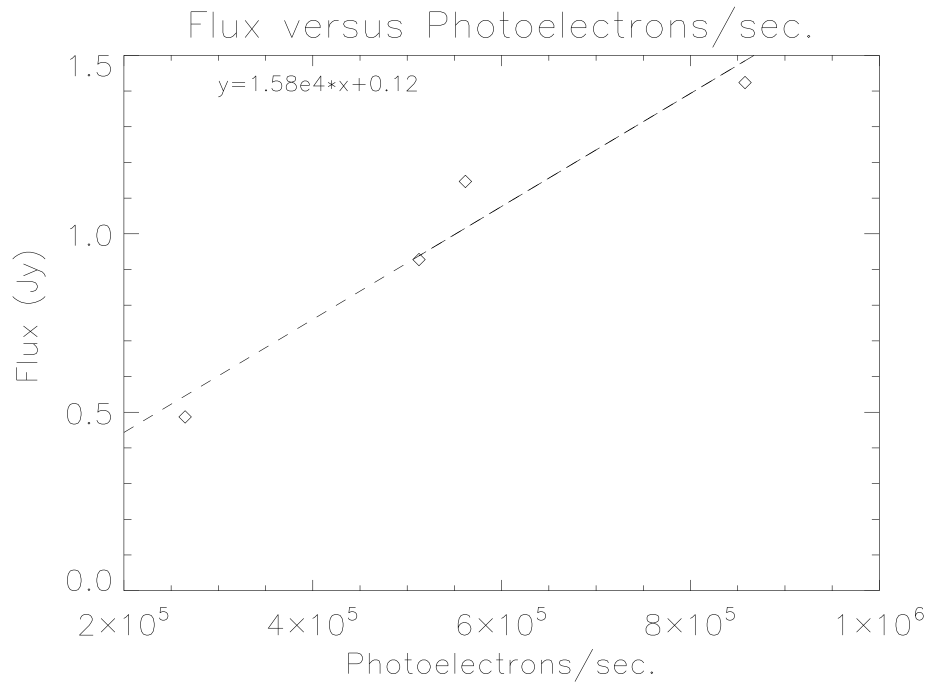

Fig. 9.— The relationship between flux and photoelectrons/sec is linearly as assumed by Eq.3. The slope of the plot gives a conversion factor of $(1.6 \pm 0.3) \times 10^{-6}$ Jy $(e^{-}/\text{sec.})^{-1}$.

and Tristan Lewis) for allowing me to use their star data. I would especially like to thank Jo for her patience in explaining to me how to do the photometry required in the last part of the experiment. Her kindness was much appreciated. Lastly, I would like to thank Matt Rocklin, Jason Curtis, Chris Sheehy, Jonah Hare, and Professor James Graham for fixing my inefficient programs and offering their sagacious wisdom.

Saturation Level	20,600 DN
Dark Current/sec.	76.0 ± 0.1 DN/s
Gain	36.850 ± 0.001 electrons/DN
Read Noise	7 ± 5 DN
Bias	0.7 ± 0.1 DN

Table 2: This table summarizes the properties of the infrared camera that must be measured and known in order to perform accurate photometry.