10 Photometry

For amateurs who want to make real contributions to astronomy, few areas offer greater opportunities than photometry. Photometric measurements can pinpoint the exchange of mass between distant binary stars, reveal the tumbling of asteroids, or track the decline in the brightness of a supernova.

Photometry is the measurement of the changing brightness of celestial objects over time. The advent of CCD imaging has made photometry easier and more practical than ever before for both professional and amateur observers; not only because the CCD is both sensitive and highly linear, but also because it captures a two-dimensional "virtual sky" for careful analysis at a later date.

Once you have made a set of observations, photometric measurements of the images are fairly straightforward. Lew Cook, an amateur astronomer and photometrist, summarized his observing philosophy this way, "Nighttime is for observing. Daytime is for data processing. Cloudy nights are for sleeping, going to the movies, and taking your wife to dinner. I shoot Friday night, reduce data and email light curves Saturday afternoon, shoot Saturday evening, reduce data and email light curves Sunday. You can make discoveries that way!"

This chapter explains the methods and practices of modern CCD photometry in enough detail to get you interested in trying a few simple projects. Perhaps you will discover the great satisfaction that comes from measuring those subtle changes in starlight that tell us what is going on in the cosmos.

10.1 Magnitudes: How Bright Is This Star?

The ancient Greeks divided stars into six classes by *magnitude*, literally by their size. Between 141 and 127 B.C., the Greek astronomer Hipparchus compiled a catalog of about one thousand naked-eye stars, listing both positions and magnitudes. Just as we do today, this catalog listed the brightest stars as first magnitude, and the faintest visible to the naked eye as sixth magnitude.

Nearly two thousand years later, the English astronomer Norman Pogson quantified measures of star brightness, and found that those ranked as first magnitude were roughly 100 times brighter than stars of the sixth magnitude. He also recognized that each step of one magnitude represented the same ratio of brightness relative to the next. In 1856, Pogson proposed that a step of one magnitude should be *defined* as a factor of $\sqrt[5]{100} = 2.512\ldots$ in brightness, thereby making five magnitudes correspond *exactly* to a brightness difference of 100 times.

The Pogson scale was subsequently formalized into our current system of magnitudes, and the basis of modern photometry laid by 1900 with a mixture of visual and photographic measurements. Visual estimates seldom have an uncertainty lower than 0.2 magnitude (about 20% accuracy), and photographic photometry cannot easily be pushed to better than 0.05 magnitude (about 5% accuracy). It was not until after World War II and the invention of the photomultiplier tube that astronomers could routinely measure stellar brightness to 0.01 magnitude (about 1% accuracy), and, with the aid of the 200-inch Hale telescope, extend reliable measurements of stellar brightness to the 20th magnitude.

Today an amateur astronomer with a CCD camera on an 8-inch telescope can reach the 20th magnitude, and more importantly, perform high-quality photometry on stars of the 14th magnitude.

10.1.1 Magnitudes Are Comparisons

Our definition of magnitude, derived from the ancient Greeks, implies a comparison between stars. Pogson defined *differences* in magnitude. In fact, the formal definition is written as the logarithm of the ratio of flux (light) from the two stars:

$$\Delta m = m_1 - m_2 = -2.5\log(F_1/F_2)\,. \qquad \textbf{(Equ. 10.1)}$$

What this equation says is that the difference between the magnitude of two stars, Δm or $m_1 - m_2$, depends on the ratio of their fluxes F_1 and F_2, and that's all.

The definition has nothing to say about magnitudes *per se*—it speaks only of magnitude differences. In other words, to determine the magnitude of a star, you must compare its brightness to the brightness of another star *whose magnitude you already know*! To find the magnitude of the unknown star, you compute a ratio of the instrumental responses, C_1/C_2, find the logarithm, multiply by –2.5, and add the accepted magnitude of a *standard star*:

$$m_1 = -2.5\log(C_1/C_2) + m_2. \qquad \textbf{(Equ. 10.2)}$$

The magnitude of the "known" star is thus the standard against which we define the magnitude of the star whose brightness we want to know. Once you grasp this crucial point, photometry makes a lot more sense.

10.1.2 Aperture Photometry

Measuring the total light in a star image is simple in principle. The image of a star is a digital copy of a small section of sky. It includes light from the star as well as background sky light. The light of the star is spread over a sizeable number of pixels, and extends to a considerably greater distance than is obvious. To extract the brightness of the star from the image, it is necessary to add up starlight from all of the pixels illuminated by it, and then to estimate the contribution from the sky background and subtract that.

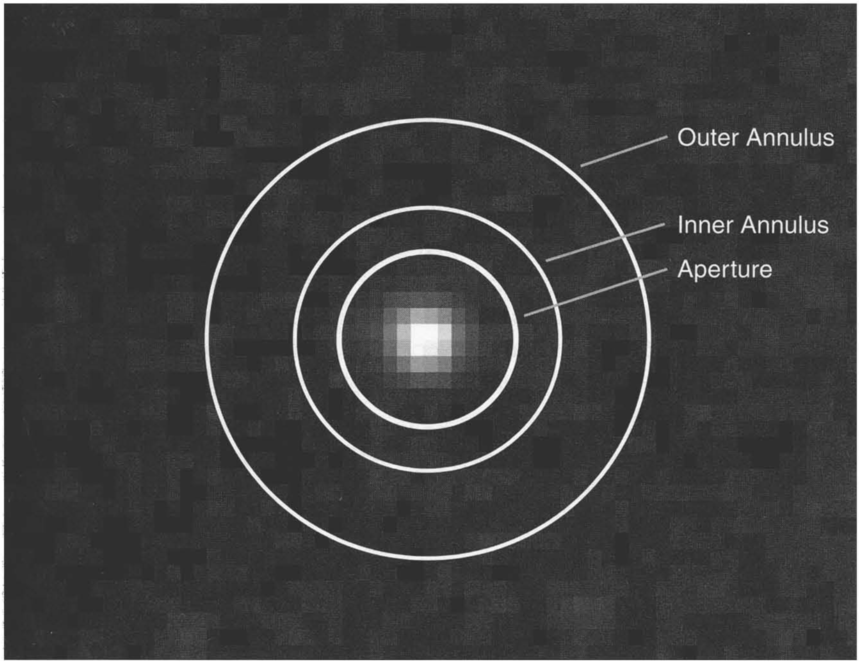

Figure 10.1 To determine a star's brightness, you find the total pixel value inside the aperture (which contains skylight as well as starlight). Next, you measure the sky brightness between the inner annulus and outer annulus and subtract the skylight from the total in the aperture. The result is the star's brightness.

In the following sections we describe how to sum the pixels in the star image, how to determine the sky contribution, and how to convert the result into a raw instrumental magnitude.

10.1.2.1 Summing the Star's Light

The classic technique for summing the light from a star is called *aperture photometry*. The *aperture* is a small patch of pixels that contains a star image. Because stars don't have sharp edges, but instead blend into the surrounding sky, to capture all of a star's light it is necessary to make the aperture larger than the apparent size of the star image.

A convenient way to express the size of a star image is to treat it as a Gaussian blur, and to express its "radius" as the Gaussian sigma (σ). Alternatively, the diameter of star images can be expressed as the *full width half maximum*, abbreviated *FWHM*. FWHM is the diameter of the star image at the point that its intensity has fallen to half its peak value. In either case, star image size is measured in pixels. For star images with a Gaussian intensity profile:

$$\mathrm{FWHM} = 2.37\sigma . \qquad \textbf{(Equ. 10.3)}$$

- ***Tip:*** *Click on any star's image with the Star Image Tool in **AIP4Win**, and you'll get back the star's (x,y) coordinates, its sigma radius, its full width half maximum, and other useful characteristics.*

To capture as much light as possible from a star image, the aperture should be sized considerably larger than it. As a rule of thumb, photometrists often set the radius of the aperture to five times the sigma radius of the star image. In an image with tight, well-focused stars, the sigma radius often measures between 0.9 and 1.4 pixels, so an aperture radius of 6 pixels is a good all-around size.

Totalling a star's light is quite straightforward. Given the location of the star image, the photometric software computes the centroid ("center of gravity") of the star image, then totals the value of every pixel inside the aperture radius. Note, however, that the total pixel value includes not only starlight, but also the background glow of the night sky.

In equation form, given n_{aperture} image pixels, $p(n)$, lying less than distance R_{aperture} from the centroid of the star image, you can compute C_{aperture}, the total pixel value inside the aperture radius:

$$C_{\text{aperture}} = \sum_{n=0}^{n_{\text{aperture}}} p(n) \ [\text{ADU}]. \tag{Equ. 10.4}$$

When R_{aperture} is very small, the aperture will be ragged at the outside edge and starlight that should be included may be lost; but whenever this radius is reasonably large, the aperture will include all pixels containing significant amounts of starlight.

10.1.2.2 Subtracting Sky Background

In classic photoelectric photometry, the sky background brightness was measured by pointing the telescope at a blank patch of sky near the star. CCD photometry offers a better option: sample the sky background in an *annulus* (donut) surrounding the star image. To avoid the inclusion of starlight, the annulus should be somewhat larger than the star aperture, and should extend far enough to provide a statistically significant sample of sky pixel values.

The computation to determine the sky background level is the same one we used for the star image: determine which pixels lie outside the inner annulus radius but inside the outer annulus radius, count and sum the pixels, and compute the average pixel value of the sky. Since the annulus probably covers a sufficiently large area to include faint background stars, it is necessary to eliminate these non-sky contributions to the sky background.

A simple and computationally robust solution is to sort the pixels in the annulus into ascending order. Those that are part of another star image will be brighter than the average pixel value of the sky, so it is necessary to exclude some percentage of the high-value pixels in the sky annulus. To avoid skewing the average, it is also necessary to exclude the same percentage of the low-value pixels.

The corrected value for the sky brightness is the mean of the remaining pixel values. Experience shows that excluding the top and bottom 20% of pixels works well for all but the most crowded sky backgrounds.

In equation form, given n_{annulus} image pixels, $p(n)$, lying greater than distance R_{inner} and less than R_{outer} from the centroid of the star image, and satisfying the condition of lying between the 20% and 80% percentile in value, you can compute C_{annulus}, the total pixel value inside the annulus:

$$C_{\text{annulus}} = \sum_{n=0}^{n_{\text{annulus}}} p(n) \text{ [ADU].} \qquad \textbf{(Equ. 10.5)}$$

Total pixel value for both the aperture and the annulus are obtained exactly the same way: by computing the sum of all pixels that meet the geometric and/or pixel value criteria needed to qualify. By the way, for reasons steeped in the history of photometry, you will sometimes hear astronomers refer to the aperture and annulus totals as "counts."

10.1.2.3 Raw Instrumental Magnitude

After the total pixel value of the star aperture and sky annulus have been counted, you can convert raw "counts" into magnitude. However, the resulting measure is not a "real" magnitude until it has been tied to standard stars in the sky. For this reason, the magnitude that you compute is called the *raw instrumental magnitude*. It's *raw* because it has not been tied to the sky, and *instrumental* because it depends on the properties of your equipment; that is, it depends on your CCD camera, your filters, and your telescope.

In measuring a star image, you have determined four parameters:

- C_{aperture}, the sum of pixel values in the star aperture,
- n_{aperture}, the number of pixels in the star aperture,
- C_{annulus}, the sum of qualified pixels in the sky annulus, and
- n_{annulus}, the number of pixels in the sky annulus.

In addition to the things you have measured on the image, you also know the integration time, *t,* used to make the image, to convert the measured accumulation during integration into the rate at which photons arrived.

Recall now that by definition magnitudes compare stars with one another (see Equation 10.2), yet you have only one star! Since we're not tying it to real stars, you can introduce a fictitious "star" called the *instrumental zero point*, or *Z*. Begin by rewriting Equation 10.2 to separate the instrument responses:

$$m_1 = -2.5\log C_1 + 2.5\log C_2 + m_2 \qquad \textbf{(Equ. 10.6)}$$

To use this fictitious second star, redefine the terms $2.5\log C_2 + m_2$ as *Z*. Since the choice of *Z* is completely arbitrary, you can choose any convenient value for it. Photometrists usually choose a value that converts raw instrumental magnitudes to magnitudes that sound reasonable for the star they are measuring.

You can convert the total counts star aperture and the sky background into a *raw instrumental magnitude*, *m*, for the star, using:

$$m = -2.5\log\left(\frac{C_{\text{aperture}} - n_{\text{aperture}}(C_{\text{aperture}}/n_{\text{annulus}})}{t}\right) + Z. \qquad \textbf{(Equ. 10.7)}$$

What we've done here is to pro-rate the sky total seen in the annulus from the number of pixels in the annulus to the number of pixels in the aperture, and then we've subtracted the resulting sky total. The only assumption we've made is that the sky around and behind the star has the same brightness as the sky that surrounds the star in the annulus. Dividing by the integration time means that without changing your zero point you will get the same raw instrumental magnitude for images taken with different integration times.

Measuring magnitudes from CCD images is both quick and easy. The observer, however, must remain alert to insure that numbers popping up on the computer screen are valid. Before measuring a star image, check the profile to be certain that it is well within the star aperture. If there are stars in the aperture or in the annulus, they can add to the measured star brightness or to the sky background reading.

Images used for photometry should be calibrated before they are measured, but they *must not be scaled* because doing so can change the relationship between photon flux on the detector and image pixel value, thereby destroying the linearity of the data in the image.

- ***Tip:*** *The Single Star Photometry Tool in* ***AIP4Win*** *computes raw instrumental magnitude using the above formula. You need to know the integration time for the image and supply a value for the zero point. The tool finds the star's centroid position, the total (star – sky) count, the mean sky background level, and the raw instrumental magnitude.*

10.1.2.4 Statistical Uncertainty

The total of detected photons that accumulates to form a star image obeys Poisson statistics. (To learn more about Poisson statistics, see Chapter 2.) This means that if a star shines with a mean brightness of 10,000 detected photons per integration, the actual number you'll see in an image will be $10,000 \pm \sqrt{10,000}$. Photometry, therefore, always has a built-in uncertainty—but you can determine what the uncertainty should be. Computing the statistical uncertainty "keeps you honest" when you are doing photometry.

Two measures are commonly used to express this uncertainty: the signal-to-noise ratio and standard deviation in magnitudes. Signal-to-noise ratio (SNR) is simply the size of the star signal divided by the amount of noise in the signal. An SNR of 100 is considered good; it means that the signal is 100 times greater than the noise. An uncertainty of 1 part in 100 in determining a magnitude corresponds to about 0.01 magnitude error. To attain a photometric accuracy of 1⁄100 of a magnitude, you need a signal-to-noise ratio of 100, an easy rule to remember.

Now let's define all of the signal and noise sources.

The signal comes from one source only: detected photons (photoelectrons) from the star that you are measuring. The star-minus-sky term,

$$S_{\text{star}} = g(C_{\text{aperture}} - n_{\text{aperture}}(C_{\text{aperture}}/n_{\text{annulus}})), \qquad \textbf{(Equ. 10.8)}$$

from Equation 10.7 gives the signal in ADU units. To convert ADUs to electrons (detected photons), we must multiply the star-minus-sky count by the conversion factor, g, electrons per ADU.

Although there is only one star signal source, there are multiple sources of noise. The most obvious of these is the noise that is associated with Poisson statistics, $N_{\text{star}} = \sqrt{S_{\text{star}}}$. If you measured a star against a completely black sky using an ideal detector, the signal to noise ratio would be:

$$\text{SNR} = \frac{S_{\text{star}}}{N_{\text{star}}} = \frac{S_{\text{star}}}{\sqrt{S_{\text{star}}}} = \sqrt{S_{\text{star}}}. \qquad \textbf{(Equ. 10.9)}$$

However, in real photometry we must also take the noise sources in the sky and the detector into account:

- C_{sky}, ADUs of sky background present in every pixel,
- C_{dark}, ADUs of dark current added to every pixel,
- σ_{ron}, readout noise in electrons r.m.s. added to every pixel,
- σ_{quant}, ADUs of quantization noise from the digitization of the CCD's analog output. Use $\sigma_{\text{quant}} = 0.29$.

Because noise from each of these contributors is added to every pixel in the star aperture, their individual total is multiplied by the total number of pixels to obtain their communal total. The noise contribution from the star aperture is:

$$N_{\text{star}} = \sqrt{S_{\text{star}} + n_{\text{aperture}}(gC_{\text{sky}} + gC_{\text{dark}} + \sigma_{\text{ron}}^2 + g^2\sigma_{\text{quant}}^2)}. \qquad \textbf{(Equ. 10.10)}$$

Because Poisson and Gaussian noise sources add quadratically, the readout and quantization noise standard deviations are squared before summing.

In the determination of the sky background in Equation 10.8, the sky background count, C_{annulus}, is normalized to the same number of pixels as the aperture and subtracted from the aperture pixel value sum. The noise associated with the sky background count is:

$$N_{\text{sky}} = \sqrt{n_{\text{annulus}}(gC_{\text{sky}} + gC_{\text{dark}} + \sigma_{\text{ron}}^2 + g^2\sigma_{\text{quant}}^2)}. \qquad \textbf{(Equ. 10.11)}$$

The noise terms in this expression are identical to those in the aperture. Now consider the case in which $n_{\text{aperture}} = n_{\text{annulus}}$; it is clear that the sky contribution to the total noise will double when this noise source is added to Equation 10.11. However, if the number of pixels in the annulus is greater than the number of pixels in the aperture, then gC_{sky} will have a lower statistical uncertainty and N_{sky} will be proportionately reduced. We can, therefore, replace the term n_{aperture} in Equation 10.10 with the following to account for this influence:

$$n_{\text{aperture}}\left(1 + \frac{n_{\text{aperture}}}{n_{\text{annulus}}}\right). \qquad \textbf{(Equ. 10.12)}$$

It is clearly desirable to have as many pixels as practical in the annulus. If the number of annulus pixels equals that of the aperture, the ratio is 2.0; i.e., sky noise doubles. However, by using an annulus with twice as many pixels as in the aperture, the ratio falls to 1.5. On the other hand, as the number of annulus pixels falls below those in the aperture, the determination of the sky value becomes increasingly uncertain and the ratio rises dramatically.

- ***Tip:*** ***AIP4Win****'s default radii for aperture photometry are 6, 9, and 15 pixels for the aperture, inner annulus, and outer annulus, respectively. The number of annulus pixels is four times the number of aperture pixels, giving a ratio of 1.25.*

Combining the signal and noise terms yields the following for the signal-to-noise ratio in aperture photometry of a star image:

$$\text{SNR} = \frac{S_{\text{star}}}{\sqrt{S_{\text{star}} + n_{\text{aperture}}\left(1 + \frac{n_{\text{aperture}}}{n_{\text{annulus}}}\right)(gC_{\text{sky}} + gC_{\text{dark}} + \sigma_{\text{ron}}^2 + g^2\sigma_{\text{quant}}^2)}}$$

(Equ. 10.13)

using the value of S_{star} computed in Equation 10.8.

It should come as no surprise that computing the statistical uncertainty in aperture photometry is more complicated than computing the raw instrumental magnitude. The magnitude is simply the excess pixel value found in the aperture over the expected sky value; whereas the noise in the signal involves factors closely associated with the CCD and its noise characteristics.

To convert SNR into magnitude error, use the following:

$$\sigma_{\text{m}} = \frac{1.0857}{\text{SNR}}. \qquad \textbf{(Equ. 10.14)}$$

The factor 1.0857 converts the fractional uncertainty into magnitudes. This allows you to express the measurement of a star's raw instrumental magnitude in the form $m \pm \sigma_{\text{m}}$, giving both the result and the uncertainty of that result.

10.2 Putting Photometry to Work

Broadly speaking, astronomers do two types of photometry: differential photometry and all-sky photometry. *Differential photometry* is focused on monitoring one "target" to observe how it changes. The target may be a variable star, an asteroid, a star with exoplanet transits, or an exotic target like a quasar or the nucleus of a Seyfert galaxy. *All-sky photometry* is aimed at establishing accurate magnitudes for an object or objects relative to standard stars with well-established magnitudes, and generally requires careful observation and rigorous data reduction with no shortcuts allowed.

Differential photometry is easy because the target and a comparison star are usually in the same field of view, and are observed at the same time, through the same atmosphere, with the same filters—and all that matters is an accurate comparison between the target and the comparison. All-sky photometry is difficult because the target objects have been captured in different images from the standard stars, have been observed at different times, through a different atmosphere, and usually have been through multiple filters.

However, observers know that making CCD integrations at the telescope and extracting magnitudes from the resulting images is just the beginning. Raw instrumental magnitudes are strongly affected by three factors:

- Filter(s) used in making the image(s). Although some observing programs do not require filtered images, many do. A standard set of filters includes U, B, V, R, and I, although just two filters, V and R, are necessary to get started.
- Atmospheric extinction that dims stars. Although this dimming is not particularly apparent to the eye, for photometry it is significant and must be corrected.
- A unique set of instrumental magnitudes defined by the peculiarities of your particular set of filters, your CCD, your observing site and your telescope. To combine your observations with those of others, your magnitudes must be transformed to a standard photometric system.

The section following describes how astronomers measure and then compensate for these factors.

10.3 Photometric Systems

The reason that the magnitude scale is defined in terms of standard stars is that it is extremely difficult to measure the absolute flux of light with any precision, but it is fairly easy to compare the flux of one source with that of another. Why should this be so?

The answer lies in another question: What do we mean by "flux?" In theory, of course, we can easily define it as the arrival of some number of photons per second in some well-defined range of wavelengths—that is, in fact, the goal in measuring flux. However, what comes out of the detector, whether that detector is a photomultiplier tube or a CCD image, is an instrumental response to the starlight—a meter reading, a chart deflection, a count in electrons per second, a total pixel value—one number. We have no idea how many photons at each wavelength