Kalamazoo Astronomical Society

Looking Up Since 1936

Introduction to Amateur Astronomy

Part 5: *The Art of Astrophotography*

www.kasonline.org

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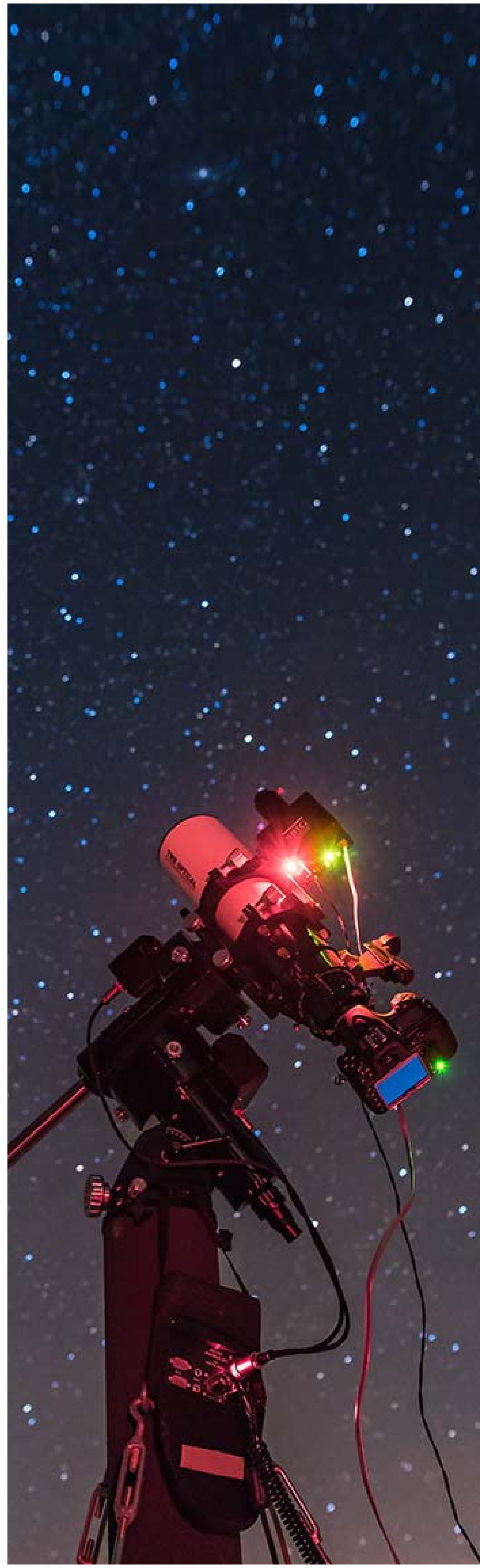


An Introduction to Astrophotography

Astrophotography is a hobby within a hobby. It's where the art of photography meets the hobby of astronomy. As with amateur astronomy, or any other hobby for that matter, you can put as much or little effort into amateur astrophotography as you'd like. Mount a camera on a stationary tripod and capture portraits of the constellations or the majestic Milky Way arcing across the sky. On the other end, you could spend tens of thousands of dollars on the best telescopes, mounts, and digital cameras available today and take stunning shots of deep-sky objects. Don't worry, great work can be done with more modest equipment.

The digital revolution has made astrophotography *much* easier than it was in the old film days. No more waiting to get your results back from the developer to see how good your focus and/or guiding were. Today, you get instant feedback on the quality of your image as soon as the exposure is complete!

The Digital Revolution

Digital cameras are now the camera of choice for almost all photographers. In 2001, sales of digital cameras exceeded sales of film cameras for the first time. At first, digital cameras for the regular consumer were fixed-lens, point-and-shoot models.

Astrophotography with these cameras was limited to holding or mounting the camera up to the eyepiece of a telescope. However, this allowed even the novice to obtain sharp pictures of the Moon and Sun (with a proper filter). Deep-sky photography was very difficult because the exposure times were limited to between 4 and 30 seconds. Even the presence of a "bulb" mode didn't help because the noise overwhelmed the signal.

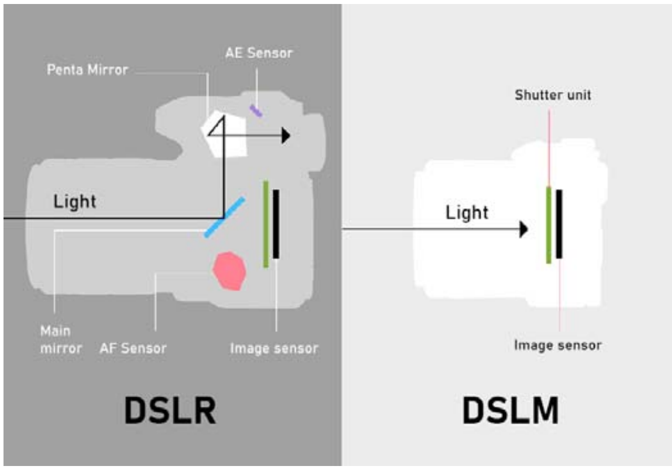
Cameras

Digital Single-Lens Reflex (DSLR) Cameras

In mid-2000, Canon introduced the 3.25-megapixel EOS D30, the first affordable DSLR, with a street price of $2,999. Then, in June 2002, Canon released its EOS D60, with a resolution of 6.3 megapixels and a reduced price of $2,399. Initial tests published for this camera showed much lower noise in long exposures than all previous models. The Canon EOS 10D was released in March 2003 and sold for approximately $1,500. Six months after the release of the 10D, Canon debuted its EOS Digital Rebel (300D), with a cost of just under $1,000.

DSLRs are built just like old-school 35mm film cameras; the only difference is that an image sensor occupies the place where film would have resided. A mirror inside the camera body reflects light coming in through the lens up to a prism (or additional mirrors) and into the viewfinder, so you can frame your shot. When you press the shutter button, the mirror flips up, the shutter opens, and the light hits the image sensor, which captures the final image.

Numerous DSLR camera models are now on the market, and they're getting better and cheaper with each new model. They are capable of all forms of astrophotography, but they are gradually being overtaken by both mirrorless and dedicated astrophotography cameras. Perhaps within a decade or two, they'll become as extinct as the 35mm SLR cameras that came before them.



Digital Single Lens Mirrorless (DSLM) Cameras

The first mirrorless camera with interchangeable lenses was introduced by Epson in 2004. Known as the RD-1, it featured a 6.1-megapixel APS-C sensor, a 200 to 1,600 ISO range, a 1:1 optical viewfinder, a 2.5-inch fixed LCD, and Leica M-mount lenses. It sold for $3,000! DSLM cameras really began to catch on in 2018. Several models released that year include the Canon EOS R, Nikon Z6 and Z7, and the Panasonic S1 and S1R. These were very competitive with DSLR cameras.

A DSLM camera lacks the single-lens reflex design and therefore has no optical viewfinder. Instead, light passes through the lens and right onto the image sensor, which displays a preview on the rear screen — just like point-and-shoot or smartphone cameras. Some models do offer an electronic viewfinder. For standard use, it's hard to say which of the two designs is better. The best traits of DSLR and DSLM cameras have been adopted by each other in recent years. However, when it comes to astrophotography, DSLM cameras have many advantages.

DSLM cameras are lighter since they lack the relative bulk of the single-lens reflex mechanism. The weight difference may not be too significant, but it can be significant if you have a light tripod or your mount or tracking platform has limited weight capacity. DSLM cameras have a shorter flange-to-sensor distance than DSLRs. This reduces the back focus distance required, making them easier to use with reflecting telescopes with a limited back focus distance. It also allows almost any lens to be adapted with an inexpensive mechanical adapter. Images from full-frame DSLR cameras can have edge shadows cast by the upraised mirror or sensor masks. DSLM cameras lack these artifacts, so their frames are clean from edge-to-edge. Lastly, DSLM cameras tend to have good on-screen focusing aids.

Please visit the following manufacturer websites to see the latest DSLR and DSLM camera models:

- **https://www.usa.canon.com/**
- **https://www.nikonusa.com/**
- **https://www.sony.com/**
- **https://us.ricoh-imaging.com/**

Digital Camera Sensor Types

The quality of a camera's images is determined by its sensor — the larger its sensor, the higher its image quality. Bigger sensors have bigger pixels, which means better low-light performance, reduced noise, good dynamic range, and the ability to obtain more information. These are all critical factors to consider in deep-sky astrophotography, since much of what we're trying to capture is fainter than anything cameras encounter during the day.

There are several sensor sizes, but only two are common in astrophotography: full-frame and APS-C. Full-frame sensors, available in both DSLR and DSLM cameras, have sensors typically 36×24mm in size, comparable to 35mm film. The APS-C (or crop-sensor) format is still the most common and is found in both DSLR and DSLM cameras. Their exact sensor size differs by manufacturer. Canon APS-C sensors usually measure 22.3×14.9mm, while brands like Nikon, Pentax, and Sony usually feature APS-C sensors 23.6×15.6mm in size. Not surprisingly, full-frame cameras and their lenses are heavier and more expensive, but they cover greater areas of the sky. A telescope's optical quality will also have to be excellent to take full advantage of the wider field.

Modified Cameras

Standard DSLR and DSLM cameras incorporate a blocking filter that cuts into the deep red end of the visible spectrum, including the all-important wavelength of hydrogen-alpha (656.3nm). This greatly hampers recording the ruby-red glow of emission nebulae.

To date, Canon has offered three astronomical versions of its cameras equipped with IR-cutoff filters that transmit higher levels of H-alpha. These include the 20Da in 2005, the 60Da in 2012, and the EOS Ra DSLM camera in 2019. The EOS Ra is especially attractive since it features 30× live-view focusing, ideal for achieving precise focus of stars.

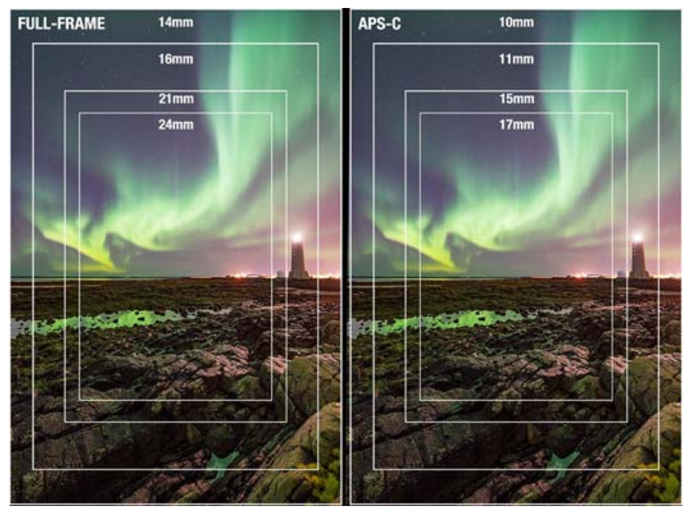
Nikon has also gotten into the act in 2015 with its D810A, a 36.3-megapixel full-frame DSLR costing $3,799.95! Several third-party vendors offer DSLR cameras that have been spectrum-enhanced to make full use of the bandwidth of the CMOS sensor through the use of custom-designed filters. Baader Planetarium sells an Astro Conversion Filter for Canon DSLR cameras with an APS-C sensor if you prefer to modify a camera yourself.

- **Spencer's Camera & Photo**
- **Baader Planetarium**

Necessary Accessories

Lenses

The standard kit lenses work well for many camera-on-tripod subjects, but you'll soon find yourself wanting a wider range of focal lengths. A standard 50mm lens is an excellent first choice. It delivers sharp-quality images even at maximum aperture settings (which are typically between f/2 and f/2.8). The most important thing for the beginner to remember is that the lower the "f" value, the larger the lens opening. If you're trying to capture a wide area of the sky (e.g., star trails), then a wide-angle lens such as a 24 or 28mm would be a good choice. Think of camera lenses like eyepieces; you'll eventually want more than one!



Basic Lenses for Astrophotography:

Fish Eye:	**10mm or 14mm**
Wide-Angle:	**24mm or 28mm**
Standard:	**50mm or 55mm**
Short Telephoto:	**85mm - 135mm**

Tripod

The tripod should be sturdy and light-weight, with the ability to pan the vertical and horizontal axes with little difficulty. The purpose of the tripod is to hold the camera steady during "long" exposure times. The word long is a relative term, meaning anything slower than 1/60th of a second. The camera has a 1/4-inch x 20 screw slot located on the bottom, while the tripod has a screw located on its top.

Just mate the two together, and you'll have a solid foundation for taking steady pictures. Manfrotto and Oben tripods are both pretty good quality.

Remote Switch

A remote switch sends a signal to the camera to open the shutter instead of pressing the camera's shutter release button. It allows you to open the camera's shutter for an extended period of time. This is a must for images that require long exposure times. The alternative to not using a remote switch is to push the shutter release button down yourself. It's not a good idea when the shutter speed dial is set to "B." Any movement of the camera during this period will result in fuzzy or out-of-focus photographs.

Intervalometer (Interval Timer)

An intervalometer is a camera controller that signals the camera to take a series of images after a set interval. It's much more convenient than bringing a laptop into the field with some sort of image acquisition software installed. Long and multiple exposures can also be combined to create star trails or time-lapse movies of the northern lights. The version made by Canon (TC-80NC) is rather pricey ($150). Cheaper Chinese clones are available, but be sure to check reviews. You get what you pay for! Some cameras now have an intervalometer built into their firmware.

Tripod Astrophotography

Novice astronomers who know absolutely nothing about telescopes, equatorial mounts, and polar alignment can take incredible photographs of the night sky with just a camera and a tripod. You probably already own most of the equipment and hardware you'll need, so it's by far the cheapest way to get started in the art of astrophotography. It may seem limiting, but there are many subjects to capture. These include Moon/planet conjunctions, atmospheric phenomena (e.g., Sun Dogs, Moon Halos, Green Flash, or Sun Pillars), the aurora, the Milky Way, constellations, star trails, bright comets, scenic eclipse shots, zodiacal light, and satellite flybys. Just to name a few!

Barn Door Tracker

If you don't own an equatorial mount with a clock drive but would like to take longer exposures of con-

Tripod Astrophotography Exposure Guidelines				
SUBJECT	**LENS**	**ISO**	**F-STOP**	**EXPOSURE**
Auroras	**14mm - 50mm**	**200 to 400**	**f/2 to f/2.8**	**5 to 40 sec.**
Constellations	**28mm - 50mm**	**400 to 3200**	**f/2 to f/2.8**	**10 to 30 sec.**
Meteors	**28mm - 50mm**	**400**	**f/2 to f/2.8**	**5 to 20 min.**
Twilight scenes	**20mm - 135mm**	**100 to 200**	**f/2 to f/2.8**	**2 to 15 sec.**
Satellites	**50mm**	**100 to 400**	**f/2 to f/2.8**	**5 to 30 sec.**
Star trails (short)	**14mm - 50mm**	**100 to 200**	**f/2.8 to f/4**	**5 to 60 min.**
Star trails (long)	**14mm - 28mm**	**100**	**f/5.6 to f/8**	**1 to 8 hours**

stellations or even large, bright comets, then consider building a barn door tracker. It's adequate for lenses in the 24 mm to 50 mm range and exposures up to 15 minutes long. The simplest models are hand-operated, but versions with a motor can be made as well. Images of deep-sky objects with telephoto lenses are not out of the question, especially for a series of short exposures stacked together. For more information, visit the following web pages:

- **Astronomy Boy: Barn Door Tracker**
- **Barn Door Mount**
- **Building a Motorized Barn Door Tracker**
- **Constructing a Barn-Door Tracker**
- **Double-Arm Barn Door Tracker**

Wide-Field Astrophotography

Wide-field astrophotography is an area where the beginner can bypass the complexities of prime-focus telescopic astrophotography yet still excel and achieve good results quickly. Exquisite prime-focus close-ups of galaxies and faint nebulae are attractive showpieces, but wide-field photographs of constellations, extended deep-sky objects, and Milky Way star clouds can make breathtaking panoramic vistas as well.

Equipment Needs

All the same items for tripod astrophotography (except a camera tripod), plus...

Piggyback Mount

If you want to mount a wide-angle or telephoto lens onto a telescope that has an equatorial mount and clock drive, then you'll need a piggyback mount. Simple versions designed for Schmidt-Cassegrains made by Meade, Celestron, and Orion simply adapt the camera to a telescope. The general price is in the $50 range.

Dovetail Plates & Mounting Rings

Some wide-field refractors are light enough to use a piggyback mount to ride on top of the main telescope. However, most refractors will need to be supported with a dovetail plate and mounting rings. ADM Accessories and Losmandy are the main sources for these items. Check their websites for prices of the dovetail plates and appropriately sized mounting rings you'll need for your telescope:

- **https://www.admaccessories.com/**
- **http://www.losmandy.com/**

Counterweights

Adding small telescopes or cameras with heavy telephoto lenses may throw your fork-mounted Schmidt-Cassegrain off balance. To take the strain off of your telescope's motors, you'll need to invest in a counterweight system. These are also available from ADM Accessories or Losmandy. With a German equatorial mount, you may need to simply re-balance or add an additional counterweight.

T-Rings & T-Adapters

You'll need a T-ring and T-adapter to attach your camera to a telescope. T-rings are camera-specific and are available from camera shops and most outfits that sell telescope accessories. They generally sell for less than $20. Newtonians and refractors use the same style of T-adapter, but Schmidt-Cassegrains require one designed specifically for them. These are also available from a wide variety of telescope shops. Most cost under $30.

Portable Tracking Mounts

Piggyback astrophotography can achieve some pretty amazing results, but what if you don't have the time or desire to set up your equatorially-mounted telescope? That's where portable tracking mounts come into play! These ultra-convenient tracking platforms have surged in popularity since Vixen released the Polarie Star Tracker in 2012. Several companies have introduced their own versions in recent years, so there's sure to be one to suit your needs and budget. Some are small enough to stuff in carry-on luggage or be carried to exotic locations – places where telescope mounts could never go!

- **AstroTrac 360**
- **Explore Scientific iEXOS-100-2**
- **iOptron SkyGuider & SkyTracker**
- **Kenko Skymemo S**
- **Losmandy StarLapse**
- **Omegon Mount Mini Track LX3**
- **Sky-Watcher Star Adventurer Mini & 2i**
- **Sky-Watcher Star Adventurer GTi**
- **Vixen Polarie Star Tracker**
- **Vixen Polarie U Star Tracker**

Some German Equatorial Mounts

Most wide-field astrophotography can be done with the inexpensive German mounts that come with mid-range beginner telescopes. You'll just have to get the necessary adapter plates to attach your camera or wide-field telescope. Here are some low-cost but good-quality German equatorial mounts:

- Celestron:
  - **Advanced VX**
  - **CGEM-II** ——→
  - **CGX**
- iOptron:
  - **CEM40** (center-balanced mount)
  - **GEM45**
  - **CEM70** (center-balanced mount)
- Losmandy:
  - **GM811G w/ LW Tripod**
  - **GM-11 w/ Gemini 2**
- Meade:
  - **LX85**
  - **LX850**
- Orion:
  - **EQ-13**
  - **EQ-26**
- Sky-Watcher:
  - **EQM-35**
  - **EQ6-R** ——→

The Moon & The Sun

In many ways, the Moon is the easiest celestial object to photograph. It's practically the only thing in the sky whose brightness is so predictable that you can determine exposures accurately from an exposure table or by a quick calculation; under some circumstances, you can even use an exposure meter. Moreover, its surface shows such a wealth of detail that you can get pleasing, dramatic pictures of it with many different kinds of equipment.

The Sun is also fairly easy to photograph; just make sure you have an appropriate solar filter to fit over the front of your telescope! The Sun is especially pleasing to photograph when a wealth of sunspots are visible on its surface. Shooting the Sun in hydrogen-alpha can also be very rewarding, but it's a bit more challenging (not to mention expensive).

Afocal Method

The aiming and aligning of a camera lens into the telescope eyepiece is called afocal photography and can be used with any camera that has a lens. The Moon is excellent for learning how to take afocal photographs. Start by using a long focal length eyepiece with a long eye relief and focus on the Moon. Next, aim the camera lens into the telescope eyepiece. Center the camera lens over the eyepiece,

being careful not to touch the camera lens with the eyepiece. Use the camera's monitor or viewfinder to adjust both the position of the camera and the telescope's focus. Press the shutter button while holding the camera steady. Take images with various camera settings, such as exposure time, f-stops, and ISO values. This is known as bracketing.

Afocal imaging has made a comeback thanks to digital cameras being incorporated into smartphones. It's challenging to take good pictures through a telescope while holding a phone's camera lens up to an eyepiece by hand. That's why many companies, such as Celestron and Orion, make smartphone adapters that attach to an eyepiece or telescope. These adapters hold the camera lens exactly parallel and at the proper distance from the eyepiece lens, which is necessary to take a sharp image.

Prime Focus
The "prime focus" of a telescope or camera lens is simply the camera mounted at the primary focal plane without any extra positive or negative auxiliary lenses, camera lenses, or eyepieces in between the optics of the main telescope and camera. The camera lens is removed from the camera body, and the telescope functions as the camera lens. This is the preferred method of photographing the entire disk of the Sun and Moon with a DSLR or DSLM camera.

Calculating Exposures for the Moon
Using your camera's built-in light meter or a table to determine exposures may work fine, but the best way to figure out the proper exposure is to calculate it using the following formula:

$$\text{Time (in seconds)} = \frac{f^2}{A \times B}$$

where f is the f-stop to which the lens is set (or focal ratio of your telescope), A is the ISO speed, and B is a constant that indicates the brightness of the object being photographed:

- 10 for a thin crescent Moon
- 20 for a wide crescent
- 40 for a quarter Moon
- 80 for a gibbous Moon
- 200 for a Full Moon

For example, if you are taking a picture of the Full Moon with an f/10 telescope at ISO 100, plug the values into the formula as follows:

$$\frac{(10)^2}{100 \times 200} = \frac{100}{20{,}000} = {}^{1}/_{200}\text{ sec.}$$

The calculated exposures are only approximations; variations in the transparency of the air and other factors can throw them off, so always bracket your exposures (meaning take the same image more than once using different settings for different exposures). Most DSLR and DSLM cameras have an Automatic Exposure Bracketing (AEB) function that takes three photos with only one click of the shutter, each in different exposures.

Eyepiece Projection
Eyepiece projection is similar to the afocal method, but the camera lens is removed, and a slightly higher-power 1.25-inch eyepiece is used for close-up shots of the Moon or sunspots. A Tele-Extender is

used with a Schmidt-Cassegrain, and a Variable Projection Camera Adapter is used with refractors and reflectors. This method has also seen an increase in popularity ever since DSLR cameras became capable of recording high-definition movies.

Solar System Imaging

Photographing the planets with film is long DEAD! This is a good thing, because trying to take pictures of the planets with a regular 35mm SLR camera was always difficult, if not impossible. Most amateurs tried it once or twice and then gave up planetary astrophotography forever.

Planetary imaging has undergone a major revolution in the past two decades. Stunning portraits of Mars, Jupiter, and Saturn have been taken with ordinary and inexpensive webcams. Imaging the planets or even close-up shots of the Sun and Moon with a webcam easily outperformed film and even digital cameras. Several manufacturers now make digital video imagers specifically built for solar system imaging. Some of the images taken with these cameras rival or even exceed those acquired by the earliest planetary close encounters in the 1960s and 1970s!

Detailed images of the Sun, Moon, and planets can be taken by recording a short video, which is composed of several hundred or (usually) thousand images. Image processing software has been created that automatically selects the clearest images from your movie and then aligns and stacks them. Further processing can then be done to bring out as much detail as possible. Excellent results can be had even under moderate seeing conditions, but your telescope must be collimated and allowed to reach thermal equilibrium.

Some popular planetary imaging cameras:

- **Celestron NexImage** (3 models)
- **FLIR** (Point Grey Flea 3)
- **Imaging Source** (a variety of models are available)
- **Orion StarShoot** (3 models)
- **Player One** (11 models available)
- **Teledyne Lumenera** (three models available)
- **ZWO** (Popular Models)
  - ASI290MC
  - ASI462MC
  - ASI174MM
  - ASI385MC

Image Acquisition Program:

- **FireCapture** by Torsten Edelmann

Image Processing Programs:

- **AutoStakkert** by Emil Kraaikamp
- **RegiStax 6 / waveSharp 1.0** by Cor Berrevoets

Electric Focuser

Planetary imagers will want to purchase an electric focuser for their refractor or an electric Crayford-

style focuser for a Schmidt-Cassegrain. Image shift caused by moving the primary mirror of SCT's can make reaching a sharp focus very difficult without the use of some style of zero image shift focuser.

Baader IR-Pass Filter

The Baader IR-Pass filter blocks wavelengths below 670nm. At these longer wavelengths, planetary images are less disturbed by wavefront distortions in the atmosphere (seeing). Dark features on Mars, Jupiter, the Moon, and the Sun are thereby rendered much sharper.

Prime-Focus Deep-Sky Astrophotography

Prime-focus deep-sky photography is challenging because a telescope's long focal length magnifies the image so much compared to a normal camera lens. It also magnifies any problems with polar alignment or tracking that the mount may have. Focus is also critical for prime-focus photography because, unlike many camera lenses that stop at the infinity focus, telescopes will focus through the infinity point. It is strongly recommended to start prime-focus deep-sky imaging with a short focal length refractor or Newtonian. Excellent results can be accomplished with modest German mounts.

Shooting in prime-focus with a telescope allows the astrophotographer to "zoom in" on deep-sky objects and record much greater detail than if shot with a shorter lens. If you already own a DSLR or DSLM camera, then start with those. Eventually, you'll want to upgrade to a thermoelectrically-cooled CCD or CMOS camera. These used to be fairly expensive (some still are), but new models from ZWO and QHY have flooded the market in recent years, making them accessible to almost everyone. Cooled cameras have considerably lower noise and are much more sensitive when chilled to -20° C. A very popular model to start with is the ZWO ASI294MC Pro. They sell new for $999. (The KAS has one available for loan to members.) Once you master that, then you could move up to monochrome cameras and take images through luminance, red, green, and blue (LRGB) filters, or even narrowband filters! That's when things get really challenging! (Comparisons between ZWO and QHY cameras can be seen in two tables starting on page 20.)

German Mounts for Prime Focus Photography

Many astrophotographers start with a fork-mounted Schmidt-Cassegrain telescope on an equatorial wedge. However, if you become obsessed with astrophotography, you'll eventually want a high-quality German equatorial mount. These have many advantages over fork-mounted telescopes.

German mounts are easier to polar align thanks to polar alignment scopes or the new QHY PoleMaster Polar Alignment Camera. Another advantage is that large CCD or CMOS cameras may not be able to fit between the rear end and base of a fork-mounted telescope. This could limit the area of the sky you could image. Also, different telescopes can be placed on German mounts, so this will increase your imaging flexibility.

One disadvantage of German mounts over fork mounts is the "meridian flip." Most German mounts must be flipped from one side to the other before they cross the meridian, the imaginary line that runs through the zenith from north to south, dividing the eastern and western sky. Fortunately, some image acquisition programs automate this process for you.

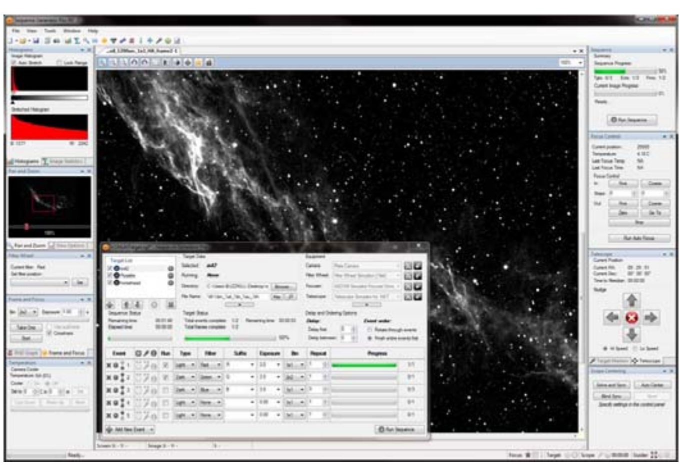
Some German mounts listed earlier will be fine performers for many years, but you'll eventually yearn for something better. Top-grade mounts are built by companies like 10-Micron, ASA, Astro-Physics, Avalon, Losmandy, Takahashi, and Software Bisque. Not only are they incredibly sturdy, but many of them can be equipped with "absolute encoders." These provide error-free tracking, so autoguiding for exposures up to at least 10 minutes becomes unnecessary, even at longer focal lengths. The only downside to absolute encoders is that they are *very* expensive.

Camera Control & Image Acquisition Programs

Serious astrophotographers spend an entire night (or several successive nights) imaging one subject. This can require hours of individual exposure. These images can be gathered manually, but it's very tedious and inefficient.

The software listed below automates this process, leaving you free to stare at the stars. With the exception of BackyardEOS, BackyardNIKON, and Sequence Generator Pro, all the programs listed below also perform image calibration and processing:

- **BackyardEOS / BackyardNIKON**
- **Images Plus**
- **MaxIm DL**
- **Nighttime Imaging 'N' Astronomy** (freeware)
- **Sequence Generator Pro** (pictured below)
- **Siril** (freeware)



Other Equipment Needs

Off-Axis Guider

Even the best telescope mounting and drive system will have small inaccuracies that will show up at the high magnifications used in prime-focus high-resolution photography. Other factors, such as atmospheric refraction, will also necessitate correcting the tracking of an object during the exposure.

Guiding is the process of making these corrections by centering a guidestar on a set of crosshairs at high magnification and using the right ascension and declination motor controls to keep the star centered when it starts to wander off, for whatever reason.

Most astrophotographers use autoguiders to automatically guide a telescope during an exposure. Whether you guide automatically or manually, you'll still need a separate guidescope or an off-axis guider. When using an off-axis guider, the object is acquired, framed, and focused. The off-axis guider is then rotated until a suitable guide star is found, and the guiding eyepiece is focused on the guide star.

Meade, Celestron, and Orion manufacture off-axis guiders for their telescopes. Higher-end models exist but are pretty pricey.

Autoguider

An autoguider is a small CCD or CMOS camera that works with a computer to monitor the position of a guidestar and make corrections to keep it exactly centered. The guidestar is monitored either with a separate guidescope or through the main telescope with an off-axis guider. The computer then automatically controls the right ascension and declination motors of the mount through the drive corrector system of the telescope to correct for drift during an exposure caused by factors such as periodic error and atmospheric refraction.

Orion's StarShoot Autoguider is a very popular model and costs $299.99. Stand-alone models that don't require a separate computer are also available from several companies. PHD2 is a very popular (and free) open-source autoguider control program. It works with most autoguiders sold today.

Illuminated Reticle Eyepiece

Guiding eyepieces come in different varieties, but the most common have a double set of cross hairs etched onto a reticle at the focal plane of the eyepiece, illuminated by a variable-power red LED. Even if you use an autoguider, you'll still need a reticle eyepiece for accurate GO-TO and polar alignment. Both Celestron and Orion make pretty good reticle eyepieces.

Focal Reducer / Field Flattener

The combination focal reducer and field corrector lens works with all Schmidt-Cassegrain telescopes. Versions are available for refracting telescopes as well. This clever accessory makes it possible to have a dual-focal-ratio instrument without sacrificing image quality. The Reducer/Corrector is f/6.3 for f/10 Schmidt-Cassegrain telescopes. It offers wide fields of view for both visual and photographic use. Standard focal reducers will not work on the new "coma-free" style SCTs made by Meade and Celestron. A custom reducer will be needed.

Focusing

There are many tips and tricks to achieve sharp focus, but an easy and widely used method is with a Bahtinov mask. The mask consists of three separate grids, positioned in such a way that the grids produce three angled diffraction spikes at the focal plane of the instrument for each bright image element (star). As the instrument's focus is changed, the central spike appears to move from one side of the star to the other. In reality, all three spikes move, but the central spike moves in the opposite direction to the two spikes, forming the 'X'. Optimum focus is achieved when the middle spike is centered on the star and symmetrically positioned between the other two spikes. Small deviations from optimal focus are easily visible.

You can make one of these masks yourself by using the Bahtinov Focusing Mask Generator program at Astrojargon:

https://astrojargon.net/

They are also available commercially from Astrozap and Kendrick Astro Instruments.

Imaging Filters

Most of us live in moderate to severely light-polluted skies. You may think this would limit your targets to the Moon, planets, and brighter deep-sky objects. New multi-band and dual-band pass filters have been introduced in recent years that greatly expand the number of targets accessible from even heavily light-polluted cities. All of these filters are engineered specifically for use with CMOS one-shot color cameras. This includes DSLR and DSLM cameras (either off-the-shelf or modified). The most popular brand of imaging filters comes from Optolong. In addition to clip filters for DSLR and DSLM cameras, they offer a wide variety of mounted and unmounted astrophotography filters.

Optolong's L-Pro and L-Quad Enhance filters are ex-

cellent filters to use for imaging star clusters, dark and reflection nebulae, and galaxies under light-polluted skies from up to Bortle 7. The L-Quad filter is currently only available as a 2-inch filter. Versions available for the L-Pro include standard 1.25-inch and 2-inch sizes, plus clip-in filters for full-frame and APS-C DSLR cameras. Many more filters are available for imaging emission and planetary nebulae in even severely light-polluted skies.

The Optolong L-eNhance filter transmits H-alpha, H-beta, and OIII emission lines and costs about $229 (for the 2-inch filter). The L-eXtreme filter passes H-alpha and OIII only, making it better for nebulae in light-polluted skies. The newer L-eXtreme F2 filter is more suitable for faster systems from f/2 to f/3.3. Their L-Ultimate filter also passes H-Alpha and OIII, but has a 3nm bandwidth. This will provide a darker sky background, more contrast in nebulae, and greater suppression of stars. Please visit **Optolong's website** to see their latest selection of filters.

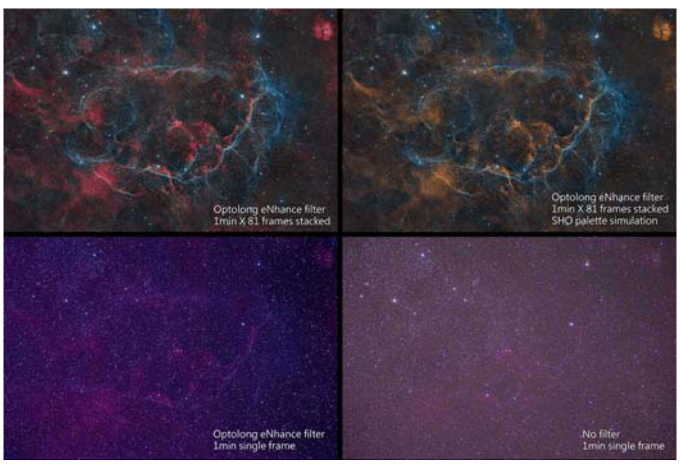


Image Calibration

Taking pictures through the telescope is just the first step toward creating a work of art. The image must be properly calibrated to remove digital noise and optical defects from your exposures.

Digital Noise

Digital cameras produce noise in every photo they take. Amp noise, bias noise, and hot pixels are always present and increase dramatically with time exposures and high ISO speeds. Two of these, amp noise and hot pixels, have the same pattern in each exposure. Bias noise is random and changes with each exposure. All of these can be reduced or removed from your images by using dark frames and bias frames. The principle is very simple: take a picture of the noise itself and subtract it from the image. This process is called dark and bias frame subtraction.

For a given ISO and exposure time, amp glow and hot pixels will be virtually identical in successive frames. Reduce them by using a lower ISO and/or shorter exposure.

Temperature Affects Digital Noise

The temperature of the camera's imaging chip has a dramatic effect on all three types of digital noise. A cooler chip results in less noise. There are various ways to reduce heat in the camera. Allow a cool-down time between exposures, or turn the camera off for a few minutes between shots. Use an AC adapter instead of the camera's internal battery (which heats up during the exposure). CCD and CMOS cameras designed for astronomical work have thermo-electric cooling units built into them.

Make sure to shoot plenty of dark and bias frames (at least a dozen of each; 20 is even better, and some folks use even more).

Making Dark & Bias Frames

When you're finished shooting your exposures for a target (these are called lights), put the cap on your lens or telescope. Shoot your dark frames exactly as you did your light frames, but with the cap on. Be sure to use the same ISO and exposure time.

After the darks have been shot, set your camera's shutter speed to its fastest exposure and shoot a set of bias frames. Be sure to use the same ISO as your darks and lights. The air temperature can drop while shooting light frames during the night. Therefore, some people prefer to shoot some dark and bias frames at the beginning and end of the session since dark and bias frames are temperature-sensitive.

Important Note: The bias signal is present in your dark frames. Many people don't use bias frames since the bias signal is removed during the process of dark frame subtraction. If you use bias frames, the bias must be applied to the darks before the darks are used.

Optical Defects & Flat Frames

All telescopes and camera lenses produce vignetting to a greater or lesser degree. Vignetting (or light fall-off) is the effect caused by more light reaching the center of an image than reaching the edges. Flat frames are used to remove this darkening of edges and also to remove blotches caused by dust on lenses and camera sensors.

Making Flat Frames

There are a number of techniques for making flat frames. You'll have to experiment to see which works best for you. Search the web to explore the many ways of flat-making. Here are a few of them.

Make sure your camera is in the same orientation and focus as when you shot your light frames. If you're using a camera lens, make sure the f/number is the same. If you used any filters during your exposures, make sure the filter is used on your flats as well. Use your camera's lowest ISO setting. Set the shutter speed for a normal, balanced exposure as determined by your exposure meter.

Tie or rubber band a white T-shirt over the front of your telescope and point it in the sky opposite the Sun during dawn or dusk. Make sure there are no clouds in the area, and do not shoot close to the horizon since the sky tends to lighten near that part of the sky. Shoot no less than 20 flats.

Instead of using the sky, many people construct a light box that fits over the end of the telescope and evenly illuminates the field of view. Some also use the flat screen of their laptops or tablets, which displays an empty white window. Tracing boards can

also be used as flat screens. Dedicated flat screens are available from Gerd Neumann, Optec (in Lowell, MI), and Pegasus Astro, but are rather expensive.

Important Note: When you're done shooting your flats, put the lens cap on and shoot a set of bias frames for your flats using identical exposure settings. Flats do not contain thermal noise, but they do contain the bias signal discussed earlier.

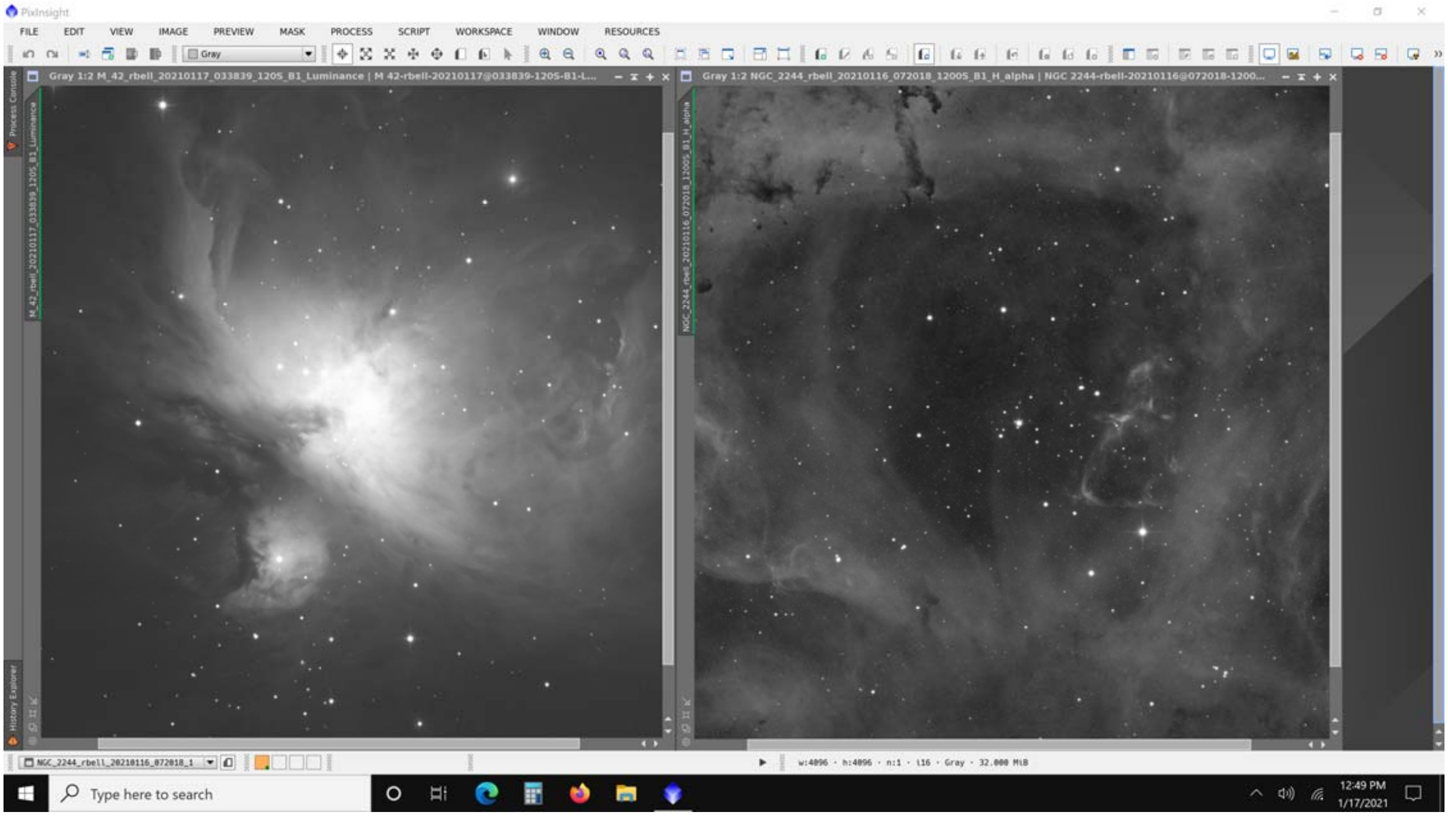
Image Processing Software

Image processing is probably the most intimidating part of digital photography for beginners. With film photography, all processing could be sidestepped completely by using color slide film, where "what you see is what you get." However, with digital astrophotography, taking the exposure is usually just the first step. To arrive at a satisfactory image, as discussed above, you will have to deal with things like noise reduction, contrast and brightness enhancements, and color correction.

Some astronomical software packages perform all of the following steps for you: Mike Unsold's ImagesPlus is an example of this; just tell it where all the files are, and it will produce a final image. Other programs, such as Nebulosity from Stark Labs, require you to perform each step individually.

The one image processing program that stands out among the rest is PixInsight from Pleiades Astrophoto. It was created by astro-imagers for astro-imagers. With PixInsight, astrophotographers "can take their images from raw data to finished fine art photographs using a single program." The current cost (as of March 2024) is €300 (euros), which converts to about $326. New users can evaluate PixInsight at no charge for 45 days. It is available for Windows, macOS, and Linux operating systems.

PixInsight does have a steep learning curve, but there are numerous resources, both online and offline, that can help educate you. The creators of PixInsight have created a 36-part series on YouTube. Adam Block, regarded as one of the best astrophotographers in the world, offers numerous training videos for a yearly subscription fee. *Inside PixInsight* by Warren A. Keller (published by Springer) offers a

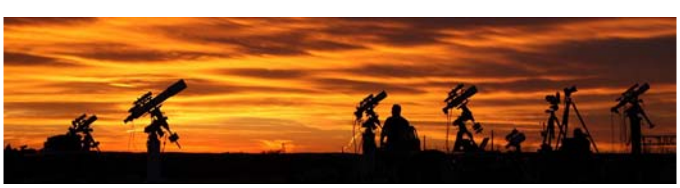


comprehensive look into the software's capabilities. The book offers numerous online resources as well.

Most experienced imagers use more than one program to supplement the way an image will be processed for brightness, contrast, color correction, etc. Many of the image processing software programs available today were created specifically for astrophotographers by astrophotographers.

Here are some popular image calibration and processing programs:

- **Adobe Photoshop/Lightroom**
- **Astronomy Tools** (action sets for Photoshop)
- **Deep Sky Stacker** (FREE)
- **Gimp** (FREE)
- **IRIS** (FREE)
- **PixInsight** (pictured above)
- **StarTools**

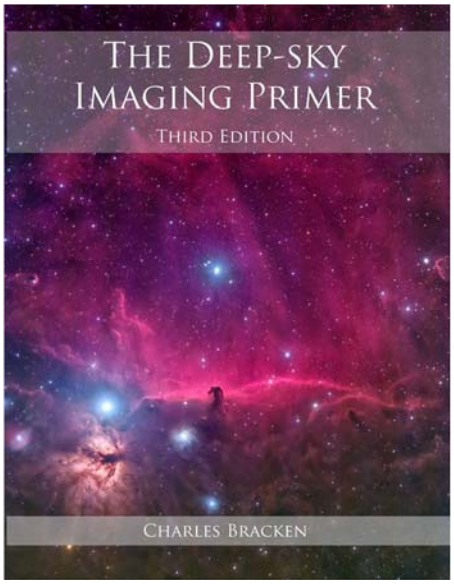


Keep a Record

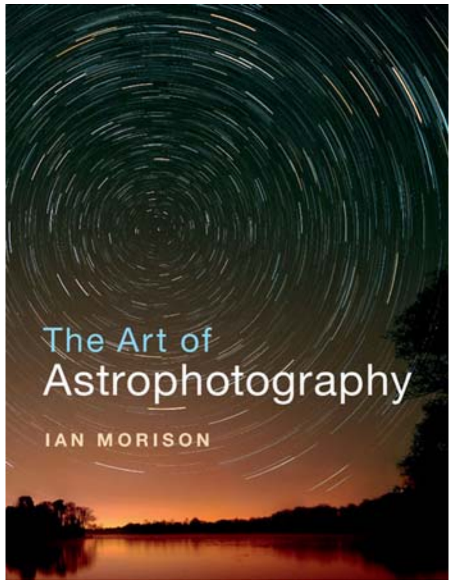
It's vital to keep a written record of your astrophotographs. You'll learn from your mistakes and be able to reproduce similar subjects should the need arise. Your DSLR or DSLM camera will record some of this information for you, and some of the rest can be included in each file name. Many image-acquisition programs also allow you to create custom file names with the most relevant information. In general, your records should include the following details:

- Subject (the object being photographed.)
- Date & Time
- Location
- Sky Conditions (Transparency & Seeing)
- Camera
- Instruments (mount, telescope, and lens used) (Be sure to record the f-stop as well.)
- Length of the Exposure(s)
- Filters (if any)
- Accessories (Focal Reducer/Field Flattener, etc.)
- Processing

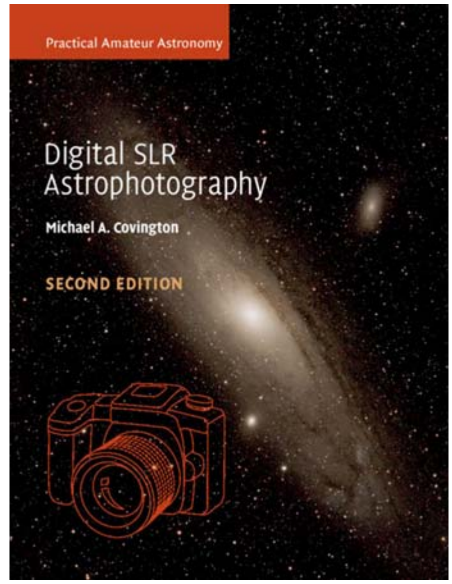
Some Recommended Astrophotography Books



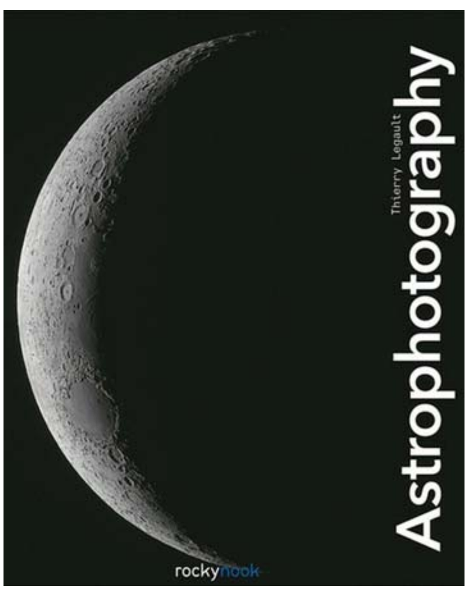
The Deep-Sky Imaging Primer
by Charles Bracken
Deep-Sky Publishing , 2022
List Price: **$49.99**



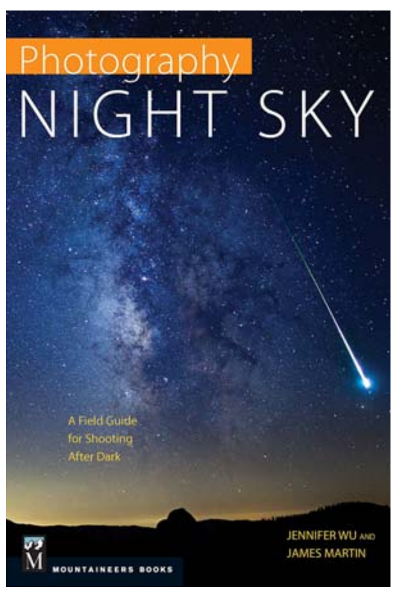
The Art of Astrophotography
by Ian Morison
Cambridge University Press, 2017
List Price: **$47.99**



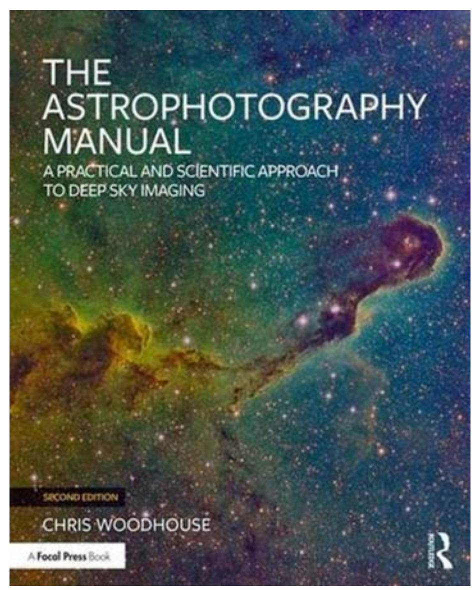
Digital SLR Astrophotography
by Michael A. Covington
Cambridge University Press, 2018
List Price: **$39.95**



Astrophotography (2nd Edition)
by Thierry Legault
Rocky Nook, 2014
List Price: **$55.00**



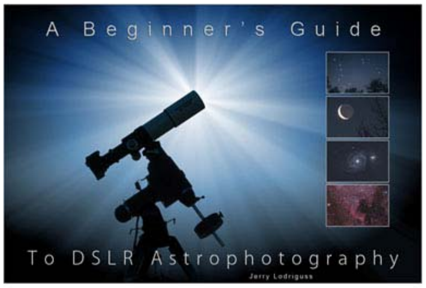
Night Sky Photography
by Jennifer Wu & James Martin
Mountaineers Books, 2014
List Price: **$21.95**

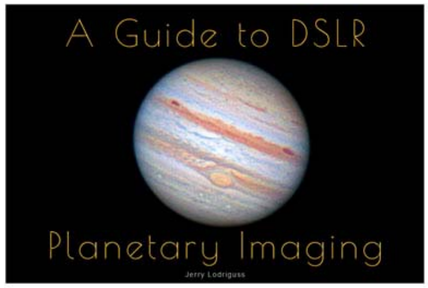


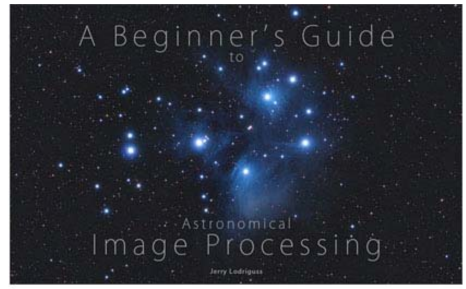
The Astrophotography Manual
by Chris Woodhouse
Rocky Nook, 2014
List Price: **$62.95**

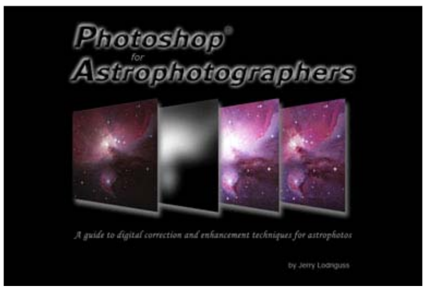
Some Recommended Astrophotography Books (cont.)

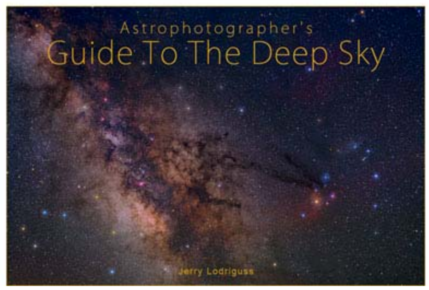
Digital Books in HTML Format by Jerry Lodriguss

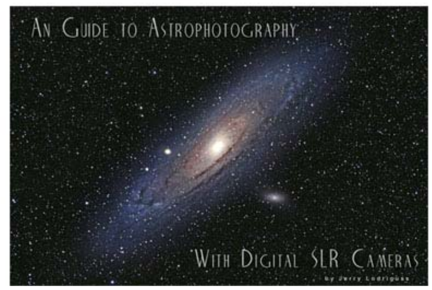






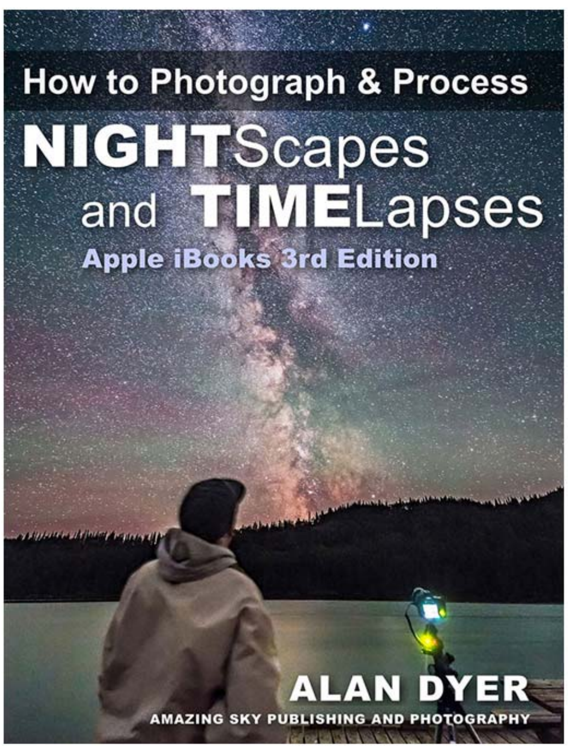


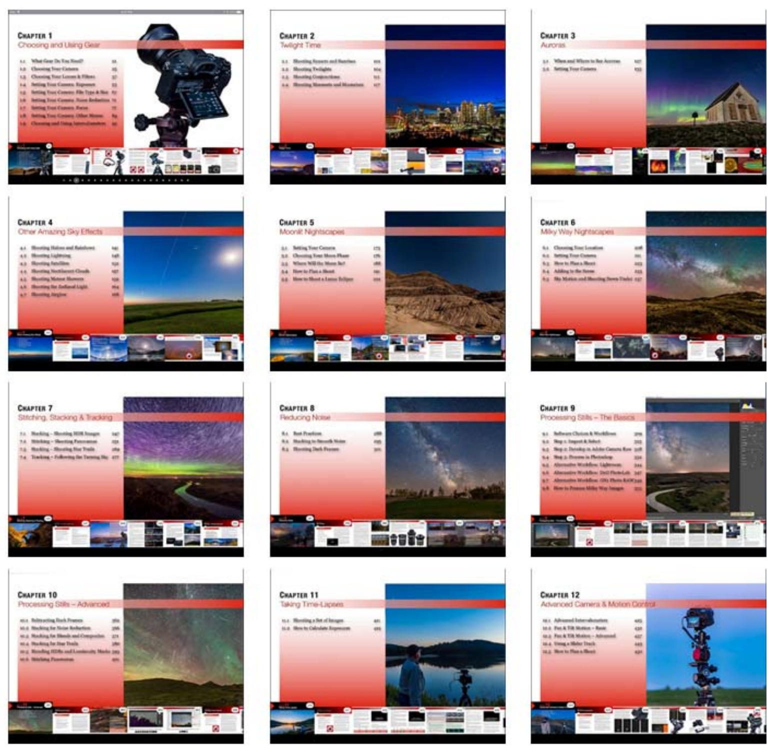




Learn More at: https://www.astropix.com/

Apple Book or PDF eBook by Alan Dyer





Learn More at: https://www.amazingsky.com/

ZWO ASI Cooled CMOS Deep Sky Camera Comparison

	ASI071	ASI183	ASI294	ASI461	ASI533	ASI2400	ASI2600	ASI6200
MC/MM:	Color	Both	Both	Mono	Both	Color	Both	Both
Resolution:	16.2MP	20.2MP	11MP	100MP	9MP	24.6MP	26MP	64MP
Pixel Array:	4944×3284	5496×3672	4144×2822	11656×8750	3008×3008	6072×4056	6248×4176	9576×6388
Sensor Size: (mm)	23.6×15.6	13.2×8.8	19.1×13.0	44.0×33.0	11.3×11.3	36.0×24.0	23.5×15.7	36.0×24.0
Pixel Size:	4.78µm	2.4µm	4.63µm	3.76µm	3.76µm	5.94µm	3.76µm	3.76µm
QE Peak:	50%	84%	90%	91%	80%	80%	91%	91%
Cooling:	-35° C	-45° C	-35° C	-35° C	-35° C	-35° C	-35° C	-35° C

QHYCCD Cooled CMOS Deep Sky Camera Comparison

	183	268	294	367	461	533	600
MC/MM:	Both	Both	Mono	Color	Mono	Both	Both
Resolution:	20MP	26MP	11.7MP	36MP	102MP	9MP	61.17MP
Pixel Array:	5544×3684	6280×4210	4164×2796	7376×4938	11760×8896	3008×3028	9576×6388
Sensor Size: (mm)	13.3×8.87	25.1×16.7	19.28×12.95	36.0×24.0	44.0×33.0	11.29×11.29	36.0×24.0
Pixel Size:	2.4µm	3.76µm	4.63µm	4.88µm	3.76µm	3.76µm	3.76µm
QE Peak:	84%	78%	75%	56%	90%	90%	80%
Cooling:	-45° C	-35° C	-35° C	-35° C	-35° C	-35° C	-35° C

Astrophotography Shared in the Presentation

From the Pleiades to the Hyades by Rogelio Bernal Andreo
https://apod.nasa.gov/apod/ap111117.html

Okie-Tex Milky Way by Richard Bell
https://www.kasonline.org/gallery/astrophotos/bell/index.html#img=mw100510.jpg

Mars in the Milky Way by Richard Bell
https://www.kasonline.org/gallery/astrophotos/bell/index.html#img=mw051701.jpg

Big Bear Above Mt. Parnon by Antonis Farmakopoulos
http://www.astrofarma.gr/en/astrophotos/category/38-astro-events

Orion the Hunter by Toshio Ushiyama
https://bit.ly/3pEQN2X

Conjunction by the Sea by Mike Black
https://apod.nasa.gov/apod/ap140626.html

22° Lunar Halo by Selina & Patrick Hochleitner
http://www.photonhunter.at/LunarHalo.html

Sun Pillar in Cerro Paranal by Miguel Claro
https://www.miguelclaro.com/wp/portfolio/sun-pillar-cerro-paranal/

Rare Solar Halo from Borlänge, Sweden by Magnus Edbäck
https://www.astrobin.com/381670/?nc=user

A Double Green Flash by Gianluca Lombardi
https://www.eso.org/public/images/potw1147a/

ISS Above the Roman Forum by Gianluca Masi
https://bit.ly/3sIxkA3

Bolide Above Cabin in Utah by Matthew Vandeputte
https://www.matjoez.com/2019/07/03/meteor-explosion-caught-on-camera/

Zodiacal Light at La Silla by Zdeněk Bardon
https://www.eso.org/public/images/zod_light_dk154/

Comet McNaught by Gordon Garradd
http://www.jupiterscientific.org/virtualastronomer/solarsystem/comets.html

2019 Total Solar Eclipse Over La Silla Observatory by Romain Lucchesi
https://www.eso.org/public/images/eso1912a/

Astrophotography Shared in the Presentation (cont.)

Morning Aurora from Healy, Alaska by Todd Salat
https://spaceweathergallery.com/indiv_upload.php?upload_id=182119

Petroglyphs & Star Trails by Tyler Sichelski
https://www.lonelyspeck.com/star-trails-and-moonlit-landscapes-tutorial/

The Cocoon Nebula (IC5146) by Bart Delsaert
https://delsaert.com/2015/10/25/results-from-my-astrophotography-week-in-the-south-of-france-2/

Comet Lemmon, 47 Tucanae & the SMC by Frank Sackenheim
http://www.pampaskies.com/gallery3/Comets-Asteroids/Lemmon_NGC104_SMC

Eastern Veil Nebula (NGC 6992) by Matthieu Tesson
http://photo.myesiltas.net/veil-nebula/

Elephant Trunk Nebula (IC 1396) by Steve Mallia
https://www.astrobin.com/5i5oap/?nc=user

Rho Ophiuchi Region by Danny Bee
https://www.astrobin.com/182210/0/

Milky Way Rising by Richard Bell
https://bit.ly/3HKdJUz

Large Magellanic Cloud by Bart Delsaert
https://delsaert.wordpress.com/2015/10/25/trip-to-south-africa/

Seven Sisters by Chris Hendren
http://hendrenimaging.net/other-wide-field-images.html

Cygnus & Lyra Region by Alan Dyer
http://amazingsky.net/2014/07/30/mt-kobau-milky-way/

Comet Lovejoy Q2, M45 & NGC 1499 by Vincent KH Cheng
http://www.astrobin.com/153464/

Rho Ophiuchi Region by Herbert Walter
http://www.skypixels.at/ic4604_herbert_info.html

M81, M82 & Integrated Flux Nebula by Sara Wager
https://www.swagastro.com/m81-and-m82.html

Astrophotography Shared in the Presentation (cont.)

Lagoon & Trifid Nebula by Richard Bell
https://www.kasonline.org/gallery/astrophotos/bell/index.html#img=M8-M20-050516.jpg

Andromeda Galaxy (M31) by Pete Mumbower
https://www.astrobin.com/t2by4q/

Elephant's Trunk Nebula (IC 1396) by Dave & Matt Garten
https://www.kasonline.org/gallery/astrophotos/garten/index.html#img=elephant_trunk.jpg

Double Cluster & Comet Hartley 2 by Richard Bell
https://www.kasonline.org/gallery/astrophotos/bell/index.html#img=DC-Hartley-100710.jpg

The Lagoon Nebula (M8) by Richard Bell
https://www.kasonline.org/gallery/astrophotos/bell/index.html#img=M8

Triangulum Galaxy (M33) by Pete Mumbower
https://www.astrobin.com/peqzca/

Plato Region by Alessandro Bianconi
https://spaceweathergallery.com/indiv_upload.php?upload_id=168675

Jupiter 2021 Season by Michel Leost
https://www.astrobin.com/x8ku9l/0/

Saturn by Steve Bemmerl
https://www.astrobin.com/ixm2te/0/

Solar Prominences by Roger Williams
https://bit.ly/34k4PiY

Hercules Cluster (M13) by Martin Pugh
https://bit.ly/3hI5T3c

Spiral Galaxy NGC 6744 by Don Goldman
https://astrodonimaging.com/gallery/ngc-6744/

Great Nebula in Orion (M42) by Don Goldman
https://astrodonimaging.com/gallery/m42-the-great-orion-nebula/