Lab 4: Differential Photometry: The Kepler Field

1 Introduction

Differential photometry is the measurement of the brightness of an astronomical object relative to a standard star that has constant brightness. While this technique doesn't give an *absolute* brightness measurement, it is very useful for determining how an object's brightness changes in time. Differential photometry is valuable for astronomical objects that vary in brightness such as:

- Pulsating variable stars (Cepheids and RR Lyrae stars)
- Eclipsing binary stars
- Gravitational lens events (a foreground star lenses a background star)
- Supernova explosions
- Transits of planets in front of stars

In fact, in the lab after this one, you are indeed going to use differential photometry to try to detect a transiting extrasolar planet. But it's going to take a lot of work to get there. In this lab, you'll develop routines to perform differential photometry on data from the Nickel.

During the night of September 15–16, we obtained a sequence of images of part of the field that will be observed by NASA's Kepler mission. This spacecraft will observe the same stars continuously for four years, with the intention of discovering hundreds of new extrasolar planets, including the first Earth-sized extrasolar planets.[1] While Kepler will be much better at *finding* planets than the Nickel could ever be, it may well be possible to *detect* these

[1] No doubt Kepler would be able to discover a wide array of other new phenomena, but due to bandwidth constraints, nearly all of the Kepler observations will be discarded — it's simply not possible to beam all the data down to Earth.

planets with the Nickel — once Kepler has told us where to look. You will analyze our data to help determine whether this is, in fact, the case.

It's extremely unlikely there are any planets in the field we observed (though it would be delightful if we turn out to be wrong about that!). It is, however, still instructive to do differential photometry with these data, because the scatter in your results will indicate how precisely we can perform photometry of Kepler stars with the Nickel. If we can make things precise enough, we'll know that it will be possible to use the Nickel to follow up on planetary detections reported by Kepler. It should be emphasized that this is a genuine scientific question — we don't know whether it's really possible to do this with the Nickel or not!

Your goals for this lab are:

- Develop software that can perform differential photometry on an astronomical image.
- Determine the uncertainties on your results.
- Come up with ways to reduce the uncertainties in future observations.

1.1 Schedule

2 weeks - Reports due Tuesday, October 9$^{\text{th}}$.

1.2 Recommended Reading

- Howell, *Handbook of CCD Astronomy*, chapters 4 & 5, especially §§5.1, 5.2, & 5.4.

2 Understanding the Task

The Kepler field images that we obtained are contained in the directory `/home/ay120/ucolick/15sep07` along with a logsheet detailing the night's observations. We obtained ten images of the Kepler field.

There are about 25 stars in the particular region we chose to image. Choose one star to be your "target" star and three others to be "reference" stars. (Hint: don't make your life unnecessarily hard. Choose the bright ones.) Your basic procedure should be, for each image, to measure the brightness of each of the stars and determine the ratio

$$R = \frac{B_{\text{target}}}{B_{\text{ref 1}} + B_{\text{ref 2}} + B_{\text{ref 3}}}.$$

Assuming that the reference stars are constant (which is safe; see Henry et al. 2000) this ratio will track the brightness of your target star. (Of course, if you're feeling adventurous, you can use more reference stars.)

We expect that the brightness of your target star is also constant. But, of course, you won't find the exact same value of R for your 10 images, because of uncertainty in your measurements. The size of this uncertainty is what interests us:

How precisely can you measure the brightness of a star?

3 Aperture Photometry

In the above outline, we glossed over the question of how exactly to determine the brightness of a star. There are several techniques for doing so, falling under the general rubric of *photometry*. For this lab, you will use *aperture photometry*, which is described in §5.4 of the *Handbook of CCD Astronomy*. The procedure is:

1. Start with a bias-corrected and flatfielded image. Remember to bias-subtract your flat-field images) This should merely be a matter of reusing the routines you developed in the previous lab. Be sure to construct new flatfield and bias images for this new data set, though; the telescope and detector performance can change from night to night, and this lab requires the best possible precision.

2. Determine the pixel coordinates of your star in this particular image. We didn't move the telescope during our observations, so each star will stay in pretty much one place, but they will have drifted around by a few pixels from one image to the next. The best results will be obtained if you track this drift.

3. Estimate the level of "sky" background per pixel near your star. This is done by considering the pixel values in an annulus around, but not including, your star. What is the median level within this annulus?

This number is your best guess as to the sky level underneath your star. These counts may not actually come entirely from the sky, but they represent an extra signal that needs to be subtracted away.

4. Estimate the combined brightness of the star and the sky. You do this by simply summing up all the pixels inside of a circular *aperture* centered on your star.

5. From this combined brightness, subtract off the sky contribution to calculate the brightness of the star alone. Given the size of your aperture and the median sky annulus value, how many counts did the sky contribute? How does this compare to the typical brightness of your stars?

Because we are only considering relative brightnesses, we don't need to worry about converting from pixel counts to a physical quantity like ergs per second.

There are clearly many choices to be made here: the radii of your annulus and aperture, the way in which pixels on the edge of your annulus are counted, where the annulus and aperture are centered, and so on. You'll have to decide what the best resolutions to these issues are. For a more thorough discussion of aperture photometry techniques that provides many useful hints, see §§5.1 and 5.4 in the *Handbook of CCD Astronomy*.

4 Analysis

Once your aperture photometry routines are working, it shouldn't be hard to generate a plot of R versus time, using one data point from each exposure. But what are the uncertainties on your value of R? We'll approach this question in two ways.

First, let's use a somewhat formal approach. Assume that the uncertainty in the pixel values of your science images is equal to the now-familiar Poisson expression $\sqrt{N}$. From your data, pick representative pixel values for each of your four stars and report them. What would the Poisson error on each of these values be? If your bias and flatfield images have Poisson uncertainties as well, what is the uncertainty on a typical star pixel value after bias correction? After flatfielding?[2] Express an analytical answer in

[2]We're ignoring the fact that your bias and flatfield images are derived from the statistics of many input images, so the uncertainties on those pixel values aren't really just the

terms of S, a pixel value from a science image, B, the bias applied to that pixel, and F, the flatfield value by which that pixel is scaled. Compute an uncertainty with the representative value you chose for your target star and representative bias and flatfield values. Given the number of pixels in the annulus and aperture you used for photometry, what is the uncertainty on a single measurement of the brightness of each of your stars, using those representative values? Finally, what is the uncertainty on a single measurement of R?

Now, a more empirical approach. As we mentioned above, your target star's brightness should be constant, so any variations in R reflect the imprecision of our measurements. What is the standard deviation of the R values that you find during these time periods?

Make a plot of R versus time measured in UT. Give each measurement error bars based on the empirical uncertainty you found. Overlay a solid line showing the mean of your R values.

5 Interpretation

We estimated the expected uncertainty in your measurements, then gauged the actual uncertainty from your results. How do these two values compare? Offer some explanations as to the differences, if any, between the two numbers you found.

How might we alter our procedures to improve the precision of future observations? We don't expect you to be completely certain of what will help, but offer a few conjectures based on your experience with this lab. For extra credit, briefly explore two alternative methods of analysis (e.g., using B band observations versus Z band observations) and report on which yields better results.

References

[1] Henry, G.W., Marcy, G.W., Butler, R.P., Vogt, S.S. 2000, ApJ Letters, 529, 41 "A Transiting 51 Peg-like Planet"

Poisson errors of those values.