These pages are from the American Association of Variable Star Observers DSLR Observing Manual, a comprehensive 110-page guide to astronomical brightness measurements with a standard, commercially-available camera. The pages here are a very quick beginner's guide to the relevant features for physics pracs. The full guide is at https://www.aavso.org/sites/default/files/AAVSO_DSLR_Observing_Manual_v1-2.pdf

# Chapter 2: Equipment Overview

DSLR cameras provide an economical way to become involved in digital photometry. In terms of hardware, there are fundamentally three things that are required: a lens or telescope to collect and focus star light, a camera capable of providing images in an unprocessed format, and some sort of mount to stabilize the camera during long exposures. These devices can be as simple as a suitable point-and-shoot camera on a fence post, or as elaborate as a professional-grade camera mounted at the prime focus of a telescope. Prior to discussing how one conducts the observations and reduces the data, it is best to first understand exactly what equipment is required for DSLR photometry. We will be discussing each of these three components in detail. But first some physical aspects of these cameras will be described so that you may better understand what happens when you adjust various camera settings.

## 2.1 What is a DSLR?

"A digital single-lens reflex camera (also called a digital SLR or DSLR) is a digital camera combining the optics and the mechanisms of a single-lens reflex camera with a digital imaging sensor, as opposed to photographic film. The reflex design scheme is the primary difference between a DSLR and other digital cameras. In the reflex design, light travels through the lens, then to a mirror that alternates to send the image to either the viewfinder or the image sensor. The alternative would be to have a viewfinder with its own lens, hence the term "single lens" for this design. By using only one lens, the viewfinder presents an image that will not perceptibly differ from what is captured by the camera's sensor." (Wikipedia)

Recently, point-and-shoot cameras have started to support features that are required for astronomical photometry. Hence, this manual may be applicable to your camera, even if it is not explicitly a DSLR.

As illustrated in Figure 2.1, a DSLR camera is made from an ensemble of optical and electronic components that are needed for capturing images. Many modern DSLR cameras also come with a plethora of settings and in-camera software processing options, most of which are not useful or downright detrimental for astronomical photometry.

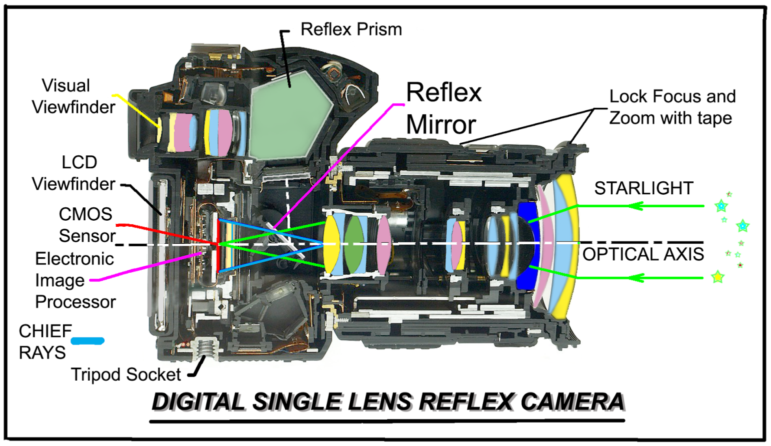


**Figure 2.1**. A cutaway of a DSLR camera showing the various components involved.

All DSLR cameras on the market today have CMOS (Complementary Metal Oxide Semiconductor) sensors, so we will concentrate on this type of device. For a discussion of CCD camera technology, please see the *AAVSO Guide to CCD Photometry*. Cameras with Foveon detectors (which have three color-specific layers of pixels instead of a single plane of different colored pixels) are not often seen. If you wish to know more about them, please ask on the AAVSO DSLR Photometry forum.

### *2.1.1 Optical path*

The camera consists of a lens attached to the front of the camera body, a shutter, several large filters, a microlens array, additional filters, and a detector. The optical components in which we are most interested are shown schematically in Figure 2.2. The first optical component is the lens. Its primary purpose is to project and focus an image onto the sensor. Behind the lens is the f-stop diaphragm. This determines the total aperture, or light gathering surface, of the lens. These components are typically contained within the lens body itself.

Within the camera body, the first element encountered is typically the shutter. The purpose of the shutter is to control the amount of light entering the camera.

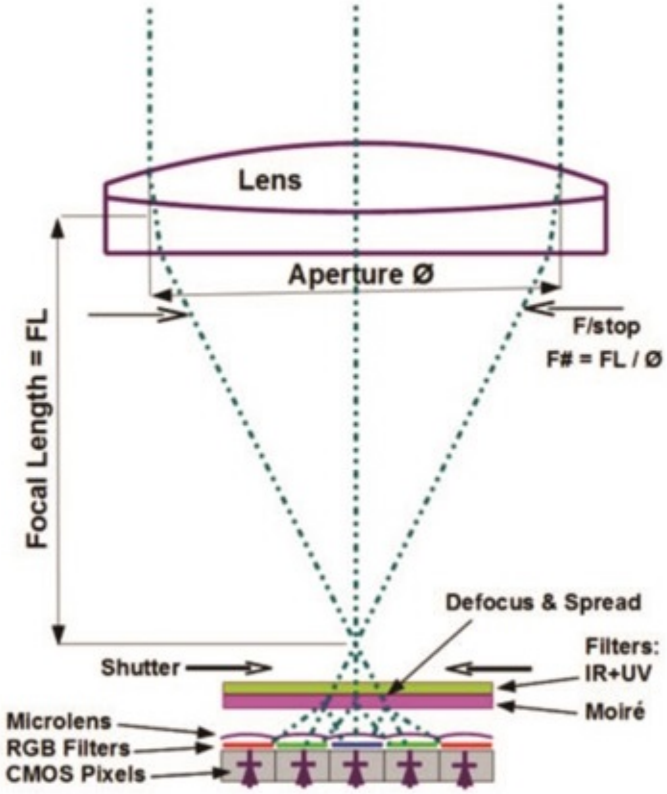


**Figure 2.2**. Typical DSLR optical layout with a CMOS detector and RGB Bayer array. (Roger Pieri)

Behind the shutter are a series of filters that perform several functions, including:

- IR dye that reduces excess sensitivity to deep red and Infrared light
- IR cut (dielectric filter) that eliminates Infrared light above 700 nm
- UV cut (dielectric filter) that eliminates Ultraviolet light below 400 nm
- low-pass filter that spreads the light to reduce the Moiré interference pattern caused by the Bayer structure (slightly reduces the resolution, and reduces the undersampling issue in photometry)

Behind these filters and immediately in front of the detector, a microlens array (cemented onto the detector) focuses the light falling on each pixel into the most sensitive part of it, improving the filling factor of the pixel to a level approaching 100%.

### *2.1.2 CMOS detectors*

DSLR CMOS detectors have a color filter array, often referred to as a Bayer array, (see Figure 2.3) of red, green, and blue (hereafter RGB) pixels. There are usually two sets of green pixels.  The RGB filters are produced by depositing different pigments directly on the top surface of each pixel of the CMOS sensor and cannot be cleaned or removed. Each pixel is therefore sensitive only to its own color of light.

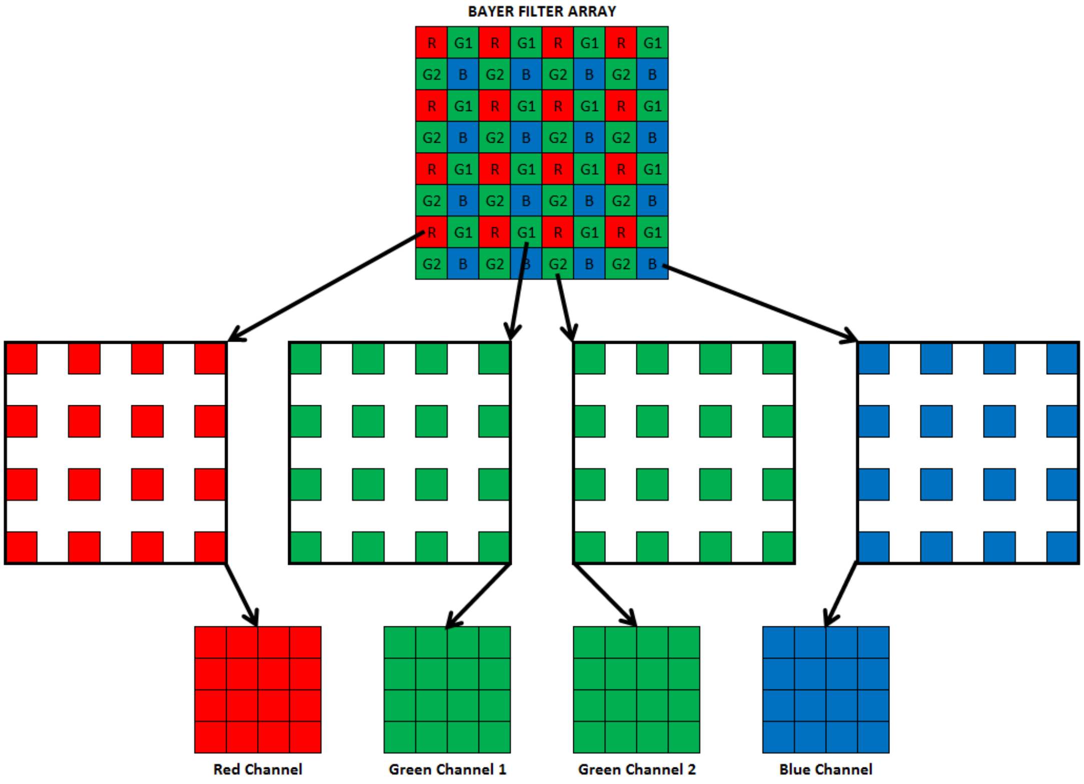
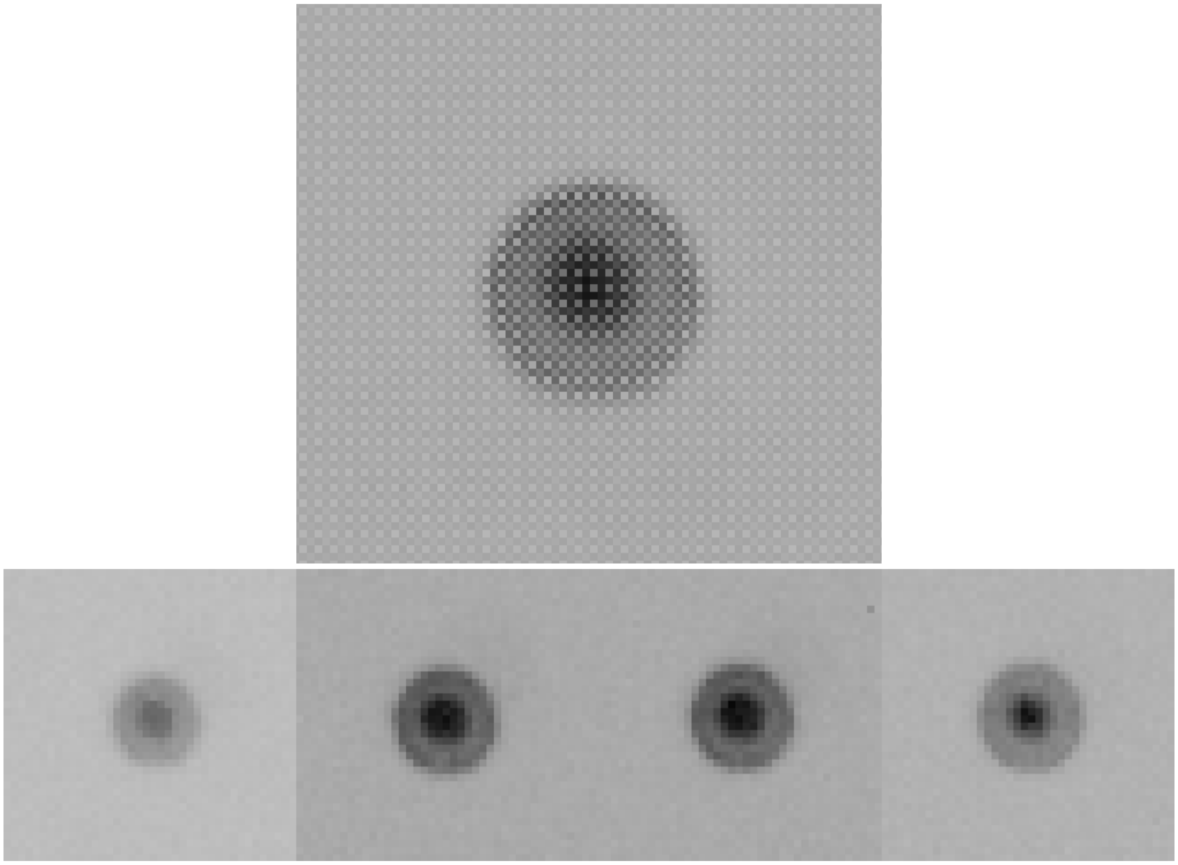


**Figure 2.3**. **Top:** Schematic showing a typical Bayer matrix color filter arrangement. **Middle:** Each color channel can be extracted separately using appropriate software, note gaps between pixels. **Bottom:** Each channel is usually displayed with dimensions half that of the original RAW image, an exception is AIP4Win where the missing pixels are filled in using interpolation algorithms. (Mark Blackford)

The specific order of colors may vary between camera manufacturers so it is important to determine which color channel in your DSLR corresponds to red, which to blue, and which to green.

Traditionally in DSLR photometry only the Green channels are used to estimate Johnson V band magnitudes. However, this ignores information contained in the Red and Blue channels which, in many situations, can be used to accurately measure stellar magnitudes in Johnson B and Cousins R bands, respectively. We will return to this topic in greater detail in later chapters.

It is important to note that RAW DSLR images are greyscale, not color images. The top panel of Figure 2.4 is an enlarged section of a RAW image of an out of focus star showing individual pixels and the checkerboard pattern of intensity resulting from the Bayer filter array. Below are images of the individual color channels extracted from the RAW image.



Red Channel Green Channel 1 Green Channel 2 Blue Channel

**Figure 2.4. Top:** magnified view of an out of focus star in a RAW DSLR image showing monochrome checkerboard pattern due to the Bayer filter array. **Bottom:** Individual color channels extracted from the RAW image. (Mark Blackford)

The voltage increase of a single photoelectric event is quite small; hence the accumulated voltage on the capacitor is similarly tiny. In order for this signal to be read, it is first passed through an amplifier before being processed by an analog-to-digital converter (ADC). The gain setting of the amplifier determines the "ISO" (a measurement of the sensitivity of the detector) that matches the signal to the fixed range of the converter. The ADU (analog to digital units) output of the ADC is proportional to the number of electrons collected by the photodiode of each pixel. When saved as a RAW data file, these ADU values are the fundamental information used in DSLR photometry. This discussion is continued in greater detail in Section 2.4.

A schematic representation of CMOS detector electronics is shown in Figure 2.5. The sensor itself is made from a silicon chip onto which the CMOS circuitry is etched. The photon-sensitive element in each pixel is a photodiode (or a MOS photogate). These devices operate by the photoelectric effect, in which a photon impacting the detector generates an electron-hole pair. Due to the construction of the photodiode, the electron is quickly moved out of the bulk material and pushed onto a nearby capacitor. At the beginning of an exposure, this capacitor is reset and its voltage read. During the exposure, each impacting photon results in a slight decrease in charge on the capacitor. At the end of the exposure, the voltage on the capacitor is read a second time.

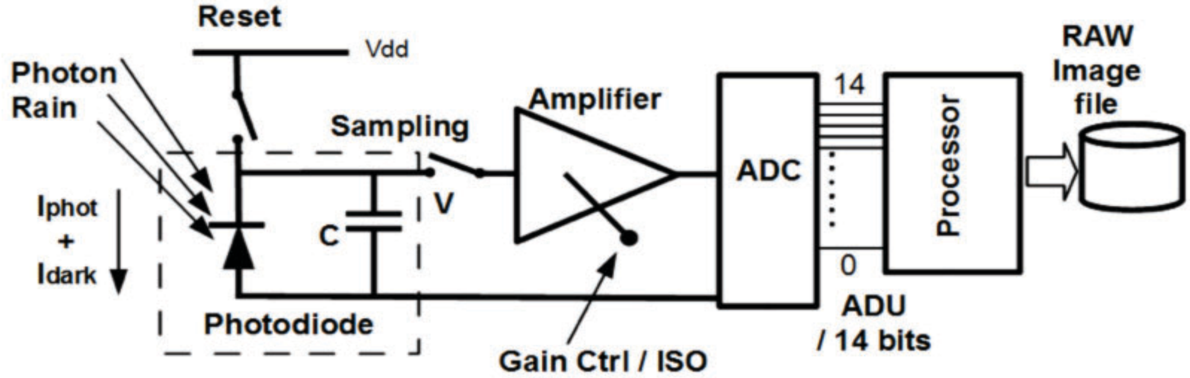


**Figure 2.5.** Schematic representation of the components of a CMOS detector. (Roger Pieri)

The most common DSLR camera sensor size is APS-C, which is 14.9 x 22.4 mm, but other formats also exist in cameras that may be used for photometry: the 4/3 system (13 x 17.3), the 1" format of some hybrids (8.8 x 13.2), the 1/1.7" used in "expert" DSC (5.7 x 7.6). The "full frame" format (24 x 36 mm) also exists, but it is not so common, relatively expensive and subject to greater vignetting problems.

### *2.1.3 DSLR camera features to avoid for photometry*

Modern DSLR cameras have a plethora of additional functions, most of which are not useful and can even be harmful for photometric measurements. Foremost, JPEG images should never be used in astronomical photometry. To generate a JPEG image, the RAW ADU values from the detector are processed to convert the image into a non-linear sRGB color space (absolutely non-photometric) and then compresses it into a JPEG file. The non-linearity and compression lead to a significant degradation of data precision (from ~14000 levels of brightness to a maximum of 256 levels) that prohibits precise flux measurement.

## 2.4 Camera settings

### *2.4.1 Manual mode*

There are many camera settings on your DSLR, most of which you will not be using. There are also many different cameras, so you will need to reference your manual to find the following settings, many of them through a series of menus. Your goal is to simplify the camera, turn off all the bells and whistles, and collect just the raw image. Your first step is to turn the mode dial to "M" to acquire manual control over the exposure time and f-stop, described below.

### *2.4.2 f-stop*

The next step is to choose an appropriate f-stop. The f-stop is a number equal to the focal length of the lens divided by the diameter of the aperture, the opening that lets light into the camera. The lower the f-stop, the more light gets in, but sometimes there are lens defects that can be minimized by avoiding the lowest f-stop. As a general rule you want to collect more light, so you want your f-stop to be a small number, such as f/2 or f/4. If you go above f/7, you have probably stopped it down too much.

### *2.4.3 ISO*

The ISO setting on your camera determines the amplification of the sensor output. Higher ISO is helpful when imaging faint stars, but with a bright star, high ISO increases the risk of saturation, which occurs when a sensor pixel receives more photons than it can accurately count. On the other hand, a low ISO number avoids the saturation problem and allows for a wider range of brightness to be measured. An ISO of 100 to 200 is typically recommended for bright stars. Higher ISO may be necessary for fainter stars, depending on the aperture, exposure time, and number of pixels illuminated by the starlight.

As mentioned above, the ADU output of the ADC is proportional to the number of electrons collected by the photodiode of each pixel. The calibration factor e/ADU is inversely proportional to the ISO number. For most common APS-C DSLR cameras having a 14-bit ADC, the ideal calibration factor of one electron per ADU is reached between ISO 100 and 300, depending on the pixel size. Below that ISO range, the finest data increment (quantization) is 1 bit on the ADC for several detected electrons, thus sensitivity is lost. This quantization regime allows higher possible photometric accuracy and dynamic range under a high flux regime (where the capacitor can be filled by electrons), but the detectability is limited to a couple of electrons. In modern cameras, the output of the converter is typically a 14-bit value, which may include some coding shift (e.g., 1024 or 2048 for Canon cameras). Thus, out of the 16384 possible values represented by a 14-bit number, only approximately 14000 are usable. At ISO 400 and above, the ADC output will record every electron collected by the photodiode. Thus, the total number of electrons readable is altered (proportionally to the ISO number) by the way the possible dynamic range and SNR are altered. Figure 2.9 shows electron linearity and saturation for the Canon 450D Green channel at various ISO settings.

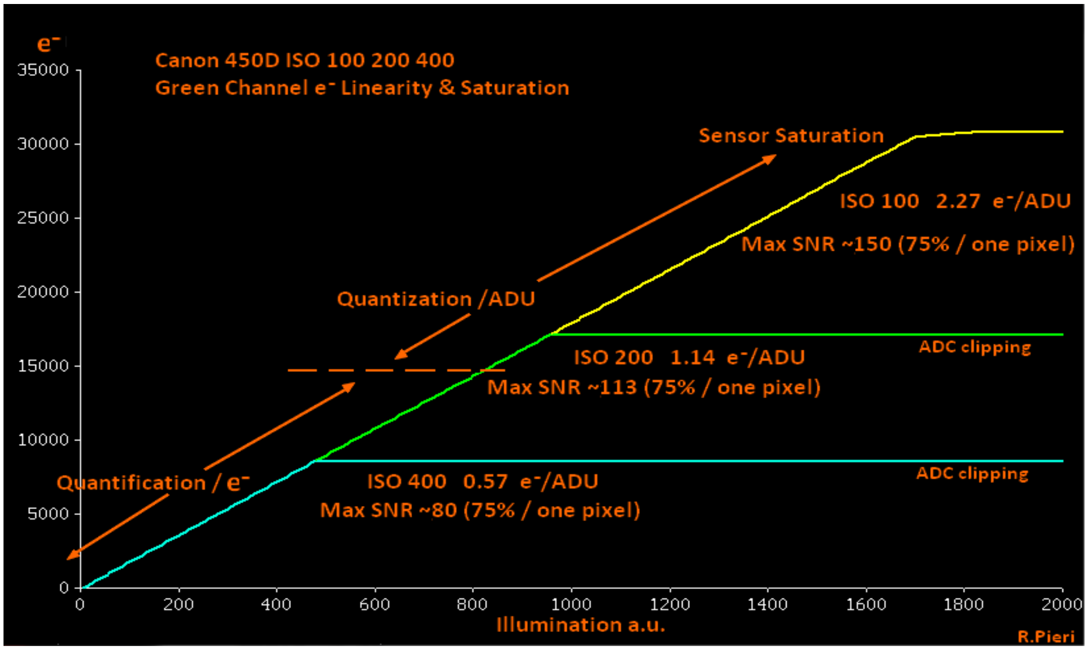


**Figure 2.9**. Electron linearity and saturation for Canon 450D Green channel at several ISO settings. (Roger Pieri)

To this point we have assumed that only stellar photons are measured by the camera, but this is in fact an oversimplification. The RAW output measured as ADU is proportional to the photon count of the star, plus sky background, plus several sources of noise. The noise comes from intrinsic fluctuations of the source, scintillation of the atmosphere, and the camera's own electronic circuitry. In particular, some of the ADU measured are in fact dark current caused by thermally generated electrons in the photodiode. Most of the time, the contribution of dark current can be mitigated by taking a series of dark frames (images where no light is permitted to enter the system) that will be subtracted from the RAW output. Random amplification noise and shot noise from the mean dark current also contribute to the measured signal. These terms are discussed in Chapter 4.

### *2.4.4 Exposure time*

Now you will set the exposure time so that you can take photos at least several seconds long. The amount of time you choose will depend on several factors, such as the brightness of the star, the f-stop, the ISO setting, and whether you wish to avoid star trailing. If the star is faint, you need to expose long enough to measure the brightness accurately. If the star is bright, a long exposure risks saturation. Since a lower f-stop allows in more light, a lower f-stop also allows a shorter exposure. As the ISO setting is lowered, the required exposure time increases. If your camera is mounted on a tripod, your exposure times are limited to about 5-20 seconds (Table 2.3) to avoid having long star trails. If your camera is on a driven mount, you can go up to about 60 seconds before worrying about the background brightness of the sky or the accuracy of the drive. For long exposures, you may need to set the exposure time to "BULB" and use a cable release to operate the shutter. You might choose to take multiple images of identical exposure time and combine them in a software process called stacking. The combined exposure of stacked images should total at least 60 seconds to properly average the variability of the signal due to atmospheric scintillation, commonly observed as twinkling. This integration time is a function of the level of photometric accuracy desired for the observation, the sky "seeing," and the aperture of the instrument. The scintillation is strong with small aperture and gets weaker when the aperture increases. It is another effect of "seeing", the turbulence of the atmosphere.

Tables 2.3 and 2.4 on the next page list estimates of the faintest magnitude reachable under an excellent sky using different optics at maximum aperture. These are calculated with the assumptions that the camera is pointed at the zenith, 400 ISO setting, without and with RA drive. The corresponding exposure time and saturation level are provided for a photometric aperture of 25 pixels at ISO 400 and 100. A much larger dynamic range can be reached using a larger defocus.

It should be noted that, although stars may be recorded in an image at the indicated limiting magnitude, their signal to noise ratio (SNR) would be extremely low. Photometry of such stars is subject to large errors and should only be attempted if longer exposures or larger aperture instruments are not available. Stacking several images will improve SNR at the expense of time resolution.

### *2.4.5 File format*

DSLR cameras offer a variety of file formats. The one required for photometry is RAW, which records directly what the sensor has detected and includes no processing or compression by the camera. The file extension used by Canon for RAW files is .CR2, Nikon uses .NEF. Consult the manual if your camera is from another manufacturer. RAW requires an enormous amount of memory storage, but all of this information is necessary for accurate photometry.

While JPG is a more common format for photographers, it does not preserve the information the universe has laboriously delivered to your camera sensor. It is recommended to avoid the combined RAW+JPG mode that exists in many DSLR cameras. The JPG output requires a lot of work for the processor (noise reduction, various camera internal corrections, de-Bayer, sRGB conversion, etc.). It uses a lot of battery power and generates heat that increases dark noise.

There are a number of other settings on your camera that are undesirable in photometry. Any function that involves the camera processing the image, such as noise reduction, must be avoided. You will also want to turn down the LCD brightness (even switch it off) to maintain your night vision and your battery life. The authors of this guide cannot know all the settings that may be available on your camera, but when in doubt, choose the one that sounds like it will not do anything fancy.

# Chapter 4. Image Acquisition

## 4.1 Acquisition overview

DSLR photometry is, in principle, a very simple process: take images of the sky, calibrate them, extract photometric data, reduce the data to magnitudes, and submit your measurements for long-term archiving. The image acquisition step is fundamentally the most important of these processes for if the input data is of poor quality, so too will be the final product.

In this chapter we dive into the details of the preparatory work you should do before snapping your first data set, how to take calibration frames, how to find your star field in a tiny viewfinder, how to acquire images and assess their quality, and finally some tricks of the trade from experienced DSLR photometrists.

## 4.2 Preparatory work

### *4.2.1 Notebooks*

Perhaps one of the most important aspects of doing science is keeping good records of what you have done. This may sound like an overly simplified concept, but a logbook of your observing setup and sessions will not only help you identify problems with your data or observing procedures, but also let other experimenters duplicate your experiment should the need arise.

At a minimum, your records should indicate the date and time of your images, the targets on which science data are being taken, the weather conditions, and anything that goes wrong during your observing session. It is also a good idea to periodically note the temperature, humidity, and sky conditions as these can alter the quality of your images. Don't forget to note anything unusual about the session or your equipment. Is your neighbor's garage light on tonight when it wasn't on last night? Did you run out of power halfway through an imaging session and change batteries?

### *4.2.2 Observing location, mounts, and camera controls*

As with any observing session, most of the work is done in the dark. You should find a location from which to observe that is free from obstructions both in the sky and on the ground. Whether you are using a tripod or a telescope mount, familiarize yourself with the location and operation of its controls and features which might be useful. For example, how do your tripod's legs extend? How does the leg bracing lock? How do the stops/breaks work on the head? Does the head feature a quick release platform? Try attaching your camera to the mount in the daylight and reaching extreme locations (e.g., zenith) to verify that nothing interferes with pointing, could get tangled, or unintentionally damaged during your session.

Concerning your camera, you should be able to find and use all of the following controls:

- Focus and zoom rings
- Manual focus (e.g., turn off auto focus)
- Image stabilization switch (turn to off)
- Exposure time
- F-stop
- ISO setting
- Image save type (set to RAW)

### *4.2.3 Camera power*

Perhaps one of the most obscure “gotchas” in DSLR photometry happens when the camera either loses power or the battery gets too low. Some observers in the past reported that their DSLRs background noise increased dramatically as the battery charge decreased or after the battery was changed. This does not appear to be an issue with newer cameras, but is something to keep in mind if you are using equipment more than a few years old. If you plan on doing long observing sessions (i.e., near the length of time that your battery lasts), it would be advisable to use external power or have a second battery on hand if external power is not practical at your observing location.

### *4.2.4 Finder Charts*

Locating a variable star and its comparison stars without a good-quality finder chart is often an exercise in futility, so be sure to bring one with you into the field. It is often particularly helpful to bring finder charts which have different fields of view, especially with fields of view which are larger than that of the camera. See Section 3.5.1.

### *4.2.5 Observing plan*

A good observing session starts with a well-defined plan. We suggest creating a checklist of the actions required to obtain scientific quality images, especially if you are just starting out with DSLR photometry. What fields do you intend to observe? Location of comparison stars relative to the target (finder charts help). What camera settings will be required? How many images are needed? These items should all be recorded in your observing logbook which may be paper or electronic.

## 4.3 Noise sources and systematic bias

One might expect all pixels in an image to have exactly the same ADU value if the camera is illuminated by a completely even light source. However, this is never the case. The detected signal is impacted by several factors including vignetting by the lens or telescope, pixel-to-pixel sensitivity variations in the sensor, dust on various optical surfaces, counting statistics due to random arrival times of photons, and electronic noise generated in the camera.