

Practical Amateur Astronomy

# Digital SLR Astrophotography

Michael A. Covington



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## Practical Amateur Astronomy Digital SLR Astrophotography

In the last few years, digital SLR cameras have taken the astrophotography world by storm. It is now easier to photograph the stars than ever before! They are compact and portable, easy to couple to special lenses and all types of telescopes, and above all, DSLR cameras are easy and enjoyable to use. In this concise guide, experienced astrophotography expert Michael Covington outlines the simple, enduring basics that will enable you to get started, and help you get the most from your equipment. He covers a wide range of equipment, simple and advanced projects, technical considerations, and image processing techniques. Unlike other astrophotography books, this one focuses specifically on DSLR cameras, not astronomical CCDs, non-DSLR digital cameras, or film. This guide is ideal for astrophotographers who wish to develop their skills using DSLR cameras and as a friendly introduction to amateur astronomers or photographers curious about photographing the night sky. Further information, useful links, and updates are available through the book's supporting website, [www.dslrbook.com](http://www.dslrbook.com).

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CAMBRIDGE UNIVERSITY PRESS

Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press

The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

[www.cambridge.org](http://www.cambridge.org)

Information on this title: [www.cambridge.org/9780521700818](http://www.cambridge.org/9780521700818)

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First published in print format 2007

ISBN-13 978-0-511-37853-9 eBook (NetLibrary)

ISBN-13 978-0-521-70081-8 paperback

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Soli Deo gloria



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# Preface

Digital SLR cameras have revolutionized astrophotography and made it easier than ever before. The revolution is still going on, and writing this book has been like shooting at a moving target. New cameras and new software are sure to become available while the book is at the factory being printed. But don't let that dismay you. All it means is that we'll have better equipment next year than we do now.

This book is not a *complete* guide to DSLR astrophotography; the time is not yet ripe for that. Nor does space permit me to repeat all the background information from my other books. For a complete guide to optical configurations and imaging techniques, see *Astrophotography for the Amateur* (1999). To get started with a telescope, see *How to Use a Computerized Telescope* and *Celestial Objects for Modern Telescopes* (both 2002). All these books are published by Cambridge University Press.

What I most want to emphasize is that **DSLR astrophotography can be easy**, easier than any earlier way of photographing the stars. It's easy to lose track of this fact because of the flurry of technical enthusiasm that DSLRs are generating. New techniques and new software tools appear almost daily, and the resulting discussion, in perhaps a dozen online forums, thrills experts and bewilders beginners.

My goal is to save you from bewilderment. You don't have to be a mathematician to get good pictures with a DSLR, just as you didn't have to be a chemist to develop your own film. I'll concentrate on simple, reliable techniques and on helping you understand how DSLR astrophotography works.

The people who contributed pictures are acknowledged in the picture captions. (Pictures not otherwise identified are my own work.) In addition, I want to thank Fred Metzler, of Canon USA, and Bill Pekala, of Nikon USA, for lending me equipment to test; Douglas George, of Diffraction Limited Ltd., for help with software; and all the members of the *Canon DSLR Digital Astro*, *Nikon DSLR Astro*, and *MaxDSLR* forums on YahooGroups (<http://groups.yahoo.com>) for

## Preface

useful discussions and information. As always I thank my wife Melody and my daughters Cathy and Sharon for their patience.

If you're a beginner, welcome to astrophotography! And if you're an experienced astrophotographer, I hope you enjoy the new adventure of using DSLRs as much as I have. Please visit this book's Web site, [www.dslrbook.com](http://www.dslrbook.com), for updates and useful links.

*Athens, Georgia  
March 7, 2007*

# **Part I**

## **Basics**



# Chapter 1

## The DSLR revolution

A few years ago, I said that if somebody would manufacture a digital SLR camera (DSLR) that would sell for under \$1000 and would work as well as film for astrophotography, I'd have to buy one.

That happened in 2004. The Canon Digital Rebel and Nikon D70 took the world by storm, not only for daytime photography but also for astronomy. Within two years, many other low-cost DSLRs appeared on the market, and film astrophotographers switched to DSLRs en masse.

There had been DSLRs since 1995 or so, but Canon's and Nikon's 2004 models were the first that worked well for astronomical photography. Earlier digital cameras produced noisy, speckled images in long exposures of celestial objects. Current DSLRs work so well that, for non-critical work, you almost don't need any digital image processing at all – just use the picture as it comes out of the camera (Figure 1.1). The results aren't perfect, but they're better than we often got with film.

As you move past the beginner stage, you can do just as much computer control and image enhancement with a DSLR as with an astronomical CCD camera. Some hobbyists bring a laptop computer into the field and run their DSLR under continuous computer control. Others, including me, prefer to use the camera without a computer and do all the computer work indoors later.

### 1.1 What is a DSLR?

A DSLR is a digital camera that is built like a film SLR (single-lens reflex) and has the same ability to interchange lenses. You can attach a DSLR to anything that will form an image, whether it's a modern camera lens, an old lens you have adapted, or a telescope, microscope, or other instrument.

Unlike other digital cameras, a DSLR does not normally show you a continuous electronic preview of the image. Instead, the viewfinder of a DSLR uses a mirror and a focusing screen to capture the image optically so that you can view

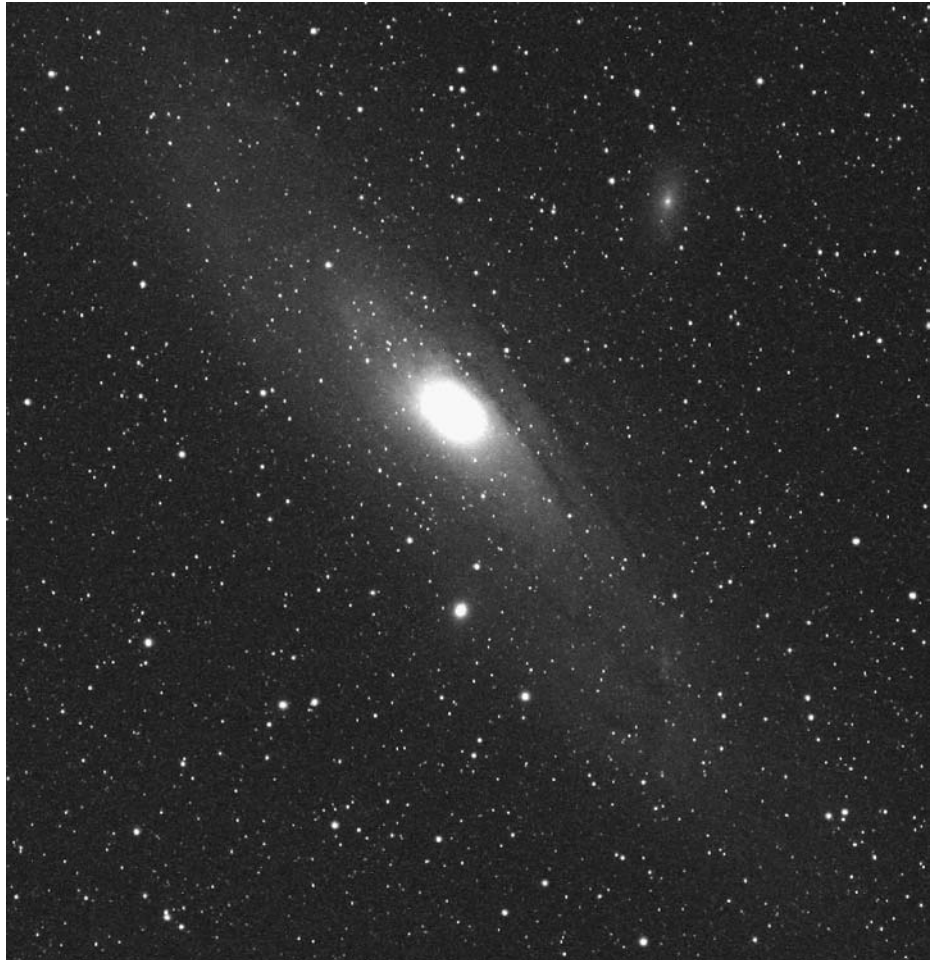


Figure 1.1. The galaxy M31 as the image came from the camera, with no processing except adjustment of brightness and contrast. Canon Digital Rebel (300D); single 6-minute exposure through a 300-mm lens at  $f/5.6$ , captured as JPEG. Some noise specks are present which newer cameras would eliminate with automatic dark-frame subtraction.

and focus through an eyepiece. When you take the picture, the mirror flips up, the image sensor is turned on, and the shutter opens.

The reason a DSLR doesn't show the electronic image continuously is that its sensor is much larger than the one in a compact digital camera. Big sensors are good because they produce much less noise (speckle), especially in long exposures, but operating a big sensor all the time would run down the battery. It would also cause the sensor to warm up, raising its noise level. That's why you normally view through the mirror, focusing screen, and eyepiece.

Some DSLRs *do* offer "live focusing" or "live previewing" for up to 30 seconds at a time. The Canon EOS 20Da, marketed to astronomers in 2005, was the first. Live previewing enables you to focus much more precisely than by looking

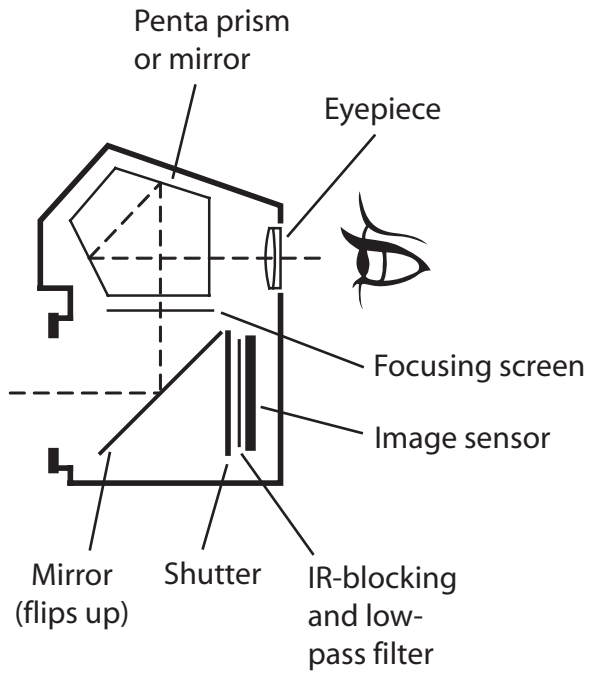


Figure 1.2. A DSLR is a single-lens reflex with a digital image sensor. Mirror and eyepiece allow you to view the image that will fall on the sensor when the mirror flips up and the shutter opens.



Figure 1.3. A more elaborate view of what's inside a DSLR. Note computer circuitry ("DIGIC II") at right. (Canon USA.)

through the eyepiece, especially since you can magnify the view. Note that some cameras, such as the Olympus E330, offer a live preview from a secondary small sensor, not the main sensor; that kind of live preview is much less useful.

It's hard to guess what the role of DSLRs will be in the history of photography. Future photographers may look back on them as an awkward transitional form, like a fish with legs, soon to be replaced by cameras that don't require mirrors. But at present, DSLRs are the best digital cameras you can get, and they are revolutionizing low-budget astrophotography.

## 1.2 Choosing a DSLR

### 1.2.1 Major manufacturers

#### Canon

Many astrophotographers have settled on the Canon Digital Rebel, XT, XTi (EOS 300D, 350D, and 400D) and their successors. These are low-priced, high-performance cameras. One reason Canon leads the market is that Canon is the only DSLR maker that has specifically addressed astrophotography, first with tutorials published in Japan<sup>1</sup> and then, briefly, by marketing a special DSLR for astrophotography (the EOS 20Da).

Also, because Canon SLR bodies are relatively compact, you can use other brands of lenses on them, including Nikon, Olympus OM, Leicaflex, Contax/Yashica, and Pentax-Praktica M42 screw mount. For more about lens adapters, see p. 80. Of course, with an adapter, there is no autofocus, but with Canon DSLRs, you can use the exposure meter and aperture-priority auto exposure (useful for eclipses) with any lens or telescope.

So far, there have been three generations of Canon DSLRs suitable for astrophotography. The EOS 10D and Digital Rebel (300D) used the original Canon DIGIC image processor and CRW raw file format. With the EOS 20D, Canon moved to a new system, DIGIC II, with the CR2 raw file format; this is used in the Digital Rebel XT (350D), XTi (400D), 20D, 20Da, 30D, and their successors. The third generation, DIGIC III, began with the EOS 1D Mark III in 2007. Each of these has its own raw file format, and software that supports one will not necessarily support another.

Canon's nomenclature can confuse you. The EOS Digital Rebel, EOS Kiss, and EOS 300D are the same camera, but the EOS 300 and EOS Rebel are film cameras from an earlier era. The EOS 30D is an excellent recent-model DSLR, but the EOS D30 is an early DSLR from before Canon developed sensors suitable for astronomy. And so on. If you want to buy a secondhand camera, study the nomenclature carefully.

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<sup>1</sup> On the Web at <http://web.canon.jp/Imaging/astro/index-e.html>.

## 1.2 Choosing a DSLR

### Nikon

Nikon also has a loyal following. At present, Nikon DSLRs are a bit awkward to use for astronomy because of a quirk called the “star eater” (p. 17). This is a problem that could disappear at any moment if Nikon made a change in the firmware, but so far, the D40, D50, D70, D70s, D80, and D200 (among others) are all afflicted. Also, it’s harder to build your own electrical accessories for Nikons because several models rely on an infrared remote control rather than a plug-in cable release.

Another Nikon drawback is that if the lens contains no electronics, the DSLR cannot use its exposure meter and cannot autoexpose. You can attach Nikon AI-mount manual-focus lenses to a Nikon DSLR, but the exposure meter is disabled. Of course, for astrophotography this is usually not a concern.

Nonetheless, Nikon cameras are easy to use for daytime photography, they are widely available, and some astrophotographers report that the sensor in the D40, D50, and D80 is more sensitive to stars than the competing Canon sensor – possibly because a Mode 3 image (p. 17) is “rawer” than Canon’s raw images. Nikon CCD sensors are reportedly made by Sony, but I cannot confirm this.

### Others

Using modified Nikon bodies, Fuji makes DSLRs for general and scientific photography. The Fujifilm S3 Pro and S5 Pro have special sensors designed for high dynamic range; each pixel actually has two sensors, one for normal exposure and one to deal with overexposed highlights. Both cameras offer live focusing, and there is a version (the S3 Pro UVIR) that is not filtered to exclude infrared light. These cameras are relatively large and heavy.

Pentax, Sony, Olympus, and other DSLR makers are highly respected but have not achieved a large following among astrophotographers, and I have not tested their products. It is widely rumored that most other manufacturers use Sony CCD sensors similar to Nikon’s, although of course the firmware and internal image processing are different. Before buying any camera, you should search the Web and get astrophotographers’ opinions of it; also make sure its file formats are supported by astrophotography software.

### 1.2.2 Shopping strategy

Because of rapid technological progress, you generally want the *newest* DSLR that works well for astrophotography, not the most ruggedly built one. It’s better to buy a low-end DSLR today and another one in three years with a new, improved sensor, rather than sink all your money into a professional-grade camera that will commit you to using today’s technology for a decade.

Of course, if you can justify the expense for other reasons, go ahead and enjoy your Canon EOS 5D or Nikon D200; these cameras have big, bright viewfinders and are a joy to use. Apart from price, one disadvantage of pro-grade DSLRs

is that they are heavy enough to unbalance a medium-sized amateur telescope. Another is that pro-grade cameras are more complicated to operate, and that can be a problem in the dark. Generally, professional cameras are designed for people who use them all the time and can easily remember a large number of controls. Entry-level cameras with simpler controls are easier to use, even for advanced work, as long as they have the features needed.

You don't have to have the best camera on the market in order to get good pictures. You just have to have a camera that is *good enough*. All astronomical instruments, including big observatory telescopes, have measurable limitations. We work so close to the limits of the laws of physics that perfection is unobtainable.

Also, buying the *very* newest camera has some drawbacks. This week's hot new DSLR may not yet be supported by your software, although updates usually come quickly. It also may not have fully debugged firmware (the software inside the camera); watch the manufacturer's Web site for firmware upgrades.

One last warning. Unreliable camera vendors are common on the Internet, and they often advertise impossibly low prices. Before dealing with a stranger, do some searching and find out whether others have had good experiences with the same merchant. You can find out the reputation of a vendor from *www.epinions.com* and *www.resellerratings.com*. Remember that even the best large-volume dealer has a few unsatisfied customers, and a "perfect" score may mean simply that not many customers have been surveyed.

Highly reliable camera dealers include B&H in New York (*www.bhphotovideo.com*), their neighbor Adorama (*www.adorama.com*), Samy's in Los Angeles (*www.samys.com*), KEH in Atlanta (*www.keh.com*), Wolf/Ritz all over the United States (*www.wolfcamera.com*), and Jessops in the UK (*www.jessops.com*). Their prices are a good indication of what you should expect to pay anywhere. You can also buy DSLRs from major computer dealers.

### 1.3 Choosing software

It's easy to get the impression that you need more software than you actually do. It's partly a matter of taste whether you accumulate a large set of special-purpose tools or just a couple of full-featured software packages. Don't buy anything unless you know what you will use it for.

At minimum, you'll need two software packages, a general-purpose photo editor to perform basic adjustments and make prints, and an astronomy-specific image processing program for stacking, dark frame subtraction, and other specialized operations.

*You don't have to use the same software I do.* Most of this book is software-neutral. For the concrete examples that I'm going to give, I've chosen two full-featured software packages, *MaxDSLr* and Adobe *Photoshop*, because they're well-established products that don't change much from version to version. But you can make do with much less expensive substitutes.

## 1.3 Choosing software

### 1.3.1 Photo editing

For general-purpose photo editing, the software that comes with your camera may be adequate, especially if you pair it up with relatively powerful astronomy software. What you need is the ability to crop and resize pictures, adjust contrast and color balance, and make prints.

The king of the photo editors is of course Adobe *Photoshop*, which is one of the basic tools of computer graphics; many scientific add-ons for it have been developed. But *Photoshop* isn't cheap. An alternative is *Photoshop Elements*, which may even come with your DSLR; this is a cut-down version of *Photoshop* that does not process 16-bit TIFFs but is otherwise satisfactory. Or you can use its leading competitor, Corel's *Paint Shop Pro* ([www.corel.com](http://www.corel.com)). Note that there are often upgrade discounts for people moving to *Photoshop* from *Photoshop Elements* or from competitors' products.

### 1.3.2 Astronomical image processing

For specifically astronomical functions I use *MaxDSLR* (from [www.cyanogen.com](http://www.cyanogen.com)) because it is well-established and reliable, follows standard Windows practices, and is organized to make important concepts clear. Thus, when telling you how to process images, I can concentrate on what you're actually accomplishing rather than the quirks of the software. What's more, *MaxDSLR* doesn't just process images; it can also control the camera, run a webcam autoguider, and capture and process video planet images.

*MaxDSLR* has a big brother (*MaxIm DL*, from the same manufacturer) and a head-on competitor (*ImagesPlus*, from [www.mlunsold.com](http://www.mlunsold.com)), both of which offer even more features but are more complex to use. They work with astronomical CCD cameras as well as DSLRs and webcams.

As an alternative to *MaxDSLR* I also use *Nebulosity* (from [www.stark-labs.com](http://www.stark-labs.com)). This is a quick and simple image processing package for DSLR users, similar in overall design to *MaxDSLR* but much lower priced. (The two make a good pair.) Like *MaxDSLR*, *Nebulosity* not only processes images, but also controls the camera in the field. It runs on the Macintosh as well as the PC.

### 1.3.3 Freeware

Excellent free software also exists. One example is Christian Buil's *Iris*, a full-featured image processing program available from <http://astrosurf.com/buil>. Based on a command-line interface, *Iris* is radically different from other image editing programs, but it is reliable and well-documented, and the price is right.

Another highly respected free program is Cor Berrevoets' *RegiStax*, which has long been the standard tool for stacking and enhancing video planet images. *RegiStax* is gradually adding features useful for processing still pictures of deep-sky objects. You can download it from <http://registax.astronomy.net>.

Also highly respected is *DeepSkyStacker* (<http://deepskystacker.free.fr>), and again the price is right – it’s free. *DeepSkyStacker* can rotate and stack images, subtract dark frames, and interconvert all major file formats, including Canon and Nikon raw. It’s not a complete image processor, but it works well with a general photo editor.

### 1.3.4 Judging software quality

I am an astrophotographer by night but a computer scientist by day, so I’m rather picky about software quality. My main concern is that *more features are not necessarily better*. “Creeping featurism” is the enemy of reliability and ease of use. Choose software on the basis of what it’s like to use it, not the length of the feature list.

Good software should cooperate with the operating system. It should not compromise the system’s security by requiring you to use administrator mode (root mode in UNIX), nor should it confuse you with non-standard menus, icons, and sounds. (One package annoyed me by making the Windows “error” beep every time it finished a *successful* computation.) Defaults matter, too; output files should go into your documents folder, not a program folder that you may not even have permission to write in.

It’s a good thing when software packages imitate each other’s user interfaces; similar things should look alike. A non-standard user interface is justifiable only if it is a work of genius.

## 1.4 Is a DSLR right for you?

All of this assumes that a DSLR is the best astrocamera for your purposes. Maybe it isn’t. Before taking the plunge, consider how DSLRs compare to other kinds of astronomical cameras (Table 1.4, Figure 1.4). Notice that the DSLR provides



Figure 1.4. Left to right: a film SLR, a DSLR, a webcam modified for astronomy, and an astronomical CCD camera.

Table 1.1 *Types of astronomical cameras and their relative advantages, as of 2007*

	Film SLR	Digital SLR	Non-SLR digital camera	Webcam or astronomical video camera	Astronomical CCD camera (smaller format)	Astronomical CCD camera (larger format)
<b>Typical cost</b>	\$200 + film and processing	<b>\$800</b>	\$200	\$150	\$2000	\$8000
<b>Megapixels (image size)</b>	Equiv. to 6–12	<b>6–12</b>	3–8	0.3	0.3–3	4–12
<b>Ease of use (for astro-photography)</b>	++	++	+++	+	+	+
<b>Also usable for daytime photography?</b>	Yes	<b>Yes</b>	Yes	No	No	No
<i>Suitability for:</i>						
<b>Moon (full face, eclipses)</b>	++	++	+++	–	–	++
<b>Moon and planets (fine detail)</b>	+	+	++	++++	+++	+++
<b>Star fields and galaxies (wide-field)</b>	++	+++	–	–	+	++++
<b>Star clusters and galaxies (through telescope)</b>	++	+++	–	–	++++	++++
<b>Emission nebulae (wide-field)</b>	+++ if suitable film is available	++ ( <b>++++ if modified</b> )	–	–	+	++++
<b>Emission nebulae (through telescope)</b>	++ if suitable film is available	++ ( <b>+++ if modified</b> )	–	–	++++	++++

*Key: – Unsatisfactory*  
*+ Usable*  
*++ Satisfactory*  
*+++ Very satisfactory*  
*++++ State of the art*

a great combination of high performance and low price – but it's not ideal for everything.

A few years ago, film SLRs were almost all we had. Their striking advantages were interchangeable lenses, through-the-lens focusing, and the availability of many kinds of film, some of them specially made for scientific use.

Most astrophotographers back then didn't fully appreciate the film SLR's real weakness, which was shutter vibration. Even with the mirror locked up to keep it from moving, the shutter always vibrated the camera enough to blur pictures of the Moon and the planets. For deep-sky work, this was not so much of a problem because the vibration didn't last long enough to spoil an exposure of several minutes.

Digital SLRs have the same vibration problem since the shutter works the same way. For that reason, DSLRs are not ideal for lunar and planetary work. Non-SLR digital cameras, with their tiny, vibration-free leaf shutters, work much better, though they aren't suitable for any kind of deep-sky work because of their tiny, noisy sensors.

For detailed lunar and planetary work, webcams and other video devices work better yet. They are totally vibration-free, and they output video images consisting of thousands of still pictures in succession. Software such as *Reg-iStax* can select the sharpest frames, align and stack them, and bring out detail in the picture. Despite its low cost, this is the gold standard for planetary imaging.

For deep-sky work and professional astronomical research, the gold standard is the thermoelectrically cooled astronomical CCD camera. These cameras are appreciably harder to use; they work only with a computer connected. They are also substantially more expensive, but the image quality is second to none. Because the sensor in such a camera is cooled, it has much less noise than the sensor in a DSLR.

Until recently, astronomical CCDs were 1-megapixel or smaller devices designed for use through the telescope. Now the gap between DSLRs and astronomical CCDs, in both performance and price, is narrowing because both are benefiting from the same sensor technology. If you are considering a high-end DSLR, you should also consider a larger-format astronomical CCD that can accept camera lenses to photograph wide fields.

### 1.5 Is film dead yet?

What about film? Right now, secondhand film SLRs are bargains, cheap enough to make up for the additional cost of film and processing. If you've always wanted to own and use an Olympus OM-1 or Nikon F3, now is the time.

Note however that the supply of film is dwindling. Kodak Technical Pan Film is no longer made; the only remaining black-and-white film that responds well to hydrogen nebulae (at 656 nm) is Ilford HP5 Plus, whose grain and reciprocity characteristics are far from ideal.

## 1.5 Is film dead yet?

Two excellent color slide films remain available that respond well to hydrogen nebulae; they are Kodak Elite Chrome 100 and 200, along with their professional counterparts Ektachrome E100G, E100GX, and E200. These films have rather good reciprocity characteristics. So do many popular color negative films except that they don't respond to light from hydrogen nebulae at 656 nm. Beware, however, of outdated film on store shelves, and even more, of outdated darkroom chemicals.

You will, of course, want to process your film images digitally (Appendix C, p. 207) to get much better pictures than film could yield in the pre-digital era.

# Chapter 2

## Main technical issues

This chapter is an overview of the main technical issues that affect DSLR astrophotography. Many of these topics will be covered again, at greater length, later in the book.

### 2.1 Image files

#### 2.1.1 File size

Compared to earlier digital astrocameras, the images produced by DSLRs are enormous. Traditional amateur CCD cameras produce images less than 1 megapixel in size; DSLR images are 6–12 megapixels, and still growing.

This has several consequences. First, you can shrink a DSLR image to a quarter of its linear size (1/16 its area) and still put a decent-sized picture on a Web page. That's an easy way to hide hot pixels and other defects without doing any other processing.

Second, you're going to need plenty of file storage space. It's easy to come home from a single evening's work with a gigabyte of image files, more than will fit on a CD-R. Invest in a relatively large memory card for the camera, a fast card reader for your PC, and perhaps a DVD burner for storing backup files.

Third, older astronomical image processing software may have trouble with large DSLR images. Regardless of what software you use, you'll need a computer with ample RAM (at least 1–2 GB recommended) and an up-to-date operating system (but not too new for your older DSLR). Smaller astronomical CCDs work well with older, smaller laptops, but DSLRs do not.

#### 2.1.2 Raw vs. compressed files

Most digital photographs are saved in JPEG compressed format. For astronomy, JPEG is not ideal because it is a "lossy" form of compression; low-contrast detail is discarded, and that may be exactly the detail you want to preserve and

## 2.2 Focusing

enhance. What's more, operations such as dark-frame subtraction rely on images that have not been disrupted by lossy compression.

For that reason, astrophotographers normally set the camera to produce raw images which record exactly the bits recorded by the image sensor (or nearly so; some in-camera corrections are performed before the raw image is saved).

The term *raw* is not an abbreviation and need not be written in all capital letters; it simply means "uncooked" (unprocessed). Filename extensions for raw images include .CRW and .CR2 (Canon Raw) and .NEF (Nikon Electronic Format). Adobe (the maker of *Photoshop*) has proposed a standard raw format called .DNG (Digital Negative) and has started distributing a free software tool to convert other raw formats into it.

Raw images are compressed – their size varies with the complexity of the image – but the compression is lossless or nearly so; the exact value of every pixel in the original image is recovered when the file is decoded in the computer. Canon and Nikon raw images occupy about 1 megabyte per megapixel, varying with the complexity of the image. Uncompressed, a 12-bit-deep color digital image would occupy 4.5 megabytes per megapixel.

### 2.1.3 "Digital film" and camera software

DSLRs record images on flash memory cards, sometimes called "digital film." Unlike real film, the choice of "digital film" doesn't affect the picture quality at all; flash cards differ in capacity and speed, but they all record exactly the same data and are error-checked during writing and reading.

To get the images into your computer, just remove the memory card from the camera, insert it into a card reader attached to your PC, and open it like a disk drive. This requires no special drivers on the PC.

Of course, there are good reasons not to ignore the software CD that comes with your camera. It contains drivers that you must install if you want to connect the camera to the computer, either for remote control or to download pictures. Also, there will be utilities to convert raw files to other formats and perform some basic manipulations. Even if you don't plan to use them, some astronomical software packages will require you to install these utilities so that DLLs (dynamic link libraries) supplied by the camera manufacturer will be present for their own software to use.

There may also be a genuinely useful photo editor, such as *Photoshop Elements*. But you do not have to install every program on the CD. If you don't care for *Grandma's Scrapbook Wizard*, skip it.

## 2.2 Focusing

Autofocus doesn't work when you're taking an astronomical image; you must focus the camera yourself. There are so many techniques for focusing a DSLR that I've devoted a whole chapter to it (Chapter 8, p. 89).

Obviously, you can focus a DSLR by looking into the eyepiece, just like a film SLR. Make sure the eyepiece diopter is adjusted so that you see the focusing screen clearly; your eyes may require a different setting at night than in the noonday sun.

But you can usually do better by confirming the focus electronically. The easiest way to do this is to take a short test exposure (such as 5 seconds for a star field) and view it enlarged on the camera's LCD screen. Repeat this procedure until the focus is as good as you can get it. If your camera offers magnified live focusing, that's even better.

## **2.3 Image quality**

### **2.3.1 Combining images**

Perhaps the single biggest difference between film and DSLR astrophotography is that DSLR images are usually combined (stacked). That is, instead of taking a single 30-minute exposure, you can take six 5-minute exposures and add them; the result is at least as good.

More importantly, if there is a brief problem, such as a tracking failure or a passing airplane, it only ruins part of your work, not the whole thing. Some image-combining algorithms will actually omit airplane trails or anything else that differs too drastically from the other images in the stack. For details of how to combine images, see p. 178.

### **2.3.2 Overcoming sky fog**

Like astronomical CCDs and unlike film, DSLRs make it easy to subtract a reasonable amount of sky fog from the picture. This is partly because their response is linear and partly because it is easy to stack multiple exposures. In the suburbs, a single 15-minute exposure might come out overexposed, but five 3-minute DSLR exposures are easy, and you can combine them and set the threshold so that the sky is relatively dark. The results are not quite equivalent to what you'd get under a dark country sky, but they are much better than what used to be possible in town.

### **2.3.3 Dark-frame subtraction**

No digital image sensor is perfect. Typically, a few pixels are dead (black) all the time, and in long exposures, many others are "hot," meaning they act as if light is reaching them when it isn't. As a result, the whole picture is covered with tiny, brightly colored specks.

Beginning with the 2004 generation of DSLRs, hot pixels are much less of a problem than with earlier digital cameras. For non-critical work, you can often ignore them.

## 2.3 Image quality

The cure for hot pixels is *dark-frame subtraction*. Take an exposure just like your astronomical image, but with the lens cap on, with the same exposure time and other camera settings, then subtract the second exposure from the first one. *Voilà* – the hot pixels are gone.

For more about dark-frame subtraction, see p. 183. It generally requires raw image files, not JPEGs.

Many newer DSLRs can do dark-frame subtraction for you. It's called "long-exposure noise reduction." On Nikons, this is an obvious menu setting; on Canons, it is deep within the Custom Function menu.

Noise reduction is very handy but time-consuming; in a long astronomical session, you don't really want every 5-minute exposure to be followed by a 5-minute dark frame. Instead, usual practice is to take a few dark frames separately, and then, on your computer, average them (to get rid of random fluctuation) and subtract them from all the exposures of the same length and ISO setting taken on the same evening.

### 2.3.4 The Nikon "star eater"

Another way to get rid of hot pixels is to check for pixels that differ drastically from their immediate neighbors. The rationale is that genuine details in the image will always spill over from one pixel to another, so if a pixel is bright all by itself, it must be "hot" and should be eliminated.

The Nikon D40, D50, D70, D70s, D80, and related DSLRs do this automatically, in the camera, even before saving the raw image, and it has an unfortunate side effect: *it eats stars*. That is, sharp star images tend to be removed as if they were hot pixels (Figure 2.1).

There is a workaround. Turn on long-exposure noise reduction, set the image mode to raw (not JPEG), take your picture, and then, while the camera is taking the second exposure with the shutter closed, *turn the camera off*. This seems like a foolish thing to do, but actually, a "truly raw" image has already been stored on the memory card. If you let the second exposure finish, that image will be replaced by one processed by the star eater. By powering the camera off, you keep this from happening. This workaround is popularly known as Mode 3 (see also p. 35).

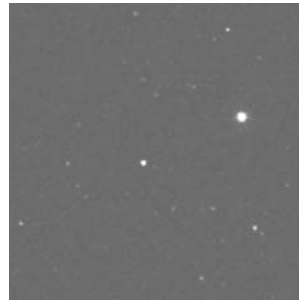
### 2.3.5 Grain

Like film, DSLR images have grain, though the origin of the grain is different. In film, it's due to irregular clumping of silver halide crystals; in the DSLR, it's due to small differences between pixels. Just as with film, grain is proportional to the ISO setting. Unfortunately, astronomical image processing techniques often increase grain, bringing out irregularity that would never have been visible in a daytime photograph.

## Main technical issues

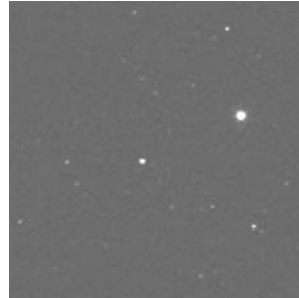
### Mode 1

Long-exposure noise  
reduction off



### Mode 2

Long-exposure noise  
reduction on



### Mode 3

Long-exposure noise  
reduction on but interrupted  
by powering off camera  
during second exposure



### Star Chart

Map of same area, prepared  
with *TheSky* version 6, to  
show which specks are  
actually stars.

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[www.bisque.com](http://www.bisque.com).

Used by permission.

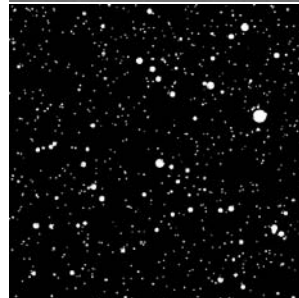


Figure 2.1. The Nikon star eater at work. Each photo is the central  $300 \times 300$  pixels of a 30-second exposure of the field of Altair with a Nikon D70s set to ISO 400 and a 50-mm lens at  $f/4$ . Note that Mode 3 shows the most stars, but also the most hot pixels. (By the author.)

## 2.5 Dust on the sensor

Combining multiple images helps reduce grain, especially if the camera was not pointed in exactly the same direction each time. There are also grain-reduction algorithms such as that used in *Neat Image* (p. 189), an add-on utility that does a remarkably good job of reducing grain without blurring the actual image.

## 2.4 Sensor size and multiplier (zoom factor)

Some high-end DSLRs have a sensor the size of a full 35-mm film frame (24 × 36 mm), but most DSLRs have sensors that are only two thirds that size, a format known as APS-C (about 15 × 23 mm). In between is the APS-H format of high-end Canons (19 × 29 mm). The rival Four Thirds (4/3) system, developed by Olympus and Kodak, uses digital sensors that are smaller yet, 13.5 × 18 mm.<sup>1</sup>

You shouldn't feel cheated if your sensor is smaller than "full frame." Remember that "full frame" was arbitrary in the first place. The smaller sensor of a DSLR is a better match to a telescope eyepiece tube (32 mm inside diameter) and also brings out the best in 35-mm camera lenses that suffer aberrations or vignetting at the corners of a full-frame image.

The sensor size is usually expressed as a "focal length multiplier," "zoom factor" or "crop factor" that makes telephoto lenses act as if they were longer. For example, a 100-mm lens on a Canon Digital Rebel covers the same field as a 160-mm lens on 35-mm film, so the zoom factor is said to be × 1.6. This has nothing to do with zooming (varying focal length) in the normal sense of the word.

My one gripe with DSLR makers is that when they made the sensor and focusing screen smaller than 35-mm film, they didn't increase the magnification of the eyepiece to compensate. As a result, the picture you see in the DSLR viewfinder is rather small. Compare a Digital Rebel or Nikon D50 to a classic film SLR, such as an Olympus OM-1, and you'll see what I mean. One argument that has been offered for a low-magnification viewfinder is that it leads snapshooters to make better-composed pictures by encouraging them to look at the edges of the frame.

## 2.5 Dust on the sensor

A film SLR pulls a fresh section of film out of the cartridge before taking every picture, but a DSLR's sensor remains stationary. This means that if a dust speck lands on the low-pass filter in front of the sensor, it will stay in place, making a black mark on every picture until you clean it off (Figure 2.2).

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<sup>1</sup> APS-C originally denoted the "classic" picture format on Advanced Photo System (APS, 24-mm) film, and APS-H was its "high-quality" format. "Four Thirds" denotes an image size originally used on video camera tubes that were nominally 4/3 of an inch in diameter. Many video CCD sensors are still specified in terms of old video camera tube sizes, measured in fractional inches.

## Main technical issues

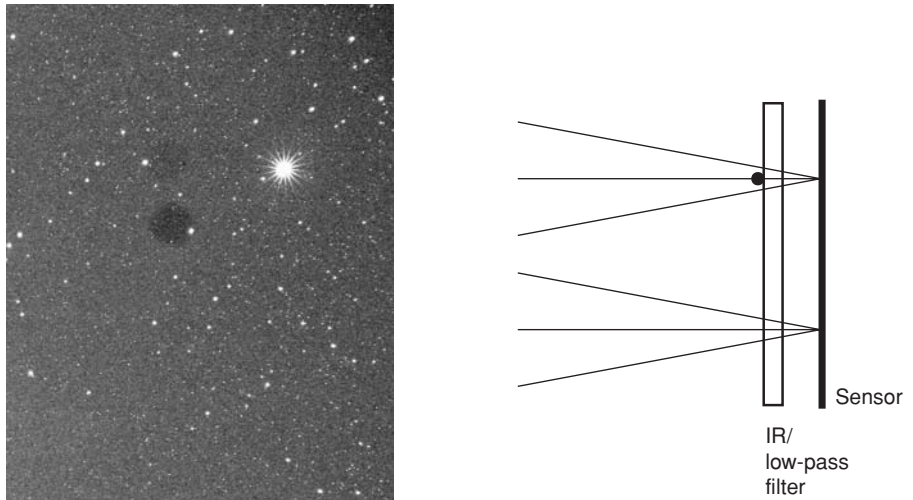


Figure 2.2. Effect of dust (enlarged). Diagram shows how light gets around the dust speck so that stars are visible through the blotch.

To keep dust off the sensor, avoid unnecessary lens changes; hold the camera body facing downward when you have the lens off; never leave the body sitting around with no lens or cap on it; and never change lenses in dusty surroundings. But even if you never remove the lens, there will eventually be some dust generated by mechanical wear of the camera's internal components.

When dust gets on the sensor (and eventually it will), follow the instructions in your camera's instruction manual. The gentlest way to remove dust is to open the shutter (on "bulb," the time-exposure setting) and apply compressed air from a rubber bulb (*not* a can of compressed gas, which might emit liquid or high-speed particles).

If you must wipe the sensor, use a Sensor Swab, made by Photographic Solutions, Inc. ([www.photosol.com](http://www.photosol.com)). And above all, follow instructions to make *sure* the shutter stays open while you're doing the cleaning.

Some newer DSLRs can vibrate the sensor to shake dust loose. This feature was introduced by Olympus and is included on the Canon Digital Rebel XTi (400D).

To a considerable extent, the effect of dust can be removed by image processing, either flat-fielding (p. 185) or "dust mapping" performed by the software that comes with the camera.

You can check for dust by aiming the camera at the plain blue daytime sky and taking a picture at  $f/22$ . Note that dust that you see in the viewfinder is *not* on the sensor and will not show up in the picture; it's on the focusing screen. Removing it is a good idea so that it does not eventually make its way to the sensor.

## 2.6 ISO speed settings

The sensor in a DSLR can be set to mimic the sensitivity of film with ISO speeds ranging from about 100 to 1600. This setting varies the amplification that is applied to the analog signal coming out of the sensor before it is digitized.

Neither the lowest nor the highest setting is generally best; I normally work at ISO 400, in the middle of the range.

The ISO setting is a trade-off. The *same* exposure of the same celestial object will look better at a higher ISO than a lower ISO, as long as it isn't overexposed. (Amplifying the sensor's output gives it more ability to distinguish levels of brightness.) So a case can certainly be made for using ISO 800 or 1600 when imaging a faint object through a telescope.

But a *longer* exposure at a lower ISO will look better than a short exposure at a higher ISO. That is, capturing more photons is better than just amplifying the signal from the ones you already have.

This is demonstrated by a test that Canon published in Japan.<sup>2</sup> With a Digital Rebel (300D), they photographed the galaxy M31 for 300 seconds at ISO 400, 150 seconds at ISO 800, and 75 seconds at ISO 1600. The first is quite smooth; the latter two are increasingly speckled with spurious color. This is not from hot pixels, but rather from irregularities in the sensor's response and noise in the amplifier.

## 2.7 No reciprocity failure

Unlike film, digital sensors don't suffer reciprocity failure. This gives them a strong advantage for photographing galaxies, nebulae, and other faint objects.

Film is inefficient at recording dim light. The silver crystals "forget" that they've been hit by a photon, and revert to their unexposed state, if another photon doesn't come along soon enough. For details, see *Astrophotography for the Amateur* (1999 edition), pp. 180–184.

Figure 2.3 shows the estimated long-exposure performance of an old-technology black-and-white film, a modern color film, and a DSLR image sensor, based on my measurements. The advantage of the DSLR is obvious. Astronomical CCD cameras have the same advantage.

A practical consequence is that we no longer need super-fast lenses. With film, if you gather twice as much light, you need *less* than half as much exposure, so film astrophotographers were willing to compromise on sharpness to use  $f/2.8$  and  $f/1.8$  lenses. It was often the only way to get a picture of a faint object.

With DSLRs,  $f/4$  is almost always fast enough. You can either use an  $f/2.8$  lens stopped down, for greater sharpness, or save money and weight by choosing an  $f/4$  lens in the first place.

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<sup>2</sup> Web address: [http://www.canon.co.jp/Imaging/astro/pages\\_e/09\\_e.html](http://www.canon.co.jp/Imaging/astro/pages_e/09_e.html).

## Main technical issues

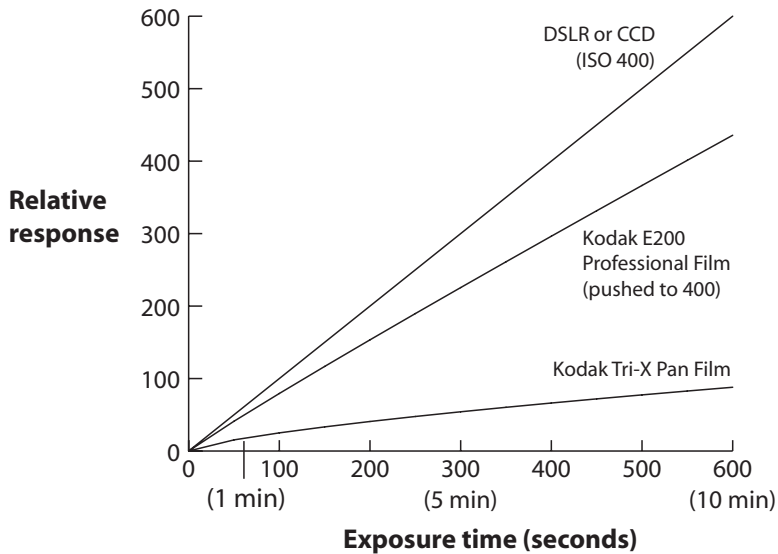


Figure 2.3. Long-exposure response of two kinds of film and a digital sensor.

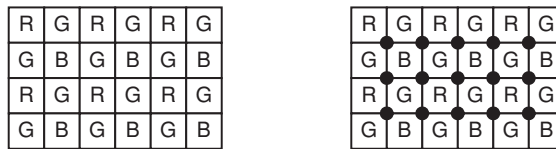


Figure 2.4. Left: Bayer matrix of red, green and blue filters in front of individual sensor pixels. Right: Dots mark “virtual pixels,” points where brightness and color can be computed accurately.

## 2.8 How color is recorded

### 2.8.1 The Bayer matrix

Almost all digital cameras sense color by using a Bayer matrix of filters in front of individual pixels (Figure 2.4). This system was invented by Dr. Bryce Bayer, of Kodak, in 1975.<sup>3</sup> Green pixels outnumber red and blue because the eye is more sensitive to fine detail in the middle part of the spectrum. Brightness and color are calculated by combining readings from red, green, and blue pixels.

At first sight, this would seem to be a terrible loss of resolution. It looks as if the pixels on the sensor are being combined, three or four to one, to make the finished, full-color image. How is it, then, that a 6-megapixel sensor yields a 6-megapixel image rather than a 2-megapixel one? Is it really as sharp as the number of pixels would indicate?

<sup>3</sup> Pronounced *BY-er*, as in German, not *BAY-er*.

## 2.9 Nebulae are blue or pink, not red

For the answer, consider the dots in Figure 2.4 (right). Each dot represents a point where pixels of all three colors come together, so the brightness and color at that point can be determined exactly. The dots are “virtual pixels” and are as closely spaced as the real pixels.

### 2.8.2 Low-pass filtering

This assumes, of course, that light falling directly on a virtual pixel will actually spread into the four real pixels from which it is synthesized. A *low-pass filter* (so called because it passes low spatial frequencies) ensures that this is so. The low-pass filter is an optical diffusing screen mounted right in front of the sensor. It ensures that every ray of light entering the camera, no matter how sharply focused, will spread across more than one pixel on the sensor.

That sounds even more scandalous – building a filter into the camera to blur the image. But we *do* get good pictures in spite of the low-pass filter, or even because of it. The blur can be overcome by digital image sharpening. The low-pass filter enables Bayer color synthesis and also reduces moiré effects that would otherwise result when you photograph a striped object, such as a distant zebra, and its stripes interact with the pixel grid.

Remember that light spreads and diffuses in film, too. Film is translucent, and light can pass through it sideways as well as straight-on. We rely on diffusion to make bright stars look bigger than faint stars. My experience with DSLRs is that, even with their low-pass filters, they have less of this kind of diffusion than most films do.

### 2.8.3 The Foveon

There is an alternative to the Bayer matrix. Sigma digital SLRs use Foveon sensors ([www.foveon.com](http://www.foveon.com)). This type of sensor consists of three layers, red-, green-, and blue-sensitive, so that each pixel is actually recorded in all three colors.

In principle, this should be a good approach, but so far, the Foveon has not found extensive use in astrophotography, and no one has reported any great success with it.

Some confusion is created by the fact that Foveon, Inc., insists on counting all three layers in the advertised megapixel count, so that, for example, their “14.1-megapixel” sensor actually outputs an image with about 4.5 million pixels (each rendered in three colors). A 14-megapixel Bayer matrix actually has 14 million virtual pixels (Figure 2.4).

## 2.9 Nebulae are blue or pink, not red

For a generation of astrophotographers, emission nebulae have always been red. At least, that’s how they show up on Ektachrome film, which is very sensitive to the wavelength of hydrogen-alpha (656 nm), at which nebulae shine brightly.



Figure 2.5. The Veil Nebula, a faint supernova remnant, photographed with an unmodified Canon Digital Rebel (300D). Stack of five 3-minute exposures through an 8-inch (20-cm) telescope at  $f/6.3$ . Extreme contrast stretching was needed; the nebula was not visible on the camera LCD screen.

But DSLRs see nebulae as blue or pinkish. There are two reasons for this. First, DSLRs include an infrared-blocking filter that cuts sensitivity to hydrogen-alpha. Second, and equally important, DSLRs respond to hydrogen-beta and oxygen-III emissions, both near 500 nm, much better than color film does.<sup>4</sup> And some nebulae are actually brighter at these wavelengths than at hydrogen-alpha. So the lack of brilliant coloration doesn't mean that the DSLR can't see nebulae.

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<sup>4</sup> The Palomar Observatory Sky Survey also didn't respond to hydrogen-beta or oxygen-III; those spectral lines fell in a gap between the "red" and "blue" plates. This fact reinforced everyone's impression that emission nebulae are red.

## 2.9 Nebulae are blue or pink, not red

DSLRs can be modified to make them supersensitive to hydrogen-alpha, like an astronomical CCD, better than any film. The modification consists of replacing the infrared filter with one that transmits longer wavelengths, or even removing it altogether. For more about this, see p. 133. Canon has marketed one such camera, the EOS 20Da.

In the meantime, suffice it to say that unmodified DSLRs record hydrogen nebulae better than many astrophotographers realize. Faint hydrogen nebulae can be and have been photographed with unmodified DSLRs (Figure 2.5).

# Chapter 3

## Basic camera operation

In what follows, I'm going to assume that you have learned how to use your DSLR for daytime photography and that you have its instruction manual handy. No two cameras work exactly alike. Most DSLRs have enough in common that I can guide you through the key points of how to use them, but you should be on the lookout for exceptions.

### 3.1 Taking a picture manually

#### 3.1.1 Shutter speed and aperture

To take a picture with full manual control, turn the camera's mode dial to M (Figure 3.2). Set the shutter speed with the thumbwheel.

To set the aperture, some cameras have a second thumbwheel, and others have you turn the one and only thumbwheel while holding down the +/- button. Note that on Canon lenses there is no aperture ring on the lens; you can only set the aperture by electronic control from within the camera. Most Nikon lenses have an aperture ring, for compatibility with older manual cameras, but with a DSLR, you should set the aperture ring on the lens to the smallest stop (highest number) and control the aperture electronically.

Naturally, if there is no lens attached, or if the camera is attached to something whose aperture it cannot control (such as a telescope), the camera will not let you set the aperture. You can still take pictures; the computer inside the camera just doesn't know what the aperture is.

#### 3.1.2 Manual focusing

In astrophotography, you must always focus manually. You must also *tell* the camera you want to focus manually, because if the camera is trying to autofocus and can't do so, it will refuse to open the shutter.

### 3.1 Taking a picture manually

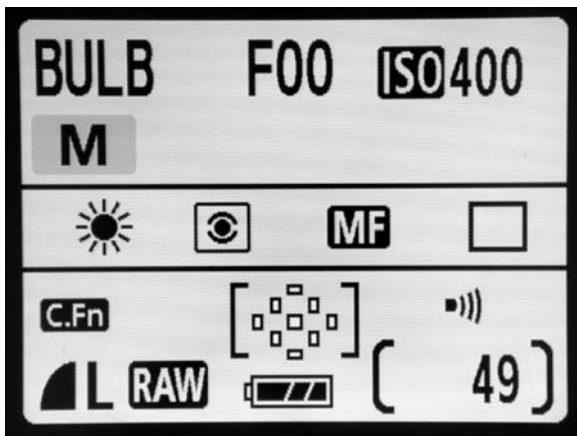


Figure 3.1. Display panel of a Canon XTi (400D) set up for deep-sky photography. *F00* means the lens is not electronic and the camera cannot determine the *f*-stop. *C.Fn* means custom functions are set.



Figure 3.2. For manual control of shutter and aperture, set mode dial to M.

On Canon cameras, the manual/autofocus switch is on the lens, but on Nikons, it is on the camera body (Figure 3.3). There may also be a switch on the lens, and if so, the two switches should be set the same way.

Astronomical photographs are hard to focus, but with a DSLR, you have a superpower – you can review your picture right after taking it. I usually focus astrophotos by taking a series of short test exposures and viewing them on the LCD at maximum magnification to see if they are sharp.



Figure 3.3. Manual/autofocus switch is on camera body, lens, or both.

Do not trust the infinity ( $\infty$ ) mark on the lens. Despite the manufacturer's best intentions, it is probably not perfectly accurate, and anyhow, the infinity setting will shift slightly as the lens expands or contracts with changes in temperature.

### 3.1.3 ISO speed

As already noted (p. 21), the ISO speed setting on a DSLR is actually the gain of an amplifier; you are using the same sensor regardless of the setting. DSLR astrophotographers have different opinions, but my own practice is to set the ISO to 400 unless I have a reason to set it otherwise: 800 or 1600 for objects that would be underexposed at 400, and 200 or 100 if I need greater dynamic range for a relatively bright object (Figure 3.4).

### 3.1.4 White balance

Color balance is not critical in astrophotography. I usually set the white balance to Daylight. That gives me the same color balance in all my pictures, regardless of their content.

Other settings may be of some use if your pictures have a strong color cast due to light pollution, or if the IR-blocking filter has been modified. Usually, though, color balance is something to correct when processing the pictures afterward.

### 3.1 Taking a picture manually



Figure 3.4. High dynamic range in this picture of the globular cluster M13 was achieved by stacking four 3-minute ISO 400 exposures. Lower ISO would have helped further. Canon Digital Rebel (300D), 8-inch (20-cm)  $f/6.3$  telescope, dark frames subtracted.

#### 3.1.5 Do you want an automatic dark frame?

If you're planning an exposure longer than a few seconds, hot pixels are an issue, and you need to think about dark frame subtraction. Done manually, this means that in addition to your picture, you take an identical exposure with the lenscap on, and then you subtract the dark frame from the picture. This corrects the pixels that are too bright because of electrical leakage.

Most newer DSLRs (but not the original Digital Rebel/300D) will do this for you if you let them. Simply enable long-exposure noise reduction (a menu setting on the camera). Then, after you take your picture, the camera will record a dark frame with the shutter closed, perform the subtraction, and store the corrected image on the memory card. *Voilà* – no hot pixels.

The drawback of this technique is that it takes as long to make the second exposure as the first one, so you can only take pictures half the time.<sup>1</sup> That's why many of us prefer to take our dark frames manually.

### 3.1.6 Tripping the shutter without shaking the telescope

Now it's time to take the picture. Obviously, you can't just press the button with your finger; the telescope would shake terribly. Nor do DSLRs take conventional mechanical cable releases. So what do you do?

There are several options. If the exposure is 30 seconds or less, you can use the self-timer (delayed shutter release). Press the button; the camera counts down 10 seconds while the telescope stops shaking; and then the shutter opens and the picture is taken.

That won't work if you're using "Bulb" (the setting for time exposures). You need a cable release of some kind.

Nikon makes an electrical cable release for the D70s and D80, but for most Nikon DSLRs, your best bet is the infrared remote control. Set the camera to use the remote control, and "Bulb" changes to "--" on the display. That means, "Press the button (on the remote control) once to open the shutter and once again to close it."

With the Canon Digital Rebel family (300D, 350D, 400D), you can buy or make a simple electrical cable release (see p. 119). This is just a cable with a 2.5-mm phone plug on one end and a switch on the other.

Some people have reported success by simply plugging a cheap mobile telephone headset into the Digital Rebel and using the microphone switch to control the shutter. This is not as silly as it sounds. The headset can't harm the camera because it contains no source of power. It may have the right resistance to work as a Canon cable release. If not, you can take it apart and build a better cable release using the cable and plug.

### 3.1.7 Mirror vibration

Much of the vibration of an SLR actually comes from the mirror, not the shutter. If the camera can raise the mirror in advance of making the exposure, this vibration can be eliminated.

Mirror vibration is rarely an issue in deep-sky work. It doesn't matter if the telescope shakes for a few milliseconds at the beginning of an exposure lasting several minutes; that's too small a fraction of the total time. On the other hand, in lunar and planetary work, my opinion is that DSLRs aren't very suitable even with mirror vibration eliminated because there's too much shutter vibration. That's one reason video imagers are better than DSLRs for lunar and planetary work.

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<sup>1</sup> The Nikon D80 takes only half as long for the second exposure as for the main one. It must scale the dark frame by a factor of 2 before subtracting it.

### 3.1 Taking a picture manually

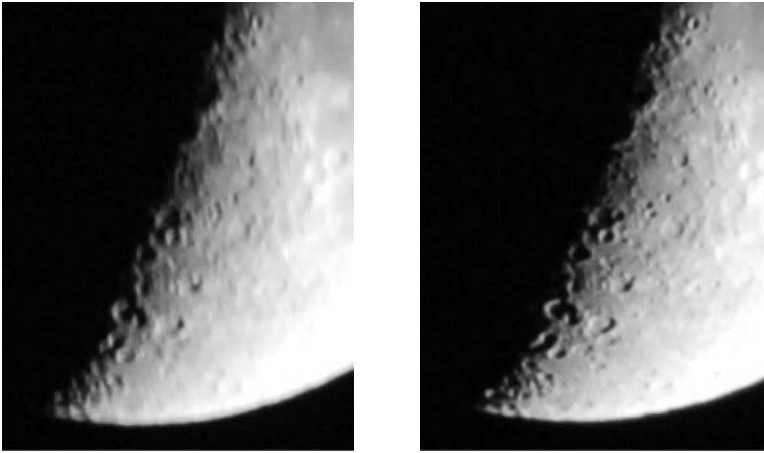


Figure 3.5. 1/100-second exposures of the Moon without (left) and with mirror prefire (right). Nikon D80, ISO 400, 300-mm telephoto lens at  $f/5.6$  on fixed tripod. Small regions of original pictures enlarged.

Nonetheless, it's good to have a way to control mirror vibration. There are two basic approaches, *mirror prefire* and *mirror lock*. To further confuse you, "mirror lock" sometimes denotes a way of locking up the mirror to clean the sensor, not to take a picture. And on Schmidt-Cassegrain telescopes, "mirror lock" means the ability to lock the telescope mirror in position so that it can't shift due to slack in the focusing mechanism. These are not what I'm talking about here.

Mirror prefire is how the Nikon D80 does it. Deep in the custom settings menu is an option called "Exposure Delay Mode." When enabled, this introduces a 400-millisecond delay between raising the mirror and opening the shutter. This delay can be slightly disconcerting if you forget to turn it off when doing daytime photography. For astronomy, though, it really makes a difference (Figure 3.5).

On the Canon XT (EOS 350D) and its successors, mirror lock is what you use. Turn it on, and you'll have to press the button on the cable release twice to take a picture. The first time, the mirror goes up; the second time, the shutter opens. In between, the camera is consuming battery power, so don't forget what you're doing and leave it that way.

There is no mirror lock (of this type, as distinct from sensor-cleaning mode) on the original Digital Rebel (300D), but some enterprising computer programmers have modified its firmware to add mirror lock. Information about the modification is available on [www.camerahacker.com](http://www.camerahacker.com) or by searching for *Russian firmware hack*. The modified firmware is installed the same way as a Canon firmware upgrade. I haven't tried it; it voids the Canon warranty.

The *sure* way to take a vibration-free lunar or planetary image is called the *hat trick*. Hold your hat (if you wear an old-fashioned fedora), or any dark object,

in front of the telescope. Open the shutter, wait about a second for vibrations to die down, and move the hat aside. At the end of the exposure, put the hat back and then close the shutter. Instead of a hat, I usually use a piece of black cardboard. I find I can make exposures as short as 1/4 second by swinging the cardboard aside and back in place quickly.

Another way to eliminate vibration almost completely is to use afocal coupling (that is, aim the camera into the telescope's eyepiece) with the camera and telescope standing on separate tripods. This technique is as clumsy as it sounds, but it's how I got my best planetary images during the film era. Today, the best option is not to use a DSLR at all, but rather a webcam or a non-SLR digital camera with a nearly vibrationless leaf shutter.

### 3.1.8 Vibration-reducing lenses

Unfortunately, vibration-reducing or image-stabilizing lenses (Nikon VR, Canon IS) are no help to the astrophotographer. They compensate for movements of a handheld camera; they do not help when the camera is mounted on a tripod or telescope. The same goes for vibration reduction that is built into some camera bodies. Just turn the vibration-reduction feature off.

## 3.2 The camera as your logbook

Digital cameras record a remarkable amount of information about each exposure. This is often called EXIF data (EXIF is actually one of several formats for recording it), and Windows itself, as well as many software packages, can read the EXIF data in JPEG files. *Photoshop* and other utilities can read the same kind of data in raw files. From this book's Web site ([www.dslrbook.com](http://www.dslrbook.com)) you can get a utility, EXIFLOG, that reads a set of digital image files and generates a list of exposures.

This fact gives you an incentive to do two things. First, keep the internal clock-calendar of your camera set correctly. Second, take each exposure as both raw and JPEG if your camera offers that option. That way, each exposure is recorded as two files that serve as backups of each other, and the JPEG file contains EXIF data that is easy to view.

The original Digital Rebel (EOS 300D) always records a small JPEG file with the .THM extension alongside every raw (.CRW) file. If you rename the .THM file to be .JPEG, your software can read the EXIF data in it.

Naturally, the camera doesn't record what it doesn't know. It can't record the focal length or  $f$ -ratio of a lens that doesn't interface with the camera's electronics. Nor does it know what object you're photographing or other particulars of the setup and conditions. Nonetheless, using EXIF data saves you a lot of effort. You don't have to write in the logbook every time you take a picture.

### 3.3 Limiting light emission from the camera

If you observe with other people, or if you want to preserve your night vision, a DSLR can be annoying. The bright LCD display lights up at the end of every picture, and on some models it glows all the time.

Fortunately, there are menu settings to change this. You can turn “review” off so that the picture isn’t displayed automatically at the end of each exposure. (Press  $\triangleright$  or “Play” when you want to see it.) And you can set cameras such as the Canon XTi (400D) so that the LCD does not display settings until you press a button to turn it on.

That leaves the indicator LEDs. In general, red LEDs aren’t bothersome; you can stick a piece of tape on top of green ones, such as the power-on LED on top of the Digital Rebel XTi (400D) (Figure 3.6).

To further protect your night vision, you can put deep red plastic over the LCD display. A convenient material for this purpose is Rubylith, a graphic arts masking material consisting of deep-red plastic on a transparent plastic base. If you peel the Rubylith off its base, it will stick to the LCD screen and you can easily peel it off later. Or you can leave it on its backing and secure it in some other way. Because it is designed to work with photographic materials, Rubylith is guaranteed to block short-wavelength light, so it’s especially good for preserving dark adaptation. Many drafting-supply stores sell Rubylith by the square foot; one online vendor is [www.misterart.com](http://www.misterart.com).

### 3.4 Menu settings

Like other digital cameras, DSLRs are highly customizable. It’s worth while to work through the instruction manual, examine every menu setting, and make an intelligent choice, since what suits you will often be different from what suits an ordinary daytime photographer. What follows is a checklist of important menu settings.

Note that the full menu is not likely to be visible unless the camera is set to one of its full-control modes, preferably M. If you turn on the camera in one of its “simple” modes, the more advanced parts of the menu will be inaccessible.

#### 3.4.1 Things to set once and leave alone

These are settings that you can probably leave unchanged as you go back and forth between astrophotography and daytime photography.

*Auto Rotate (Rotate Tall): Off.* Tell the camera not to rotate images if it thinks you are holding the camera sideways or upside down. Doing so can lead to very confusing astrophotos.

*CSM/Setup Menu: Full.* This is a Nikon option to show the full custom settings menu rather than a shortened version. You’ll need it to get to some of the other settings.



Figure 3.6. Dots punched out of red vinyl tape make good covers for the power-on LED and self-timer indicator.

*High ISO NR: Normal.* This is a Nikon setting that apparently improves picture quality but does not affect the “star eater.”

*Magnified View: Image Review and Playback.* This is a Canon XTi (400D) setting that makes it easier for you evaluate focus right after taking a picture. With this option enabled, you don’t have to press  $\triangleright$  (“Play”) to magnify the picture. You can press “Print” and “Magnify” together to start magnifying the picture while it is still being displayed for review.

### 3.4.2 Settings for an astrophotography session

*Picture Quality: Raw + JPEG.* If the memory card has room, I like to have the camera save each picture in both formats. Each file serves as a backup of the other, and the JPEG file contains exposure data that can be read by numerous software packages. This takes only 20% more space than storing raw images alone.

*Review: Off.* At an observing session with other people, you’ll want to minimize the amount of light emitted by your camera.

*LCD Brightness: Low.* In the dark, even the lowest setting will seem very bright.

### 3.5 Determining exposures

*LCD Display When Power On: Off.* On the Canon XTi (400D) and similar cameras that use their LCD screen to display camera settings, you probably don't want the display shining continuously at night. Instead, switch it on with the DISP button when you want to see it.

*Auto Power Off: Never.* You don't want the camera turning itself off during lulls in the action; at least, I don't.

*Long-Exposure Noise Reduction: Your decision.* If turned on, this feature will eliminate the hot pixels in your images by taking a dark frame immediately after each picture and automatically subtracting it. This takes time, and as you become more experienced, you'll prefer to take dark frames separately and subtract them during image processing.

#### 3.4.3 Using Nikon Mode 3

In Nikon parlance, long-exposure noise reduction off is called Mode 1, and on is called Mode 2.

Mode 3 is a trick for defeating the "star eater" (p. 17). It is not a menu setting. To use Mode 3, turn long-exposure noise reduction on, take the picture, and then, when the camera is taking the second exposure with the shutter closed, *switch the camera off*. At this point a "truly raw" image has already been stored on the memory card, and you are preventing the camera from replacing it with a processed image that shows fewer stars. Of course, no dark frame subtraction has been done either; you will have to take dark frames and subtract them later using your computer.

### 3.5 Determining exposures

Nearly 20 pages of *Astrophotography for the Amateur* were devoted to exposure calculations and tables. Guess what? We don't need to calculate exposures any more. With a DSLR or any other digital imaging device, it's easy to determine exposures by trial and error.

For a bright object that fills the field, such as the Moon, the Sun, or an eclipse, auto exposure can be useful. The rest of the time, what you should do is make a trial exposure and look at the results. For deep-sky work, I almost always start with 3 minutes at ISO 400. One reason for standardizing on 3 minutes is that I happen to have built a 3-minute timer. The other is that if all the exposures are the same length, dark-frame subtraction is easier; dark frames must match the exposure time and ISO setting of the image to which they are being applied.

If the 3-minute, ISO 400 image is underexposed, I switch to ISO 800 and 6 minutes, then take multiple exposures and stack them. If, on the other hand, the image contains a bright object, I reduce the ISO speed (to gain dynamic

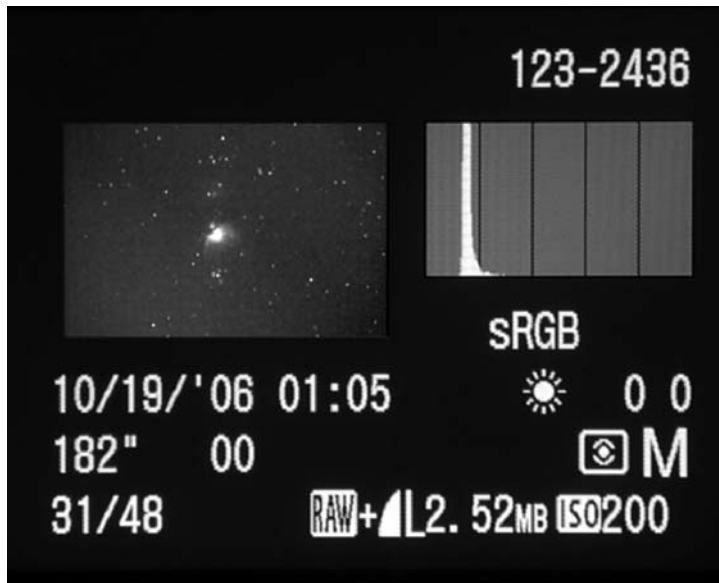


Figure 3.7. Histogram of a well-exposed deep-sky image as displayed on the Canon XTi (400D).

range) and possibly the exposure time. Under a bright suburban sky, 30 seconds at  $f/4$ , ISO 400, will record star fields well.

To judge an exposure, look at the LCD display just the way you do in the daytime. Better yet, get the camera to display a histogram (Figure 3.7) and look at the hump that represents the sky background. It should be in the left half of the graph, but not all the way to the left edge. Increasing the exposure moves it to the right; decreasing the exposure moves it to the left.

When viewing the histogram, you also see a small preview image in which overexposed areas blink. It is normal for bright stars to be overexposed. For more about histograms, see p. 169.

### 3.6 Cool-down between long exposures

Like all electronic devices, the sensor in your camera emits some heat while it's being used. As the sensor warms up, its noise level increases, leading to more speckles in your pictures. This effect is usually slight and, in my experience, often unnoticeable; it is counteracted by the fact that the temperature of the air is usually falling as the night wears on.

Nonetheless, for maximum quality in images of faint objects, it may be beneficial to let the sensor cool down for 30 to 60 seconds, or possibly even longer, between long exposures.<sup>2</sup>

<sup>2</sup> I want to thank Ken Miller for drawing my attention to this fact.

### 3.6 Cool-down between long exposures

Most of the heat is generated while the image is being read out, not while the photoelectrons are being accumulated. For this reason, live focusing, with continuous readout, will really heat up the sensor, and you should definitely allow at least 30 seconds for cool-down afterward, before taking the picture. The LCD display is also a heat source, so it may be advantageous to keep it turned off.

No matter how much heat it emits, the sensor will not keep getting warmer indefinitely. The warmer it becomes, the faster it will emit heat to the surrounding air. Even if used continuously, it will stabilize at a temperature only a few degrees higher than its surroundings.

# Chapter 4

## Four simple projects

After all this, you're probably itching to take a picture with your DSLR. This chapter outlines four simple ways to take an astronomical photograph. Each of them will result in an image that requires only the simplest subsequent processing by computer.

All of the projects in this chapter can be carried out with your camera set to output JPEG images (not raw), as in daytime photography. The images can be viewed and further processed with any picture processing program.

### 4.1 Telephoto Moon

Even though the Moon is not ultimately the most rewarding object to photograph with a DSLR, it's a good first target.

Put your camera on a sturdy tripod and attach a telephoto lens with a focal length of at least 200 and preferably 300 mm. Take aim at the Moon. Initial exposure settings are ISO 400,  $f/5.6$ , 1/125 second (crescent), 1/500 second (quarter moon), 1/1000 (gibbous), or 1/2000 (full); or simply take a spot meter reading of the illuminated face of the Moon. An averaging meter will overexpose the picture because of the dark background.

If the camera has mirror lock (Canon) or exposure delay (Nikon), turn that feature on. Let the camera autofocus and take a picture using the self-timer or cable release. View the picture at maximum magnification on the LCD display and evaluate its sharpness. Switch to manual focus and try again, varying the focus slightly until you find the best setting. Also adjust the exposure for best results. If you have mirror lock or prefire, you can stop down to  $f/8$  and use a slower shutter speed.

Figures 4.1 and 4.2 show what you can achieve this way. Images of the Moon benefit greatly from unsharp masking in *Photoshop* or *RegiStax*; you'll be surprised how much more detail you can bring out.

To make the face of the Moon fill the sensor, you'll need a focal length of about 1000–1500 mm. In the next example, we'll achieve that in a very simple way.



Figure 4.1. The Moon. Nikon D80 and 300-mm  $f/4$  ED IF telephoto lens at  $f/8$ ,  $1/200$  second at ISO 400. This is just the central area of the picture, enlarged. Some unsharp masking was done in *Photoshop* to bring out detail.

## 4.2 Afocal Moon

Another easy way to take an astronomical photograph with a digital camera (DSLR or not) is to aim the telescope at the Moon, hold the camera up to the eyepiece, and snap away.

This sounds silly, but as you can see from Figure 4.3, it works. The telescope should be set up for low power ( $\times 50$  or less, down to  $\times 10$  or even  $\times 5$ ; you can use a spotting scope or one side of a pair of binoculars). Use a 28-, 35-, or 50-mm fixed-focal-length camera lens if you have one; the bulky design of a zoom lens may make it impossible to get close enough to the eyepiece.

Set the camera to aperture-priority autoexposure (*A* on Nikons, *Av* on Canons) and set the lens wide open (lowest-numbered  $f$ -stop). Focus the telescope by eye and let the camera autofocus on the image. What could be simpler?

This technique also works well with non-SLR digital cameras (see Appendix A). Many kinds of brackets exist for coupling the camera to the telescope, but (don't laugh) I get better results by putting the camera on a separate tripod so that it cannot transmit any vibration.

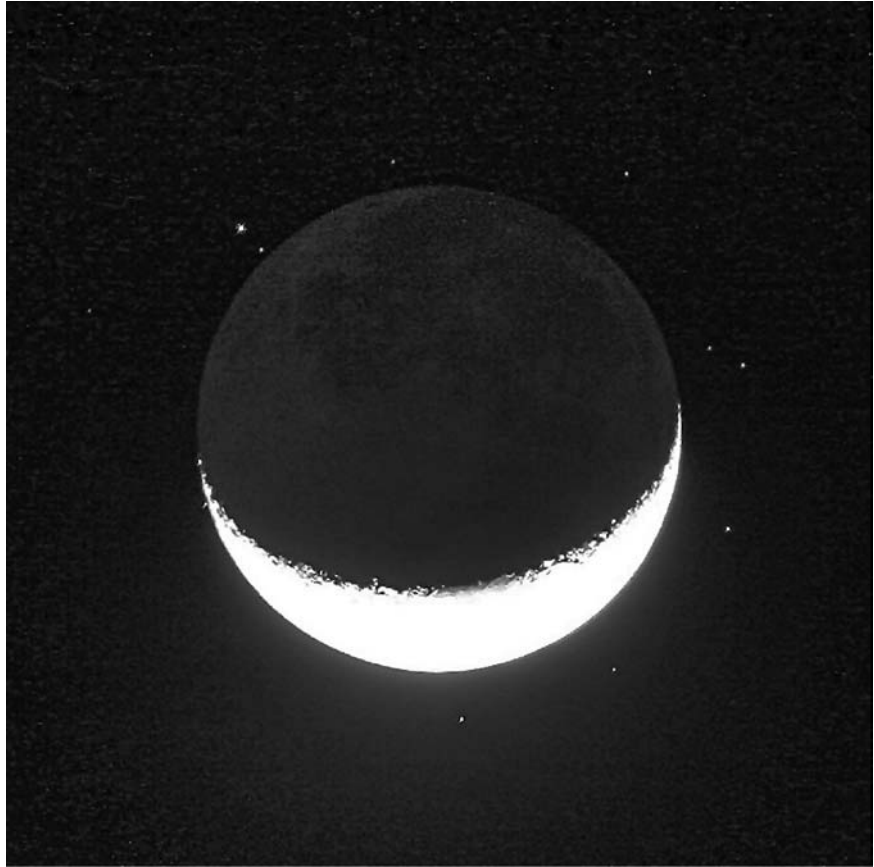


Figure 4.2. The Moon passing in front of the Pleiades star cluster. Half-second exposure at ISO 200 with Canon Digital Rebel (300D) and old Soligor 400-mm telephoto lens at  $f/8$ . Processed with *Photoshop* to brighten the starry background relative to the Moon.

This setup is called afocal coupling. The effective focal length is that of the camera lens multiplied by the magnification of the telescope – in Figure 4.3,  $28 \times 50 = 1400$  mm.

### 4.3 Stars from a fixed tripod

Now for the stars. On a starry, moonless night, put the camera on a sturdy tripod, aim at a familiar constellation, set the aperture wide open, focus on infinity, and take a 10- to 30-second exposure at ISO 400 or 800. You'll get something like Figure 4.5 or Figure 4.6.

For this project, a 50-mm  $f/1.8$  lens is ideal. Second choice is any  $f/2.8$  or faster lens with a focal length between 20 and 50 mm. Your zoom lens may fill the bill. If you are using a "kit" zoom lens that is  $f/3.5$  or  $f/4$ , you'll need to

#### 4.3 Stars from a fixed tripod



Figure 4.3. The Moon, photographed by holding a Canon Digital Rebel (with 28-mm  $f/2.8$  lens wide open) up to the eyepiece of an 8-inch (20-cm) telescope at  $\times 50$ . Camera was allowed to autofocus and autoexpose at ISO 200. Picture slightly unsharp-masked in *Photoshop*.

make a slightly longer exposure (30 seconds rather than 10) and the stars will appear as short streaks, rather than points, because the earth is rotating.

If your camera has long-exposure noise reduction, turn it on. Otherwise, there will be a few bright specks in the image that are not stars, from hot pixels. If long-exposure noise reduction is available, you can go as high as ISO 1600 or 3200 and make a 5-second exposure for crisp star images.

Focusing can be problematic. Autofocus doesn't work on the stars, and it can be hard to see a star in the viewfinder well enough to focus on it. Focusing on a



Figure 4.4. Lunar seas and craters. Nikon D70s with 50-mm  $f/1.8$  lens wide open, handheld at the eyepiece of a 5-inch (12.5-cm) telescope at  $\times 39$ , autofocused and autoexposed. Image was unsharp-masked with *Photoshop*.

very distant streetlight is a good starting point. Then you can refine the focus by taking repeated 5-second exposures and viewing them magnified on the LCD screen as you make slight changes.

The picture will benefit considerably from sharpening and contrast adjustment in *Photoshop* or a similar program. You'll be amazed at what you can photograph; ninth- or tenth-magnitude stars, dozens of star clusters, and numerous nebulae and galaxies are within reach.

This is of course the DSLR equivalent of the method described at length in Chapter 2 of *Astrophotography for the Amateur* (1999). It will record bright comets, meteors, and the aurora borealis. In fact, for photographing the aurora, a camera with a wide-angle lens on a fixed tripod is the ideal instrument.



Figure 4.5. Orion rising over the trees. Canon Digital Rebel (300D) at ISO 400, Canon 18–55-mm zoom lens at 24 mm,  $f/3.5$ , 30 seconds. Star images are short streaks because of the earth's motion.

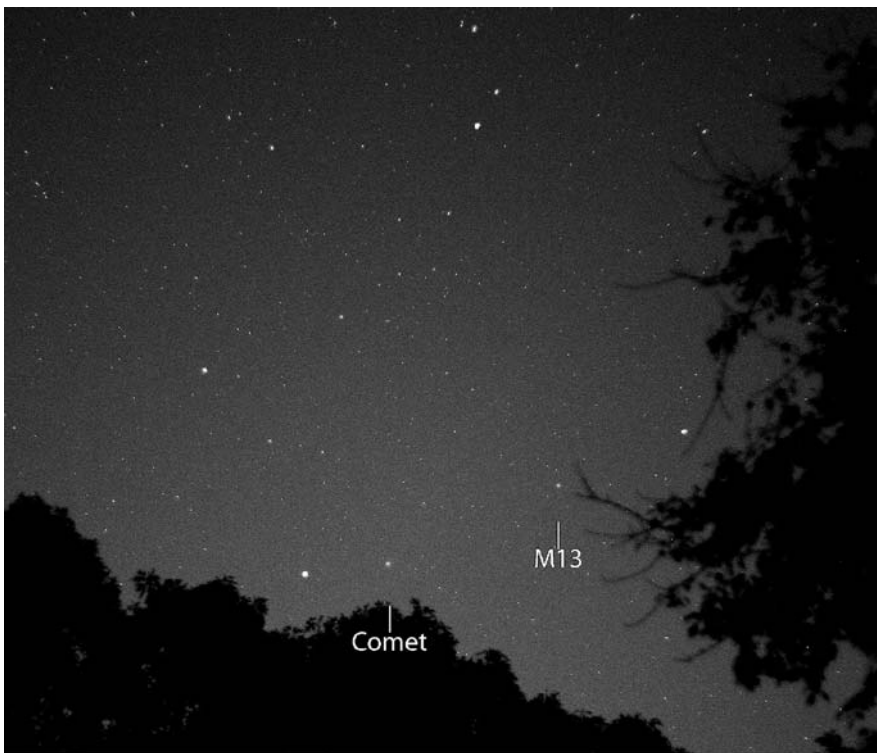


Figure 4.6. Blitzkrieg astrophotography. With only a couple of minutes to capture Comet SWAN (C/2006 M4) in the Keystone of Hercules, the author set up his Digital Rebel on a fixed tripod and exposed 5 seconds at ISO 800 through a 50-mm lens at  $f/1.8$ . JPEG image, brightness and contrast adjusted in *Photoshop*. Stars down to magnitude 9 are visible.

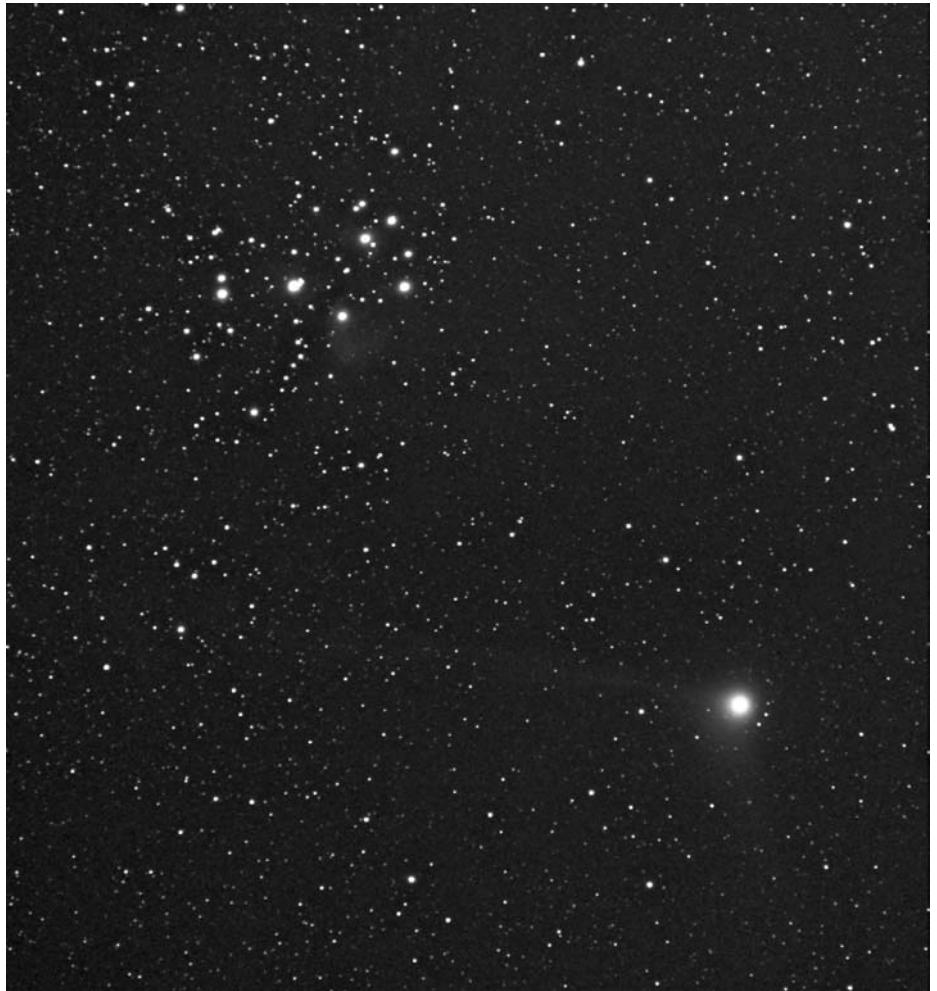


Figure 4.7. Comet Machholz and the Pleiades, 2005 January 6. Canon Digital Rebel (300D) with old Pentax 135-mm  $f/2.5$  lens using lens mount adapter, piggybacked on an equatorially mounted telescope; no guiding corrections. Single 3-minute exposure at ISO 400, processed with *Photoshop*.

#### 4.4 Piggybacking

If you have a telescope that tracks the stars (whether on an equatorial wedge or not), mount the camera “piggyback” on it and you can take longer exposures of the sky. For now, don’t worry about autoguiding; just set the telescope up carefully and let it track as best it can. Expose no more than 5 minutes or so. As in the previous project, long-exposure noise reduction should be turned on if available. Figure 4.7 shows what you can achieve.

With an equatorial mount (or a fork mount on an equatorial wedge), you can theoretically expose as long as you want, but both hot pixels and tracking errors

#### 4.5 Going further

start catching up with you if the exposure exceeds 5 minutes. If the telescope is on an altazimuth mount (one that goes up-down and left-right, with no wedge), then you have to deal with field rotation (Figure 9.2, p. 101). As a rule of thumb, this won't be a problem if you keep the exposure time under 30 seconds in most parts of the sky. You can expose up to 2 minutes if you're tracking objects fairly low in the east or west.

### 4.5 Going further

If your piggybacking experiments are successful, you can get better pictures by stacking multiple images. These can be the same JPEG images you're already capturing, but jump into the procedures in Chapter 12 at the appropriate point and combine the images. If you're using an altazimuth mount, be sure to "rotate and stack" rather than just "stack" or "translate and stack" (*translate* means "move up, down, and/or sideways").

For even better results, switch your camera to raw mode and do the full procedure in Chapter 12. Be sure to take some dark frames right after your series of exposures; leave the camera settings the same but put the lens cap on and expose for the same length of time. If your camera is a Nikon, take both the images and the dark frames in Mode 3 (see p. 17); that is, turn on long-exposure noise reduction but turn off power to the camera after the shutter closes, while the automatic dark frame is being taken.



## **Part II**

### Cameras, lenses, and telescopes



# Chapter 5

## Coupling cameras to telescopes

How do you take a picture through a telescope? Any of numerous ways. This chapter will cover the basic optical configurations as well as some (not all) ways of assembling the adapters. The most important thing to remember is that it's not enough to make everything fit together mechanically; you must also consider the spacings between optical elements, and not all configurations work with all telescopes.

### 5.1 Optical configurations

#### 5.1.1 Types of telescopes

Figure 5.1 shows the optical systems of the most popular kinds of telescopes. Several new types have appeared on the market in recent years.

The diagram doesn't show whether the curved surfaces are spherical or aspheric, but that makes a lot of difference. Refractors normally use lenses with spherical surfaces; for higher quality, they sometimes use extra elements or extra-low-dispersion (ED) glass.

The Newtonian reflector, invented by Sir Isaac Newton, was the first aspheric optical device; its mirror is a paraboloid. The modern Schmidt–Newtonian is similar, but its mirror is spherical (hence cheaper to manufacture) and it has an additional corrector plate of an unusual shape, making up the difference between a sphere and a paraboloid.

The classical Cassegrain reflector has two aspheric mirrors, a paraboloidal primary and a hyperboloidal secondary. The classical Ritchey–Chrétien looks just like it, but both mirrors are hyperboloidal, making it better at forming sharp images over a wide field on a flat sensor.<sup>1</sup>

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<sup>1</sup> The name *Cassegrain* is pronounced, roughly, *kahs-GRAN* in the original French but is nowadays normally *CASS-egg-rain* in English. *Chrétien* is pronounced, approximately, *kray-TYAN*.

## Coupling cameras to telescopes

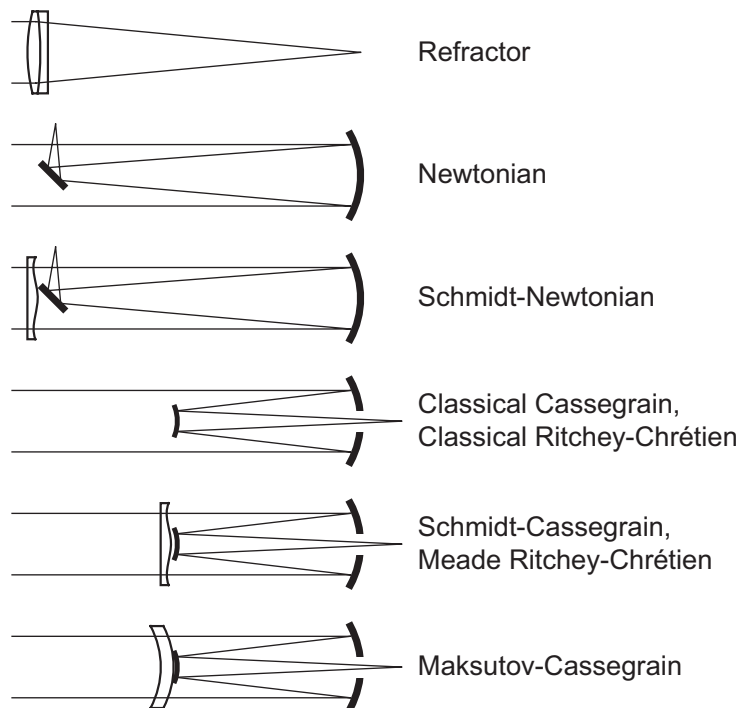


Figure 5.1. Optical elements of popular kinds of telescopes. Ritchey–Chrétien differs from related types only in use of aspherical surfaces.

Most amateurs use compact Schmidt–Cassegrain telescopes (SCTs). Here the two mirrors are both spherical, and the corrector plate makes up the difference between these and the desired aspheric surfaces. This type of telescope is sharp at the center of the field but suffers appreciable field curvature; that is, the periphery of the picture and the center are not in focus at the same time.

Recently, Meade Instruments introduced a design they call Ritchey–Chrétien which is actually a Schmidt–Cassegrain with an aspherized secondary. It overcomes the field curvature problem and is highly recommended for photography. However, the decision to call it Ritchey–Chrétien is controversial, and the name may not stick.

The Maksutov–Cassegrain is a classic high-resolution design for planetary work. It also works at least as well as the Schmidt–Cassegrain for deep-sky photography, except that the  $f$ -ratio is usually higher and the image is therefore not as bright.

### 5.1.2 Types of coupling

Figure 5.2 shows, from an optical viewpoint, how to couple a camera to a telescope. Optical details and calculations are given in *Astrophotography for the Amateur* and in Table 5.1.

## 5.1 Optical configurations

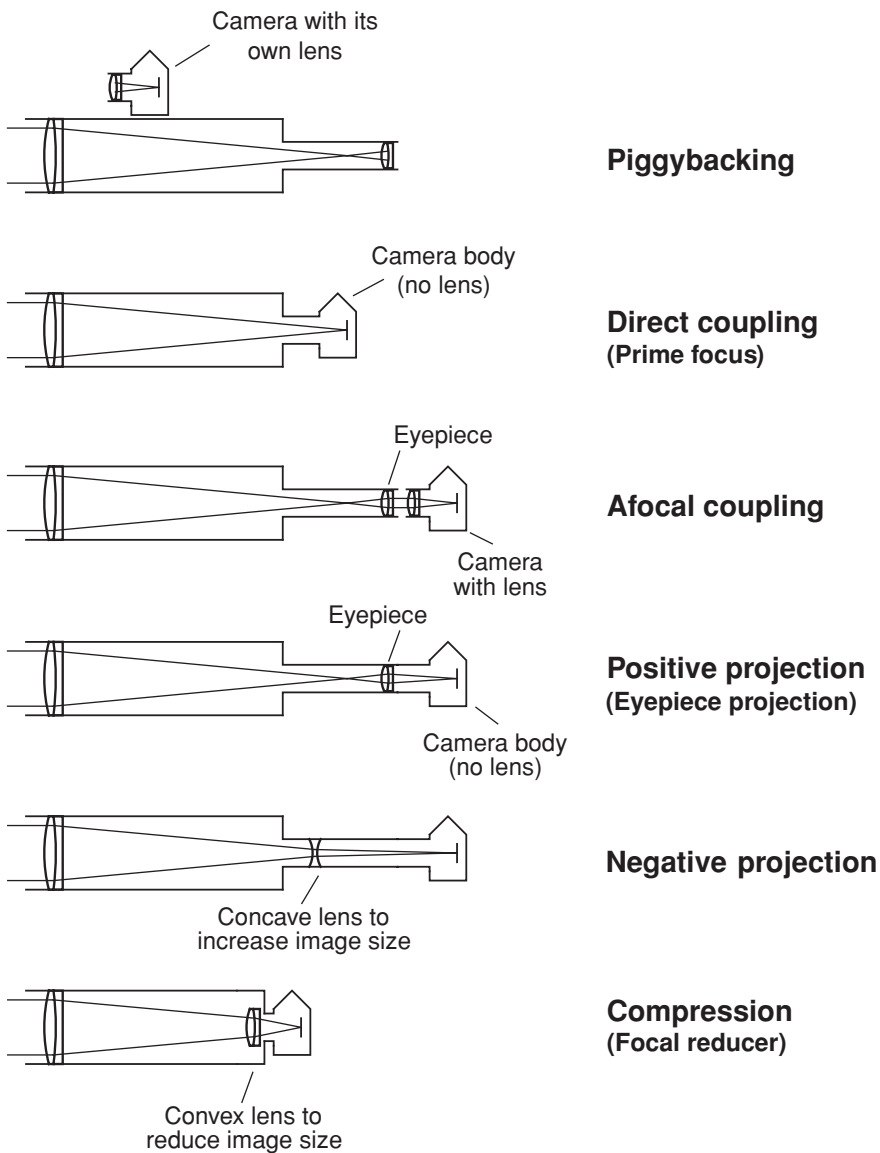


Figure 5.2. Ways of coupling cameras to telescopes. Piggybacking, direct coupling, and compression are main modes for deep-sky work.

Not all of these modes work equally well, for several reasons. First, DSLRs excel at deep-sky work, not lunar and planetary imaging. Accordingly, we want a bright, wide-field image. That means we normally leave the focal length and  $f$ -ratio of the telescope unchanged (with direct coupling) or reduce them (with compression). The modes that magnify the image and make it dimmer – positive and negative projection and, usually, afocal coupling – are of less interest.

Table 5.1 *Basic calculations for camera-to-telescope coupling.***Direct coupling**

Focal length of system = focal length of telescope

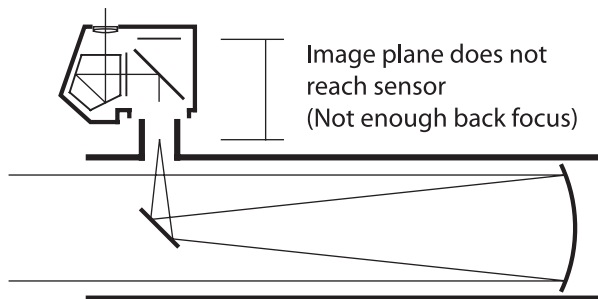
 $f$ -ratio of system =  $f$ -ratio of telescope**Afocal coupling**Projection magnification =  $\frac{\text{focal length of camera lens}}{\text{focal length of eyepiece}}$ Focal length of system = focal length of telescope  $\times$  projection magnification $f$ -ratio of system =  $f$ -ratio of telescope  $\times$  projection magnification**Positive projection, negative projection, and compression***If you get negative numbers, treat them as positive.* $A$  = distance from projection lens to sensor or film $F$  = focal length of projection lens  
(as a positive number even with a negative lens)Projection magnification =  $\frac{A-F}{F}$ Focal length of system = focal length of telescope  $\times$  projection magnification $f$ -ratio of system =  $f$ -ratio of telescope  $\times$  projection magnification

Figure 5.3. Why some Newtonians won't work direct-coupled to a camera. The solution is to use positive projection, or else modify telescope by moving the mirror forward in the tube.

Second, if you *do* want to increase the focal length, positive projection (eyepiece projection) is seldom the best way to do it. Positive projection increases the field curvature that is already our primary optical problem. Negative projection, with a Barlow lens in the telescope or a teleconverter on the camera, works much better. The appeal of positive projection is that, like afocal coupling, it works with any telescope that will take an eyepiece; you don't have to worry about the position of the focal plane (Figure 5.3). Indeed, positive projection with a 32- or 40-mm eyepiece can give a projection magnification near or below 1.0, equivalent to direct coupling or compression.

Regarding negative projection, note two things. First, a teleconverter on the camera has a convenient, known, magnification, and the optical quality can be

## 5.2 Fitting it all together

superb, but the DSLR may refuse to open the shutter if the electrical system in the teleconverter isn't connected to a camera lens. The cure is to use thin tape to cover the contacts connecting the teleconverter to the camera body.

Second, Barlow lenses make excellent negative projection lenses, but the magnification is not the same as with an eyepiece; it is greater, and the best way to measure it is to experiment. The reason is the depth of the camera body, putting the sensor appreciably farther from the Barlow lens than an eyepiece would be.

Compression is the opposite of negative projection. Meade and Celestron make focal reducers (compressors) designed to work with their Schmidt-Cassegrain telescopes. These devices work even better with DSLRs than with film SLRs, and they are very popular with DSLR astrophotographers. As well as making the image smaller and brighter, they help to flatten the field.

## 5.2 Fitting it all together

How do all these optical gadgets attach to the telescope? Figures 5.4–5.7 show a few of the most common kinds of adapters. The key to all of them is the *T-ring* or *T-adapter* that attaches to the camera body. Originally designed for cheap “T-mount” telephoto lenses in the 1960s, the T-ring is threaded  $42 \times 0.75$  mm so that other devices can screw into it, and its front flange is always 55 mm from the film or sensor.

T-rings differ in quality; some are noticeably loose on the camera body. All contain small screws that you can loosen to rotate the inner section relative to the outer part; do this if your camera ends up upside down or tilted and there is nowhere else to make the correction.

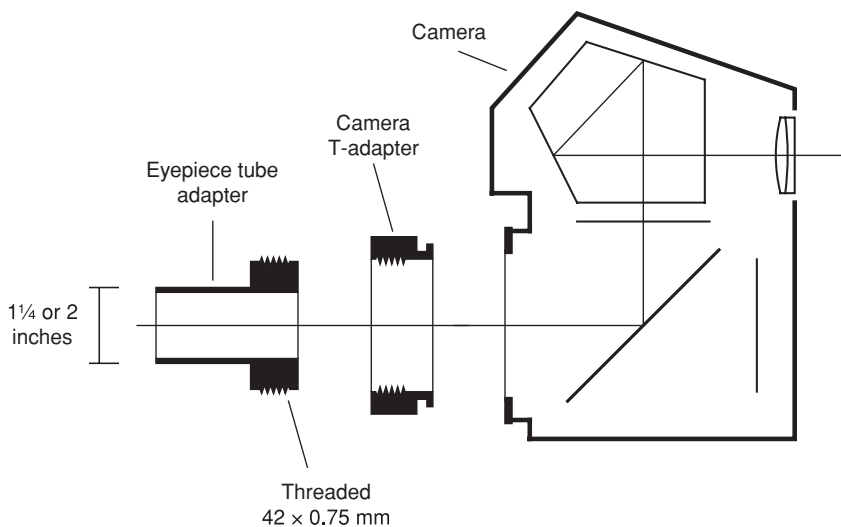


Figure 5.4. Simplest camera-to-telescope adapter fits into telescope in place of eyepiece.

## Coupling cameras to telescopes

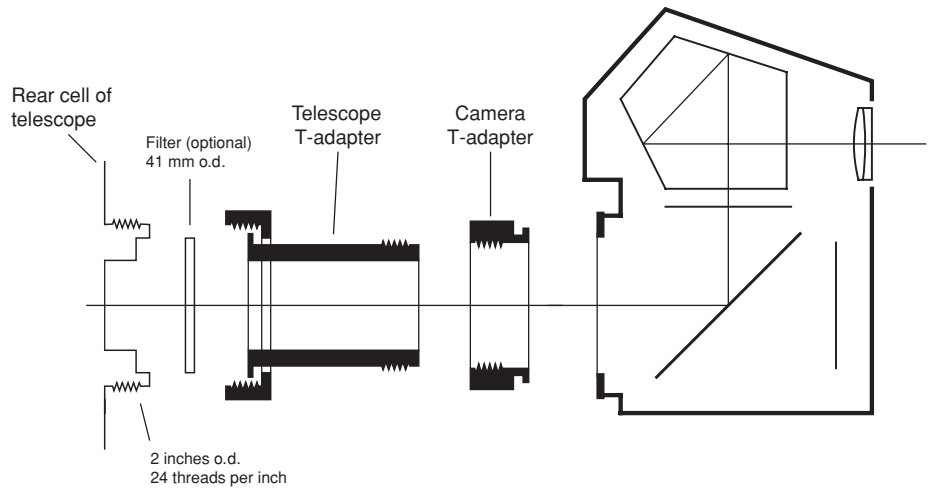


Figure 5.5. Schmidt-Cassegrains have a threaded rear cell and accept a matching T-adapter.

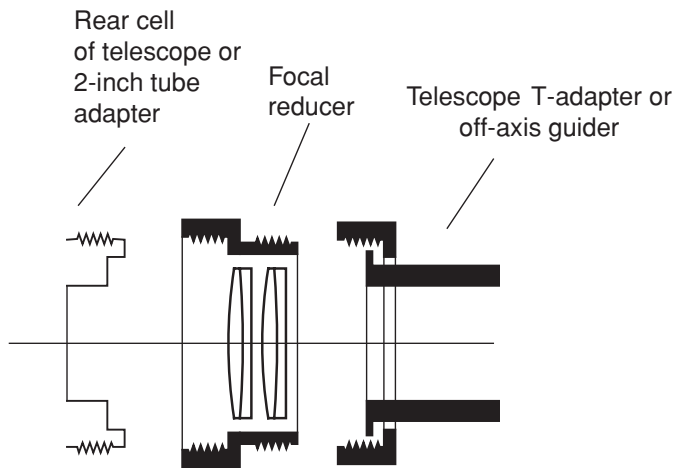


Figure 5.6. Meade or Celestron focal reducer screws onto rear cell of telescope.

You can get a simple eyepiece-tube adapter that screws into the T-ring (Figure 5.4) or a telescope T-adapter for other types of telescopes (Figure 5.5). Here you'll encounter the other screw coupling that is common with telescopes, the classic Celestron rear cell, which is 2 inches in diameter and has 24 threads per inch. Meade adopted the same system, and telescope accessories have been made with this type of threading for over 30 years. In particular, that's how the Meade and Celestron focal reducers attach to the telescope (Figure 5.6).

If your telescope doesn't have Celestron-style threads on its rear cell, or you're using an electric focuser that makes them inaccessible, then Meade's

## 5.3 Optical parameters

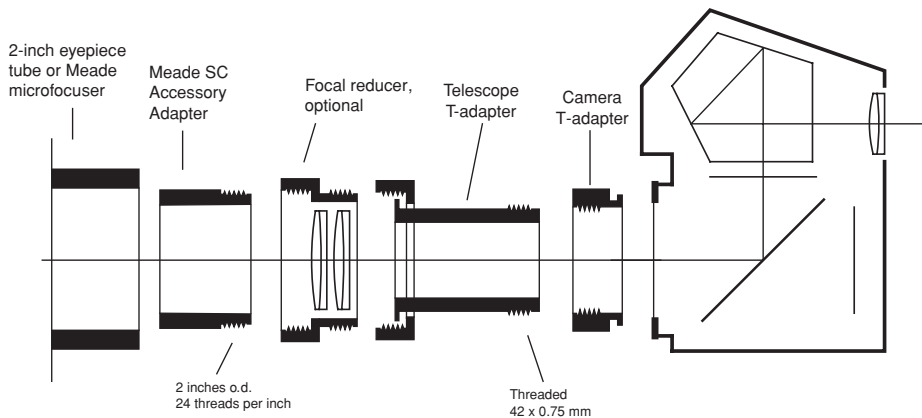


Figure 5.7. One way to use a Meade or Celestron focal reducer with a telescope that lacks a threaded rear cell, or with a 2-inch-diameter electric focuser.

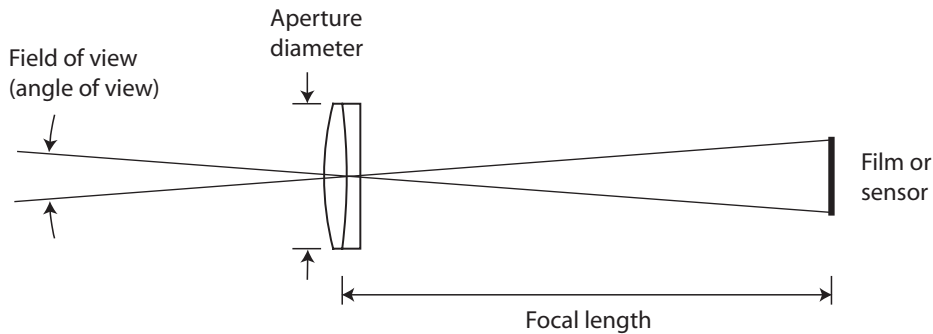


Figure 5.8. Every telescope or camera lens has an aperture, a focal length, and a field of view.

“SC accessory adapter” (Figure 5.7) comes to the rescue. It has the appropriate threads and fits into a 2-inch-diameter eyepiece tube or focuser.

Besides these common adapters, there are also adapters for many other configurations; check the catalogs or Web sites of major telescope dealers.

## 5.3 Optical parameters

### 5.3.1 Focal length

The *focal length* of a telescope or camera lens is a parameter that determines the size of objects in the image (Figure 5.8). In conjunction with the film or sensor size, the focal length also determines the field of view.<sup>2</sup>

<sup>2</sup> If you're new to optical diagrams, you may wonder why Figure 5.8 shows rays of light spreading apart while Figure 5.1 shows them coming together. The answer is that Figure 5.1 shows two rays from the same point on a distant object, but Figure 5.8 shows one ray from each of two points some distance apart.

If your telescope is a refractor or Newtonian, the focal length is also the length of the tube (the distance from the lens or mirror to the sensor or film). Technically, the focal length is the distance at which a simple lens forms an image of an infinitely distant object, such as a star.

Telescopes in the Cassegrain family have a focal length longer than the actual tube length because the secondary mirror enlarges the image. For example, the popular 8-inch (20-cm)  $f/10$  Schmidt–Cassegrain packs a 2000-mm focal length into a telescope tube about 500 mm long.

The way a camera is coupled to a telescope affects the focal length of the resulting system (Table 5.1). With direct coupling, you use the telescope at its inherent focal length, unmodified. Positive projection and afocal coupling usually increase the focal length; negative projection always does. Compression always reduces it.

### 5.3.2 Aperture

The aperture (diameter) of a telescope determines how much light it picks up. A 10-cm (4-inch) telescope picks up only a quarter as much light from the same celestial object as a 20-cm (8-inch), because a 10-cm circle has only a quarter as much surface area as a 20-cm circle.

Telescopes are rated for their aperture; camera lenses, for their focal length. Thus a 200-mm camera lens is much smaller than a 20-cm (200-mm) telescope.

In this book, apertures are always given in centimeters or inches, and focal lengths are always given in millimeters, partly because this is traditional, and partly because it helps keep one from being mistaken for the other.

In the context of camera lenses, “aperture” usually means  $f$ -ratio rather than diameter. That’s why I use the awkward term “aperture diameter” in places where confusion must be avoided.

### 5.3.3 $f$ -ratio and image brightness

The  $f$ -ratio of a telescope or camera lens is the ratio of focal length to aperture:

$$f\text{-ratio} = \frac{\text{Focal length}}{\text{Aperture diameter}}$$

One of the most basic principles of photography is that the brightness of the image, on the film or sensor, depends on the  $f$ -ratio. That’s why, in daytime photography, we describe every exposure with an ISO setting, shutter speed, and  $f$ -ratio.

To understand why this is so, remember that the aperture tells you how much light is gathered, and the focal length tells you how much it is spread out on the sensor. If you gather a lot of light and don’t spread it out much, you have a low  $f$ -ratio and a bright image.

### 5.3 Optical parameters

The mathematically adept reader will note that the amount of light gathered, and the extent to which it is spread out, are both *areas* whereas the *f*-ratio is calculated from two *distances* (focal length and aperture). Thus the *f*-ratio is actually the square root of the brightness ratio. Specifically:

$$\text{Relative change in brightness} = \left( \frac{\text{Old } f\text{-ratio}}{\text{New } f\text{-ratio}} \right)^2$$

So at *f*/2 you get twice as much light as at *f*/2.8 because  $(2.8/2)^2 = 2$ . This allows you to take the same picture with half the exposure time, or in general:

$$\begin{aligned} &\text{Exposure time at new } f\text{-ratio} = \\ &\text{Exposure time at old } f\text{-ratio} \left( \frac{\text{New } f\text{-ratio}}{\text{Old } f\text{-ratio}} \right)^2 \end{aligned}$$

For DSLRs, this formula is exact. For film, the exposure times would have to be corrected for reciprocity failure.

Low *f*-ratios give brighter images and shorter exposures. That's why we call a lens or telescope "fast" if it has a low *f*-ratio.

#### Comparing apples to oranges

A common source of confusion is that lenses change their *f*-ratio by changing their diameter, but telescopes change their *f*-ratio by changing their focal length.

For instance, if you compare 200-mm *f*/4 and *f*/2.8 telephoto lenses, you're looking at two lenses that produce the same size image but gather different amounts of light. But if you compare 8-inch (20-cm) *f*/10 and *f*/6.3 telescopes, you're comparing telescopes that gather the same amount of light and spread it out to different extents.

Lenses have adjustable diaphragms to change the aperture, but telescopes aren't adjustable. The only way to change a telescope from one *f*-ratio to another is to add a compressor (focal reducer) or projection lens of some sort. When you do, you change the image size.

That's why, when you add a focal reducer to a telescope to brighten the image, you also make the image smaller. Opening up the aperture on a camera lens does no such thing because you're not changing the focal length.

There are no focal reducers for camera lenses, but there are Barlow lenses (negative projection lenses). They're called *teleconverters*, and – just like a Barlow lens in a telescope – they increase the focal length and the *f*-ratio, making the image larger and dimmer.

#### What about stars and visual observing?

The received wisdom among astronomers is that *f*-ratio doesn't affect star images, only images of extended objects (planets, nebulae, and the like). The reason is that star images are supposed to be points regardless of the focal length. This is only partly true; the size of star images depends on optical quality, focusing

accuracy, and atmospheric conditions. The only safe statement is that the limiting star magnitude of an astronomical photograph is hard to predict.

The  $f$ -ratio of a telescope does not directly determine the brightness of a *visual* image. The eyepiece also plays a role. A 20-cm  $f/10$  telescope and a 20-cm  $f/6.3$  telescope, both operating at  $\times 100$ , give equally bright views, but with different eyepieces. With the same eyepiece, the  $f/6.3$  telescope would give a brighter view at lower magnification.

### Why aren't all lenses $f/1$ ?

If low  $f$ -ratios are better, why don't all telescopes and lenses have as low an  $f$ -ratio as possible? Obviously, physical bulk is one limiting factor. A 600-mm  $f/1$  camera lens, if you could get it, would be about two feet in diameter, too heavy to carry; a 600-mm  $f/8$  lens is transportable.

A more important limitation is lens aberrations. There is no way to make a lens or mirror system that forms perfectly sharp images over a wide field. This fact may come as a shock to the aspiring photographer, but it is true.

Consider for example a Newtonian telescope. As Sir Isaac Newton proved, a perfect paraboloidal mirror forms a perfect image at the very center of the field. Away from the center of the field, though, the light rays are no longer hitting the paraboloid straight-on. In effect, they are hitting a shape which, to them, is a distorted or tilted paraboloid, and the image suffers coma, which is one type of off-axis blur. A perfectly made Cassegrain or refractor has the same problem.

The lower the  $f$ -ratio, the more severe this problem becomes. An  $f/10$  paraboloid is nearly flat and still looks nearly paraboloidal when approached from a degree or two off axis. An  $f/4$  paraboloid is deeply curved and suffers appreciable coma in that situation. For that reason, "fast" telescopes, although designed for wide-field viewing, often aren't very sharp at the edges of the field.

Complex mirror and lens systems can reduce aberrations but never eliminate them completely. Any optical design is a compromise between tolerable errors. For more about aberrations, see *Astrophotography for the Amateur* (1999), pp. 71–73.

Incidentally,  $f/1$  is not a physical limit. Canon once made a 50-mm  $f/0.95$  lens. Radio astronomers use dish antennas that are typically  $f/0.3$ .

### 5.3.4 Field of view

Astronomers measure apparent distances in the sky in degrees (Figure 5.10); a degree is divided into 60 arc-minutes ( $60'$ ), and an arc-minute is divided into 60 arc-seconds ( $60''$ ).

The exact formula for field of view is:

$$\text{Field of view} = 2 \tan^{-1} \frac{\text{Sensor width (or height, etc.)}}{2 \times \text{Focal length}}$$

### 5.3 Optical parameters



Figure 5.9. The star clusters M35 and NGC 2158 (smaller), imaged at the prime focus of a 14-cm (5.5-inch)  $f/7$  TEC apochromatic refractor. Stack of three 5-minute exposures at ISO 800 with a filter-modified Nikon D50 through a Baader UV/IR-blocking filter, using a Losmandy equatorial mount and an autoguider on a separate guidescope. (William J. Shaheen.)

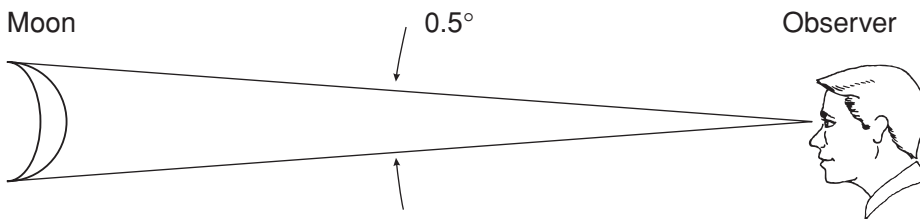


Figure 5.10. The apparent size of objects in the sky is measured as an angle. (From *Astrophotography for the Amateur*.)

For focal lengths much longer than the sensor size, such as telescopes, a much simpler formula gives almost exactly the same result:

$$\text{Field of view} = 57.3^\circ \times \frac{\text{Sensor width (or height, etc.)}}{\text{Focal length}}$$

Figure 5.11 shows the field of view of a Canon or Nikon APS-C sensor (Digital Rebel family, Nikon D70 family, and the like) with various focal lengths, superimposed on an image of the Pleiades star cluster. For the same concept applied to telephoto lenses, see p. 71, and for more about field of view, see *Astrophotography for the Amateur* (1999), pp. 73–75.

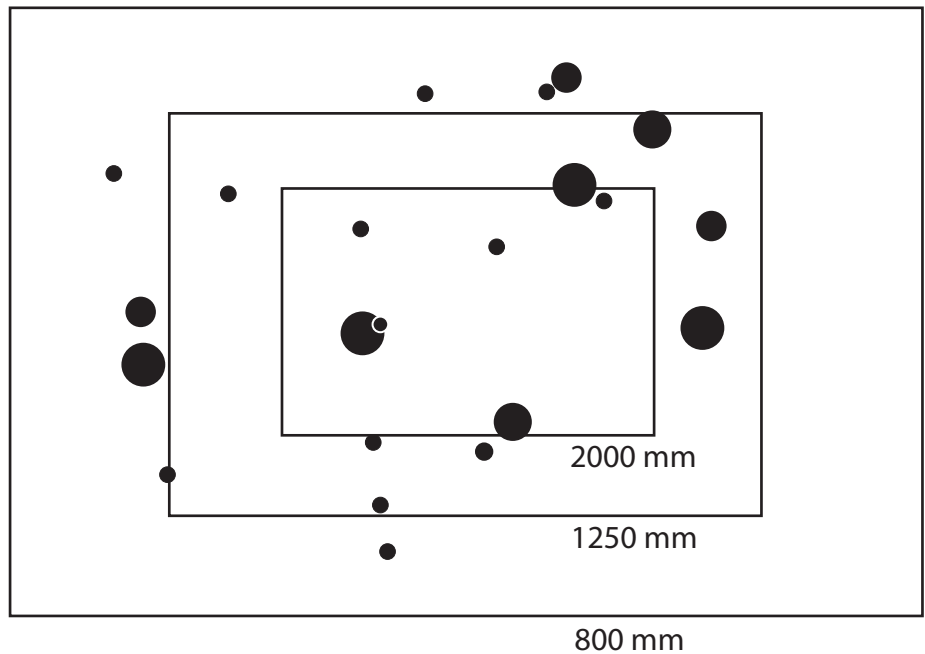


Figure 5.11. Field of view of an APS-C-size sensor with various focal lengths, relative to the Pleiades star cluster. Compare Figure 7.1 on p. 71.

Note however that the focal length may not be what you think it is. Schmidt-Cassegrains and similar telescopes change focal length appreciably when you focus them by changing the separation of the mirrors. Even apart from this, the focal length of a telescope or camera lens often differs by a few percent from the advertised value. To determine focal length precisely, use *TheSky*, *Starry Night*, or another computerized star atlas to plot the field of view of your camera and telescope, then compare the calculated field to the actual field.

### 5.3.5 Image scale in pixels

Unlike astronomical CCD camera users, DSLR astrophotographers do not often deal with single pixels because there are too many of them. Even a pinpoint star image usually occupies six or eight pixels on the sensor. This is a good thing because it means that star images are much larger than hot pixels.

Still, it can be useful to know the image scale in pixels. To find it, first determine the size of each pixel in millimeters. For instance, the Canon XT*i* (400D) sensor measures 14.8 × 22.2 mm, according to Canon's specifications, and has 2592 × 3888 pixels. That means the pixel size is

$$\frac{14.8}{2592} = 0.00571 \text{ mm vertically}$$

## 5.4 Vignetting and edge-of-field quality

and also

$$\frac{22.2}{3888} = 0.00571 \text{ mm horizontally}$$

Now find the field of view of a single pixel; that is, pretend your sensor is 0.00571 mm square. Suppose the telescope is a common 20-cm (8-inch)  $f/10$  Schmidt–Cassegrain with a focal length of 2000 mm. Then:

$$\text{Field of one pixel} = 57.3^\circ \times \frac{0.00571 \text{ mm}}{2000 \text{ mm}} = 0.000\,016\,359^\circ = 0.59''$$

As with astronomical CCD cameras, the pixel size works out to be close to the resolution limit of the telescope.

### 5.3.6 “What is the magnification of this picture?”

Non-astronomers seeing an astronomical photograph often ask what magnification or “power” it was taken at.

In astronomy, such a question almost has no answer. With microscopes, it does. If you photograph a 1-mm-long insect and make its image 100 mm long on the print, then clearly, the magnification of the picture is  $\times 100$ .

But when you tell people that your picture of the Moon is  $1/35\,000\,000$  the size of the real Moon, somehow that’s not what they wanted to hear. Usually, what they mean is, “How does the image in the picture compare to what I would see in the sky with my eyes, with no magnification?” The exact answer depends, of course, on how close the picture is to the viewer’s face.

But a rough answer can be computed as follows:

$$\text{“Magnification” of picture} = \frac{45^\circ}{\text{Field of view of picture}}$$

That is: If you looked through a telescope at this magnification, you’d see something like the picture. Here  $45^\circ$  is the size of the central part of the human visual field, the part we usually pay attention to, and is also the apparent field of a typical (not super-wide) eyepiece.

So a picture that spans the Moon (half a degree) has a “magnification” of 90. Deep-sky piggyback images often have rather low “magnification” computed this way, anywhere from 10 down to 2 or less.

## 5.4 Vignetting and edge-of-field quality

As *Astrophotography for the Amateur* explains at length, few telescopes produce a sharp, fully illuminated image over an entire 35-mm film frame or even an entire DSLR sensor. The reason is that telescopes are designed to work with eyepieces, and with an eyepiece, what you want is maximum sharpness at the very center of the field.

Except for a few astrographic designs, telescopes just don't work like camera lenses. Of course, if you put an eyepiece on even the finest camera lens, you'd probably find it falling far short of diffraction-limited resolution. Photographic objectives and telescopes are different instruments. Telescopes will generally show some coma or astigmatism away from the center of the field.

A more noticeable problem is *vignetting*, or lack of full illumination away from the center. An APS-C-size DSLR sensor is slightly larger, corner to corner, than the inside diameter of a standard eyepiece tube. Thus, to reduce vignetting, you should avoid working through a 1 $\frac{1}{4}$ -inch eyepiece tube if possible; switch to a 2-inch focuser or a direct T-adapter. But even then, a telescope with glare stops designed to work well with eyepieces will not fully illuminate the edges of the field.

Vignetting can be corrected by image processing (p. 188), but I prefer to take a more optimistic approach. It's not that the image is small; it's that the sensor is big. A DSLR sensor has far more pixels than a typical astronomical CCD, and that means the picture is croppable. You can use a couple of megapixels from the middle of a 10-megapixel sensor and get a very fine image.

# Chapter 6

## More about focal reducers

Focal reducers are invaluable for deep-sky work with DSLRs because they make the image smaller and brighter. Since the DSLR sensor is smaller than 35-mm film, you can switch from film to a DSLR, add a focal reducer, and cover the same field with a brighter image.

The most popular Meade and Celestron focal reducers multiply the focal length and  $f$ -ratio by 0.63 (giving  $f/6.3$  with an  $f/10$  telescope). That's a handy reduction factor because it shrinks an image from the size of 35-mm film to the size of an APS-C sensor. What's more, the image comes out  $(1/0.63)^2 = 2.52$  times as bright, cutting the exposure time to 40% of what it would have been.

But focal reducers are sadly misunderstood, and they don't always work the way the users expect. In what follows, I'll try to clear up some misconceptions.

### 6.1 Key concepts

The first thing to understand is that *a focal reducer makes the image smaller – it doesn't make the field wider*. It doesn't turn your telescope into a wider-field instrument than it was originally.

It's true that the field of view increases when the image becomes smaller, because more of the image fits on the sensor. But that is only true of the image that the telescope captured in the first place. A focal reducer will not make the telescope see things that were outside its field altogether.

That is one reason some vignetting is almost inevitable with a focal reducer. (Roughly, with a  $\times 0.63$  reducer, you'll get the same vignetting on a DSLR sensor that you got on film without it.) Another cause of vignetting is the limited diameter of the reducer itself.

Second, *there is always some loss of image quality* because, just like any other lens, the focal reducer introduces aberrations. In the best case, when the focal reducer is well matched to the telescope, the resulting image can be quite good. But focal reducers do not automatically produce sharp, aberration-free images. There are always some compromises.

## More about focal reducers

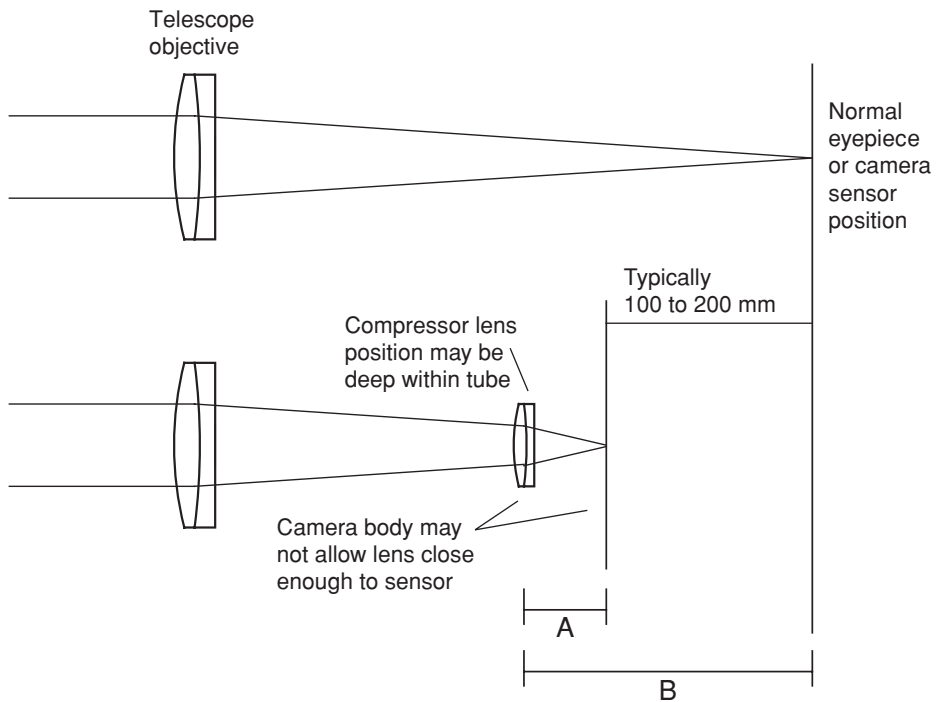


Figure 6.1. Not all telescopes can accommodate a focal reducer.

Third, a focal reducer gives its rated magnification only at a specific distance from the sensor. If you put a  $\times 0.63$  focal reducer the wrong distance from the sensor, it may come out  $\times 0.5$ , or  $\times 0.8$ , or it may fail to form an image at all. After you install a focal reducer, I recommend that you measure how much it actually compresses the image with your setup.

Fourth, a focal reducer requires a lot of back focus. It has to intercept the converging light rays at a position far forward of where an eyepiece or Barlow lens would go (Figure 6.1).

That is why you generally can't use a focal reducer with a Newtonian telescope; it would have to go deep within the tube. The same is true of some refractors. Schmidt-Cassegrains and other catadioptric telescopes work well with focal reducers because they focus by shifting the primary mirror forward, and the shift is greatly magnified by the secondary mirror (Figure 6.2).

## 6.2 Optical calculations

To calculate the position and magnification of the image formed by a focal reducer, see Figure 6.1 and Table 6.1. If you look back at Table 5.1 on p. 52, you'll see that one of the formulae has been rearranged to avoid giving negative numbers in this situation. Both tables are equally valid if you follow the instructions.

## 6.2 Optical calculations

Table 6.1 *Calculations for compression, arranged to avoid negative numbers.*  
(Compare Table 5.1, p. 52.)

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### Compression

$A$  = distance from focal reducer lens to sensor or film

$F$  = focal length of focal reducer lens

$$B \text{ (defined in Figure 6.1)} = \frac{A}{\text{Projection magnification}} = \frac{F \times A}{F - A}$$

Additional back focus required =  $B - A$

$$\text{Projection magnification (always less than 1)} = \frac{A}{B} = \frac{F - A}{F}$$

Focal length of system = focal length of telescope  $\times$  projection magnification

$f$ -ratio of system =  $f$ -ratio of telescope  $\times$  projection magnification

$$\text{Exposure time needed with focal reducer} = \frac{\text{exposure time without reducer}}{(\text{projection magnification})^2}$$


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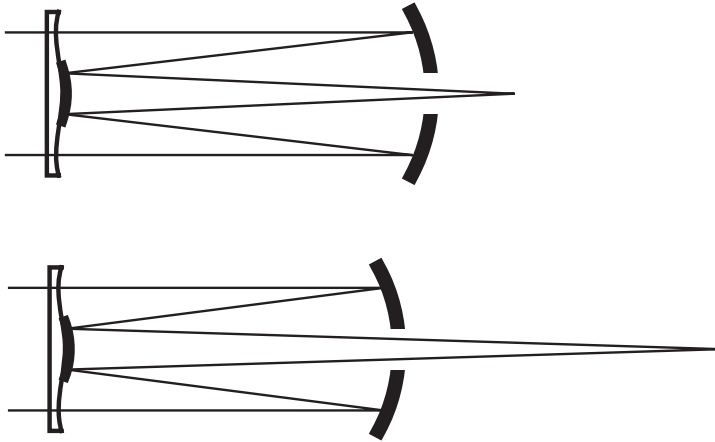


Figure 6.2. Schmidt–Cassegrains, Maksutov–Cassegrains, and related telescopes focus by moving the main mirror, shifting the focal plane over a wide range and overcoming the problem in Figure 6.1. Telescope focal length increases when this is done.

The projection magnification with a focal reducer is always less than 1, typically 0.3–0.7. A magnification of 0.707 will double the image brightness and cut your exposure time in half.

You must generally find  $F$ , the focal length of the compressor lens, by experiment; Figure 6.4 shows how to do so. Make sure the light source is really distant – at least on the other side of the room – and measure from the middle of a multi-lens focal reducer.  $F$  is always appreciably greater than  $A$  and  $B$ .

## More about focal reducers



Figure 6.3. The Trifid Nebula (M20). Stack of four 3-minute exposures at ISO 400 with a Canon Digital Rebel (300D) through an 8-inch (20-cm)  $f/10$  Schmidt–Cassegrain telescope with  $\times 0.63$  focal reducer giving effective  $f/6.3$ . Cropped from a larger image; processed with *MaxIm DL*, *Photoshop*, and *Neat Image*.

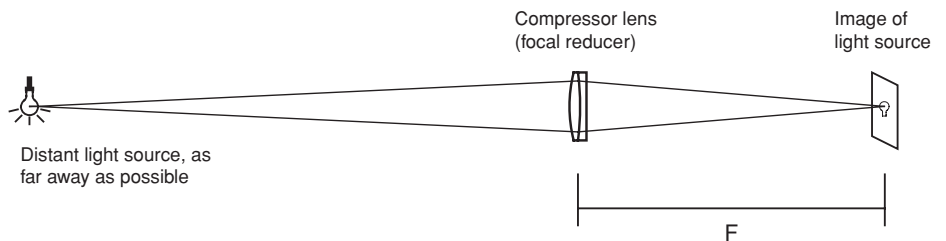


Figure 6.4. To find the focal length of a compressor lens (focal reducer), use it to form an image of a distant light source.

## 6.3 Commercially available focal reducers

### 6.3.1 Lens types

If field curvature is not a concern, you can make your own focal reducer using an objective lens from binoculars or a small telescope. The first focal reducers were made from 50-mm binocular objectives with  $F \approx 200$  mm.

The field curvature of a Schmidt–Cassegrain, however, will be worsened by a focal reducer that is not specifically designed to counteract it. Meade and Celestron focal reducers do flatten the field, and, in my experience, the field of an  $f/10$  Schmidt–Cassegrain is flatter with the  $f/6.3$  reducer in place than without it. For relevant optical theory, see H. Rutten and M. van Venrooij, *Telescope Optics* (Willmann–Bell, 1988), pp. 152–154.

### 6.3.2 Meade and Celestron $f/6.3$

The Meade and Celestron “ $f/6.3$ ” reducers (actually  $\times 0.63$ ) are similar if not identical. The focal length is about 240 mm and the intended lens-to-sensor distance ( $A$ ) is about 110 mm.

If you do the calculation, you’ll see that this lens-to-sensor distance should give  $\times 0.54$ . But in fact it gives a perfect  $f/6.3$  with an 8-inch (20-cm)  $f/10$  Schmidt–Cassegrain telescope. Why? Because the focal length of a Schmidt–Cassegrain changes as you rack the mirrors closer together (Figure 6.2), and Meade and Celestron take this into account. After all, when you focus to accommodate the focal reducer, you are increasing the effective tube length (from secondary to focal plane) nearly 20%.

To complicate matters, there are reliable reports that when Meade first switched the manufacturing of focal reducers from Japan to China, there was a batch of “ $f/6.3$ ” reducers with a much shorter focal length (about 150 mm). These of course gave much more than the expected amount of compression and produced severe vignetting.

### 6.3.3 Meade $f/3.3$

The Meade “ $f/3.3$ ” reducer is designed for astronomical CCD cameras and works at  $\times 0.3$  to  $\times 0.5$  depending on how you use the spacers provided with it. Its focal length is about 85 mm. For the rated magnification of  $\times 0.33$ , the lens-to-sensor distance is just under 55 mm.

Note that you cannot get  $\times 0.33$  with a DSLR. The front of the camera’s T-ring is 55 mm from the sensor, and the T-thread adapter provided by Meade takes up approximately another 8 mm without spacers, so  $A = 63$  mm (or a little more) and the magnification is about  $\times 0.25$ .

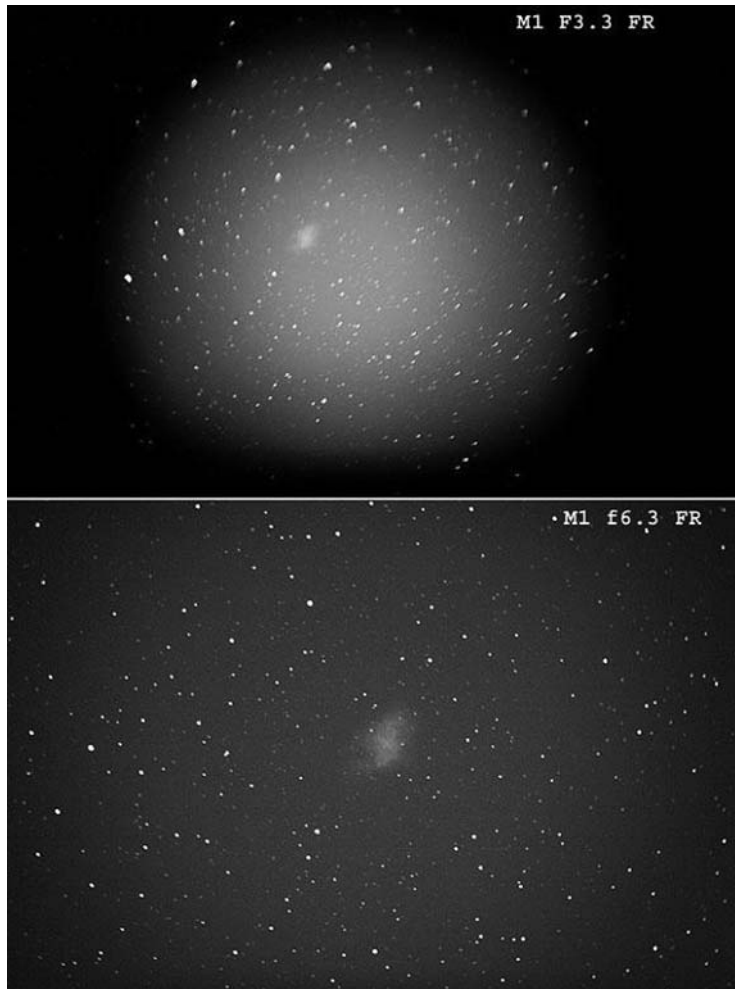


Figure 6.5. Compression, extreme and moderate. Uncropped 1-minute exposures of the Crab Nebula (M1) with a Nikon D100 at ISO 1600 through an equatorially mounted 12-inch (30-cm)  $f/10$  Schmidt–Cassegrain telescope. Top: With Meade  $\times 0.33$  focal reducer working at  $\times 0.25$ , giving effective  $f/2.5$ . Bottom: With Meade  $\times 0.63$  focal reducer giving effective  $f/6.3$  or slightly less. (Rick Jackimowicz.)

Aberrations in such an extreme compressor are a serious problem, and optical image quality leaves something to be desired. You will probably find that the lens-to-sensor spacing greatly affects the correction of off-axis aberrations. Still, the focal reducer provides a way to image faint objects under difficult conditions.<sup>1</sup>

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<sup>1</sup> I am grateful to Rick Jackimowicz for the focal length measurements and related information, as well as for Figure 6.5.

#### 6.3.4 Others

Several other telescope manufacturers make focal reducers matched to their telescopes; among them are Vixen ([www.vixenamerica.com](http://www.vixenamerica.com)) and Takahashi ([www.takahashiamerica.com](http://www.takahashiamerica.com)). General-purpose focal reducers are made by Astro-Physics ([www.astro-physics.com](http://www.astro-physics.com)), Optec ([www.optecinc.com](http://www.optecinc.com)), Lumicon ([www.lumicon.com](http://www.lumicon.com)), William Optics ([www.williamoptics.com](http://www.williamoptics.com)), and other vendors. Lumicon, in particular, makes large-diameter focal reducers to reduce vignetting with larger telescopes.

Before buying a focal reducer, check carefully whether it is designed to work with an SLR camera body (some have  $A$  too small) and whether it corrects the aberrations of your type of telescope, since refractors, for instance, are quite different from Schmidt–Cassegrains. Test it carefully when you get it and make sure it works as intended.

# Chapter 7

## Lenses for piggybacking

### 7.1 Why you need another lens

You will have gathered that I think piggybacking is one of the best astronomical uses for a DSLR. But the “kit” lens that probably came with your DSLR is not very suitable for piggyback astrophotography. It has at least three disadvantages:

- It is slow (about  $f/4$  or  $f/5.6$ ).
- It is a zoom lens, and optical quality has been sacrificed in order to make zooming possible.
- It is plastic-bodied and not very sturdy; the zoom mechanism and the autofocus mechanism are both likely to move during a long exposure.

Fortunately, you have many alternatives, some of which are quite inexpensive. One is to buy your camera maker’s 50-mm  $f/1.8$  “normal” lens; despite its low price, this is likely to be the sharpest lens they make, especially when stopped down to  $f/4$ . Another alternative is to use an inexpensive manual-focus telephoto lens from the old days. There are several ways of doing this; Nikon DSLRs take Nikon manual-focus lenses (though the autofocus and light meter don’t work), and Canons accept several types of older lenses via adapters.

#### 7.1.1 Big lens or small telescope?

But wait a minute – instead of a lens, should you be looking for a small telescope, perhaps an  $f/6$  “short-tube” refractor? Some of these have ED glass or even three-element lenses and perform very well for astrophotography.

In my opinion and experience, good telephoto lenses perform even better. After all, they have more elements and more sophisticated optical designs. If two or three lens elements were enough, even with ED glass, that’s how camera makers would build telephoto lenses. It isn’t.

## 7.1 Why you need another lens

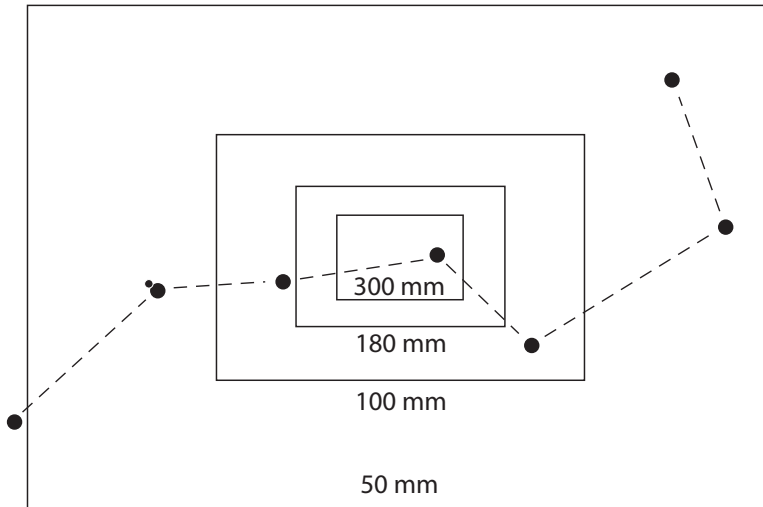


Figure 7.1. Field of view of various lenses with Canon or Nikon APS-C sensor compared to the Big Dipper (Plough).

The advantage of the telescope is its versatility. You can use it visually as well as photographically, and it may well come with a mount and drive of its own, whereas the telephoto lens would have to be piggybacked on an existing telescope. It may also accommodate a focal reducer, which telephoto lenses never do. There is certainly a place for both types of instruments in astrophotography.

### 7.1.2 Field of view

The first question to ask about a lens is of course its field of view – how much of the sky does it capture?

Figure 7.1 and Table 7.1 give the field of view of several common lenses with DSLRs that have an APS-C-size sensor. The numbers in Table 7.1 are exact for the Canon Digital Rebel family (EOS 300D, 350D, 400D); with the Nikon D50, D70, and their kin, the field is about 5% larger.

Field of view is measured in degrees, and some lens catalogs give only the diagonal “angle of view” from corner to corner of the picture. The exact formula for field of view is given on p. 58.

### 7.1.3 $f$ -ratio

Faster is better, right? The  $f$ -ratio of a lens determines how bright the image will be, and hence how much you can photograph in a short exposure. Lower  $f$ -numbers give a brighter image.

But there’s a catch: speed is expensive. Nowadays, fast lenses are quite sharp but cost a lot of money. In earlier years, the cost was in performance, not just

Table 7.1 *Field of view of various lenses with APS-C sensor.*

Focal length	Field of view		
	Height	Width	Diagonal
28 mm	30°	43°	50°
35 mm	24°	35°	42°
50 mm	17°	25°	30°
100 mm	8.5°	12.7°	15°
135 mm	6.3°	9.4°	11°
180 mm	4.7°	7.1°	8.5°
200 mm	4.2°	6.3°	7.6°
300 mm	2.8°	4.2°	5.1°
400 mm	2.1°	3.2°	3.8°

price, and lenses faster than  $f/2.8$  were not completely sharp wide open. Until about 1990, it was a rule of thumb that every lens performed best if you stopped it down a couple of stops from maximum aperture, but in this modern era of ED glass and aspheric designs, some lenses are actually sharpest wide open.

Because DSLRs do not suffer reciprocity failure, deep-sky photography is no longer a struggle to get enough light onto the film before it forgets all the photons. We no longer need fast lenses as much as we used to. Under dark skies, I find that  $f/4$  is almost always fast enough.

#### 7.1.4 Zoom or non-zoom?

In my experience, some of the best zoom lenses are *just* acceptable for astrophotography. Most zoom lenses aren't. A zoom lens, even a high-technology zoom lens from a major manufacturer, is designed to be tolerable at many focal lengths rather than perfect at one.

Dealers have learned that a zoom lens gives a camera "showroom appeal" – it's more fun to pick up the camera, look through it, and play with the zoom. People have gotten used to extreme zoom lenses on camcorders, which are low-resolution devices not bothered by optical defects. And some photographers just don't like to change lenses (especially if there's a risk of getting dust on the sensor). For these reasons, zoom lenses, including those with extreme ratios, have become ubiquitous.

One look at Nikon's or Canon's published MTF curves should make it clear that a mediocre fixed-length lens is usually better than a first-rate zoom. If you have nothing but zoom lenses, try a non-zoom ("prime") lens; you're in for a treat.

If you do attempt astrophotography with a zoom lens – as I have done – beware of “zoom creep.” During the exposure, the zoom mechanism can shift. You may have to tape it in place to prevent this.

## 7.2 Lens quality

### 7.2.1 Sharpness, vignetting, distortion, and *bokeh*

Piggybacking is a very tough test of lens quality. The stars are point sources, and any blur is immediately noticeable. Every star in the picture has to be in focus all at once; there is no out-of-focus background. And we process the picture to increase contrast, which emphasizes any vignetting (darkening at the edges).

Having said that, I should add that the situation with DSLRs is not quite the same as with film. High-speed film is itself very blurry; light diffuses sideways through it, especially the light from bright stars. When you put a very sharp lens on a DSLR and this blurring is absent, the stars all look alike and you can no longer tell which ones are brighter.

For that reason, less-than-perfect lenses are not always unwelcome with DSLRs. A small amount of uncorrected spherical or chromatic aberration, to put a faint halo around the brighter stars, is not necessarily a bad thing. What is most important is uniformity across the field. The stars near the edges should look like the stars near the center.

All good lenses show a small amount of vignetting when used wide-open; the alternative is to make a lens with inadequate glare stops. Vignetting can be corrected when the image is processed (p. 188), so it is not a fatal flaw. Another way to reduce vignetting is to close the lens down one or two stops from maximum aperture.

Distortion (barrel or pincushion) is important only if you are making star maps, measuring positions, or combining images of the same object taken with different lenses. Zoom lenses almost always suffer noticeable distortion, as you can demonstrate by taking a picture of a brick wall; non-zoom lenses almost never do.

One lens attribute that does not matter for astronomy – except in a backhanded way – is *bokeh* (Japanese for “blur”).<sup>1</sup> *Bokeh* refers to the way the lens renders out-of-focus portions of the picture, such as the distant background of a portrait.

The physical basis of “good *bokeh*” is spherical aberration. Years ago, it was discovered that uncorrected spherical aberration made a lens more tolerant of focusing errors and even increased apparent depth of field. But in astronomy, there is no out-of-focus background. The spherical aberration that contributes

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<sup>1</sup> Also transliterated *boke*. Another Japanese word with the same pronunciation but a different etymology means “idiot.”

## Lenses for piggybacking

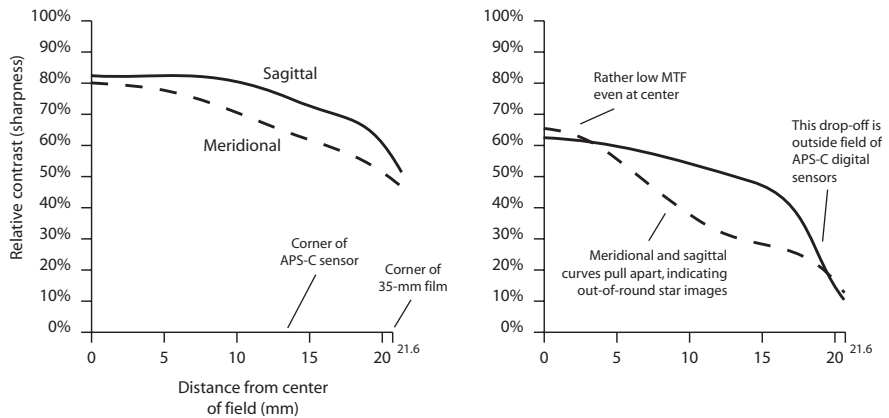


Figure 7.2. MTF curve from a good lens (left) and from one that warrants concern (right). Star fields are very demanding targets.

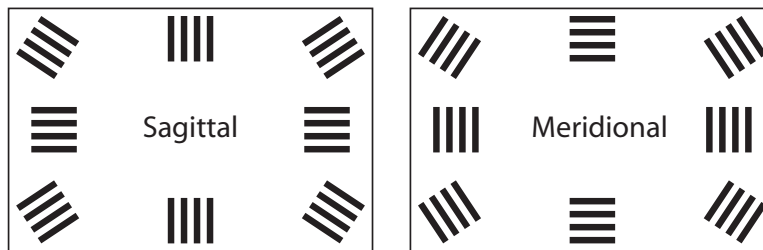


Figure 7.3. Orientation of targets for sagittal and meridional MTF testing.

to “good *bokeh*” could help the bright stars stand out in a star field; apart from that, it is just a defect.

### 7.2.2 Reading MTF curves

No longer can we say that a particular lens “resolves 60 lines per millimeter” or the like. This kind of measurement is affected by contrast; high-contrast film brings out blurred details. Instead, nowadays opticians measure *how much* blurring occurs at various distances from the center of the picture. That is, they measure the *modulation transfer function* (MTF).

Figure 7.2 shows how to read MTF graphs. Each graph has one or more pairs of curves for details of different sizes (such as 10, 20, and 40 lines per millimeter). Each pair consists of a solid line and a dashed line. Usually, the solid line indicates *sagittal* resolution (Figure 7.3) and the dashed line indicates *meridional* resolution.

What should the MTF of a good lens look like? My rule of thumb is that everything above 50% is sharp. I’m more concerned that the sagittal and meridional

## 7.2 Lens quality

curves should stay close together so that the star images are round, and that there shouldn't be a dramatic drop-off toward the edge of the picture. On that point, DSLR sensors have an advantage because they aren't as big as 35-mm film.

MTF curves do not measure vignetting or distortion. Also, most camera manufacturers publish *calculated* MTF curves (based on computer simulation of the lens design); the real MTF may not be as good because of manufacturing tolerances. An exception is Zeiss, which publishes *measured* MTF curves for all its lenses. You can also find measured MTF curves of many popular lenses on [www.photodo.com](http://www.photodo.com).

One last note. Lens MTF curves plot contrast against distance from center, with separate curves for different spatial frequencies (lines per mm). Film MTF curves plot contrast versus spatial frequency. See *Astrophotography for the Amateur* (1999), p. 187. The two kinds of curves look alike but are not comparable.

### 7.2.3 Telecentricity

Digital sensors perform best if light reaches them perpendicularly (Figure 7.4). At the corners of a picture taken with a conventional wide-angle lens, there is likely to be color fringing from light striking the Bayer matrix at an angle, even if film would have produced a perfect image.

A *telecentric* lens is one that delivers bundles of light rays to the sensor in parallel from all parts of the image. The obvious drawback of this type of lens is that it requires a large-diameter rear element, slightly larger than the sensor.

Telecentricity is one of the design goals of the Olympus Four Thirds system, which uses a lens mount considerably larger than the sensor. Other DSLRs are adapted from 35-mm SLR body designs, and the lens mount is not always large enough to permit lenses to be perfectly telecentric.

MTF curves do not tell you whether a lens is telecentric, and some excellent lenses for film cameras work less than optimally with DSLRs, while some mediocre lenses work surprisingly well. It's a good sign if the rear element of the lens is relatively large in diameter and is convex (positive); see for example the Olympus 100-mm  $f/2.8$  and the digitally optimized Sigma lens in the left-hand

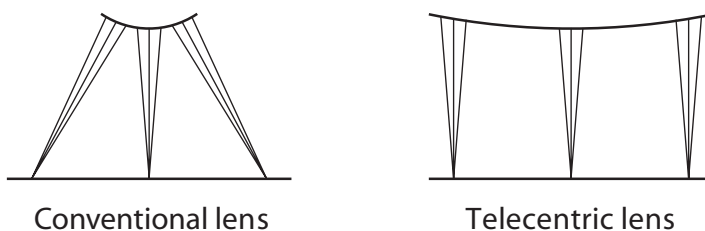


Figure 7.4. With a telecentric lens, light from all parts of the image arrives perpendicular to the sensor.

column of Figure 7.12, p. 85. Telescopes and long telephoto lenses are always close to telecentricity because all the elements are so far from the sensor.

#### 7.2.4 Construction quality

It's remarkable how flimsy a lens can be and still produce good pictures when there's an autofocus mechanism holding it in perfect focus. When piggybacking, that autofocus mechanism is turned off, and what's more, the camera and lens move and tilt as the telescope tracks the stars. Lenses that are very good for everyday photography can perform poorly in such a situation.

That's why older manual-focus lenses appeal to me, as well as professional-grade autofocus lenses that are built to survive rough handling. Almost any lens from the 1970s will seem to be built like a tank compared to today's products.

Another advantage of manual-focus lenses is that they are easier to focus manually. That sounds like a tautology, but it's important. Autofocus lenses *can* be focused manually – some more easily than others – but they are often very sensitive to slight movement of the focusing ring. Older manual-focus lenses are easier to focus precisely.

Of course, optical quality is also a concern, and it's where older lenses often fall down. Only the best lenses from yesteryear are likely to perform well by today's standards; too many of them had excessively simple designs or loose manufacturing tolerances.

#### 7.2.5 Which lenses fit which cameras?

##### Canon

In its long history, Canon has made two completely different kinds of SLRs, F (FD) and EOS. All the autofocus cameras, film and digital, belong to the EOS line, also referred to as AF (autofocus) or EF (electronic focus). The older FD-series manual-focus lenses do not fit EOS cameras at all, not even with an adapter.

Canon also makes a few EF-S lenses ("electronic focus, smaller"?) that fit only the newer DSLRs. They have an EOS-type mount that protrudes slightly farther into the camera body.

If all you need is a T-ring, the situation is simple. Any T-ring marked "Canon EOS," "Canon AF," or "Canon EF" is the right kind for an EOS camera. The other kind, Canon F, FD, or FL, will not fit on the DSLR at all.

Beware of Canon lenses made by Sigma and other third-party manufacturers in the early days of the EOS system. Sigma and some competitors reverse-engineered the EOS aperture system and got it slightly wrong, so the older lenses will not stop down to the selected aperture on a modern DSLR. Instead, you get the error message *Err 99*. At one time, Sigma could "rechip" older lenses, replacing internal microchips to make them work correctly, but this service is no longer offered. The lenses can be bargains if you are content always to use them wide open.

### Nikon

With Nikon, there is only one kind of SLR lens mount – introduced on the Nikon F in 1959 – but there are many variations.

All Nikon T-rings fit all Nikon SLRs and DSLRs. But when the lens has to communicate its aperture or other information to the camera, the situation is complicated. The old “pre-AI” Nikon F lens mount used a prong on the outside of the aperture ring to connect to the light meter. It was followed by Nikon AI (which may or may not still have the prong), and then Nikon AF for autofocus. Each of these exists in many variations (AI-S, AF-S, AF-D, etc.).

To find out which lenses fit your DSLR, and with what level of functionality, consult your camera’s instruction manual. Pre-AI lenses do not, in general, fit modern Nikon cameras at all.

## 7.3 Testing a lens

Every lens, especially one bought secondhand, should be tested as soon as you get it. The stars make excellent test targets.

What you need is a piggyback exposure, with good tracking, of a rich star field. I often use the field of  $\alpha$  Persei or the Pleiades.

Exposures need not be long, nor do you need a dark country sky. Take several 30-second exposures of the star field, both in focus and slightly out of focus. On the pictures, look for:

- excessive vignetting;
- excessive degradation of star images away from the center;
- internal reflections (showing up as large haloes or arcs);
- miscollimation (one side of the picture in focus and the other side not);
- out-of-round star images in the center of the field.

The last of these is the most serious, and over the years, I’ve encountered it with three different lenses from reputable makers. Figure 7.5 shows what to look for, and the cause is an off-center lens element, either from imprecise manufacturing or because of mechanical damage.

It is normal for star images to be asymmetrical at the edges of the picture, but those in the very center should be perfectly round. If out of focus, they should be the shape of the lens diaphragm, which may be round or hexagonal. If you get distorted star images, judge the severity of the problem by comparing one lens to another, since no lens is perfect. Also, check the star atlas; don’t let a nebula, cluster, or multiple star fool you into thinking you’ve found a defect.

Spherical and chromatic aberration, both resulting in round haloes around the stars, are not necessarily serious problems in deep-sky work. They can even help the brighter stars stand out, making up for the lack of sideways diffusion of light in the digital sensor compared to film.

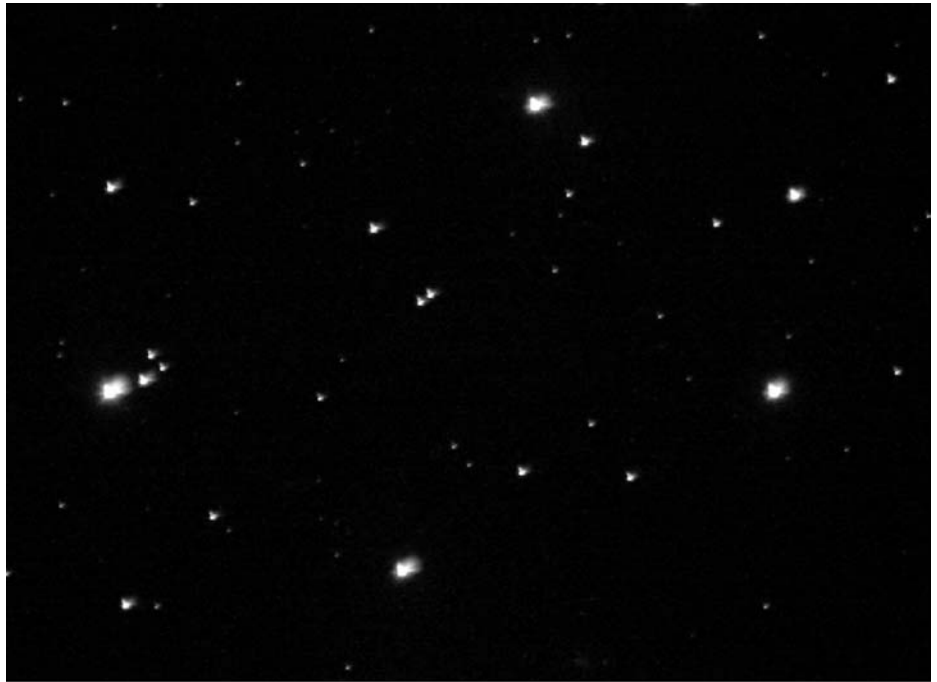


Figure 7.5. Asymmetrical star images (enlarged) from lens with decentered element. At center of field, even out-of-focus stars should be round.

Optical defects usually diminish when the lens is stopped down. Telecentricity issues (p. 75) stay the same or get worse. Thus, if there are “comet tails” on stars around the edge of the picture, and they persist at  $f/5.6$  or  $f/8$  as well as wide open, then what you are seeing is fringing within the sensor. With film or with a different sensor, the same lens may perform much better.

Particularly with lenses 20 or 30 years old, quality is partly a matter of luck; there’s a lot of unit-to-unit variation. One reason newer lenses have more elements is so that a slight error in the curvature of one surface will have less total effect. Compare a Newtonian reflector, whose quality depends entirely on one perfect paraboloid, to a refractor, which has four optical surfaces and is more tolerant of slightly incorrect curvature in each of them.

## 7.4 Diffraction spikes around the stars

Bright stars stand out better in a picture if they are surrounded by diffraction spikes. Normally, a high-quality lens, wide open, will not produce diffraction spikes because its aperture is circular. If you close it down one stop, you may be rewarded with a dramatic pattern. Figure 7.6 shows an example, from a Canon lens whose aperture is, roughly speaking, an octagon with curved sides.

Another way to get diffraction spikes is to add crosshairs in front of the lens (Figure 7.7). The crosshairs can be made of wire or thread; they should be opaque,

#### 7.4 Diffraction spikes around the stars



Figure 7.6. Dramatic diffraction patterns from a Canon 300-mm  $f/4$  EF L (non-IS) lens at  $f/5.6$ .



Figure 7.7. Homemade wire crosshairs mounted in the lens hood of a Sigma 105-mm  $f/2.8$  lens.



Figure 7.8. Result of using crosshairs in Figure 7.7. Canon Digital Rebel (300D) at ISO 400, Sigma 105-mm  $f/2.8$  lens wide open. Stack of five 3-minute exposures of the North America Nebula, dark-frame subtracted, cropped.

thin, and straight. Figure 7.8 shows the result. A piece of window screen, serving as multiple crosshairs, would produce a similar but much stronger effect.

Whatever their origin, diffraction spikes are a stiff test of focusing accuracy. The sharper the focus, the more brightly they show up. For that reason, many people find crosshairs or window screen useful as a focusing aid even if they don't use them for the actual picture.

## 7.5 Lens mount adapters

Besides the ubiquitous T-ring, originally designed for a line of cheap telephoto lenses, there are other adapters for putting one kind of lens onto another kind of camera body.

Obviously, any adapter has to contain a receptacle to fit the lens and a flange to fit the camera body. The trouble is, all of this takes up space, placing the lens farther from the film or sensor than it was designed to be. There are three ways to deal with this problem:

- Add a glass element (typically a  $\times 1.2$  Barlow lens) so that the lens will still focus correctly. This is a common practice but degrades the image quality.
- Leave out the glass element and give up the ability to focus on infinity. The adapter is now a short extension tube and the lens can only take close-ups.
- If the camera body is shallower than the one the lens was designed for, then make the adapter exactly thick enough to take up the difference. In this case, the lens focuses perfectly, without a glass element.

## 7.5 Lens mount adapters



Figure 7.9. Mid-grade and high-grade Nikon to EOS adapters. Avoid cheap imitations.

The third kind of adapter is the only one that interests us, and it's only possible if the camera body is shallower, front to back, than the body the lens was designed for. In that case, the adapter makes up the difference. For example, a Nikon lens can fit onto a Canon EOS body with an adapter 2.5 mm thick.

Olympus Four Thirds System DSLRs are much smaller than 35-mm film cameras, almost any film SLR lens should be adaptable to fit them. The Canon EOS is one of the shallowest full-size SLR bodies, and adapters exist to put Nikon, Contax-Yashica, Olympus, M42, and even Exakta lenses on it. The one thing you *can't* do is put older Canon FD lenses on an EOS body, because the FD body was even shallower.

Nikon bodies generally can't take non-Nikon lenses because the Nikon body is one of the deepest in the business. Only the Leicaflex is deeper.

One curious zero-thickness adapter does exist. Pentax's adapter to put screw-mount lenses on K-mount cameras simply wraps around the screw-mount threads, taking advantage of the K-mount's larger diameter. More commonly, though, screw-mount-to-K-mount adapters are about 1 mm thick and do not preserve infinity focus.

### 7.5.1 Adapter quality

Not all lens mount adapters are equally well made. Novoflex ([www.novoflex.com](http://www.novoflex.com)) markets top-quality adapters through camera stores, but the prices are high, presumably to allow the dealer a good markup on a slow-selling item. A respected supplier with more competitive prices is Fotodiox ([www.fotodiox.com](http://www.fotodiox.com)). On eBay you can buy adapters directly from the machinists in China who make them.

Figure 7.9 shows what to look for. Good adapters are usually made of chrome-plated brass or bronze and often include some stainless steel. Some are made of high-grade aluminum. For higher prices you get more accurate machining, more elaborate mechanisms to lock and unlock the lens, and more blackening of parts that could reflect light.

M42 screw mount to Canon adapters are the simplest, and my experience is that they always work well. I have also had good results with an inexpensive



Figure 7.10. Homemade tripod collar for heavy lens consists of wooden block with large round hole, slot and bolt to allow tightening, and a  $\frac{1}{4}$ "-20 threaded insert on the underside.

Olympus to Canon adapter. Each of these holds the lens tightly in place and is easy to attach and remove.

But Nikon to Canon adapters are tricky and always lack mechanical strength. When using one, *always let the lens support the camera* – don't let the adapter bear the weight of a heavy lens (Figure 7.10). And insist on a well-made adapter in the first place. I had a cheap one actually come apart in use as the screws stripped their threads.

The problem is that the Nikon lens mount contains springs. An adapter doesn't have room for good leaf springs like those in a Nikon camera body. Instead, the adapter relies on flexure of tabs that protrude from the lens mount itself. If these improvised springs are too weak, the lens and camera can pull apart slightly under the camera body's weight, and your pictures will be out of focus.

Another mark of a well-made Nikon adapter is that it makes it easy to remove the Nikon lens. Cheaper adapters require you to pry up a tab with your thumbnail; better ones give you a button to press.

### 7.5.2 The classic M42 lens mount

Canon DSLRs with adapters have given a new lease on life to many classic lenses with the M42 (Pentax-Praktica) screw mount. Here "M42" means "metric, 42 mm" and has nothing to do with the Orion Nebula, Messier 42.

## 7.5 Lens mount adapters



Figure 7.11. Classic M42 (Pentax-Praktica) screw mount. Note 42×1-mm threads, aperture stop-down pin, and manual/auto switch (for diaphragm actuation, not autofocus).

These lenses are mechanically sturdy and free of flexure in long exposures. Optical quality varies from brand to brand, but Pentax SMC Takumars and East German (Jena) Zeiss lenses are often quite good. In their own time, these Zeiss lenses were not marketed in the United States, and we Americans didn't know what we were missing.<sup>2</sup> Today, these lenses are abundant on the secondhand market, which is fully international thanks to eBay.

Because of its simplicity and great ruggedness, M42 is a standard that won't die. It was introduced by East German Zeiss on the Contax S in 1949 and promoted by Pentax as a "universal mount" in the 1960s. Pentax switched to a bayonet mount in 1976, but Zenit brand M42-mount cameras and lenses were made in Russia until 2005, and to this day Cosina makes the M42-mount Voigtländer Bessaflex, marketing it as a living antique for people who prefer older cameras.

Figure 7.11 shows what an M42 lens mount looks like. Don't confuse it with the T-mount, whose threads are closer together. The pin enables the camera to stop the lens down to the selected aperture when taking a picture; the rest of the time, the lens is wide open so you can view and focus easily. When using an adapter, you'll want to disable this feature by switching the lens to manual (M). Older versions of the mount have only manual diaphragms and no pin.

Beware of M42 mounts with extra protrusions that may interfere with the use of an adapter. In the 1970s, Pentax, Olympus, Mamiya, and other manufacturers added aperture indexing so that the exposure meter could sense the selected

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<sup>2</sup> From 1945 to 1990, like Germany itself, Zeiss was partitioned into separate eastern and western companies, and in America only the western Zeiss could use the trademarks and product names.

$f$ -stop without stopping the lens down. Unfortunately, they each did it in their own way. Pentax added a small, retractable pin that usually does not cause problems; the others made larger modifications.

## 7.6 Understanding lens design

### 7.6.1 How lens designs evolve

Most of us have seen dozens of diagrams of lens designs without any explanation of how to understand them. Figure 7.12 is an attempt to make lens diagrams comprehensible. It shows how nearly all modern lenses belong to four groups.

Looking at the historical development, you can see that the usual way to improve a design is to split an element into two or more elements. Thus the three-element Cooke Triplet gradually develops into the 11-element Sigma 105-mm  $f/2.8$  DG EX Macro, one of the sharpest lenses I've ever owned.

The reason for adding elements is that every lens design is, fundamentally, an approximate solution to a system of equations describing the paths of rays of light. By adding elements, the designer gains more degrees of freedom (independent variables) for solving the equations.

But there are also other ways to add degrees of freedom. One is to use more kinds of glass, and many new types have recently become available. Another is to use aspheric surfaces, which are much easier to manufacture than even 20 years ago.

Perhaps the most important recent advance is that anti-reflection coatings have improved. It is now quite practical to build a lens with 20 or 30 air-to-glass surfaces, which in the past would have led to intolerable flare and reflections.

There have also been changes in the way designs are computed. Fifty years ago, designers used a whole arsenal of mathematical shortcuts to minimize aberrations one by one. Today, it's easy to compute the MTF curve (not just the individual aberrations) for any lens design, and by dealing with MTF, the designer can sometimes let one aberration work against another.

Manufacturers usually describe a lens as having "X elements in Y groups," where a group is a set of elements cemented together. How many elements are enough? It depends on the  $f$ -ratio and the physical size of the lens. Faster lenses need more elements because they have a wider range of light paths to keep under control. Larger lenses need more elements because aberrations grow bigger along with everything else.

Zoom lenses (Figure 7.13) need numerous elements to maintain a sharp image while zooming. In essence, the designer must design dozens of lenses, not just one, and furthermore, all of them must differ from each other only in the spacings between the groups! That is why zooms are more expensive and give poorer optical performance than competing fixed-focal-length lenses.

## 7.6 Understanding lens design

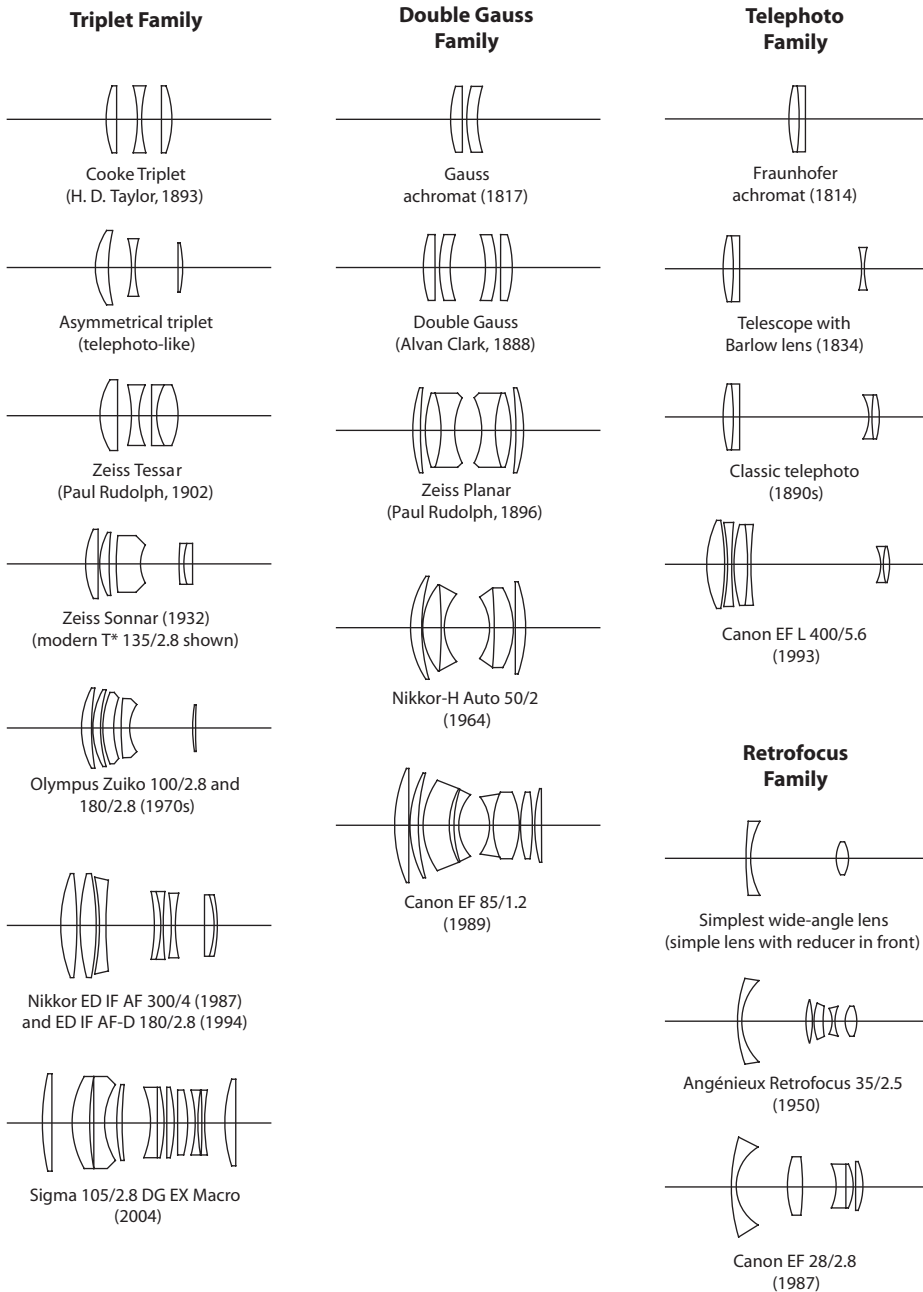
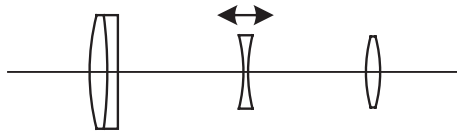


Figure 7.12. Lineage of many familiar lens designs. In all these diagrams, the object being photographed is to the left and sensor or film is to the right.

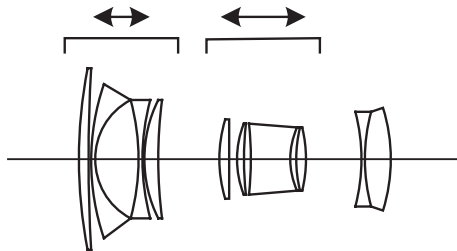
### Lenses for piggybacking



Zoom principle: moving Barlow lens changes focal length of telescope



Adding positive element reduces focus shift when zooming



Canon EF 28-80/3.5-5.6 zoom lens  
(two sets of elements move separately)

Figure 7.13. A zoom lens is like a telescope with a variable Barlow lens. A simple, low-cost zoom is shown here; others have as many as 22 elements moving in six or eight independent sets.

## 7.6.2 The triplet and its descendants

Multi-element lens design began in 1729 when Chester Moore Hall discovered that convex and concave lenses made of different kinds of glass could neutralize each other's chromatic aberration without neutralizing each other's refractive power. The same discovery was made independently by John Dollond in 1758. Later, the mathematicians Fraunhofer and Gauss perfected the idea, and telescope objectives of the types they invented are still widely used.

Early photography led to a demand for lenses that would cover a wider field of view, and in 1893 H. Dennis Taylor designed a high-performance triplet for Cooke and Sons Ltd. ([www.cookeoptics.com](http://www.cookeoptics.com)).

## 7.6 Understanding lens design

Modern medium-telephoto lenses are often descendants of the Cooke Triplet. The key parts of the design are a convex lens or set of lenses in the front, a set of concave lenses in the middle, and a convex lens at the rear. A particularly important triplet derivative is the Zeiss Sonnar, which originally used a very thick concave element with other elements cemented to it to minimize the number of air-to-glass surfaces. Lenses of this type were made in East Germany through the 1970s, and you can recognize them by their weight. The famous Nikon 105-mm  $f/2.5$  telephoto is a Sonnar derivative with a thick element.

Around 1972, Yoshihisa Maitani, of Olympus, designed a very compact, lightweight 100-mm  $f/2.8$  lens which is a Sonnar derivative with the thick central element split into two thinner ones. Other camera manufacturers quickly brought similar designs to market, and even the Sonnar itself has shifted toward thinner, air-spaced elements. Over the years, Sonnar derivatives have become more and more complex.

### 7.6.3 The double Gauss

Present-day 50-mm “normal” lenses are almost always the double Gauss type (Figure 7.12, middle column), derived from the Zeiss Planar of 1892. Back in the 1800s, several experimenters discovered that if you put two Gauss achromats back-to-back, each cancels out the distortion introduced by the other. The same thing was tried with meniscus lenses and other kinds of achromats, resulting in various “rectilinear” lens designs.

Double Gauss designs were not practical until the advent of anti-reflection lens coatings in the 1950s; before then, their sharply curved air-to-glass surfaces led to internal reflections. Previously, the standard camera lens had usually been a variant of the Zeiss Tessar, which is classified as a triplet derivative but was actually invented as a simplified Planar.

### 7.6.4 Telephoto and retrofocus lenses

Very long telephoto lenses often work like a telescope with a Barlow lens (Figure 7.12, upper right). Technically speaking, *telephoto* means a lens whose focal length is much longer than its physical length, and the classic achromat-with-Barlow design is the standard way of achieving this, although asymmetrical triplets and asymmetrical double Gauss designs can do the same thing to a lesser degree.

The opposite of a telephoto is a *retrofocus* wide-angle lens, one whose lens-to-film distance is longer than its focal length. To leave room for the mirror, the lens of an SLR can be no closer than about 50 mm from the sensor. To get an effective focal length of, say, 28 mm, the wide-angle lens has to work like a backward telescope; it is a conventional lens with a large concave element in front of it.

### 7.6.5 Macro lenses

A macro lens is one whose aberrations are corrected for photographing small objects near the lens rather than distant objects. This does not imply a different lens design; it's a subtle matter of adjusting the curvatures and separations of elements.

Since the 1970s, many of the best macro lenses have had *floating elements*, elements whose separation changes as you focus. As a result, they are very sharp at infinity as well as close up. I have had excellent results photographing star fields with Sigma 90-mm and 105-mm macro lenses.

At the other end of the scale, cheap zoom lenses often claim to be "macro" if they will focus on anything less than an arm's length away, even if they don't perform especially well at any distance or focal length.

# Chapter 8

## Focusing

Perhaps the biggest disappointment to any beginning astrophotographer is finding out how hard it is to focus the camera accurately. With DSLRs, the problem is even worse than with film SLRs because the viewfinder is smaller and dimmer, and also because standards are higher.

We want to focus DSLRs more precisely than film SLRs because we *can*. Unlike film, the DSLR sensor doesn't bend. Nor does light diffuse sideways in the image. It's easy to view the image tremendously magnified on the computer, so we are much less tolerant of focusing errors than we used to be (to our detriment) back in the film era.

### 8.1 Viewfinder focusing

Many astrophotographers find it unduly hard to focus an SLR manually by looking through the viewfinder. If you're one of them, it's a good idea to investigate the problem and try to build your skill. Now that we have several means of confirming focus electronically, I don't think optical focusing should stand alone, but let's get as much use out of it as we can.

#### 8.1.1 The viewfinder eyepiece

The eyepiece on a DSLR is commonly out of focus. Most DSLRs have an adjustment called the *eyepiece diopter* (Figure 8.1) which you are expected to adjust to suit your eyes. This is rarely done, because for daytime photography with an autofocus camera, it doesn't matter. To someone who always uses autofocus, the viewfinder is just for sighting, not for focusing, and the image in it need not be sharp.

Here's how to adjust it. Hold the camera up to your eye as if to take a picture and ask yourself whether you can see the focusing screen clearly. (If you need glasses, wear them.) Keep the camera turned off and the lens out of focus so that your attention is directed to the screen.



Figure 8.1. Eyepiece diopter should be adjusted to give a clear view of the focusing screen.

Adjust the diopter so that the screen is as sharp as possible. Pay attention to its granular texture and the indicator boxes or lines on it. With a Canon, focus on the boxes, not the black or red indicator LEDs just beyond them.

Then do the same thing again in dimmer light. Your eyes focus differently in the dark than in the daytime. If you can touch up the eyepiece diopter under relatively dim conditions, it will serve you better for astronomy.

Now go outdoors in the daytime, set the lens to manual focus, and practice focusing the camera manually. Your goal at all times should be to look *at* the screen, not *through* it. That is, keep your attention on whatever features of the screen you can see – boxes, lines, or granularity – and bring the image from the lens into the same focal plane.

Half an hour of doing this will greatly build your skill. Before long, you should be able to focus your daytime pictures better than the camera's autofocus mechanism does. Try it.

When you master the technique I've just described, it will still be very hard to focus on celestial objects. The secret is always to focus on the brightest star you can find, then aim the camera at the object you actually want to photograph. Everything in the sky, from airplanes to galaxies, is so far away that, for all practical purposes, it all focuses in the same plane.

### 8.1.2 The Canon Angle Finder C

Viewfinder focusing is much easier and more accurate if you add magnification. The best device for this purpose, whether your camera is a Canon, Nikon,

## 8.1 Viewfinder focusing



Figure 8.2. Canon Angle Finder C fits almost any SLR with a rectangular eyepiece frame – even a Nikon.

Olympus, or Pentax, is the Canon Angle Finder C (Figure 8.2). This is a magnifying right-angle viewer that comes with adapters to fit rectangular eyepiece frames of two sizes. It works like the time-honored Olympus Varimaghi Finder and the popular Hoodman Universal Right Angle Finder, but the Canon Angle Finder C has a larger entrance pupil and gives a much brighter image. At the flip of a lever, it changes magnification from  $\times 1.25$  to  $\times 2.5$ .

The Angle Finder C has its own focus adjustment. The way this interacts with the camera's eyepiece diopter can be somewhat confusing. I offer two pieces of advice.

*Initial setup.* To get everything at least approximately correct, first take the Angle Finder C off the camera, set it to  $\times 2.5$ , and use it as a small telescope to look at objects around you. Focus it on objects about 1 meter away. Then put it on the camera and adjust the camera's eyepiece diopter so that you have a clear

view of the focusing screen. You should then be able to switch back and forth between  $\times 1.25$  and  $\times 2.5$  with minimal refocusing of the Angle Finder.

*In the field.* To set up an astronomical photograph, aim the telescope and camera at a reasonably bright star in the same general area of the sky (not far away so that nothing will shift as you slew back to the object of interest). “High precision mode” on Meade computerized mounts is handy for this; it takes you to a bright star which you can focus and center before returning to the selected celestial object.

Focus the telescope *and* the Angle Finder to get as sharp an image as possible. The two interact. Only one of them affects the image that will actually be recorded, but both of them affect your view; my technique is to alternate adjusting one and then the other. When the star is a bright pinpoint, correct focus has been achieved, or at least a very good starting point for refinement by electronic means.

### 8.1.3 Viewfinder magnification

The magnification of a viewfinder is a confusing quantity because DSLRs are still rated by an obsolete standard for 35-mm film cameras. For example, the nominal magnification of the Canon XTi viewfinder is  $\times 0.7$ . This means that the camera and viewfinder would work like a  $\times 0.7$  telescope if you put a 50-mm lens on it – which is not the standard lens for a DSLR.

That, in turn, is equivalent to viewing the focusing screen through a  $\times 3.5$  magnifier (because a 50-mm lens alone would be a  $\times 5$  magnifier).

Add the Angle Finder C, giving  $\times 2.5$ , and you have a total magnification of  $2.5 \times 3.5 = 8.75$ . That’s more power than you’d normally use viewing a 35-mm slide through a loupe. It should be – and, in my experience, it is – enough to judge the focus accurately.

### 8.1.4 Modified cameras

One cautionary note. If your DSLR has been modified by removing or replacing the low-pass/IR filter, viewfinder focusing may no longer be accurate. The optical thickness of the new filter is probably not exactly the same as the old one. You can send your camera to a repair shop for adjustment with an autocollimator, or you can do your focusing by electronic means.

## 8.2 LCD focusing

### 8.2.1 Confirmation by magnified playback

No matter how well you can focus optically, *you should always confirm the focus electronically.* The easiest way to do so is to play back the image on the LCD screen

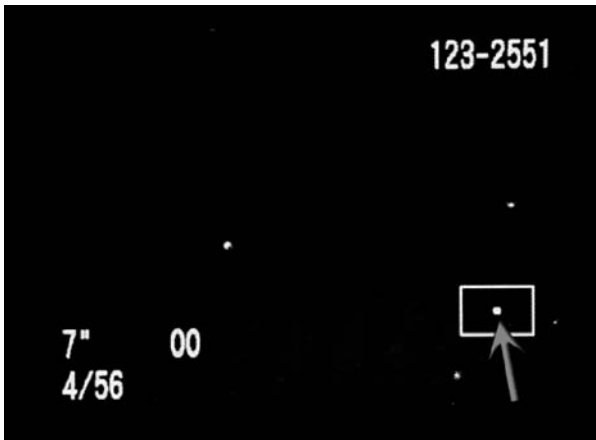


Figure 8.3. Confirming focus on the Canon 300D LCD screen. Compare the star images to the dot that indicates magnification (marked by the arrow here).

and view it with maximum magnification (Figure 8.3). On a Canon DSLR, it is easy to compare the star images to the dot that indicates the portion of the picture being displayed. As you press the + button repeatedly, the dot gets smaller and the star images get bigger. If, at maximum magnification, the star images are still smaller than the dot, they're in focus.

Your test image can be a much shorter exposure than what you eventually plan to make. All you need is to capture a few stars. In most situations, a 5-second exposure is enough.

If your DSLR provides magnified live focusing, you don't even have to take a test exposure. Just aim the camera at a star and adjust the focus while watching the image. This feature was introduced on the Canon EOS 20Da (now discontinued) and is gradually spreading through the world of DSLRs.

Live focusing is a delight to use. My very first picture with a Canon EOS 20Da took only 5 seconds to focus perfectly. Canon warns us that if live focusing is used for more than 30 seconds at a time, the sensor will warm up and the noise level will increase. The reason is that when the sensor must constantly take images and output them, all the transistors in it are working hard and emitting heat. Simply taking an image (even a long exposure) and outputting it once is a lot less work.

An ersatz kind of live focusing is provided by the Zigview Digital Angle Finder ([www.zigview.co.uk](http://www.zigview.co.uk)) and other gadgets that aim a tiny video camera into the eyepiece of the DSLR. It's important to note that you are viewing the focusing screen, not the actual image captured by the camera. The Zigview device displays the viewfinder image on a small LCD screen. I suspect that it does not have enough magnification to be useful to astrophotographers. Its main purpose seems to be framing, not focusing.

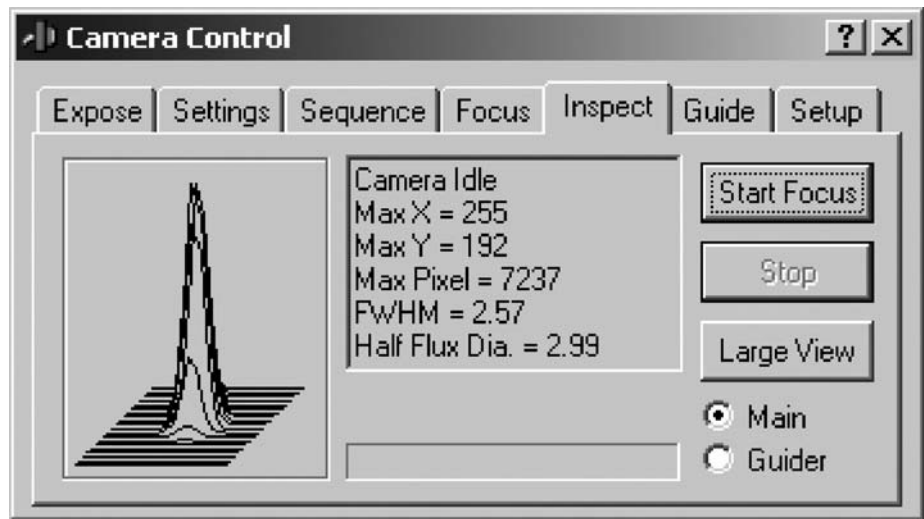


Figure 8.4. Analysis of a focused star image in *MaxDSLR*. The camera takes short exposures over and over and downloads them immediately for computer analysis.

### 8.2.2 LCD magnification

Although the pixels on the LCD do not correspond exactly to those in the picture, the actual magnification is quite ample. On the Canon XTi (400D), for instance, the screen measures  $4 \times 5$  cm (not the same aspect ratio as the picture), and the maximum magnification is  $\times 10$  (relative to showing the whole picture on the screen). That means the maximum magnification is like looking at a  $16 \times 20$ -inch ( $40 \times 50$ -cm) enlargement.

You can connect a video cable to almost any DSLR (Canon, Nikon, or others) and see its LCD display on a bigger screen. DSLRs and other digital cameras can be set to produce NTSC (American) or PAL (British) video signals.

## 8.3 Computer focusing

If you're using a computer to control your DSLR, the computer can also help you focus. Many software packages for DSLR control include the ability to take short exposures over and over, download them, and display each image immediately together with an analysis of its sharpness. We always focus on stars, which are perfect point sources, and the computer can analyze exactly how compact each image is.

Figure 8.4 shows a typical star image analysis from *MaxDSLR*, which includes focusing among its many other functions. A sharply focused star is a tall, narrow peak and has a small FWHM ("full-width-half-maximum," the diameter of the portion of the image that is at least 50% as bright as the central peak).

## 8.4 Other focusing aids

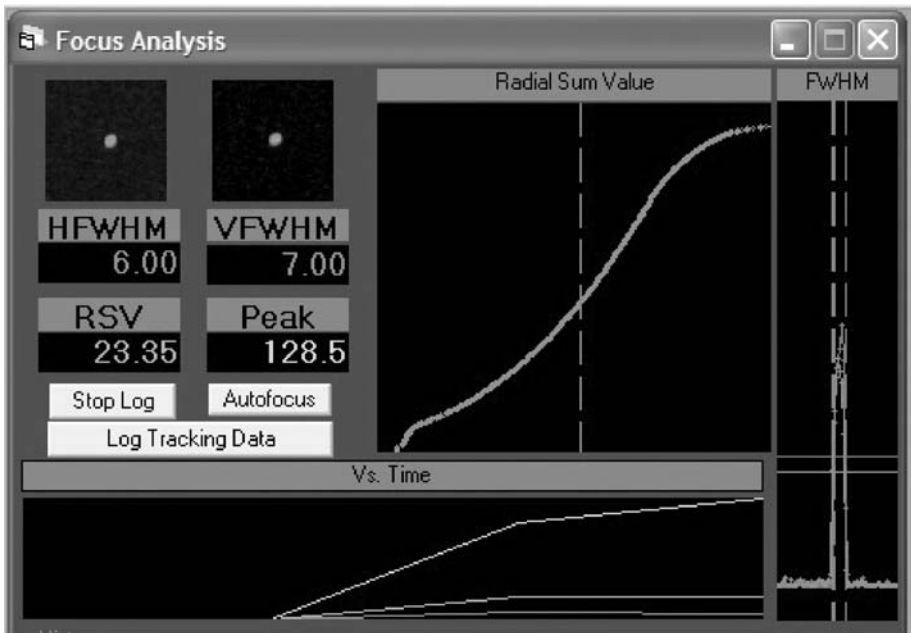


Figure 8.5. Elaborate star image analysis by *DSLR Focus*. Note the sharpness-versus-time graph to compare a series of test images taken in succession.

Many other software packages provide the same function. One of the best known and most elaborate is *DSLR Focus* ([www.dslrfocus.com](http://www.dslrfocus.com), Figure 8.5), which has gradually evolved into an all-purpose camera-control program.

If the telescope has an electric focuser, the computer can even adjust the focus for you. *MaxDSLR*, *ImagesPlus*, and *DSLR Focus* all support automatic focusing with most computerized telescopes.

The autofocus system inside the DSLR is not useful for astronomy. It usually does not respond to stars at all.

## 8.4 Other focusing aids

### 8.4.1 Diffraction focusing

A piece of window screen held in front of the telescope or lens will produce prominent diffraction spikes on the stars (see p. 78). The spikes become much longer and more prominent as the star comes into sharp focus. This is a useful supplementary indication with any focusing method, visual or electronic. The brighter the star, the more it helps. Because the window screen does not contain glass, it does not affect the focus of the system, and it can be moved away before the actual exposure is taken.

### 8.4.2 Scheiner disk (Hartmann mask)

A Scheiner disk or Hartmann mask (Figure 8.6 b) is an opaque piece of cardboard with two large holes in it, placed in front of the telescope or camera lens. Its purpose is to make out-of-focus images look double. Some people find that it helps them judge when the stars are in focus. You can easily make one out of a pizza box. For more details see *Astrophotography for the Amateur* (1999), p. 86.

### 8.4.3 Parfocal eyepiece

For rough focusing only, and for centering deep-sky objects that are too faint to show up on the SLR screen, a *parfocalized eyepiece* is handy (Figure 8.6 c). That is an eyepiece that you have adjusted to focus at the same position as your camera. Once you've found an eyepiece that is approximately correct, you can fit a *parfocalizing ring* around it to control how far it goes into the eyepiece tube. To match a DSLR, you'll probably need to fit the eyepiece with an extension tube, easily made from a  $1\frac{1}{4}$ -inch (35-mm) sink trap extension from the hardware store.

A parfocalized eyepiece is particularly handy for moving quickly to the correct focus after a big change in optical configuration, such as adding or removing a focal reducer. Many flip-mirror systems and other elaborate camera adapters include one.

But parfocal eyepieces don't give exact results. The focusing mechanism of your eye affects how they focus. The error is usually small but significant.

### 8.4.4 Knife-edge and Ronchi focusing

#### In theory

A time-honored way to find the focal plane of a telescope is to remove the eyepiece, or set it out of focus, and run a knife edge across the focal plane (Figure 8.6 d). While doing so, look at a star through the telescope; you will see a large, out-of-focus disk or doughnut.

If the knife edge intercepts the focal plane precisely, then the big, blurred star will suddenly wink out all at once. If the knife edge is ahead of or behind the focal plane, the knife edge will sweep across the blurred star from one side to the other (*Astrophotography for the Amateur*, 1999, p. 86).

Instead of a knife edge, you can use a Ronchi grating, which is a piece of glass with a series of black stripes.<sup>1</sup> In that case, the stripes appear superimposed on the out-of-focus star, and as you approach the focal plane they seem to get farther and farther apart. This makes it easy to approach correct focus from a grossly incorrect setting; a knife edge doesn't tell you how far you are off, but a Ronchi grating does. At perfect focus, the edge of a stripe acts like a knife edge.

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<sup>1</sup> Invented by Vasco Ronchi (1897–1988). The name is pronounced *RON-kee*.

8.4 Other focusing aids

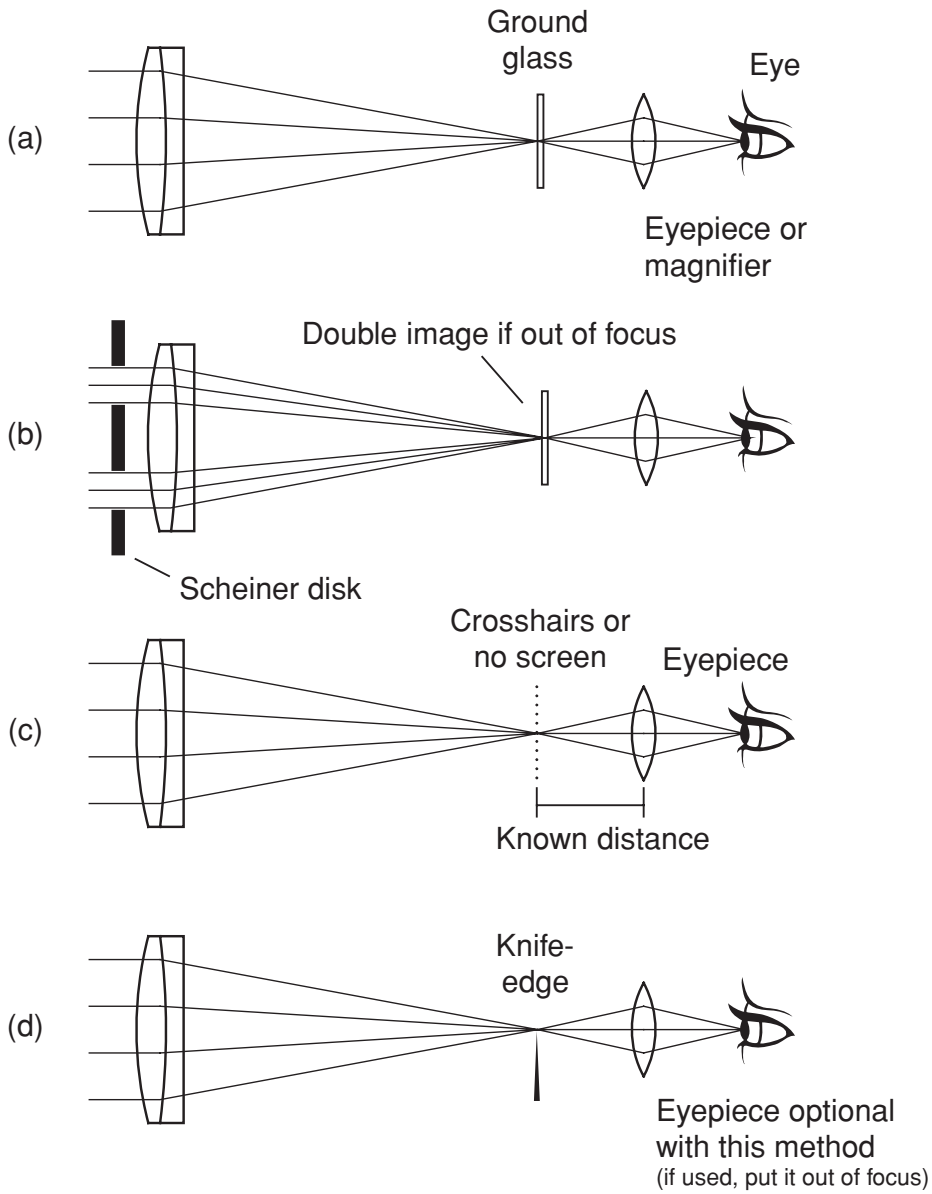


Figure 8.6. Four ways of focusing: (a) ground glass or SLR focusing screen; (b) Scheiner disk; (c) parfocal eyepiece (not recommended); (d) knife-edge or Ronchi grating. From *Astrophotography for the Amateur*.

Knife-edge or Ronchi focusing gives a very precise result – you can't be off by even 0.1 mm – and is totally unaffected by the focus of your eyes. You need not have sharp vision at all; if you need glasses, you can leave them off, and the results will be the same.

### In practice

The trouble with Ronchi or knife-edge focusing is that you can't do it with your DSLR in place. You must remove the DSLR and substitute a film camera body with no film in it, then run the knife edge across the film plane or put the grating there. The two camera bodies must match perfectly – but a film SLR body is unlikely to be a perfect match to a filter-modified DSLR because changing the filter changes the focal plane.

In place of a second camera body, you can use a Stiletto focuser ([www.stellar-international.com](http://www.stellar-international.com)). This is a convenient, ready-made device that goes in place of a camera and has a knife edge or Ronchi grating at the right position. It has its own eyepiece so that you view from the same position each time.

Many astrophotographers feel that the Stiletto or an equivalent device is the gold standard of focusing. I don't use one myself for two reasons. First, anything that requires me to swap camera bodies will increase the risk of getting dust on the sensor. Second, it is easy to sample the actual DSLR image electronically, and that's what I'd rather use for my final focusing.

## 8.5 Focusing telescopes with moving mirrors

Because Schmidt–Cassegrains and Maksutov–Cassegrains usually focus by moving the main mirror (Figure 6.2, p. 65), you may observe a couple of annoying effects. One is *lateral image shift* – the image moves sideways a short distance as you focus. This problem generally diminishes if you run the focuser through its range a few times to redistribute the lubricants.

The other problem is that if you are moving the mirror backward, it may continue to subside for a few seconds after you let go of the focuser knob. More generally, you cannot “zero in” on perfect focus by turning the knob first one way and then the other. There's a “dead zone” and when you try to undo a movement, results are somewhat hard to control.

For best results, always turn the knob clockwise first, to overshoot the desired position, and then do your final focusing counterclockwise. That way, you are pushing the mirror away from you, working against gravity and taking up any slack in the system.

# Chapter 9

## Tracking the stars

To take exposures longer than a few seconds, you must track the stars. That is, the telescope must compensate for the earth's rotation so that the image stays in the same place on the sensor while the earth turns.

This book is not the place to give a complete survey of the art of tracking and guiding; see *Astrophotography for the Amateur* and *How to Use a Computerized Telescope*. In this chapter I'll review the essentials, with an emphasis on recent developments.

### 9.1 Two ways to track the stars

Figure 9.1 shows the two major kinds of telescope mounts, altazimuth and equatorial. Until the 1980s, only an equatorial mount could track the stars; it does so with a single motor that rotates the telescope around the polar axis, which is parallel with the axis of the earth. In order to use an equatorial mount, you have to make the polar axis point in the right direction, a process known as *polar alignment* and long considered somewhat mysterious, although actually, correct polar alignment can be achieved quickly (see p. 102).

Computerized telescopes can track the stars with an altazimuth mount, or, indeed, a mount whose main axis points in any direction. During setup, the computer has to be told the exact positions of at least two stars. It then calculates how far to move along each axis, moment by moment, to compensate for the earth's rotation.

Altazimuth mounts can track the stars, but they can't stop the field from rotating (Figure 9.2). With an altazimuth mount, "up" and "down" are not the same celestial direction throughout a long exposure. As a result, the image twists around the guide star. Some large altazimuth telescopes include field de-rotators, which are motors that rotate the camera to keep up with the image. More commonly, though, if you're tracking with an altazimuth mount, you simply take short exposures and combine them through a rotate-and-stack operation (p. 110).

## Tracking the stars

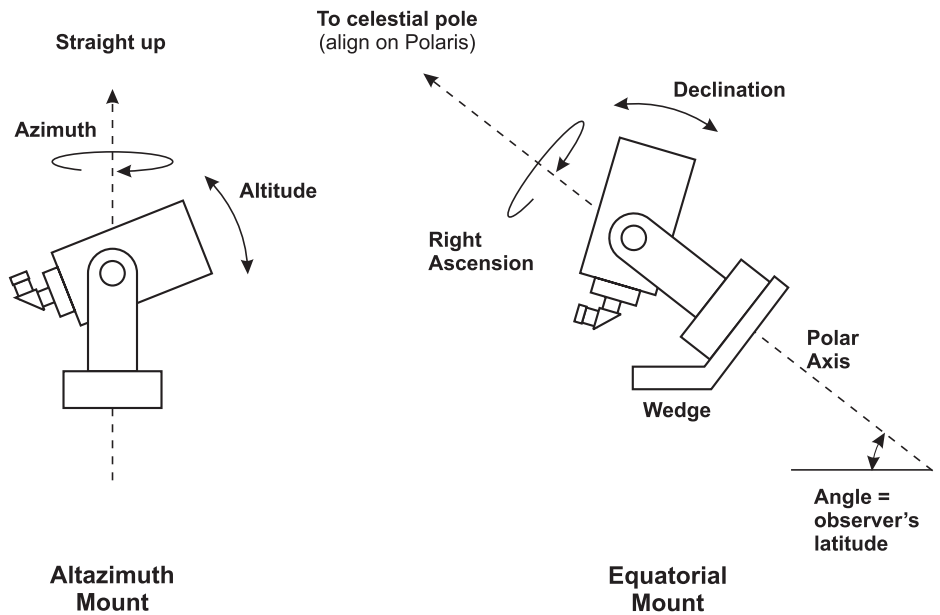


Figure 9.1. Two ways to track the stars. The altazimuth mount requires computer-controlled motors on both axes; equatorial needs only one motor, no computer. (From *How to Use a Computerized Telescope*.)

## 9.2 The rules have changed

The rules of the tracking and guiding game are not what they used to be. In the film era, the telescope had to track perfectly for 20 or 30 minutes at a time. Only equatorial mounts could be used because an altazimuth mount can only go a minute or two without excessive field rotation. Guiding corrections had to be made constantly, either by an autoguider or by a human being constantly watching a star and pressing buttons to keep it centered on the crosshairs. One slip and the whole exposure was ruined.

It was also important to guard against flexure and mirror shift. During a half-hour exposure, the telescope and its mount could bend appreciably. Also, notoriously, the movable mirror of a Schmidt–Cassegrain telescope would shift slightly. For both of these reasons, guiding was usually done by sampling an off-axis portion of the image through the main telescope.

Today, we commonly take 3- to 5-minute exposures and combine them digitally. That makes a big difference. Tracking errors that would be intolerable over half an hour are likely to be negligible. If there is a sudden jump, we can simply throw away one of the short exposures and combine the rest. We can even work with very short exposures on an altazimuth mount, using software to rotate as well as shift the images so that they combine properly.

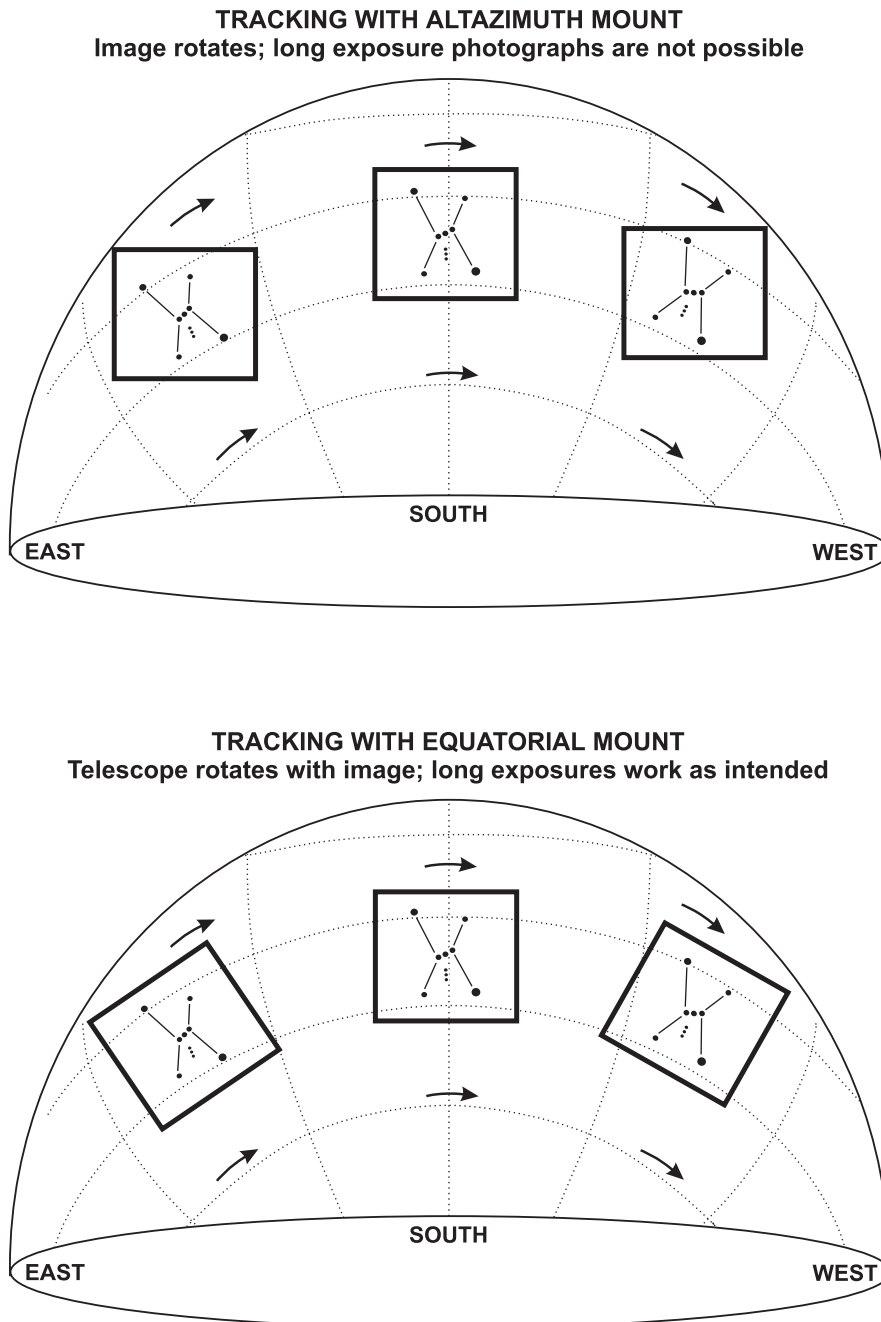


Figure 9.2. Tracking the stars with an altazimuth mount causes field rotation, which can be overcome by taking very short exposures and doing a rotate-and-stack. (From *How to Use a Computerized Telescope*.)



Figure 9.3. The author's DSLR astrophotography setup. Meade LX200 telescope with piggyback autoguider (Figure 9.9), 8 × 50 finderscope, Canon 300-mm  $f/4$  lens, and Canon XTi (400D) camera, mounted equatorially on a permanent pier in the back yard.

## 9.3 Setting up an equatorial mount

### 9.3.1 Using a wedge

An equatorial mount is simply an altazimuth mount tilted toward the celestial pole. The typical fork-mounted amateur telescope becomes equatorial when mounted on a wedge of the proper inclination, pointed north (or south in the Southern Hemisphere).

Well-made wedges are sturdy, easy to adjust, and *heavy*. To save weight and to take advantage of the vibration-damping properties of wood, I built the wooden wedge shown in Figure 9.4. Its obvious drawback is that there are no adjustments; the only way to adjust it is by moving the tripod legs or altering their length, and it only works at latitudes close to  $34^\circ$  north.

Would-be wedge builders should note that the mounting bolts of a Meade or Celestron telescope are not in an equilateral triangle. Measure their positions carefully before you drill the holes.

### 9.3 Setting up an equatorial mount



Figure 9.4. The author's homemade wooden wedge, held together with large screws whose heads were countersunk and filled with putty before painting. Polar alignment is done by moving the tripod legs.

#### 9.3.2 Finding the pole

The whole procedure for setting up an equatorial mount is covered in your telescope's instruction book and in *How to Use a Computerized Telescope*. Here I'll only give a few pointers.

If your telescope is computerized, I don't recommend letting the computer help with polar alignment. In my experience, a small error in this procedure can easily turn into a long wild-goose chase. Instead, do the polar alignment with the finderscope. It's easy to get within half a degree of the pole on the first try.

First, make sure you can point your telescope exactly parallel to its polar axis. Don't trust the  $90^\circ$  mark on the declination circle; check its accuracy. (I was once frustrated by a telescope that was about  $2^\circ$  off without my knowing it.) If you have a German-style equatorial mount (with counterweight), there may actually be a polar-alignment finderscope built into the polar axis; if so, you're truly fortunate.

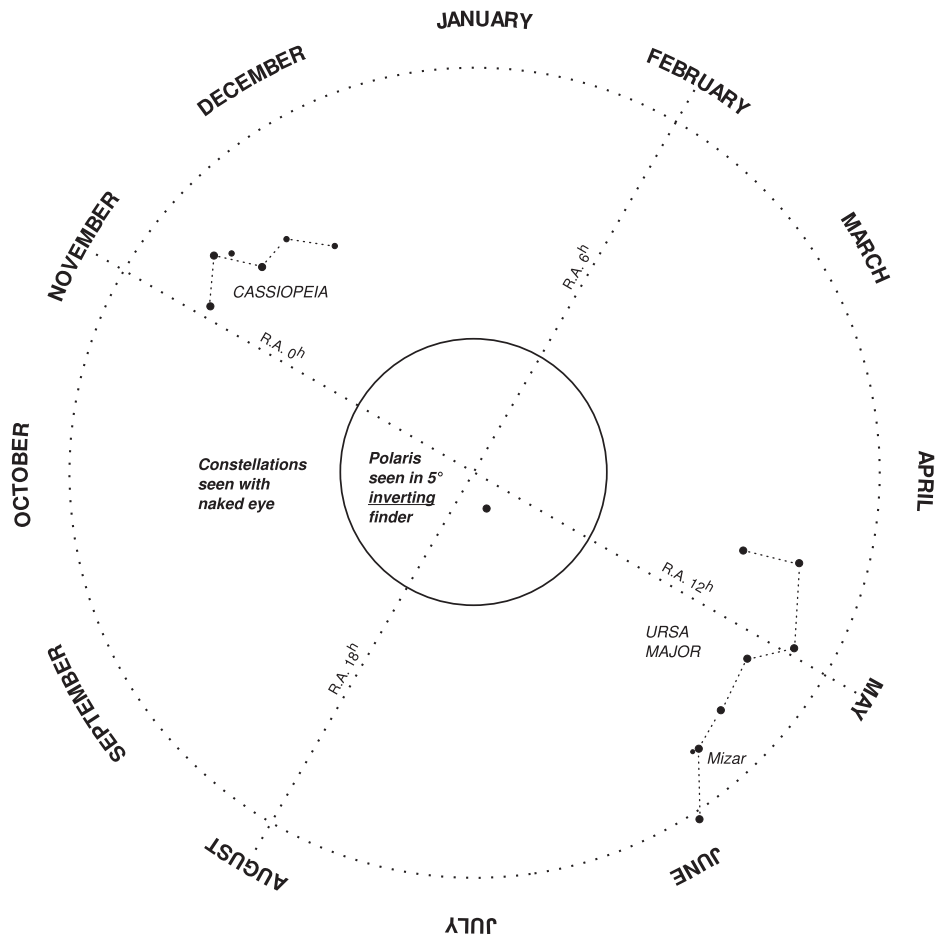


Figure 9.5. Finder chart for Polaris. Rotate the chart until the outer constellations match your naked-eye view of the sky; the center of chart then shows the view of Polaris through a common inverting  $8 \times 50$  finder ( $5^\circ$  field).

Also make sure the finder is lined up with the main telescope.

Then find the celestial pole. In the Northern Hemisphere, the chart in Figure 9.5 makes this a snap. When the outer part of the chart is lined up with the constellations in the sky, the inner circle shows how Polaris should look in the finderscope.

Adjust the mount so that Polaris is in the specified position, and you're done.

### 9.3.3 The drift method

I recommend that you confirm your polar alignment using the drift method, i.e., by measuring how well the telescope actually tracks a star. This can be done with the drive turned off, simply moving the telescope by hand around

### 9.3 Setting up an equatorial mount

Table 9.1 How to adjust your polar axis using the drift method. If an autoguider is used, alignment to within 1° of the pole is sufficient; if guiding corrections are not made, greater accuracy is desirable.

<b>Drift method alignment</b>			
<b>Star high in the SOUTH, near declination 0°</b>			
<b>In S. Hemisphere, star high in the NORTH, near declination 0°</b>			
<i>If star drifts</i>	NORTH 2"	per minute, move polar axis	1/8° RIGHT.
	NORTH 4"		1/4° RIGHT.
	NORTH 8"		1/2° RIGHT.
	NORTH 16"		1° RIGHT.
<i>If star drifts</i>	SOUTH	<i>do the opposite.</i>	
<b>Star at 40° N, low in EAST, &gt; 60° from meridian</b>			
<b>In S. Hemisphere, star at 40° S, low in WEST, &gt; 60° from meridian</b>			
<i>If star drifts</i>	NORTH 2"	per minute, move polar axis	1/8° DOWN.
	NORTH 4"		1/4° DOWN.
	NORTH 8"		1/2° DOWN.
	NORTH 16"		1° DOWN.
<i>If star drifts</i>	SOUTH	<i>do the opposite.</i>	

the right-ascension axis, or with the drive turned on *if* you are sure it is only tracking on one axis.

You'll need an eyepiece with double crosshairs whose separation corresponds to a known distance in the sky. To measure the distance, compare the crosshairs to a double star of known separation, or point the telescope at a star near the celestial equator and time its motion with the drive turned off. Such a star will move 15" per second of time.

Then turn on the drive motor and track a couple of stars. First track a star near declination 0°, high in the south. Measure how fast it seems to drift north or south, and the upper part of Table 9.1 will tell you how to adjust your tripod.

Only northward or southward drift is significant. If the star drifts east or west, bring it back into the center of the field (by moving east or west only) before making the measurement. In fact, you can perform this whole test with the drive turned off, tracking the star by moving the telescope by hand in right ascension only.

Once you've adjusted the polar axis in the left-right direction (azimuth), track a star that is low in the east, around declination +40°, and use the lower half of Table 9.1 to adjust the polar axis in altitude.

Table 9.1 also gives directions for drift method alignment in the Southern Hemisphere, where the drift method is more necessary because there is no bright pole star.

## 9.4 Guiding

Guiding is what we call the process of correcting the telescope's tracking so that it follows the stars more accurately than it would on its own.

### 9.4.1 Why telescopes don't track perfectly

There are two main reasons a telescope doesn't track perfectly: polar alignment error (which you can correct) and irregularities in its mechanism (which you cannot). A third factor is atmospheric refraction: objects very close to the horizon appear slightly higher in the sky than they ought to, and the extent of the effect depends on humidity, so it's not completely predictable.

Mechanical tracking errors can be *periodic* or *random*. In real life, you get a combination of the two. Periodic errors recur with every revolution of a gear – typically once every 4 or 8 minutes – and some computerized telescopes can memorize a set of corrections and play it back every time the gear turns. This is known as *periodic-error correction* (PEC) and you have to “train” it by putting in the corrections, by hand or with an autoguider; the latter is preferable. On the Meade LX200, the PEC retains its training when turned off, and you can retrain it by averaging the new corrections with the existing set, hopefully ending up with something smoother than either one would be by itself.

### 9.4.2 Must we make corrections?

Many DSLR enthusiasts make no any guiding corrections during the exposure. In the film era, this would have been absurd, but it's possible today for several reasons. Equatorial mounts are better built than they used to be; they track more smoothly. Drift-method alignment has come into wide use, leading to more accurate polar alignment.

Most importantly, exposures are shorter. It's much easier to get 2 minutes of acceptable tracking than 20. In fact, periodic gear error being what it is, some 1-minute exposures are bound to be well-tracked even with a cheaply made mount. You can select the best ones and discard the rest. You can even work with 30-second or 15-second exposures if that's all your tracking mechanism will permit.

Figure 9.6 shows what can be achieved without guiding corrections. This was taken with a PEC-equipped Meade LX200 on a precisely polar-aligned permanent pier. It's not quite as sharp as a comparable image taken with the autoguider turned on, but it's close. And that is with a focal length of 1250 mm and considerable subsequent cropping and enlargement. For piggybacking with a 200-mm or 300-mm lens, guiding corrections are hardly needed with this telescope and mount.



Figure 9.6. The galaxy M51, without guiding corrections. Enlarged central part of a much larger picture. Stack of three 3-minute exposures, minus dark frames, with 8-inch (20-cm) telescope at  $f/5.6$  and Canon Digital Rebel (300D) camera at ISO 400, processed with *ImagesPlus*, *Photoshop*, and *Neat Image*.

### 9.4.3 Guidescope or off-axis guider?

If your telescope is a Newtonian, classical Cassegrain, or refractor, you can guide with a separate guidescope piggybacked on the main one (or reverse the roles and photograph through the smaller telescope while guiding with the big one). Telescopes of these kinds are not vulnerable to mirror shift, and tube flexure is not likely to be a problem.

With a Schmidt–Cassegrain or Maksutov–Cassegrain, though, the telescope focuses by moving its main mirror, which may shift further during the exposure. This is less of a problem today than during the film era for two reasons. First, many newer telescopes of these types give you a way to lock the mirror in position and do the final focusing with a separate mechanism. Second, and more importantly, significant movement is not likely to occur during a 3-minute DSLR exposure. Mirror movement was more of a problem back in the days of 30- or 60-minute film exposures.

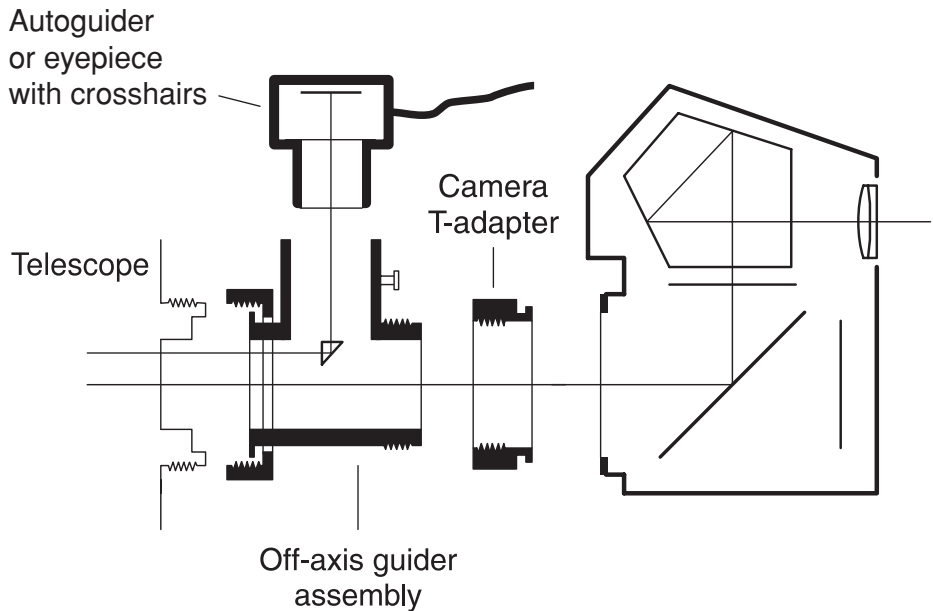


Figure 9.7. Off-axis guider intercepts a small area near the edge of the image and directs it to an eyepiece or autoguider. Alternative is to use a separate guidescope.

The traditionally recommended guiding setup for a Schmidt–Cassegrain is an *off-axis guider* like that shown in Figure 9.7. It intercepts a small part of the image in a position that wouldn't have reached the film or sensor anyway. You view the intercepted image with an eyepiece or feed it to an autoguider.

As you might imagine, it's very tricky to get the guiding eyepiece or autoguider in focus at the same time as the camera. There may be adjustments on the off-axis guider to help with this; with mine, I ended up having to insert a short extension tube ahead of the camera. When everything is in focus, there probably won't be a star visible in the guider at the same time that the camera is aimed at your chosen object. For these reasons, I am glad to leave the off-axis guider behind and use a guidescope.

#### 9.4.4 Autoguiders

What do I mean by "guide?" Either of two things. You can watch the guide star through an eyepiece with crosshairs, holding a control box and slewing the telescope at the slowest possible speed to keep the star centered on the crosshairs. (The art of doing this is discussed in *Astrophotography for the Amateur*.) Or you can let electronics do the work.

Traditionally, an *autoguider* is a small astronomical CCD camera, with built-in circuitry to produce commands to slew the telescope so that the guide star stays in a constant position on its sensor. I use an SBIG ST-V, which is one of the best

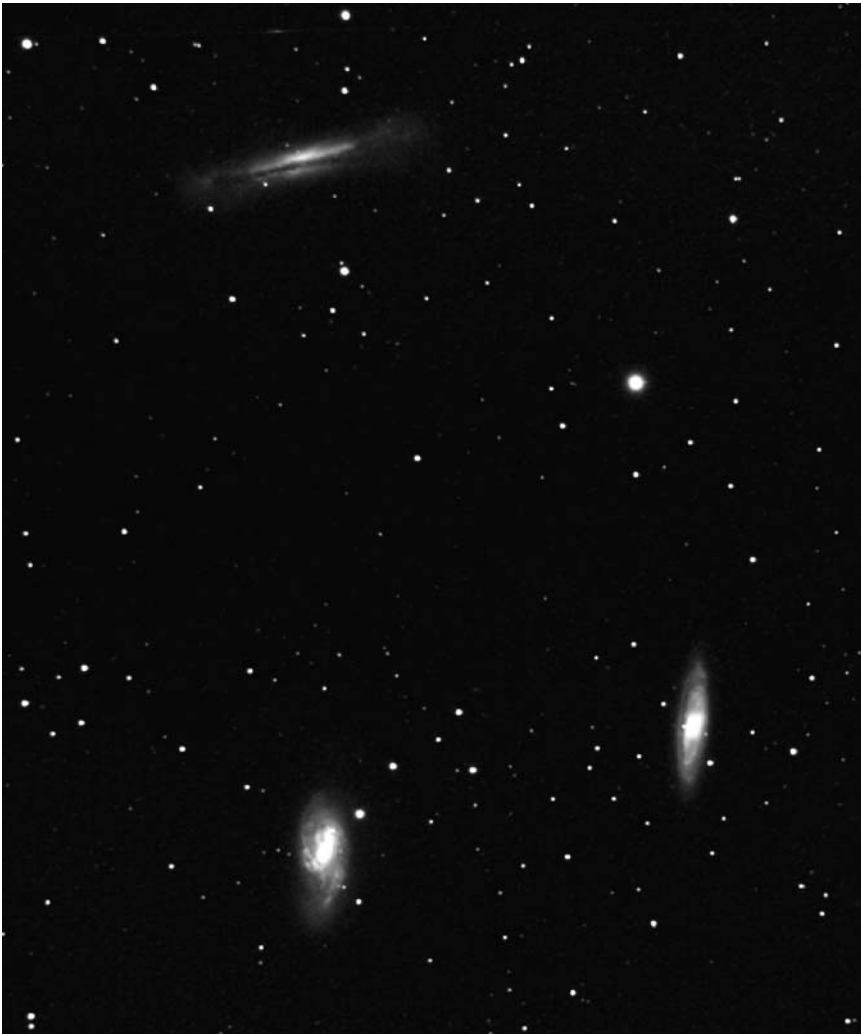


Figure 9.8. The Leo Triplets (M65, M66, NGC 3628). Stack of six 10-minute exposures at ISO 800 with Canon 20D and 10.2-cm (4-inch)  $f/5.9$  apochromatic refractor (Takahashi FS-102 with focal reducer) on an equatorial mount, guided with an SBIG ST-402 CCD camera as an autoguider on a separate telescope piggybacked on the main one. (William J. Shaheen.)

autoguiders of this type ever made. Its control box is slightly larger than a laptop computer and includes a video screen.

A newer and much cheaper approach is to use an astronomical video camera as an autoguider, with a laptop computer interpreting its signals. The camera can be a modified webcam (as in Appendix B), or a specifically astronomical device such as the Meade Deep Sky Imager or Celestron NexImage. The laptop computer runs *GuideDog* (free from [www.barkosoftware.com](http://www.barkosoftware.com)) or a general-purpose astronomical software package that supports autoguiding, such as *MaxDSLR*.

There are two ways the autoguider can issue slewing commands to the telescope. Older autoguiders use relays that simulate the buttons on a traditional control box connected to a six-pin modular socket (sometimes called an SBIG-type or ST-4-type port); for a wiring diagram, see *How to Use a Computerized Telescope* (2002), p. 158. The newer approach, favored when the autoguiding is controlled by a laptop computer, is to issue slewing commands to the telescope through its serial port.

Autoguiders normally achieve *subpixel accuracy*. That is, each star image can be located with a precision that is a fraction of the pixel size. This is possible because each star image falls on more than one pixel of the sensor, and the autoguider calculates the position of its central peak by determining the proportion of the image that reached each pixel. This means that a good autoguider can achieve accuracy limited only by atmospheric steadiness even when attached to a relatively small guidescope.

It is seldom possible to guide more precisely than 1 arc-second because of atmospheric steadiness. In fact, you probably don't want the autoguider to perform unnecessary movements with every slight shimmer of the air. You can generally adjust the *aggressiveness* of the autoguider to tell it whether to try to correct the whole error each time or only part of it. If the telescope seems to be slewing constantly back and forth, to either side of the ideal position, turn down the aggressiveness.

#### 9.4.5 A piggyback autoguider

Figure 9.9 shows the lowest form of guidescope – a high-quality autoguider connected to a 30-mm-diameter binocular objective. I built this myself; it is similar to a now-discontinued SBIG product called the eFinder. The tube consists of a Meade eyepiece projection adapter (which is T-threaded at one end and is adjustable in length) and a custom lens mount made for me by Pete Albrecht ([www.petealbrecht.com](http://www.petealbrecht.com); he also makes other custom telescope accessories).

Using a cheap lens does not cost me any guiding accuracy because of the way the autoguider computes centroids. Further, the real advantage of using a small  $f/4$  lens is that there are almost always stars in the field; that is, the SBIG ST-V autoguider can almost always find a guide star immediately, without requiring me to shift the guidescope in various directions looking for one.

### 9.5 How well can you do with an altazimuth mount?

I hinted at the end of Chapter 4 that you can do deep-sky work successfully with an altazimuth mount. The trick is to make relatively short exposures and stack them with rotation.

The reason you must “rotate and stack” with software is that even if the individual images are sharp, there is cumulative rotation from one to the next. Over 10 minutes you get 10 minutes' worth of rotation, but if it's divided up

## 9.5 How well can you do with an altazimuth mount?



Figure 9.9. The author's piggyback autoguider, consisting of an SBIG ST-V and a homemade adapter to hold a lens salvaged from a pair of binoculars, similar to the now-discontinued SBIG eFinder.

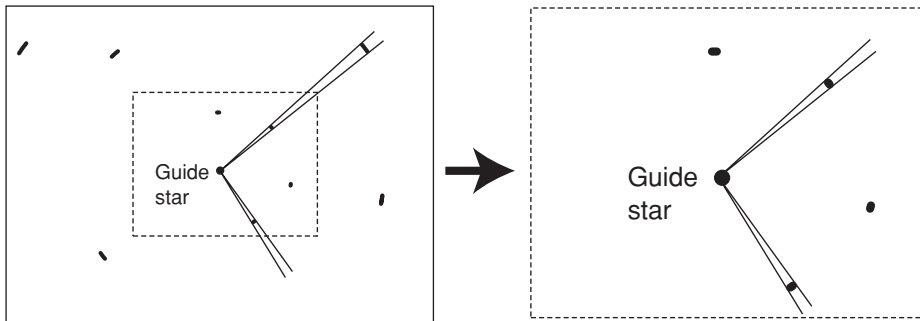


Figure 9.10. Field rotation causes all stars to rotate through the same angle, which is not changed by enlarging the center of the picture.

into twenty 30-second snapshots, the individual images can be turned to line up with each other.

### 9.5.1 The rate of field rotation

How much field rotation can we tolerate? About  $0.1^\circ$ , in my experience, without visibly skewing the stars at the corners of the image. As long as the guide star is in the middle of the picture, this limit is unaffected by focal length or magnification (Figure 9.10).

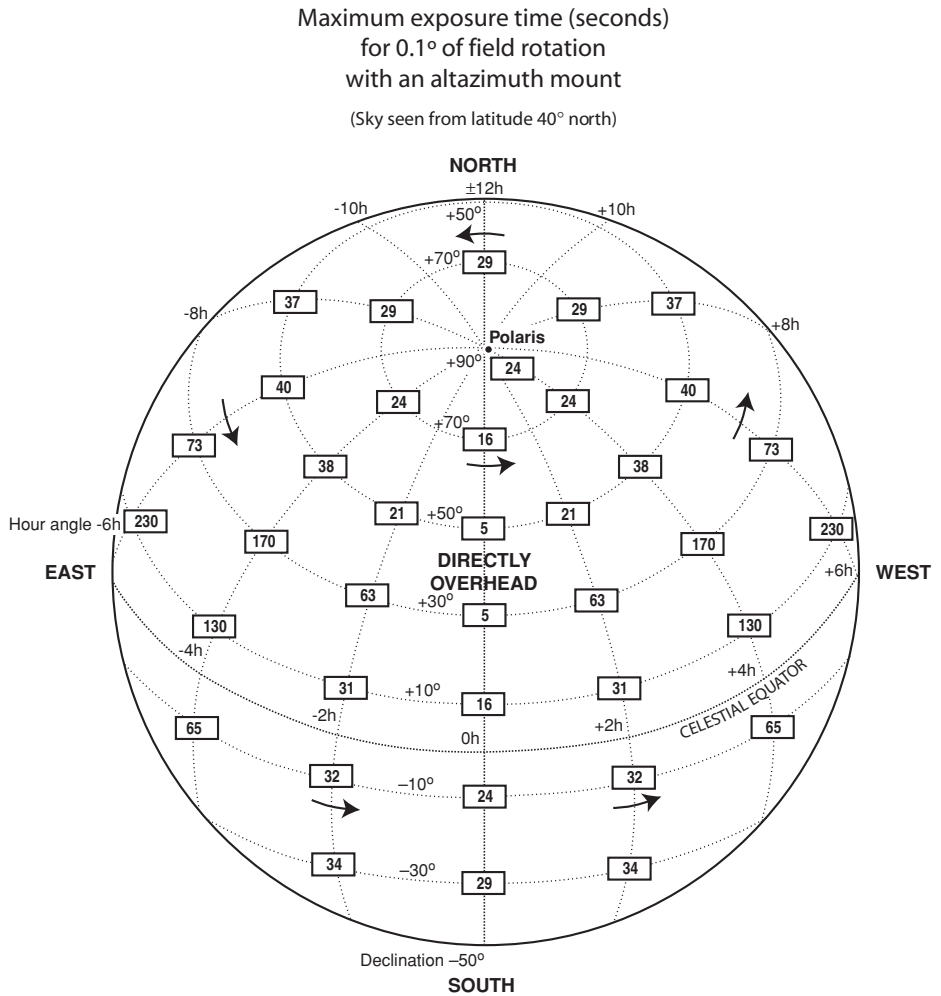


Figure 9.11. Maximum exposure times in various parts of the sky if you are tracking with an altazimuth mount. Avoid the zenith; longest exposures are possible low in the east and west.

So how long does it take for the field to rotate 0.1°? Complex formulae for computing field rotation were presented in Appendix B of *Astrophotography for the Amateur*, but Bill Keicher has derived a much simpler formula that is equally accurate:

$$\text{Rotation rate (degrees per second)} = 0.004167^\circ \cos(Lat) \frac{\cos(Az)}{\cos(Alt)}$$

where  $Lat$  is the latitude of the observer and  $Alt$  and  $Az$  are the altitude and azimuth of the object, taking north as 0° and east as 90° azimuth respectively.<sup>1</sup>

<sup>1</sup> Bill Keicher, "Mathematics of Field Rotation in an Altitude-over-Azimuth Mount," *Astro-Photo Insight*, Summer 2005, now online in <http://www.skyinsight.net/wiki/>. The constant in Keicher's

9.5 How well can you do with an altazimuth mount?



Figure 9.12. The nebula M27 photographed with a Meade LX90 telescope on an altazimuth mount. Stack of nine 30-second exposures with the 8-inch (20-cm)  $f/10$  Schmidt-Cassegrain direct-coupled to a Canon Digital Rebel (300D) at ISO 400, rotated and stacked with *MaxDSLR*. (David Rosenthal.)

Assuming  $0.1^\circ$  of rotation is acceptable in a picture, then the number of seconds you can expose at any particular point in the sky is:

$$\text{Time (seconds)} = \frac{0.1^\circ}{\text{Rotation rate}} = \frac{0.1^\circ \cos(\text{Alt})}{0.004167^\circ \cos(\text{Lat}) \cos(\text{Az})}$$

Figure 9.11 plots the exposure time limit over the whole sky as seen from latitude  $40^\circ$  north. (From other temperate latitudes the situation is very similar.) As you can see, most of the sky can tolerate a 30-second exposure; the areas to avoid are near the zenith, where rotation is especially fast. The rotation rate is zero at azimuth  $90^\circ$  and  $270^\circ$ , due east and west of the zenith, but only momentarily since objects do not remain at those azimuths. The “sweet spots,” where you can expose for several minutes, are below altitude  $40^\circ$  in the east and west.

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published formula was 0.004178, the earth’s rotation rate in degrees per sidereal second; I have converted it to degrees per ordinary second.



Figure 9.13. This is not field rotation; it's a lens aberration. Clues: the effect is not proportional to exposure time, and bright stars are affected more than faint ones. (Film image with Olympus 40-mm  $f/2$  lens, from *Astrophotography for the Amateur*.)

### 9.5.2 Success in altazimuth mode

Figure 9.12 shows what can be accomplished by stacking short exposures tracked on an altazimuth mount. In this picture of M27, the slight left–right elongation of the star images is probably caused by less-than-perfect tracking, since, after all, altazimuth mounts are designed for visual rather than photographic use. Each exposure was only 30 seconds long, and no field rotation is visible.

Naturally, an equatorial wedge would have made the tracking easier and

## 9.5 How well can you do with an altazimuth mount?

smoother (because only one of the telescope's two motors would be running), but, as the picture shows, altazimuth mode is far from useless.

Presumably, you can use an autoguider in altazimuth mode, but I have yet to hear from anyone who has done so. It may not be necessary. There is no drift from polar alignment error because there is no polar alignment. There is periodic error in the gears of both motors (azimuth and altitude), but as Figure 9.12 shows, it can easily be negligible. If a few images in the series have tracking problems, they can be left out while the others are stacked.

### 9.5.3 What field rotation is not

Figure 9.13 shows a common lens aberration that looks like field rotation. The picture, however, was an exposure of only a few seconds on a fixed tripod; field rotation definitely did not occur.

Further evidence that this is a lens aberration comes from the fact that the brightest stars are more affected than fainter stars the same distance from the center, and the entire effect goes away if the lens is stopped down to a smaller aperture.

## Chapter 10

# Power and camera control in the field

### 10.1 Portable electric power

Although my main observing sites are blessed with AC power, most amateurs rely on batteries in the field, as I sometimes do. For much more advice about portable electric power, see *How to Use a Computerized Telescope*. Here I'll review the basics.

#### 10.1.1 The telescope

Most telescopes operate on 12 volts DC and can be powered from the battery of your parked car. Doing this can be risky; what if you drain the battery and the car won't start when you're ready to go home?

It's much better to use portable lead-acid batteries, either gel cells or deep-cycle boat batteries. Check the battery voltage periodically during use and don't let it get below 12.0. Recharge the battery before storing it.

The capacity of a rechargeable battery is rated in ampere-hours (amp-hours, AH), thus:

$$\text{Hours of battery life} = \frac{\text{Battery capacity in ampere-hours}}{\text{Current drain in amperes}}$$

If possible, you should measure the current drawn by your equipment using an ammeter. If you have to guess, a telescope draws about 1 ampere, a dew heater system draws 2 or 3, and an autoguider or laptop computer may draw 2 to 5 amperes. That's enough to run down a commonly available 17-AH battery pack very quickly.

In such a situation, a 60-AH deep-cycle battery is worth paying for, even though it isn't cheap. Better yet, put the telescope on one battery, the laptop on another, and the dew heater on a third. This will prevent ground loop problems (see p. 118) and will ensure that a mishap with one piece of equipment doesn't disrupt everything.

Don't use a car battery; it is not designed for deep discharge, and if you use it within its rated limits, it won't do you any more good than a much smaller, lighter gel cell pack. If you discharge it deeply, it will wear out prematurely.

### 10.1.2 The computer and camera

The most convenient way to power a laptop computer in the field is to use its own battery, which is good for two or three hours; you can bring a fully charged spare or two. To save power, turn down the LCD brightness, reduce the CPU speed if you have that option, and turn off the network adapter.

Second choice is to equip the laptop with a 12-volt power supply, such as you would use in a car or aircraft, and connect it to the main 12-volt battery.

Third choice, distinctly less efficient, is to use an inverter to convert 12 volts DC to 120 or 240 volts AC, and feed that to the laptop's AC line power supply. The problem is that every voltage conversion wastes energy; even the best switchmode converters are not 100% efficient. But a big advantage of DC-to-AC inverters is that they provide transformer isolation, eliminating ground loops (see next section).

The same goes for the camera. My own approach is to bring three or four fully charged batteries and swap them as needed. I can keep them in my pocket (in insulated wrappers, of course) so that they don't get too cold. The alternative is to use an external power supply for the camera. Generally, these require 120 or 240 V AC, but some enterprising experimenters have built versions that operate on 12 V DC.

### 10.1.3 Care of Li-ion batteries

The lithium-ion (Li-ion) batteries commonly used in cameras and laptop computers have a big advantage over earlier NiCd and NiMH types: they retain much more of their charge while unused. You can charge a battery, put it away, and expect it to work without recharging a month later.

Li-ion batteries always require a "smart charger" rather than just a source of regulated voltage or current. The smart charger senses the state of the battery to charge it rapidly without overcharging.

This means no harm will result if you "top up" your already-charged Li-ion batteries before an observing session. In fact, I usually do so. This is done by putting them in the charger in the usual way. In a few minutes, it will report that the battery is fully charged, but keep the battery in the charger anyway; it continues to gain charge for as much as an hour after the full-charge indicator comes on.

As batteries age, they lose capacity. There is no quick trick for restoring old Li-ion batteries, but sometimes, all they need is another charging cycle. One of my Canon batteries became almost unusable, but I ran it through the charging routine twice, and since then, it has worked fine. Perhaps one of the measurements used by the smart charger had come out of calibration.

#### 10.1.4 Ground loop problems

If you use one battery for several pieces of equipment, you may have problems with *ground loops*. A ground loop is what happens when two devices are tied together through “circuit ground” (typically at USB or serial ports), and also share a power supply, but the voltage of circuit ground relative to the power supply is not the same in both devices.

Here’s an example. If you power a laptop through a 12-volt power supply, its circuit ground will be tied to the negative side of the battery. But circuit ground in a classic (non-GPS) Meade LX200 telescope is a fraction of a volt higher than the negative side of the battery; the current-indicating circuit (LED ammeter) is between them. If you connect the laptop to the telescope, serial port to serial port, you’ll have a ground loop. Fortunately, in this case only the LED ammeter will be disrupted.

Fortunately, ground loops are not common. You should suspect a ground loop if you have equipment that malfunctions only when it shares the battery of another piece of equipment to which it is connected.

One way to eliminate ground loops is to power each device from a separate battery. Another is to use an AC inverter. Despite wasting a few percent of the energy, an AC inverter provides true transformer isolation between battery and load. In fact, one inverter can power several accessories, all of which are isolated by their own AC power supplies.

#### 10.1.5 Safety

Think of any rechargeable battery as something like a fuel canister. It contains a tremendous amount of energy, and if short-circuited, it can produce intense heat, explode, and start a fire.

It’s obvious that a large lead-acid battery deserves respect; it’s big, heavy, and full of sulfuric acid. There should always be a fuse between a lead-acid battery and whatever it is powering, preferably a separate fuse for each piece of equipment, as in the electrical system of a car or boat.

Small rechargeable batteries for cameras or laptops are also potentially perilous. *Always keep camera batteries wrapped in insulating material.* If you drop an uncovered DSLR battery into your pocket along with your keys, you may soon find your clothing on fire. I keep camera batteries in thick plastic bags, and I only put them in my pocket if the pocket doesn’t contain anything else.

The AC line at your observing site, if there is one, must be protected by a ground-fault circuit interrupter (GFCI). This does not totally prevent electric shock, but it does protect you in situations where electricity tries to flow through your body from the power lines to the earth. Remember that there will be heavy dew during the night; keep high-voltage connections dry. Also remember that AC from an inverter is almost as dangerous as AC from the mains; the only difference is that the output of the inverter is isolated from the earth.

## 10.2 Camera control

### 10.2.1 Where to get special camera cables

The following pages describe a number of homemade cable releases and computer interface devices. *Please do not build these circuits unless you understand them thoroughly and can use test equipment to verify that they are assembled correctly.* It would be a pity to damage an expensive camera while trying to save money on accessories.

Makers of camera control software can tell you where to get the special cables if you can't make them for yourself. One major supplier is Shoestring Astronomy ([www.shoestringastronomy.com](http://www.shoestringastronomy.com)), which has plenty of up-to-date information as well as products for sale. Another is Hap Griffin ([www.hapg.org](http://www.hapg.org)). By the time you read this, there will probably be others; some Internet searching is in order.

### 10.2.2 Tripping the shutter remotely

To trip the shutter without shaking the camera, and to hold it open for a long exposure, you need some kind of remote control cable. Unfortunately, DSLRs don't accept the mechanical cable releases that we relied on with our film cameras. Instead, they use electrical cables, or in some cases infrared signals.

It's useful to know which other cameras take the same cable release or infrared controller as yours. For example, Canon's literature says that the Canon Digital Rebel (EOS 300D) takes the Canon RS-60E3 "remote switch," which has a 2.5-mm (3/32-inch) phone plug. So do the EOS 350D and 400D. The same accessories will plug into the cable release socket of any of these.

But the EOS 20D, 20Da, 30D, and higher-end Canons require the RS-80N3, which has a three-pin connector all its own (Figure 10.4, p. 122). Canon also makes the TC-80N3, a cable release for the same cameras that has a digital timer built in.

All current Nikon DSLRs work with the Nikon ML-L3 infrared remote release. The D70s and D80 also take an electrical cable release, the MC-DC1.

Third-party manufacturers make cable releases equivalent to Canon's and Nikon's. Some of them have special advantages, such as extra-long cables, but some are shoddily made and apt to come loose from the camera. Shop carefully.

#### **Making a cable release for the Digital Rebel**

It's easy to make your own cable release for the Canon Digital Rebel family (EOS 300D, 350D, 400D, or any camera that takes the RS-60E3). Figure 10.1 shows how. The connector is a 2.5-mm phone plug. That's the smallest of three sizes, used on headsets for mobile telephones; in fact the easiest way to get one may be to take apart a cheap mobile phone headset.

## Power and camera control in the field

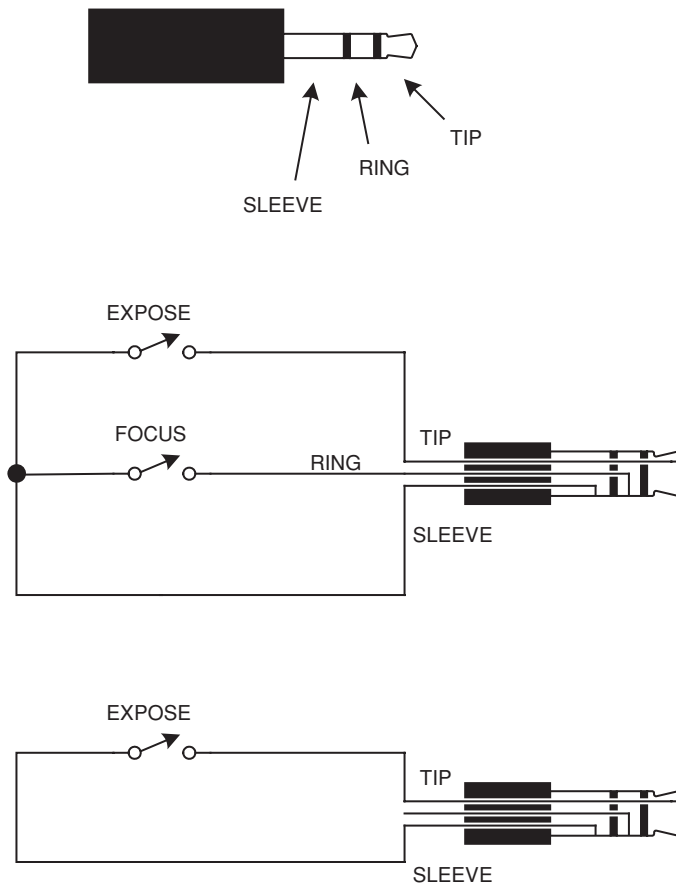


Figure 10.1. How to make a cable release for Canons that take the E3 connector (2.5-mm phone plug).

As the illustration shows, the three connectors on the plug are called *Tip*, *Ring*, and *Sleeve*. Connecting Ring to Sleeve triggers autofocus; connecting Tip to Sleeve trips the shutter.

In astronomy, we don't use autofocus, so only one switch is really needed, from Tip to Sleeve. The bottom circuit in Figure 10.1 is for DSLRs. Some film EOS cameras require you to tie Tip and Ring together if you are only using one switch.

What's inside the camera? Figure 10.3 shows an equivalent circuit determined by voltage and current measurements from outside the camera (and suitable application of Thévenin's Theorem). The equivalent circuit shows that you cannot harm the camera by shorting any of the three terminals together, or, indeed, by connecting anything to them that does not contain its own source of power.

In fact, some Canon owners have reported that they can plug a mobile telephone headset into the DSLR and use its microphone switch to control the shutter. Mine didn't work, but there's no harm in trying.

## 10.2 Camera control



Figure 10.2. Cable release built with toggle switch in a small bottle.

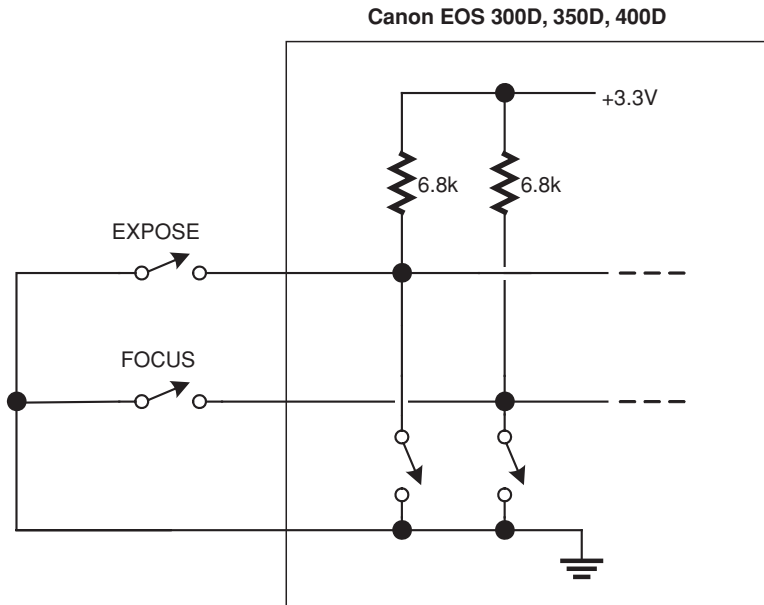


Figure 10.3. Internal circuit of Canon camera as revealed by voltage and current measurements from outside.

### Customizing a cable release for higher-end Canons

You can't make your own cable release for the Canon 20D, 20Da, 30D, or higher models because the so-called "N3" connector used on it is not available separately.

However, you may want to modify an existing Canon RS-80N3 or equivalent cable release so that it will accept the same phone plug as a Digital Rebel, making it compatible with serial port cables, custom timing devices, and whatever other accessories you may have built.

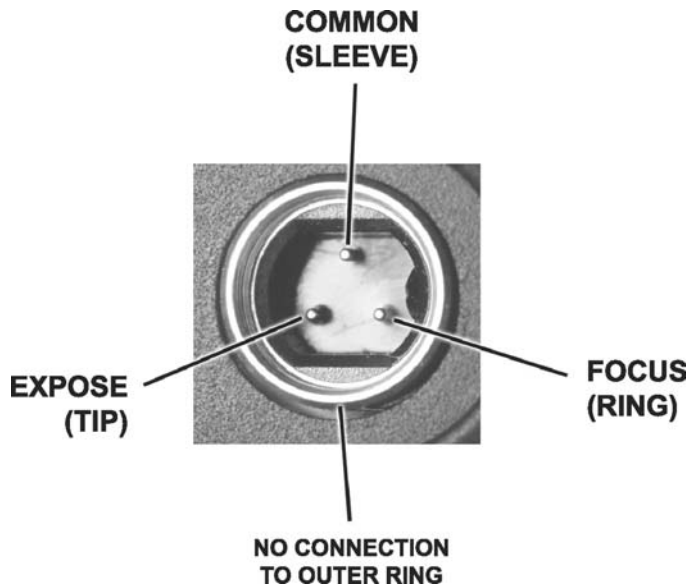


Figure 10.4. Pins on Canon N3 connector (used on 20D and higher models) have the same function as Tip, Ring, and Sleeve on Digital Rebel series. Do not short Tip and Ring together; they have different voltages.

Figure 10.4 identifies the pins on the camera. You can trace the connections into the RS-80N3 and add a short piece of cable with a female phone jack to match the Digital Rebel, connected to the corresponding wires, so that whatever you plug in will operate in parallel with the existing switches. On the wires entering the RS-80N3, Tip is red, Ring is yellow or white, and Sleeve is the copper shield. These are the same colors used on stereo cables, so if you get your 2.5-mm phone jack by taking apart a stereo extension cable, you can simply match colors – but always verify the connections with an ohmmeter.

Going in the other direction, you can fit a 2.5-mm stereo phone plug onto a Canon TC-80N3 timer unit in order to use it with the Digital Rebel series of DSLRs and time your exposures digitally. The best way to modify a TC-80N3 is to interrupt its cable, inserting a stereo plug and jack. That way, you can plug the TC-80N3 into the rest of its own cable when you want to use it with a higher-end EOS camera.

### 10.2.3 Controlling a camera by laptop

#### The USB link

Every DSLR has a USB interface through which a computer can change the settings, trip the shutter, and download pictures. The USB connector on the camera is a very small type not used elsewhere, but it is standardized (“Mini-USB-B”) and you can buy suitable cables from numerous vendors. In fact, the

## 10.2 Camera control

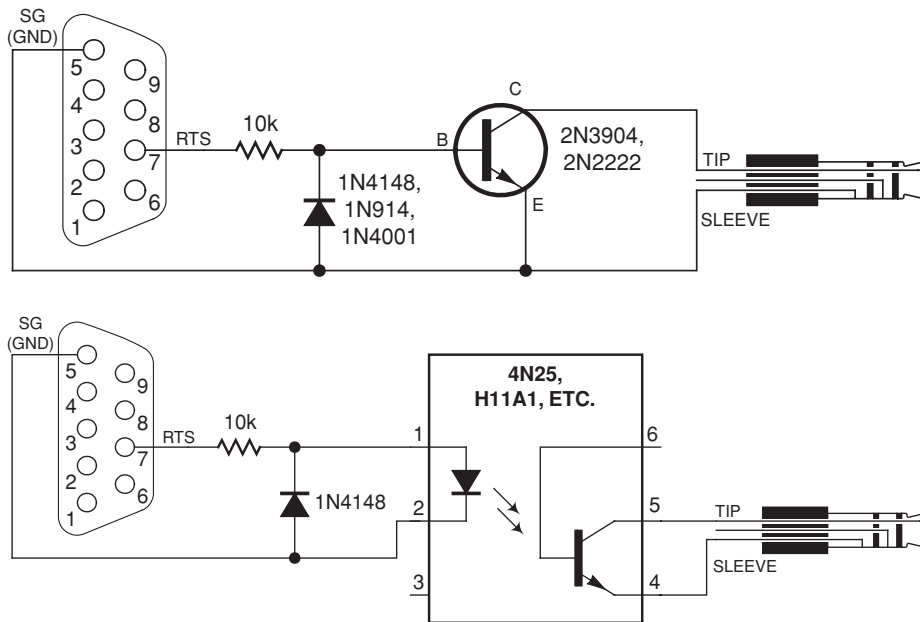


Figure 10.5. Two ways to control a Canon shutter from the serial port of a computer. For parallel port cable, use pins 2 and 18 (of 25-pin connector) in place of pins 7 and 5, respectively.

cable that came with your camera is almost certainly too short; you'll need a longer one immediately, or else an extension cable.

For the USB interface to work, you must install the WIA or TWAIN drivers that came on a CD with your camera. These can also be downloaded from the manufacturer. They enable the computer to recognize the camera, communicate with it, and download files from it. Astronomical camera-control software relies on these drivers.

### Parallel- and serial-port cables

One crucial function is missing from the USB interface of Canon and Nikon DSLRs, at least so far. There is no "open shutter" or "close shutter" command. Through the USB port, the computer can set an exposure time and take a picture, but only if the exposure time is within the range of selectable shutter speeds (up to 30 seconds). There are no separate operations to begin and end an exposure on "bulb."

Accordingly, you'll need an ersatz cable release, plugged into the cable release socket of the camera (or wired to an infrared controller) and controlled by the parallel or serial port of your computer. In conjunction with software such as *DSLR Shutter* (freeware from [www.stark-labs.com](http://www.stark-labs.com)) or any major DSLR astrophotography package, the computer can then "press the button" for as long as it wants.

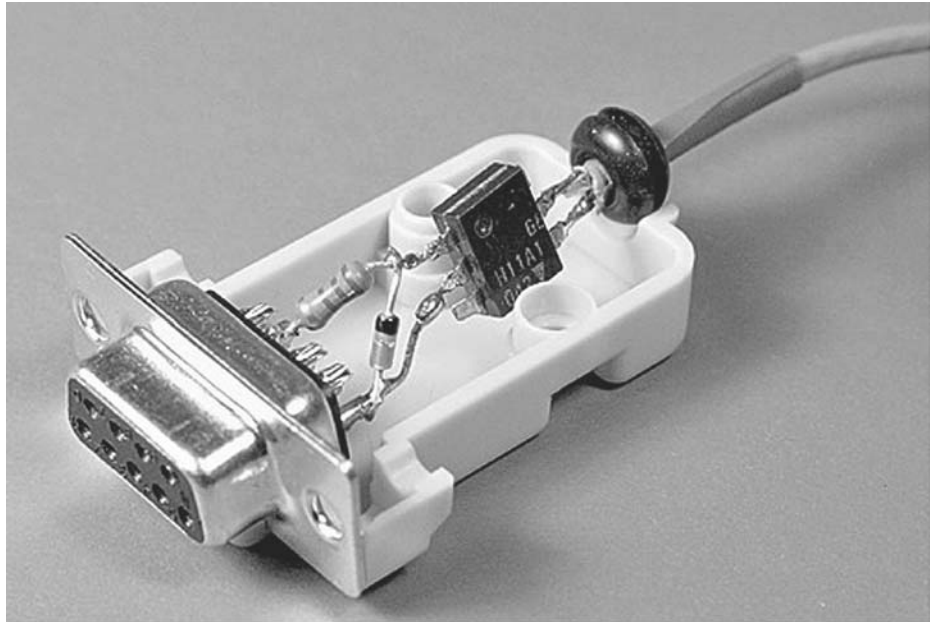


Figure 10.6. The serial cable circuit can be assembled in a large nine-pin connector, then connected directly to the computer or to a USB serial cable.

For details of the cable needed, consult the instructions that accompany your software; there are many variations. Figure 10.5 shows one popular type.

The software interface is very simple. Instead of outputting data to the serial or parallel port, the software simply sets one pin positive instead of negative. On a serial port, this is usually the RTS line (pin 7; pin 5 is ground); on a parallel port, pin 2 (and pin 18 is ground).

The value of the resistor can vary widely; erring on the side of caution, I chose 10 k $\Omega$ , but some published circuits go as high as 47 k $\Omega$ . The second version of the circuit uses an optoisolator to eliminate a ground loop, but if the camera and computer are also tied together by their USB ports, this is a moot point.

If your DSLR isn't one of the Canons with the 2.5-mm phone plug, Figure 10.7 shows what to do. You'll need a cable release or infrared controller for your camera. Find the switch in it that trips the shutter; use a voltmeter to identify the positive and negative sides of it; and wire the transistor across it.

### 10.3 Networking everything together

Now it's time to sum up. The typical modern DSLR astrophotographer uses a laptop computer for control, a webcam for autoguiding, and a computerized telescope. Here are all the connections that have to be taken care of:

## 10.4 Operating at very low temperatures

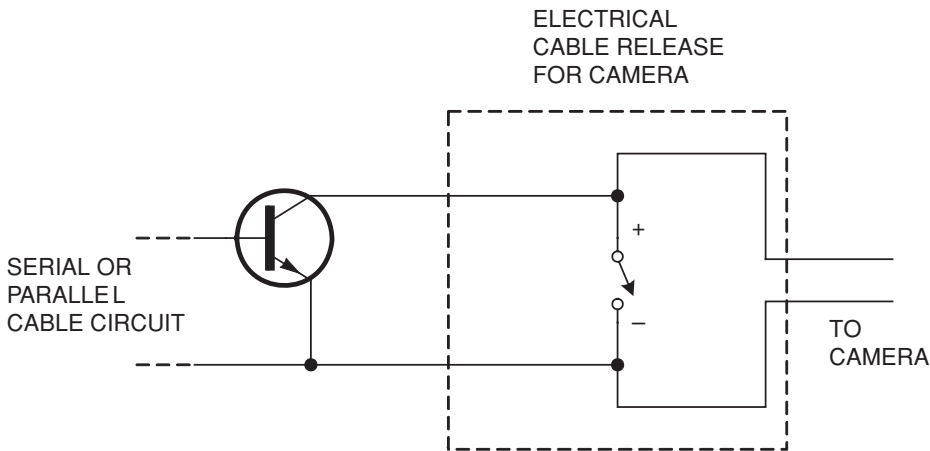


Figure 10.7. Strategy for adapting a serial or parallel port cable to a non-Canon DSLR. Use a voltmeter to identify the + and - sides of switch.

- Power for the telescope, the computer, and the camera (preferably all separate).
- USB or serial connection from the computer to the telescope for guiding, and possibly also for telescope control (finding objects) and electric focusing.
- USB connection from the computer to the webcam for autoguiding (this also supplies power to the webcam).
- USB connection from the computer to the DSLR to control settings and download images.
- Serial- or parallel-port cable from the computer to the DSLR cable release socket to control long exposures.

If the telescope is an older one with a six-pin modular autoguider port, you can use cables available from [www.shoestringastronomy.com](http://www.shoestringastronomy.com) that interface it to the computer's parallel or USB port. And if you need serial or parallel ports that you don't have, use USB-to-serial or USB-to-parallel converters.

Now count the connections. You may need as many as five USB ports, in which case a USB hub enters the picture. Small USB hubs, powered from the USB port itself, are to be preferred if they work adequately.

In a few years, we will be using short-range wireless communication instead of a rat's nest of USB cables. Then the only cables that we have to deal with will be for power, and the case for running each device off its own battery will be compelling.

## 10.4 Operating at very low temperatures

The most obvious effect of low temperatures on DSLRs is that there are a lot fewer hot pixels. This is a good thing and is why astronomical CCDs are internally cooled. It's also why we take dark frames at the same temperature as the exposures from which they are to be subtracted.

A second effect, not so benign, is that batteries lose some of their capacity. If you remove a "dead" battery from a camera and warm it up in your hand, it will often come back to life. LCD displays may also lose contrast in the cold, but the effect is temporary.

At temperatures down to about 0° F (−18° C), those are probably the only effects you will notice. At lower temperatures, though, electronic components may begin to malfunction. Those most likely to be affected are flash memory devices and data communication chips because they rely on voltage thresholds that can shift with temperature. This means your camera memory card may have problems, as well as the flash ROM, USB port, and serial port of a microprocessor-controlled camera or telescope. "Microdrives" (tiny disk drives built into memory cards) are not rated to work below 32° F (0° C).

Do not bring a very cold camera directly into warm, humid air, or moisture will condense on it. Instead, put it in a plastic bag, or at least a closed case, and let it warm up gradually. If condensation forms, do not use the camera until it has dried.

# Chapter 11

## Sensors and sensor performance

### 11.1 CCD and CMOS sensors

Electronic image sensors work because light can displace electrons in silicon. Every incoming photon causes a valence electron to jump into the conduction band. In that state, the electron is free to move around, and the image sensor traps it in a capacitive cell. The number of electrons in the cell, and hence the voltage on it, is an accurate indication of how many photons arrived during the exposure. Modern sensors achieve a *quantum efficiency* near 100%, which means they capture an electron for nearly every photon.

The difference between CCD and CMOS sensors has to do with how the electrons are read out. *CCD* stands for *charge-coupled device*, a circuit in which the electrons are shifted from cell to cell one by one until they arrive at the output (Figures 11.1, 11.2); then the voltage is amplified, digitized, and sent to the computer. The digital readout is not the electron count, of course, but is exactly proportional to it.

CMOS sensors do not shift the electrons from cell to cell. Instead, each cell has its own small amplifier, along with row-by-column connections so that each cell can be read out individually. There is of course a main amplifier along with other control circuitry at the output.<sup>1</sup>

Which is better? Originally, CCDs had the advantage; CMOS image sensors were designed to be made more cheaply, with lower-grade silicon. CMOS sensors were noisy and had low quantum efficiency because most of the photons fell on the amplifiers rather than the photosensors.

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<sup>1</sup> The term *CMOS* means *complementary metal-oxide semiconductor* and describes the way the integrated circuit is made, not the way the image sensor works. Most modern ICs are CMOS, regardless of their function.

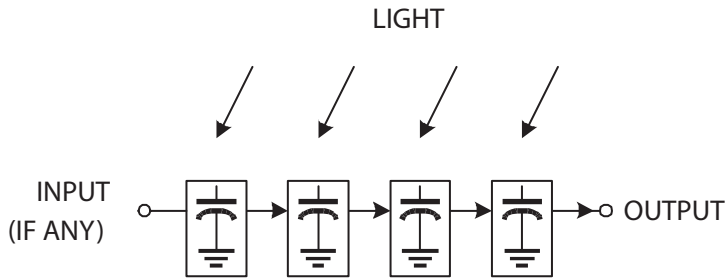


Figure 11.1. Charge-coupled device (CCD) consists of cells (pixels) in which electrons can be stored, then shifted from cell to cell and retrieved. Light makes electrons enter the cells and slowly raise the voltage during an exposure. (From *Astrophotography for the Amateur*.)

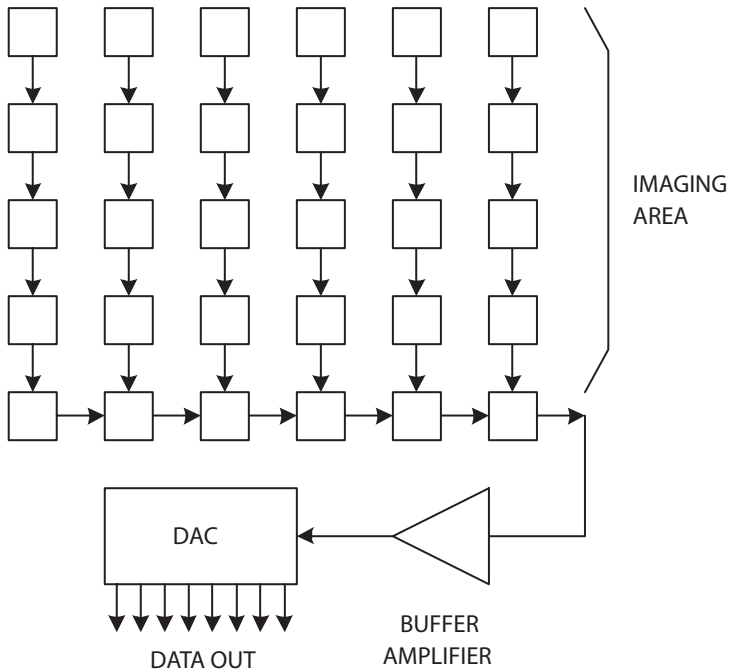


Figure 11.2. CCD array shifts the contents of each cell, one after another, through other cells to the output for readout. CMOS arrays have an amplifier for each pixel, with row and column connections to read each pixel directly. (From *Astrophotography for the Amateur*.)

Today, however, CCD and CMOS sensors compete on equal ground. The CMOS amplifiers are under the pixels, not between them, and the quantum efficiency is comparable to CCDs. So are all other aspects of performance, including noise. Canon DSLRs use CMOS sensors (to which Canon has devoted a lot of work), most others use CCDs, and neither one has a consistent advantage over the other. Nikon adopted a Sony CMOS sensor for the high-end D2X camera.

## 11.2 Sensor specifications

### 11.2.1 What we don't know

DSLR manufacturers do not release detailed specifications of their sensors. Accordingly, the sensitivity curves in Figure 11.5 (p. 134) reflect a certain amount of guesswork.

What's more, the "raw" image recorded by a DSLR is not truly raw. Some image processing is always performed inside the camera – but manufacturers are extremely tight-lipped about what is done. For example, Canon DSLRs apparently do some kind of bias frame subtraction on every image, and Nikon's "star eater" speckle-removing algorithm is notorious.

We can hope that in the future, DSLRs will come with the equivalent of film data sheets, giving at least the spectral response, characteristic curve, and signal-to-noise ratio. Until that happens, we have to rely on third-party tests.

For detailed investigations of astronomical DSLR performance, see the web sites of Christian Buil ([www.astrosurf.net/buil](http://www.astrosurf.net/buil)) and Roger N. Clark ([www.clarkvision.com](http://www.clarkvision.com)). Buil focuses on astronomical performance and spectral response, while Clark sets out to measure sensor parameters such as full-well electron capacity and signal-to-noise ratio.<sup>2</sup>

Another way to test a DSLR is to ignore the internal details and use well-established measures of picture quality, such as dynamic range and color fidelity. This is the approach taken by the *Digital Photography Review* web site ([www.dpreview.com](http://www.dpreview.com)) and by the reviews published in European magazines such as the *British Journal of Photography*, *Chasseur d'Images* (France), and *Super Foto* (Spain).

All of these tests point to one important result: DSLRs are improving steadily and rapidly. The latest models have more dynamic range and less noise than those even two years older, and all current DSLRs perform much better than film.

### 11.2.2 Factors affecting performance

#### Pixel size

The pixels in a DSLR sensor are much larger than those in a compact digital camera. That's why DSLRs perform so much better. Typically, a DSLR pixel is 5–8  $\mu\text{m}$  square and can accumulate over 40 000 electrons. Besides the desired signal, a few electrons always leak into the cell accidentally at random, but each of them will constitute only 1/40 000 of the total voltage. In the smaller pixels of a compact digital camera, the same electrons would do much more harm.

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<sup>2</sup> Clark is also the author of *Visual Astronomy of the Deep Sky* (Cambridge University Press, 1990, now out of print), a groundbreaking study of the factors that determine the visibility of faint deep-sky objects to the human eye.

### Quantization

Each cell has to contain an integral number of electrons. You can have 23 624 electrons or 23 625, but not  $23\,624\frac{1}{2}$  because there's no such thing as half an electron. This is why the camera cannot distinguish an infinite number of different brightness levels. But then, neither can light itself; there's no such thing as half a photon, either.

A much coarser kind of quantization takes place at the output of the amplifier, when the cell voltage is turned into a digital signal. Normally, DSLRs perform 12-bit digitization, meaning that each cell voltage is rendered into a whole number between 0 (black) and 4095 (white). This number is of course less precise than the actual electron count.

These 12-bit numbers are often called *ADUs* (analog-to-digital units). They can be stored in a 16-bit TIFF file, where they do not use the whole available range. Such a file, viewed directly, looks very dark until it is "stretched" by multiplying all the values by a constant. Even then, it may look rather dark because it needs gamma correction (p. 170).

### ISO speed adjustment

To provide adjustable ISO speed, the camera lets you amplify the voltages during the digitization process. That is, you don't have to use the full capacity of the cells. Suppose your cells hold 50 000 electrons. You can multiply all the output voltages by 2, and then 25 000 electrons will be rendered as maximum white (and so will anything over 25 000). This means you need only half as much light, but the image will be noisier because every unwanted electron now has twice as much effect.

### Dynamic range

The *dynamic range* of a sensor is the range of brightness levels that it can distinguish, usually measured in *stops*, where (as in all photography) "*N stops*" means a ratio of  $2^N$  to 1. Tests by Roger Clark show that, in raw mode, DSLRs can cover a brightness range of 12 to 15 stops (that is, about 4000:1 to 30 000:1), which is appreciably greater than the 9- or 10-stop range of film. However, when pictures are output as JPEG, the usable dynamic range is no more than 8 or 9 stops. The rest of the range is used for ISO adjustment.

DSLRs normally have the largest dynamic range at ISO 100 or 200, as well as the best signal-to-noise ratio. The earliest DSLRs got steadily worse as you turned up the ISO speed. But tests by Roger Clark, as well as my own experience, show that with newer DSLRs, there is very little difference up to ISO 400. After that, compromises become evident, but higher settings can still be justified when the object being photographed is faint.

### Color balance

Color balance is similar to ISO speed adjustment except that the red, green, and blue pixels are adjusted by differing amounts. This corrects for the inherently

uneven sensitivity of a CCD (stronger in red than in green or blue) and allows for variations in the light source. The two obvious choices for astrophotography are daylight balance, to get the same color rendition all the time, or automatic white balance, to try to avoid a strong overall color cast. Color balancing is done after digitization and only affects JPEG images, not raw image files. In software such as *MaxDSLR*, you get to specify multiplication factors for the three colors yourself.

### 11.2.3 Image flaws

#### Bad pixels

Every sensor has a few flaws. *Hot pixels* are pixels that always read out as an excessively high number due to excessive electrical leakage (dark current); *dead pixels* always read out as zero.

Of the two, hot pixels are more of a problem. You can see them by making a 5-minute exposure with the lens cap on. Most of them will look bright red, green, or blue because they hit only one spot in the Bayer color matrix. Indeed, vividly colored stars in a DSLR photograph should be viewed with suspicion; they may not be stars at all.

In general, the hot pixels in a sensor are reproducible; they will be the same if you take another exposure soon afterward. That's why dark-frame subtraction is effective at eliminating them.

Even among the pixels that are not hot or dead, there is inequality. No two pixels have exactly the same sensitivity to light, the same leakage, or the same *bias*. Bias is the starting voltage, non-zero because you can't get all the electrons out of every cell before starting an exposure. Reproducible inequality between pixels is called *fixed-pattern noise*. Besides appearing as random grain, it may also have a striped or tartan-like pattern.

With modern DSLRs, fixed-pattern noise is usually very slight and is strongly corrected by the computer inside the camera.

#### Effect of temperature

Leakage, or dark current, is affected by temperature; that's why astronomical CCD cameras have thermoelectric coolers. Even DSLRs are noticeably less noisy in the winter than in the summer; that's why dark frames should always be taken at the same temperature as the images from which they will be subtracted.

Theoretically, the dark current of a silicon CCD sensor doubles for every 8° C (15° F) rise in temperature.<sup>3</sup> This relationship is affected by the way the sensor is fabricated, and I have not investigated whether it is accurate for the latest

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<sup>3</sup> Extrapolating from the curve on p. 47 of Steve B. Howell, *Handbook of CCD Astronomy*, 2nd ed. (Cambridge University Press, 2006), to normal DSLR camera temperatures. At lower temperatures the change per degree is greater.



Figure 11.3. Amplifier glow (*arrow*) mars this image of the Rosette Nebula. Single 10-minute exposure at ISO 800, unmodified Nikon D50, 14-cm (5.5-inch)  $f/7$  TEC apochromatic refractor. Dark-frame subtraction was later used to remove the amp glow. (William J. Shaheen.)

DSLR sensors. What is definite is that there's less noise in the winter than in the summer.

At this point you may be thinking of chilling the camera. This has been tried, but one obvious drawback is that moisture from the atmosphere will condense on the sensor if the sensor is cold enough.

### **Blooming**

Blooming is a phenomenon that makes an overexposed star image stretch out into a long streak. It is uncommon with DSLRs though common with astronomical CCDs. Blooming occurs when electrons spill over from one cell into its neighbors.

### **Amplifier glow (electroluminescence)**

The main amplifier for the CCD or CMOS sensor is located at one edge of the chip, and, like any other working semiconductor, it emits some infrared light. Some sensors pick up a substantial amount of "amp glow" in a long exposure (Figure 11.3). Dark-frame subtraction removes it.

### **Cosmic rays**

Even if the sensor is perfect, pixels will occasionally be hit by ionizing particles from outer space. These often come two or three at a time, byproducts of collisions of the original particle with atoms in the air (Figure 11.4). Like hot pixels, cosmic ray hits are likely to be vividly colored because of the Bayer matrix.

Cosmic rays are a source of non-reproducible hot pixels. They are also the reason you should not believe just *one* digital image if it seems to show a nova

### 11.3 Nebulae, red response, and filter modification

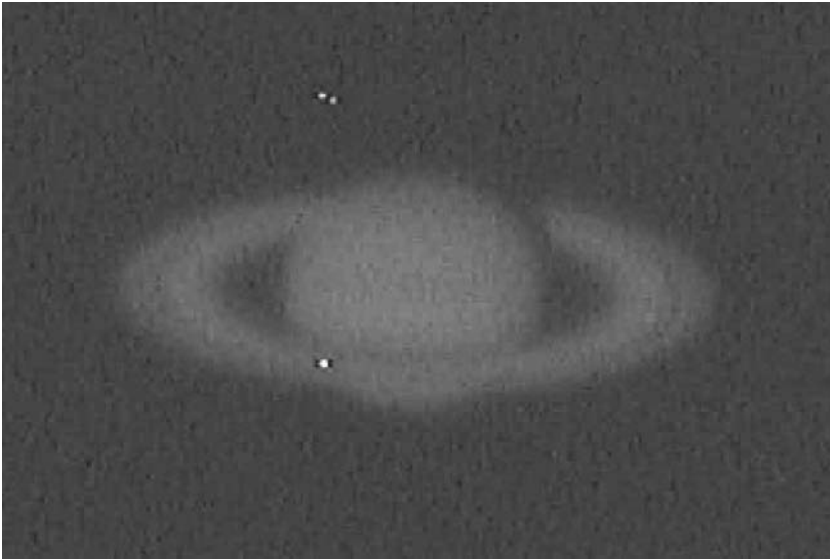


Figure 11.4. Cosmic ray impacts in a single frame of a webcam video recording of Saturn. All three particles arrived during the same 1/30-second exposure, indicating their origin in a single cosmic ray. With DSLRs, the effect of cosmic rays is usually much less noticeable than this.

or supernova. When conducting a search for new stars, take every picture at least twice.

#### 11.2.4 Binning

A simple way to reduce noise and remove flaws is to *bin* the pixels, i.e., combine them in  $2 \times 2$  or  $3 \times 3$  squares. This results in a picture with, respectively,  $1/4$  or  $1/9$  as many pixels as the original.

It takes about a million pixels to make a pleasing full-page picture. This means the output of a 10-megapixel DSLR can be binned  $3 \times 3$  with pleasing results.

The easiest way to accomplish binning is simply to resize the image to  $1/2$  or  $1/3$  of its original linear size using *Photoshop* or another photo editing program. Many astronomical software packages offer binning as an explicit operation.

### 11.3 Nebulae, red response, and filter modification

#### 11.3.1 DSLR spectral response

Figure 11.5 sums up a lot of information about the wavelengths of light to which cameras respond. Reading from the top, the first thing you'll notice is that color film has a gap in its response between green and blue, and DSLRs don't. This is important because the strong hydrogen-beta and oxygen-III lines from emission nebulae fall in that gap. That's one reason nebulae that look red on film may come out blue with a DSLR.

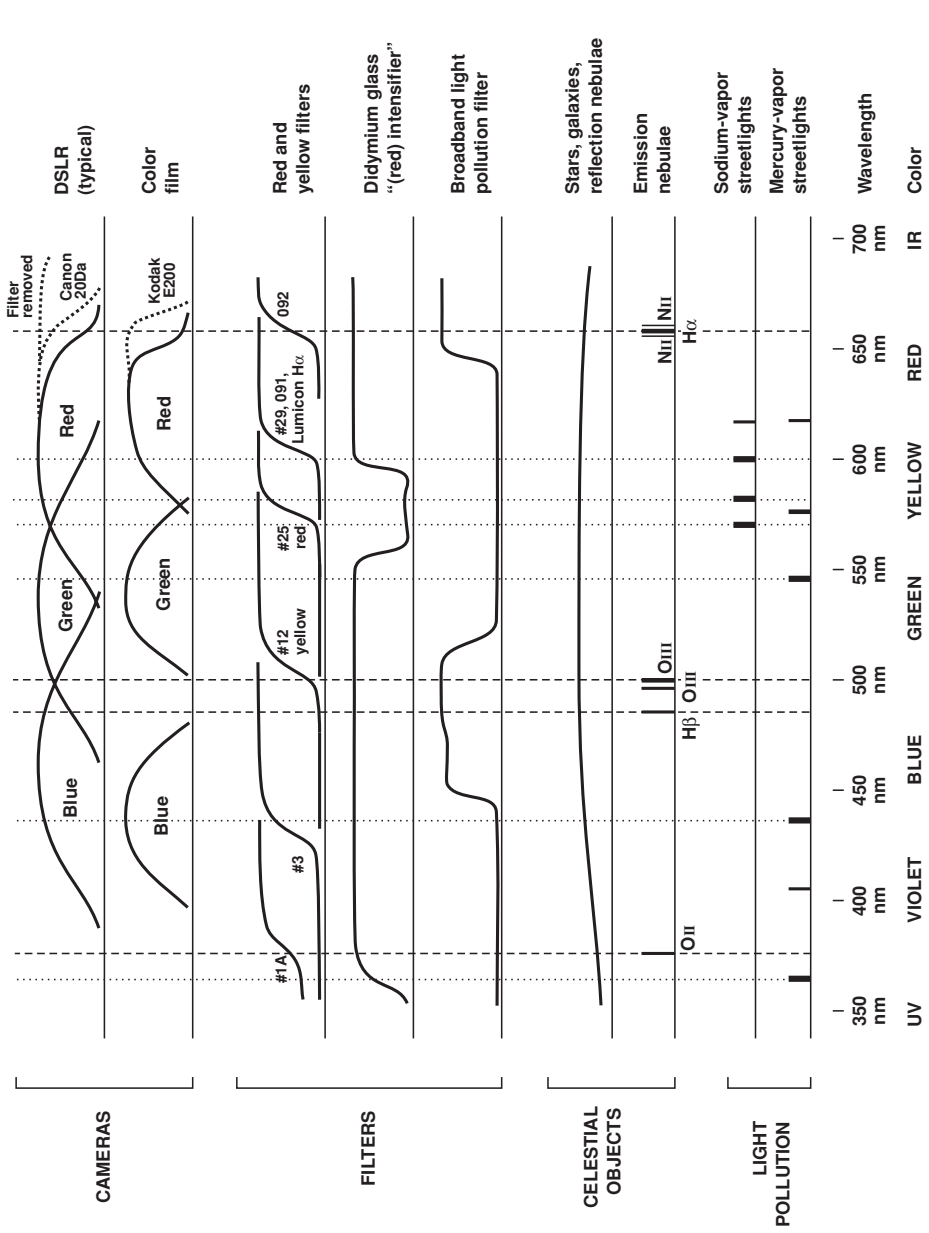


Figure 11.5. How the visible spectrum is emitted by streetlights and celestial objects, transmitted or blocked by filters, and detected by film or DSLR sensors. Data are approximate; consult actual specification sheets when possible.

DSLR makers don't publish spectral response curves, so the curves at the top of Figure 11.5 are estimated from Sony CCD data sheets plus a number of published tests. What is most uncertain is the effect of the infrared-blocking filter in front of the sensor. We know that with this filter removed, the sensor has strong response up to 700 nm or further.

#### 11.3.2 Filter modification

There are two reasons astrophotographers often have their DSLRs modified for extended red response. One is the strong hydrogen-alpha ( $H\alpha$ ) emission from nebulae at 656.3 nm. The other is that working in deep red light, with filters blocking out the rest of the spectrum, is a good way to overcome skyglow in cities.

Canon's EOS 20Da (now discontinued) and some Fuji DSLRs have been manufactured with extended red response. Usually, though, astrophotographers rely on third parties to modify their cameras. Reputable purveyors of this service include Hutech ([www.hutech.com](http://www.hutech.com)), Hap Griffin ([www.hapg.org](http://www.hapg.org)), and LifePixel ([www.lifepixel.com](http://www.lifepixel.com)). For those who have confidence in their ability to work on delicate precision instruments, there are also modification instructions published on the Internet.

The simplest modification is to simply remove the filter. This has three drawbacks. One is that the red response increases so much that the camera no longer produces realistic color images; red always predominates. The second is that the camera no longer focuses in the same plane; neither the autofocus mechanism nor the SLR viewfinder gives a correct indication of focus. The camera can only be focused electronically. The third is that, with such a camera, camera lenses may no longer reach infinity focus at all.

It's better to replace the filter with a piece of glass matched in optical thickness (not physical thickness) to the filter that was taken out. Then the focusing process works the same as before. Better yet, replace the filter with a different filter. Firms such as Hutech offer a selection of filters with different cutoff wavelengths, as well as options for inserting additional filters for daytime color photography.

How much more  $H\alpha$  response do you get? An increase of  $\times 2.5$  to  $\times 5$ , depending on how much  $H\alpha$  light was blocked by the original filter and whether the new filter is fully transparent at the wavelength. The original IR-blocking filter always has nearly full transmission at 600 nm and nearly zero transmission at 700 nm.

#### 11.3.3 Is filter modification necessary?

Figure 11.6 shows what filter modification accomplishes. In this case, the modified camera is a Canon EOS 20Da, whose sensitivity at  $H\alpha$  is 2.5 times that of the unmodified version. The 20Da was designed to work well for daytime color photography, so it doesn't have as much of an  $H\alpha$  boost as it could have had.



Figure 11.6. Effect of filter modification. *Top*: unmodified Canon XTi (400D). *Bottom*: Canon 20Da with extended hydrogen-alpha sensitivity. Each is a single 3-minute exposure of the Orion Nebula (M42) with 420-mm  $f/5.6$  lens, processed with *Photoshop* to give similar color balance and overall contrast. See the back cover of this book for the same pictures in color.

Other modified cameras show somewhat more of an increase. In the picture, the right-hand edge of the nebula is representative of thinner, redder hydrogen nebulae elsewhere.

What is striking is how well the *unmodified* camera works. Yes, the modification helps – but it's not indispensable. The unmodified camera shows the nebula reasonably well.

### 11.3 Nebulae, red response, and filter modification

Table 11.1 *Intensities of main spectral lines from emission nebulae (as percentage of H $\beta$  from the same nebula).*

Line	Wavelength (nm)	M42 (Orion Nebula)	M16 (Eagle Nebula)	NGC 6995 (Veil Nebula)	Theoretical thin H II region (2500 K)
O II	372.6 + 372.8	119	157	1488	—
Ne III	386.9	13	2	118	—
H $\gamma$	434.0	41	36	44	44
O III	436.3	—	—	47	—
H $\beta$	486.1	100	100	100	100
O III	495.9	102	29	258	—
O III	500.7	310	88	831	—
N II	654.8	26	104	124	—
H $\alpha$	656.3	363	615	385	342
N II	658.3	77	327	381	—
S II	671.7 + 673.1	9	116	68	—

O II, O III, etc., denote ionization states of elements, each of which emits more than one wavelength. The H $\alpha$ , H $\beta$ , and H $\gamma$  lines of hydrogen are all from H II.

**M42** is a dense, strongly photoionized H II region; measurements were taken just north of the Trapezium, very close to the illuminating stars. Data from D. E. Osterbrock, H. D. Tran, and S. Veilleux (1992), *Astrophysical Journal* 389: 305–324.

**M16** is a photoionized H II region less dense than M42 and considerably reddened by interstellar dust. Data from J. García-Rojas, C. Esteban, M. Peimbert, M. T. Costado, M. Rodríguez, A. Peimbert, and M. T. Ruiz (2006), *Monthly Notices of the Royal Astronomical Society* 368: 253–279.

**NGC 6995** is part of the Veil Nebula or Cygnus Loop, a supernova remnant, and is ionized by the expanding shock wave from the supernova, rather than by light from nearby stars. Each value shown in the table is the mean of the authors' reported fluxes from five positions in the brightest part of the nebula. Data from J. C. Raymond, J. J. Hester, D. Cox, W. P. Blair, R. A. Fesen, and T. R. Gull (1988), *Astrophysical Journal* 324: 869–892.

Theoretical values for a thin, weakly excited region of pure hydrogen are from D. E. Osterbrock and G. J. Ferland, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei* (Sausalito, Calif.: University Science Books, 2006), p. 72.

To understand why this is so, remember that H $\alpha$  is not the only wavelength at which nebulae emit light. There are also strong hydrogen-beta (H $\beta$ ) and oxygen-III (O III) emissions which color film does not pick up. Depending on the type of nebula, there may be more than that. As Table 11.1 shows, the Veil Nebula is actually brightest in blue and near-ultraviolet wavelengths, not hydrogen-alpha.

For that matter, a  $\times 2.5$  or even  $\times 5$  difference in  $H\alpha$  sensitivity is not gigantic. In photographic terms, it is a difference of 1.3 to 2.6 stops, no more than a third of the usable dynamic range of the image.

And, most importantly, deep red sensitivity matters only when you are photographing emission nebulae or using a deep red filter to overcome light pollution. Even then, excellent work can be done with an unmodified DSLR (Figure 11.8 p. 140). The rest of the time, when photographing galaxies, star clusters, or reflection nebulae, modified and unmodified DSLRs will certainly give the same results.

## 11.4 Filters to cut light pollution

Now look at the middle part of Figure 11.5, showing the transmission of various filters. Some of them are quite effective at cutting through the glow of city lights.

### 11.4.1 Didymium glass

The “poor man’s nebula filter” is didymium glass, which blocks the brightest emissions of sodium-vapor (orange) streetlights. Didymium glass looks bluish by daylight and purplish by tungsten light. It contains a mixture of praseodymium and neodymium. Glassblowers look through didymium glass to view glass melting inside a sodium flame.

Today, didymium glass is sold in camera stores as “color enhancing” or “intensifier” filters. Nature photographers use it to brighten colors because it blocks out a region of the spectrum where the sensitivities of the red and green layers of color film overlap.

The highest-quality didymium filter that I know of is the Hoya Red Intensifier (formerly just Intensifier). As Figure 11.7 shows, it has a useful effect, but even the multi-coated version is not invulnerable to reflections if there is a bright enough star in the field. Avoid Hoya’s Blue Intensifier and Green Intensifier, which are less transparent at the desired wavelengths. Hoya’s Portrait or Skintone Intensifier is a weaker kind of didymium glass with less blockage of the unwanted wavelengths.

### 11.4.2 Interference filters

Interference filters are made, not by adding dye or impurities to glass, but by depositing multiple thin, partly reflective coatings on the surface. The thickness and spacing of the coatings resonate with particular wavelengths of light. In this way it is possible to select which parts of the spectrum to transmit or block.

For DSLR photography, a “broadband nebula,” “galaxy,” or “deep-sky” filter is what you want (see the middle of Figure 11.5). The goal is to block light pollution while transmitting as much light as possible of the rest of the spectrum. The

#### 11.4 Filters to cut light pollution



Figure 11.7. Didymium glass (Hoya Intensifier filter) cuts through skyglow from sodium-vapor streetlights. Each image is a single 3-minute exposure of the field of Zeta and Sigma Orionis with a Canon Digital Rebel (300D) at ISO 400 and a 180-mm lens at  $f/5.6$ . Note reflection of bright star caused by filter (arrow).



Figure 11.8. The Horsehead and other faint nebulae captured under light-polluted skies 10 miles from central London. Stack of 20 3-minute exposures and 23 2-minute exposures with unmodified Canon EOS 30D camera, 10-cm (4-inch)  $f/8$  Takahashi apochromatic refractor, and Astronomik CLS broadband light pollution filter. No dark frames were subtracted. (Malcolm Park.)

## 11.4 Filters to cut light pollution

narrow-band nebula filters used by visual observers are usually disappointing for photography; they block too much light.

Most telescope dealers sell several brands of interference filters; one of the most respected vendors, offering a very broad product line, is Lumicon ([www.lumicon.com](http://www.lumicon.com)). Another is Astronomik ([www.astronomik.com](http://www.astronomik.com)).

Interference filters are not always available in sizes to fit in front of camera lenses. Instead, they are sized to fit  $1\frac{1}{4}$ -inch and 2-inch eyepiece barrels and the rear cell of a Schmidt–Cassegrain telescope (see Figure 5.5, p. 54). Those threaded for 2-inch eyepieces will fit 48-mm camera-lens filter rings; the thread pitch is not the same, and only one thread will engage, but that is enough.

One last note. Not every filter that works well on an eyepiece will work equally well when placed in front of a long lens. The long lens magnifies optical defects. I have only had problems with the optical quality of a filter once, but it's definitely something to check.

### 11.4.3 Imaging with deep red light alone

Even near cities, there is comparatively little light pollution at wavelengths longer than 620 nm. Accordingly, if you use deep red light alone, you can take pictures like Figure 11.8 even in a light-polluted sky.

A modified DSLR is helpful but not absolutely necessary. What is important is the right filter, either an Astronomik interference filter that passes a narrow band around  $H\alpha$ , or a dye filter that cuts off wavelengths shorter than 620 nm or so. The common Wratten 25 (A) or Hoya R60 red filter is not red enough; it transmits some of the emissions from sodium-vapor streetlights. Suitable filters include Wratten 29, B+W 091, Hoya R62, Schott RG630, and the Lumicon Hydrogen-Alpha filter. For more about filters and their nomenclature, see *Astrophotography for the Amateur*.

### 11.4.4 Reflections

Reflections from filters are more of a problem with DSLRs than with film cameras because the sensor in the DSLR is itself shiny and reflective. The sensor and a filter parallel with it can conspire to produce multiple reflections of bright stars. The reflection risk seems to be much greater when the filter is in front of the lens than when it is in the converging light path between telescope and camera body. To minimize the risk, use multi-coated filters whenever possible. This is only practical with dye filters; interference filters are inherently shiny.



## **Part III**

# Digital image processing



# Chapter 12

## Overview of image processing

This chapter will tell you how to start with raw image files from your camera, perform dark-frame correction, decode the color matrix, combine multiple images into one, and carry out final adjustments.

*Vita brevis, ars longa.* Digital image processing is a big subject, and I don't plan to cover all of it here. In particular, in this and the following chapters I'm going to skip almost all of the mathematics. To learn how the computations are actually done, see *Astrophotography for the Amateur* (1999), Chapter 12, and other reference books listed on p. 195.

This is also not a software manual. For concreteness, I'm going to give some specific procedures for using *MaxDSLR* (including its big brother *MaxIm DL*) and, in the next chapter, Adobe *Photoshop*, but in general, it's up to the makers of software to tell you how to use it. My job is to help you understand what you're trying to accomplish. *Many different software packages will do the same job equally well*, and new software is coming out every day.

### 12.1 How to avoid all this work

Before proceeding I should tell you that you don't have to do all this work. A much simpler procedure is to let the camera do most of it for you. Here's how:

- Turn on long-exposure noise reduction in your camera. That way, whenever you take a celestial photograph, the camera will automatically take a dark frame and subtract it.
- Tell the camera to save the images as JPEG (not raw).
- Open the resulting image files in *Photoshop* or any photo editor and adjust the brightness, contrast, and color balance to suit you.

Why don't we always take the easy way out? For several reasons.

First, we usually want to combine multiple images. With digital technology, ten 1-minute exposures really *are* as good as one 10-minute exposure – almost. They're certainly a lot better than *one* 1-minute exposure. Combining

images improves the signal-to-noise ratio because random noise partly cancels out.

Second, having the camera take automatic dark frames is time-consuming; the dark frames will take up half of every observing session. It's more efficient to take, say, 10 images of the sky and then three dark frames which can be averaged together and applied to all of them. Averaging several dark frames together gives more accurate correction than using just one.

Third, we often want to do processing that wouldn't be easy with a photo editor, such as digital development (a combination of curve correction and unsharp masking) or deconvolution (deliberate correction of a known blur). In subsequent chapters I'll tell you more about these operations.

If you don't want to avoid *all* the work, you can avoid *some* of it. You don't have to start with camera raw images; JPEGs can be aligned, stacked, and enhanced. Dark-frame subtraction is marginally possible with JPEGs and completely feasible with linear TIFFs. These techniques are discussed at the end of this chapter.

## 12.2 Processing from camera raw

To process a set of images, in general, you do four things:

- *calibrate* the images by removing hot pixels and the like;
- *de-Bayerize (demosaic)* the images, converting the Bayer matrix into color pixels;
- *combine* the images by aligning and stacking them; and
- *adjust* the brightness, contrast, color, sharpness, and other attributes.

Besides the images of the celestial object, you'll need some calibration frames (Table 12.1). These enable you to measure and counteract the flaws in your camera. The most important part of calibration is subtraction of dark frames to remove hot pixels, and it's the only part I'll describe in this chapter. If you also use bias and flat frames, they enter the software process in much the same way; for more about them, see p. 185.

One important difference between DSLRs and astronomical CCDs is that DSLRs do some calibration of their own. Manufacturers don't say much about it, but apparently, some calibration data are recorded in the camera at the factory, and some measurements (e.g., of bias) are made every time you take a picture. The computer inside the camera performs as much calibration as it can before delivering the "raw" image file to you. Accordingly, in the raw image file, you are seeing not the defects of the sensor *per se*, but the residual errors after the camera has done its best to correct them.

The whole path to a processed image is shown in Figure 12.1. This is not as complicated as it looks; good software helps you organize the work and consolidates closely related steps.

### 12.3 Detailed procedure with *MaxDSLR*

Table 12.1 *Types of calibration images.*

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<b>Dark frame</b>	An exposure taken with no light reaching the sensor (lens cap on and camera eyepiece covered), at the same ISO setting, exposure time, and camera temperature as the images to be calibrated. <i>Purpose:</i> To correct hot pixels and amp glow. (Images of celestial objects, as opposed to calibration frames, are sometimes called <b>light frames</b> .)
<b>Bias frame</b>	A zero-length or minimum-length exposure, at the same ISO setting and camera temperature as the images to be calibrated. <i>Purpose:</i> To correct the non-zero offsets of the pixel values, which vary from pixel to pixel. Bias frames are needed if a dark frame is to be scaled to a different exposure time. They are not needed if the dark frames match the exposure time and ISO setting of the images from which they are to be subtracted, since dark frames contain bias information.
<b>Flat field</b>	An exposure of a blank white surface taken through the same telescope as the astronomical images, with the same camera at the same ISO setting, and preferably on the same occasion so that dust particles will be in the same positions. Ideally, the flat-field image should be dark-frame adjusted, so take a dark frame to match it. <i>Purpose:</i> To correct for dust, vignetting, and unequal light sensitivity of the pixels. Often unnecessary if your sensor is clean and vignetting is not a serious problem, or if you plan to correct vignetting in other ways.

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### 12.3 Detailed procedure with *MaxDSLR*

Let's take the plunge. In what follows, I'll tell you exactly how processing is done with *MaxDSLR* and *MaxIm DL*, using the versions that were current at the time this book was written. (They are alike except that *MaxIm DL* offers more features.) The overall workflow in *Nebulosity* is similar, although the details are different. Regardless of what software you're using, reading this procedure will help you understand what is to be done.

I assume you are starting with:

- one or more (identical) exposures of a deep-sky object, taken with the camera set to raw mode with long-exposure noise reduction turned off;
- one or more (identical) dark frames, which are exposures taken with the lenscap on, matching the original exposures in duration and ISO setting, with the camera at the same or a slightly lower temperature (lower because it is better to undercorrect than overcorrect).

You can also include flat fields at the same step as dark frames.

## Overview of image processing

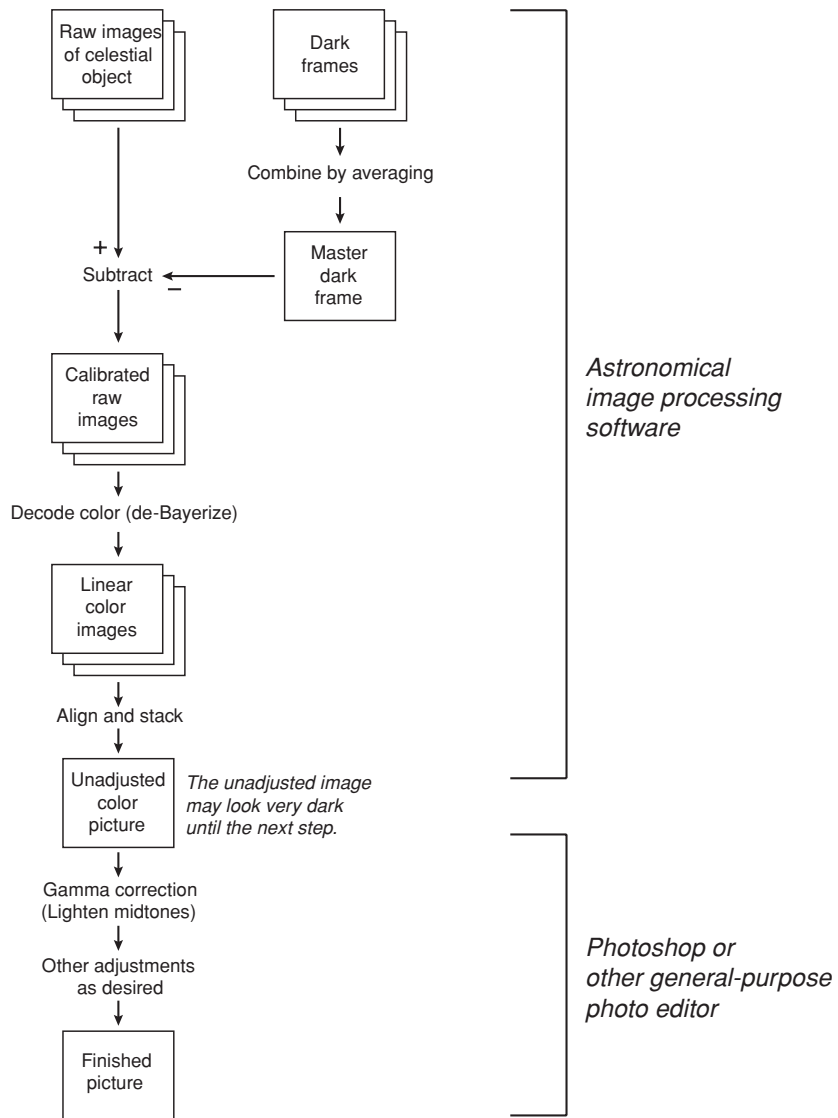


Figure 12.1. The path to a high-quality digital image from raw image files and dark frames. Good software automates much of the process.

### 12.3.1 Screen stretch

*MaxDSLR* (and *Nebulosity*) will mystify you if you don't know about *screen stretch*. The key idea is that you view the image with much more contrast than the image actually has. That is, the contrast on the screen is much higher than in the image file, and you see only a portion of the image's brightness range (hence the term "stretch"). Think of it like magnification in the dimension of contrast rather than height or width.

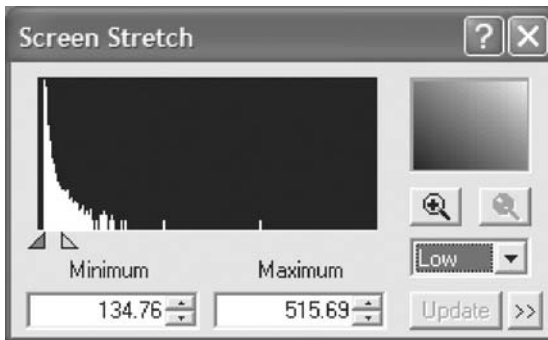


Figure 12.2. Screen stretch window allows you to view the image with more contrast than it actually has. The actual image is not affected, only the visible display.

Screen stretch only affects how you view the image, not the image itself. Changes to screen stretch do not affect the image and will not be saved when you save it to disk.

Screen stretch is controlled by a small window shown in Figure 12.2. If it's not visible, go to the main menu and choose *View, Screen Stretch Window*.

What you are looking at is a histogram of the image. It usually takes the form of a big pileup at the left (consisting of very dark background pixels) and a few much brighter pixels trailing off to the right. Below the histogram are two triangular sliders that control how much of this brightness range you are looking at. *MaxDSLR* tries to set them automatically to help you see the detail in your image (not to make it look good – it often looks awful!). You can pull the sliders to the left or right manually. You can also set the amount of automatic stretching; I usually set it to “Low.”

### 12.3.2 Subtracting dark frames

#### Telling *MaxDSLR* about your dark frames

*MaxDSLR* will automatically combine your dark frames and subtract the average of them from your images. For this to happen, you must tell *MaxDSLR* where to find the dark frames and how you want them handled. The easiest way to do this is to choose *Process, Calibration Wizard*. This will step you through the process of filling out the *Set Calibration* menu, shown in Figure 12.3.

The key idea is to define one or more “groups” of calibration frames (darks, flats, etc.). The files in each group are combined before being used. In this case, there is just one group, containing the dark frames, and they are combined by averaging without scaling.

If the dark frames did not match the exposure time, ISO setting, or temperature of the original images, *MaxDSLR* could scale them in an attempt to make them match. In my experience, scaling is more useful with small astronomical CCDs than with DSLRs. But it's a technique to keep in mind if you have a valuable image and no dark frame to match it.

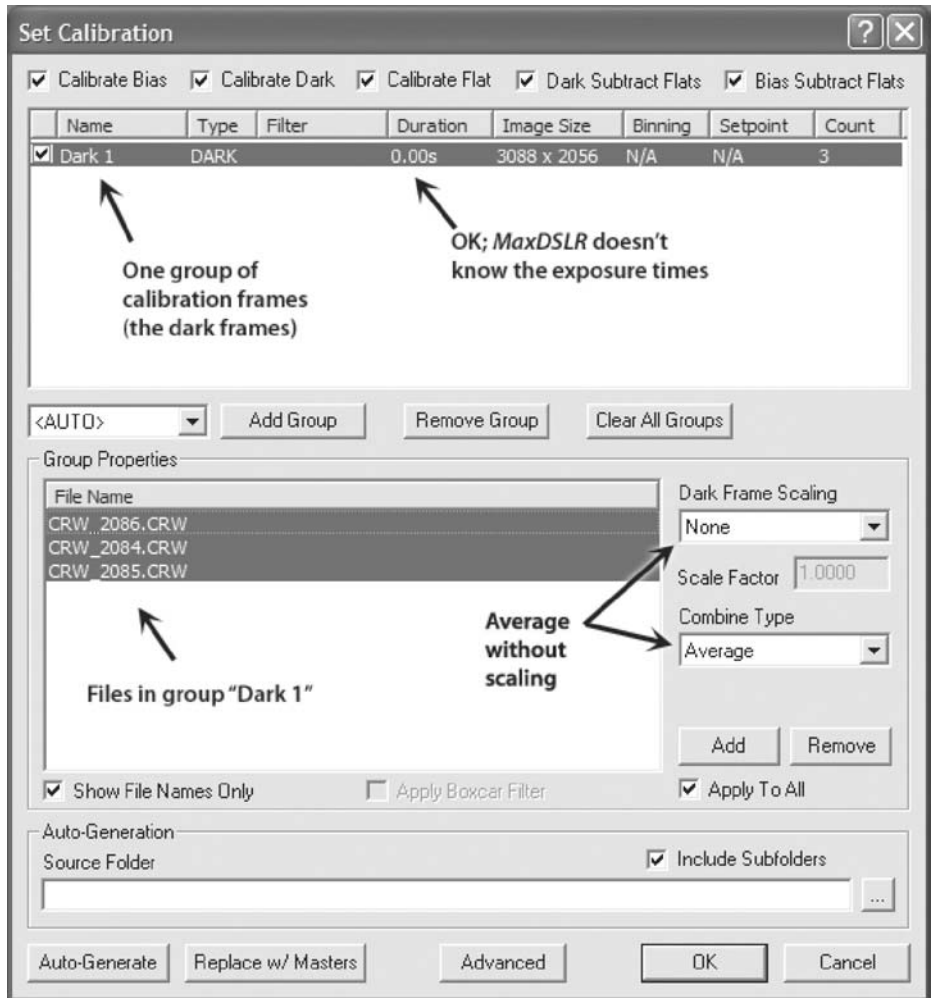


Figure 12.3. *Set Calibration* menu specifies where your dark frame files are located and how to handle them. These settings are remembered from one session to the next.

Don't be alarmed that the exposure time is shown as 0.00 in the menu. If your image files were in FITS format rather than Canon or Nikon raw, *MaxDSLR* would be able to recognize the dark frames and read their parameters. Here, 0.00 simply means the exposure information is unavailable or unused. It actually exists in the raw files, but *MaxDSLR* does not decode it.

### Performing the subtraction

It's finally time to open your image files and perform the dark-frame subtraction. The first step is to go to *File, Open*, and open the raw files, taking care *not* to decode the color matrix (Figure 12.4).

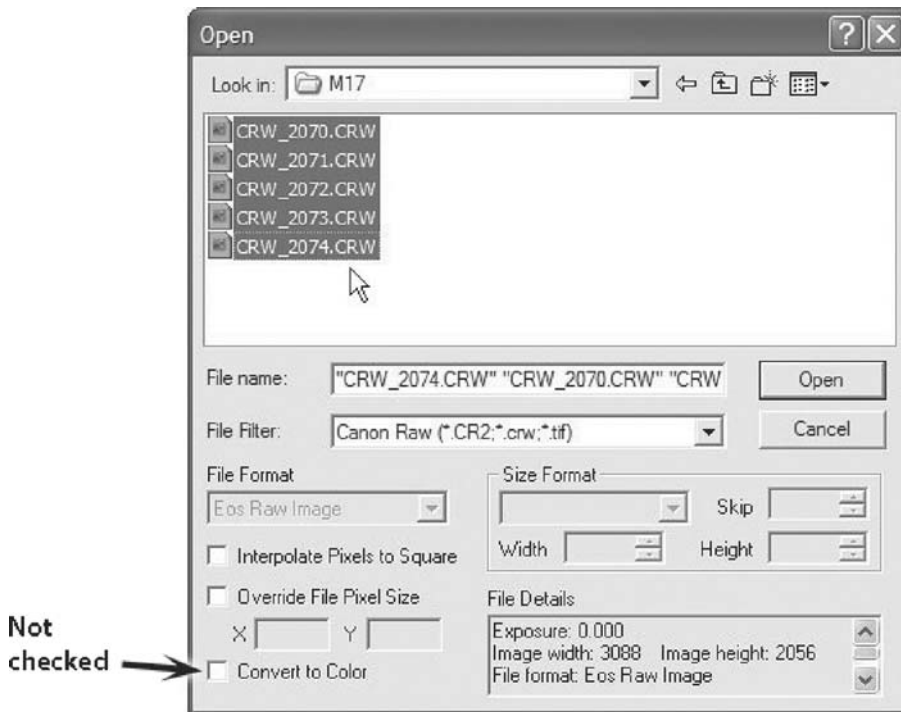


Figure 12.4. When opening files, do not de-Bayerize (“convert to color”).

The images will be displayed at 100% magnification, which means the pixels on your screen correspond to the pixels in the image. Since your screen has only 1 or 1.5 megapixels, you are viewing only the upper left corner of what the DSLR captured. Figure 12.5 shows what to expect. Don’t be alarmed if the star images at the corner of the picture are distorted by aberrations; you are viewing them highly magnified.

On the main menu, go to *Process* and choose *Calibrate All*. This actually performs the subtraction. After a moment, the images will be appreciably less speckled, as shown in Figure 12.6.

You can save the images at this or any other stage of processing. *MaxDSLR* will not save them as Canon or Nikon raw files, of course; instead, by default, it will create FITS files.

### 12.3.3 Converting to color (de-Bayerization, demosaicing)

So far, you’ve been looking at black-and-white raw images that have a strange checkerboard pattern superimposed on them. Now it’s time to *de-Bayer* or *demosaic* them – that is, interpret the pixels as red, green, or blue, and combine them according to the Bayer algorithm.

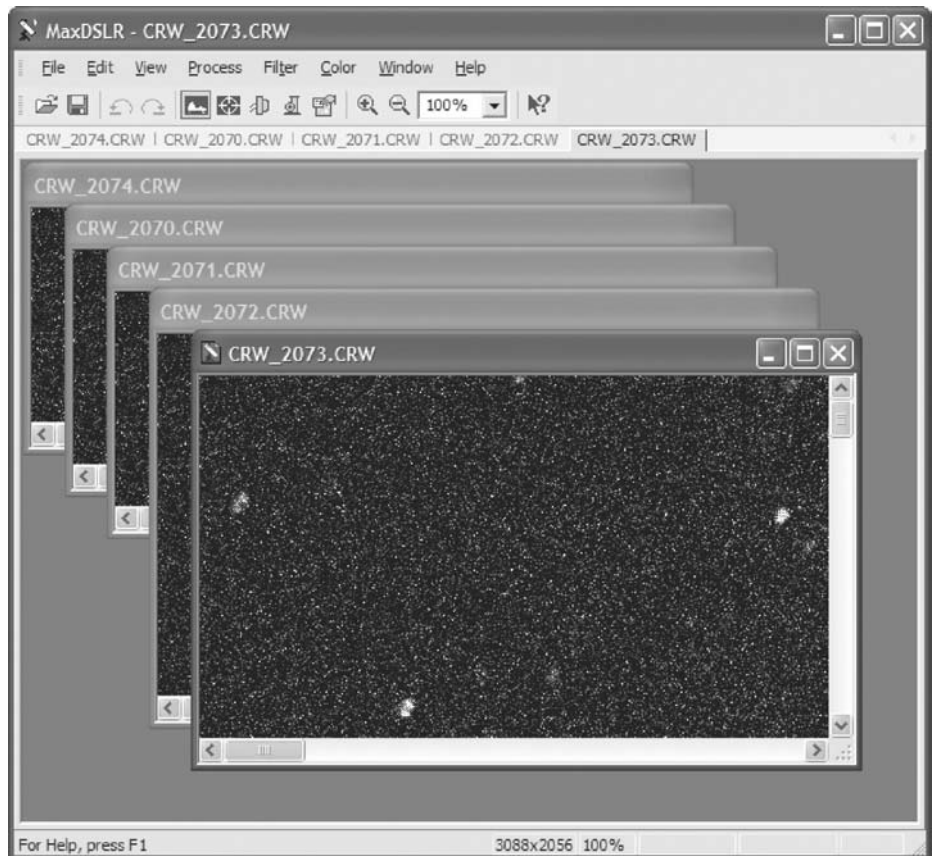


Figure 12.5. Images before dark-frame subtraction. Each window shows the upper left corner of an image, greatly magnified, with aberrated star images.

Unfortunately, *MaxDSL* does not have a “Convert RGB all” command, so you are going to have to click on each open image and convert it individually. (A later version may add this feature, so check for it.)

For *each* of the images, do the following:

- Click on the image.
- In the main menu, choose *Color, Convert RGB* and look carefully at the menu, making settings as shown in Figure 12.7. See the *MaxDSL* help file for advice specific to your camera.
- Click *OK*.

Then go to the next image and do the same thing. The settings won’t need to be changed; just click *OK* each time. Although they may not look like much, you should now be able to tell that you have color images.

### 12.3 Detailed procedure with *MaxDSLR*

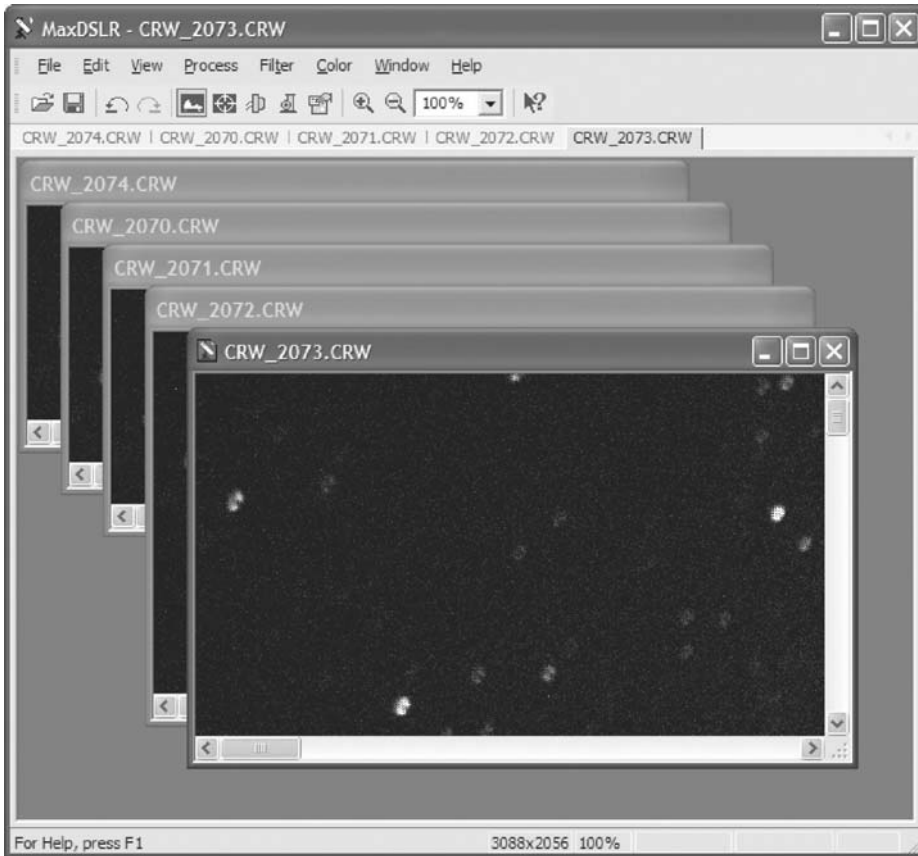


Figure 12.6. Same as Figure 12.5, after dark-frame subtraction.

The crucial settings are *X Offset* and *Y Offset*. Recall that the canonical Bayer matrix is:

```
R G R G ...  
G B G B  
R G R G  
G B G B  
⋮
```

Some cameras start the matrix with the R in the upper left, but others start this pattern with its second row or second column. That's what the X and Y offsets refer to. Other software packages automatically use the right offset for each type of camera, but for maximum versatility, *MaxDSLR* leaves it up to you.

To check the offset, *I urge you to process a daytime picture or two* (skipping the dark-frame step, of course). It's OK if your pictures have a color cast, but they should not swap colors, rendering yellow as blue or the like. Only a picture of a familiar, colorful daytime object can confirm this.

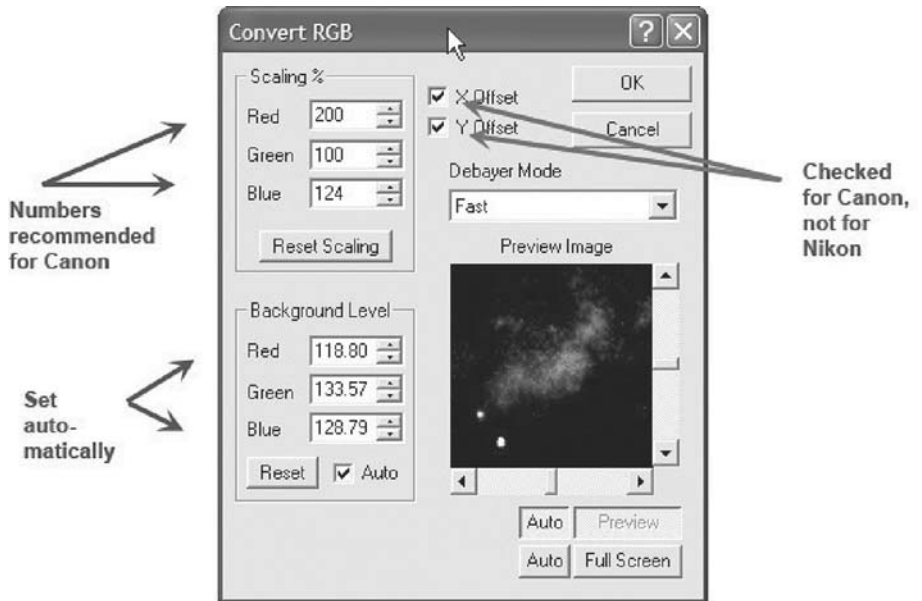


Figure 12.7. Settings to de-Bayerize (demaosaic) the raw images and convert them to color.

### 12.3.4 Combining images

#### How to align and stack

Now it's time to stack (combine) your color images. *MaxDSLR* can usually do this automatically. But you have some decisions to make:

- Whether the alignment will include rotation or just shifting (translation). In *MaxDSLR*, rotation is always included unless you say to use only one alignment star.
- How to line up the images. *Auto-Star Matching* is usually best for deep-sky images; *MaxDSLR* will automatically find star images that line up. Second choice is *Auto-Correlation*, for planet images and for star fields that do not initially match very closely. If neither of these works, you can pick the alignment stars manually (see *MaxDSLR*'s help screens); this may be necessary if the images are not very similar. If you pick the stars manually, you should choose two stars near opposite corners.

You can also *combine images without aligning*. That's the right thing to do if the pixels are already in matching positions, such as when you're combining a set of flat fields or a set of dark frames. Just select *None* as the type of alignment.

Conversely, you can *align without combining* – that is, shift and rotate the images, but then save them separately with the pixels in the shifted positions, rather than making one image out of the set. To do this, choose *Align* rather

than *Combine* on the *Process* menu. Perform the alignment and then save the images individually. This is what you'll want to do if you are going to combine the images some other way, such as with layer masks in *Photoshop*.

- How to combine the images. I prefer to average them if there are just two or three, take the median if there are at least four, or sum them if they are severely underexposed and dark all over.

The advantage of taking the median is that pixels are ignored if they differ wildly from the other images. Taking the median will actually remove an airplane trail or the like if it is present in only one image in the set. More advanced techniques, combinations of taking the median and averaging, are offered in *MaxIm DL*. The idea is to reject bad pixels no matter what the source, but average good ones.

Go to *Process, Combine*, and on the image selection menu, choose *Add All* (i.e., add to the combination set all the files that are open). Then click *OK*. That will bring up the menu shown in Figure 12.8.

After making appropriate selections, click *OK*. *MaxDSLR* will compute for a few minutes, and then a new image will appear with a name ending in *X* (Figure 12.9). Now is a good time to zoom out (reducing the magnification to 50% or 25%) and see what you've achieved. Our example is the Omega Nebula (M17).

#### **Alternative: Combining from files**

If you're combining more than three or four images, I strongly recommend combining from files rather than combining images that are open on the screen. That will keep *MaxDSLR* from running out of memory. Here's how it's done:

1. If your color images are open on the screen, choose *File, Save All*. They will be saved as FITS files, not DSLR raw files.
2. Choose *File, Close All*. You no longer need to keep the images open.
3. Choose *File, Combine Files* and choose the files to be combined.
4. Fill out the *Combine Files* menu (just like Figure 12.8), and click *OK*.

The files will be combined and the result will appear on your screen.

You can also use this method to combine JPEG or TIFF files. Don't use it on camera raw files, even though *MaxDSLR* is willing to try; it will disrupt the Bayer matrix.

### **12.3.5 Stretching and gamma correction**

At this stage, particularly if you were to view it without screen stretch, two problems with the image would become obvious:

- It doesn't use the right range of pixel values, which should be 0 to 255 or 0 to 65535 depending on whether you're aiming for an 8-bit or 16-bit file format.  
Instead, the raw output of a DSLR usually ranges from 0 to 4095 (from 12-bit digitization). The maximum pixel values in your image may be higher due to

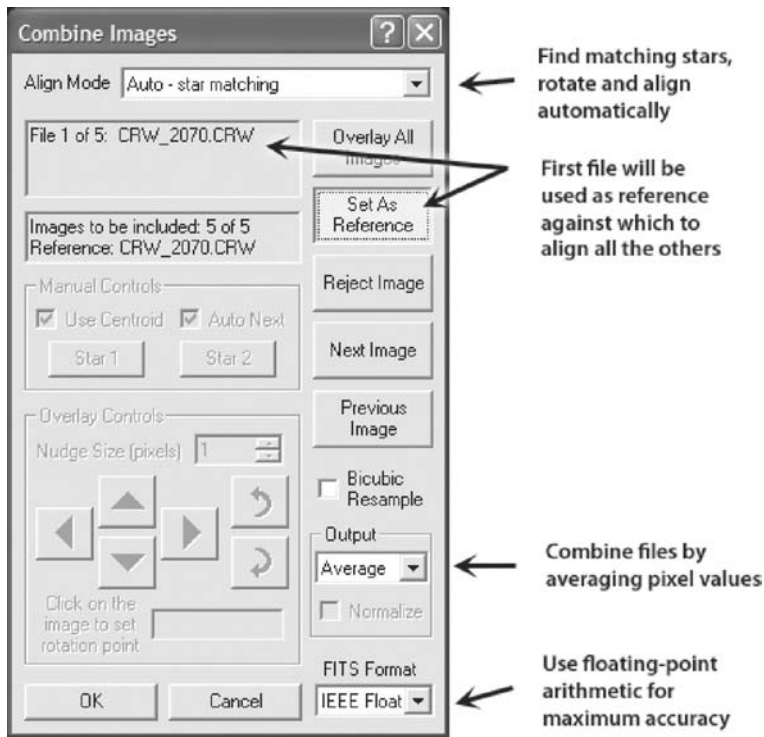


Figure 12.8. To stack images, you must specify how to align them and how to combine them.

scaling during de-Bayerization, but they still don't extend to 65 535. The image needs *stretching*.

- Even taking this into account, the midtones are too dark relative to the highlights.

Besides stretching, the image needs *gamma correction* (p. 170). Briefly, the problem is that the numbers in a DSLR raw file are linearly proportional to the amount of light, but computer monitors and printers render brightness on a roughly logarithmic scale. To correct for this, the midtones need to be lightened substantially.

In *MaxDSLR*, you can take care of both problems in a single step.

### Making screen stretch permanent

The first thing you'll want to do is stretch the brightness range of the whole image, allowing the centers of the stars to be overexposed (maximum white). The easiest way to do this is to take the effect of screen stretch and turn it into a permanent change in the image.

To do this, set screen stretch so that the image looks good, though a bit dark in the midtones. *Do not let anything important become too light*, since the maximum whites are going to be chopped off.

### 12.3 Detailed procedure with *MaxDSLR*

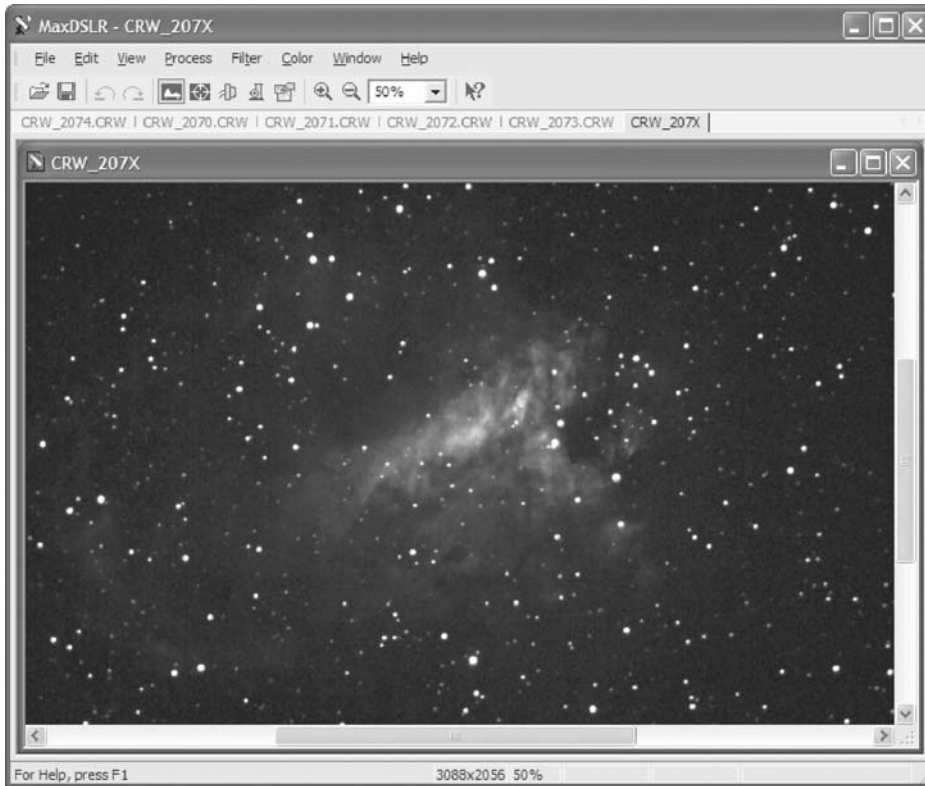


Figure 12.9. Result of combining images. Remember that this is viewed through screen stretch; the real image is much darker than this.

Then choose *Process, Stretch*, and you'll see the menu in Figure 12.10. Check the settings and click *OK*.

You may want to fine-tune the process by immediately doing another stretch of the same kind. Just remember that at every step, you are chopping off part of the brightness range. Everything outside the range selected by screen stretch will become minimum black or maximum white.

#### **Gamma correction**

*MaxDSLR* provides a particularly elegant way to lighten the midtones to fit a specific amount of gamma correction. Use the *Process, Stretch* operation again, but this time make the settings as shown in Figure 12.11.

You should be working with an image that has already been stretched to approximately the right brightness range. Now you'll be leaving the brightness range the same but altering the midtones relative to the highlights and shadows. The number that you specify, typically 0.5, is the reciprocal of the gamma of a typical computer screen (1.8 to 2.2). As Figure 12.12 shows, this brings out the fainter areas of the nebula.

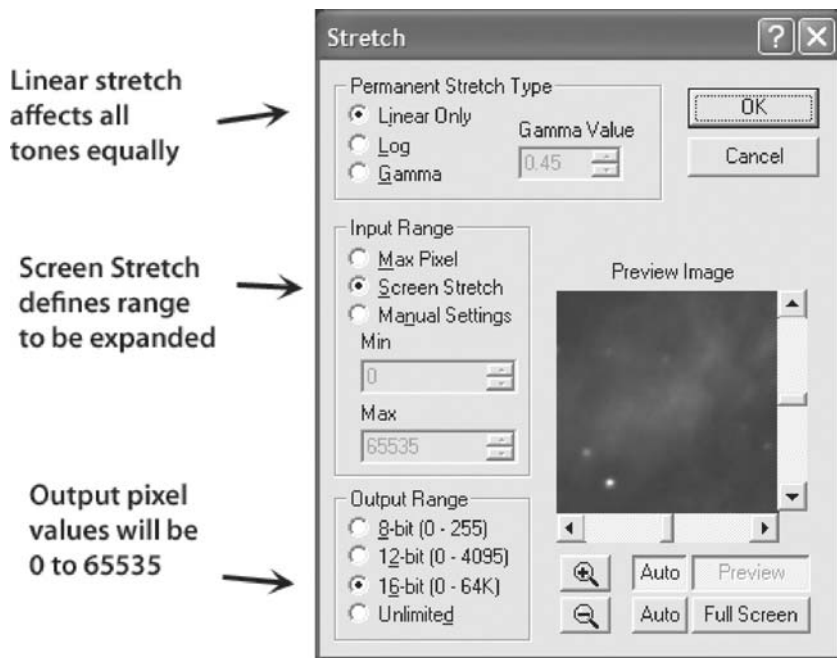


Figure 12.10. Brightness range selected by screen stretch can be expanded to constitute pixel values 0 to 65 535. Everything outside the range becomes either minimum black or maximum white.

### Curves

Another way to lighten the midtones is to use *Process, Curves* and raise the portions of the response curve that need to be brighter. Figure 12.13 shows a curve shape that often works well with nebulae. Note that the output range is set to *16-bit*.

By unchecking “Luminance only,” you can edit the red, green, and blue curves separately. For instance, if you have blue sky fog, you can make the blue curve sag while raising red and green. The same adjustment can also be done in *Photoshop* and works much the same way.

### Levels

*MaxDSLR* also offers a *Levels* control that works much like its counterpart in *Photoshop* (Figure 12.14). You view a histogram of the image with three sliders under it for minimum black, maximum white, and midtones. As with *Curves*, you can work on the red, green, and blue pixel values separately.

## 12.3.6 Saving the result

I normally do my final processing with *Photoshop*, so my goal at this point is to save the picture onto a file that *Photoshop* can process. Accordingly, my last step is to go to *File, Save*, and make the choices shown in Figure 12.15.

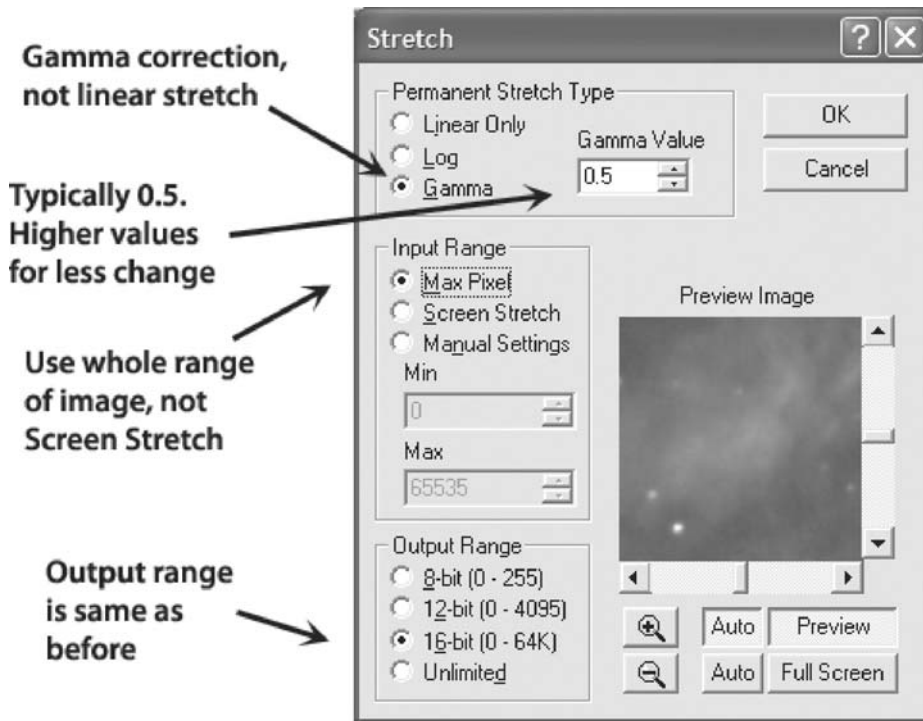


Figure 12.11. Gamma stretching is an elegant, numerically defined way to lighten midtones.

Note carefully: 16-bit integer TIFF, Packbits compression, and Auto Stretch. (Here “Stretch” is something of a misnomer; with Auto Stretch checked, *MaxDSLR* will *reduce* the brightness range if necessary to fit in the file format, but will not expand it.) If using *Photoshop Elements*, you’ll want to specify 8-bit TIFF instead.

When I get the image to *Photoshop*, I perform further level adjustment, unsharp masking, cropping, and color adjustment, and then I convert the image to 8-bit RGB data (instead of 16-bit) and save it as JPEG or as a properly compressed TIFF file. (LZW compression, which *Photoshop* supports but *MaxDSLR* does not, produces a much smaller file; the compression is lossless.) Figure 12.16 shows the finished product.

## 12.4 Processing from linear TIFFs

If your astronomical image processing software doesn’t support your camera’s raw files, you can work with linear TIFFs instead. A linear TIFF file is one that has not been gamma-corrected – the pixel values in it are linearly proportional to the numbers output by the camera.

The reason we want TIFFs is that (unlike JPEGs) they contain the full detail of the image. The reason they need to be linear is so that dark-frame subtraction

## Overview of image processing

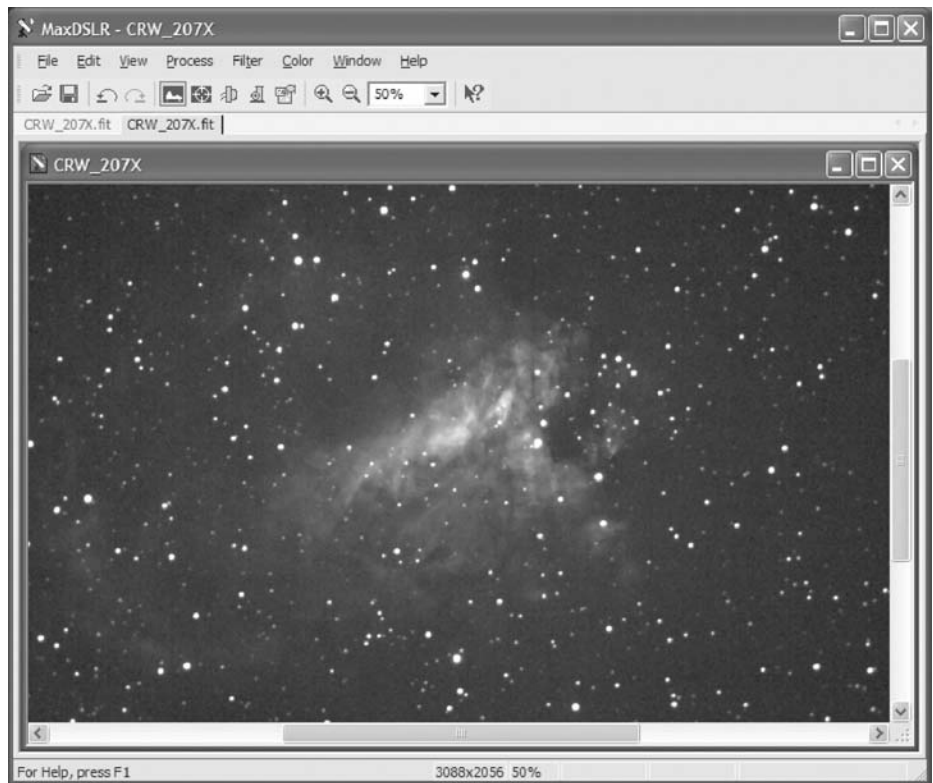


Figure 12.12. After gamma stretching, more of the nebula is visible.

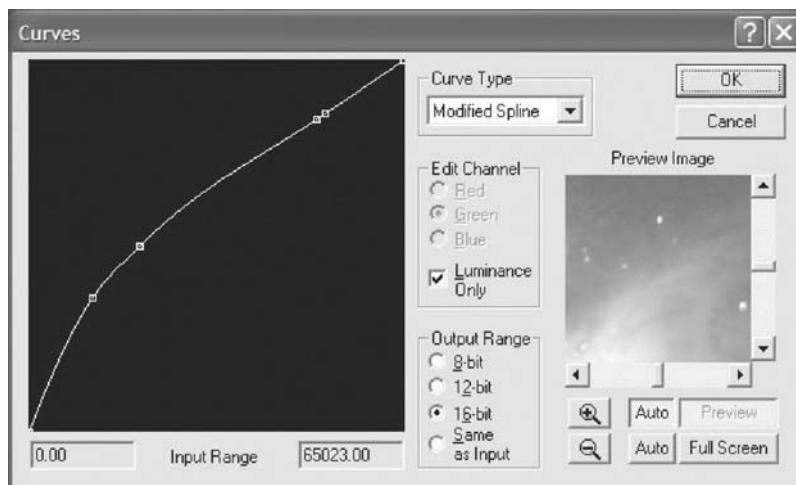


Figure 12.13. Raising the middle of the curve is another way to lighten the midtones.

## 12.4 Processing from linear TIFFs

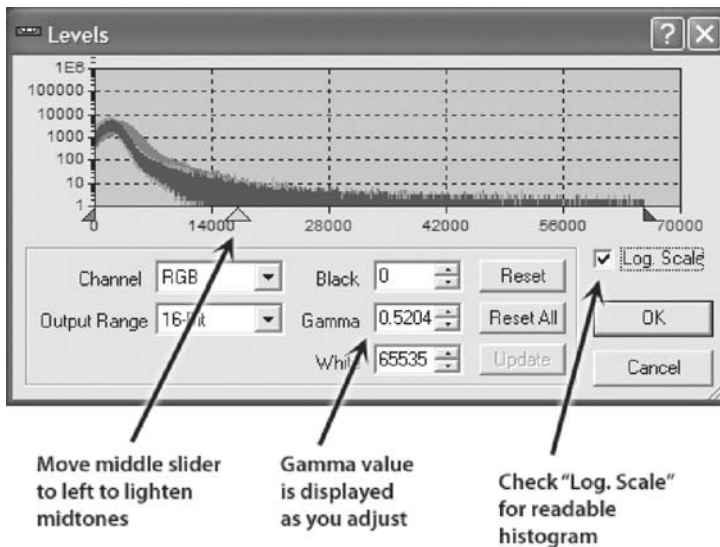


Figure 12.14. Another way to lighten midtones is to drag the middle slider to the left in the *Levels* menu.

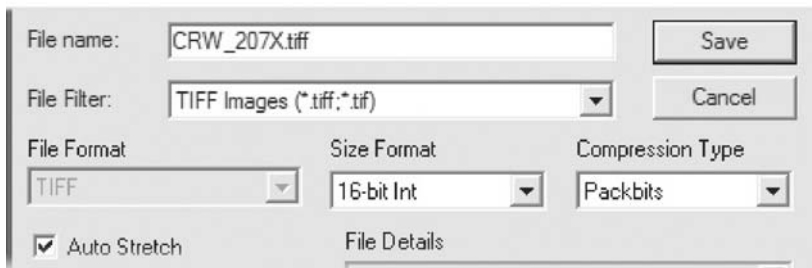


Figure 12.15. Important settings for saving a file for subsequent editing with *Photoshop*.

will be possible. If the image has been gamma-corrected, then it is no longer the case that  $2 + 2 = 4$ . That is, a pixel with dark current  $D$  and signal  $S$  will no longer have the value  $D + S$  and can no longer be corrected by subtracting  $D$ .

### 12.4.1 Making linear TIFFs

One way to convert raw files to linear TIFFs is to use the software that came with your camera. For example, in Canon's *Digital Photo Professional*, do the following:

- Open the raw image file.
- Choose *Edit, Tools* or press Ctrl-T to bring up the Tools palette.
- Check *Linear* as shown in Figure 12.17.
- Choose *File, Convert and Save* and save the file as 16-bit TIFF.



Figure 12.16. Finished product: the Omega Nebula (M17). Stack of five 3-minute exposures with a Canon Digital Rebel (300D) and an 8-inch (20-cm) telescope at  $f/6.3$ , processed as described in the text. This is an enlargement of the central part of the picture.

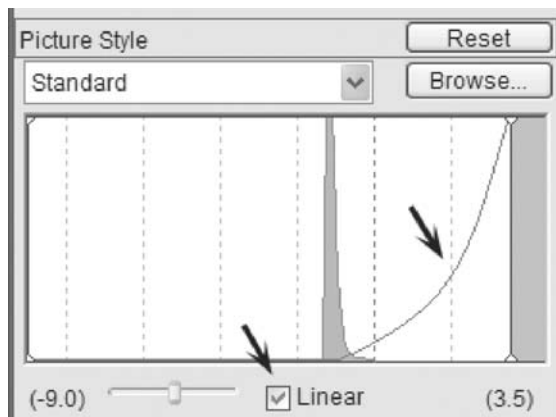


Figure 12.17. To make linear TIFFs with Canon's *Digital Photo Professional*, just check *Linear*. The curve does not appear to be a straight line because the horizontal scale is logarithmic but the vertical scale is linear.

## 12.5 Processing from JPEG files or other camera output

This procedure produces an uncompressed TIFF file, which is very large; re-save it in compressed form at your first opportunity. Also, don't be put off by the fact that the "linear" curve on the screen is strongly bent; it's being plotted on a logarithmic scale that would make it straight if it had been gamma-corrected.

Other cameras generally include software with the same capability. You can also make linear TIFFs with *BreezeBrowser* ([www.breezesys.com](http://www.breezesys.com)) and other image-management programs.

A word of caution: *Photoshop CS2* does not produce linear TIFFs, as far as I can determine (though this feature may be added in the future). When you open a raw image with the "linear" tone curve, what you get is a fully gamma-corrected image. To *Photoshop*, "linear" means "no curvature besides gamma correction." A sufficiently clever *Photoshop* user could, of course, experiment and create a curve that undoes the gamma correction, which could then be saved for future use.

Also, the "linear" version of Adobe's DNG file format has to do with the way the pixels are arranged in the file, not the relation between photon counts and pixel values. All DNG files contain raw, uncorrected data.

To test whether you are getting linear TIFFs, take two pictures, one with half as much exposure as the other. Its pixel values, displayed in the information window of *Photoshop* or *MaxDSLR*, should be exactly half as high.

### 12.4.2 Processing procedure

To process linear TIFFs with *MaxDSLR*, go through all the steps in Section 12.3 except that:

- All the files you open will be TIFF rather than raw.
- The convert-to-color step (de-Bayerization) is skipped.

That's all there is to it.

## 12.5 Processing from JPEG files or other camera output

If all you have are JPEG files, or other files that have already been gamma-corrected, you can still align and stack multiple images. Proceed just as with raw files or linear TIFFs, but leave out de-Bayerization and gamma correction.

You can't subtract dark frames in the normal manner, if the images have been gamma-corrected, because the dark current and the signal no longer add linearly. But the situation is not hopeless.

In some of my early experiments, I scaled a JPEG dark frame to half its original brightness (using the Curves adjustment in *Photoshop*) and then subtracted it from an astronomical image; results were imperfect but much better than if no dark frame had been subtracted.

## Overview of image processing

Then I found *BlackFrame NR*, a free software utility (from [www.mediachance.com](http://www.mediachance.com)) that subtracts dark frames correctly from JPEGs. Apparently, it undoes the gamma correction and some of the JPEG compression artifacts, performs the subtraction, and re-encodes the result as a JPEG file. Intended for terrestrial photographers working in dim light, it is also useful to astronomers.

# Chapter 13

## Digital imaging principles

This chapter is a crash course in the principles of digital image processing. For more about most of these concepts, see *Astrophotography for the Amateur* (1999), Chapter 12.

### 13.1 What is a digital image?

A digital image is fundamentally an array of numbers that represent levels of brightness (Figure 13.1).

#### 13.1.1 Bit depth

Depending on the *bit depth* of the image, the numbers may range from 0 to 255 (8 bits), 0 to 65 535 (16 bits), or some other range.

The eye cannot distinguish even 256 levels, so 8-bit graphics are sufficient for finished pictures. The reason for wanting more levels during manipulation is that we may not be using the full range at all stages of processing. For instance, a badly underexposed 16-bit image might use only levels 0 to 1000, which are still enough distinct levels to provide smooth tones. An 8-bit image underexposed to the same degree would be unusable.

For greatest versatility, some software supports floating-point data, so that levels can be scaled with no loss of precision; in a floating-point system, you can divide 65 535 by 100 and get 655.35. You can also use large numbers without going out of range; if you do something that produces a value greater than 65 535, it will not be clipped to maximum white.

Note that *Photoshop* always reports brightness levels on a scale of 0 to 255, regardless of the actual bit depth of the image. This is to help artists match colors.

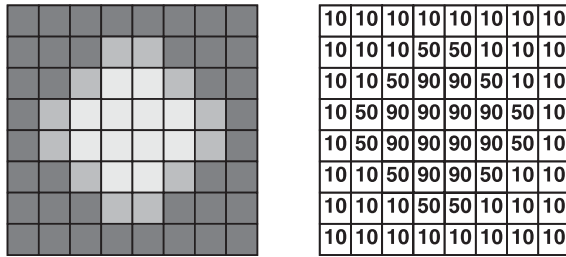


Figure 13.1. A digital image is an array of numbers that represent levels of brightness. (From *Astrophotography for the Amateur*.)

### 13.1.2 Color encoding

A color image normally has three numbers for each pixel, giving the brightness in red, green, and blue (*RGB color*). The alternative is *CMYK color*, which describes color in terms of cyan, magenta, yellow, and black printing inks; the two are interconvertible. Further alternatives are the *Lab* and *L\*a\*b\** systems, which use three coordinates based on the two-dimensional CIE chromaticity chart plus luminosity.

Astronomical images are sometimes constructed by combining the luminosity (L) from one image with the color (RGB) from another; this technique is called *LRGB*. It is not normally done with DSLRs, whose output is already in full color.

## 13.2 Files and formats

### 13.2.1 TIFF

The TIFF file format is often the most convenient way to store digital images. Compression is optional and, if used, is completely lossless; you always get exactly the pixels that you saved.

There are several varieties of TIFF files. The pixels may be 8 or 16 bits; the color can be grayscale, RGB, or CMYK; the compression may be none, LZW, or RLE (Packbits); and there may or may not be multiple layers.

Because LZW (Lempel-Ziv-Welch) compression was protected by a patent until late 2006, low-cost software usually does not support it. For maximum interchangeability, use single-layer RGB color images with Packbits compression or no compression at all.

Uncompressed TIFF files are large:

$$\text{File size (bytes)} = \text{Width (pixels)} \times \text{Height (pixels)} \times \text{Colors (usually 3)} \times \frac{\text{Bit depth}}{8}$$

(plus a few hundred bytes for the header). More concisely:

$$\text{8-bit uncompressed TIFF} = 3 \text{ megabytes per megapixel}$$

$$\text{16-bit uncompressed TIFF} = 6 \text{ megabytes per megapixel}$$

#### 13.2.2 JPEG

Digital cameras normally deliver their output as JPEG files which have undergone gamma correction and other automatic adjustments in the camera. JPEG files are compressed by discarding some low-contrast detail. The degree of compression is adjustable, and if it is too high, there will be ripples around edges in the decoded image. Minimally compressed (highest-quality) JPEG files approach TIFF quality.

RGB JPEG is the usual format for photographs on the World Wide Web. If you encounter a JPEG file that will not display in your web browser, check whether its color encoding is CMYK.

#### 13.2.3 FITS

The Flexible Image Transport System (FITS) is the standard file format for astronomical images. Unfortunately, non-astronomers rarely use it, and non-astronomical software seldom supports it. You can enable *Photoshop* and *Photoshop Elements* to open (not save) some types of FITS files by downloading and installing NASA's *FITS Liberator* from [www.spacetelescope.org](http://www.spacetelescope.org). This is intended mainly for image files from the Hubble Space Telescope and other observatories, and at present, *FITS Liberator* does not make *Photoshop* fully FITS-compatible, although features are being added with every release.

FITS is the most adaptable graphics file format. It allows you to use 8-bit, 16-bit, 32-bit, 64-bit, or floating-point pixels, with or without lossless compression. In addition, the FITS file header has room for copious *metadata* (information about the file's contents), such as the date, time, telescope, observatory, exposure time, camera settings, and filters. The header consists of ASCII text and can be read with any editor.

### 13.3 Image size and resizing

"Change the size of the image" can mean either of two things: set it to print with a different number of pixels per inch, or change the number of pixels. The first of these is innocuous; the second almost always removes information from the picture.

#### 13.3.1 Dots per inch

Consider dots per inch (dpi), or pixels per millimeter, first. A sharp color print requires 100 to 200 dots per inch (4 to 8 pixels/mm). Recall that a full frame from a 6-megapixel DSLR is about  $2000 \times 3000$  pixels. At 150 dpi (6 pixels/mm), such an image makes a full-frame print about  $13 \times 20$  inches ( $333 \times 500$  cm).

A much smaller, cropped portion of a picture can look sharp when printed the size of this book; one megapixel (about  $1000 \times 1000$  pixels) is generally

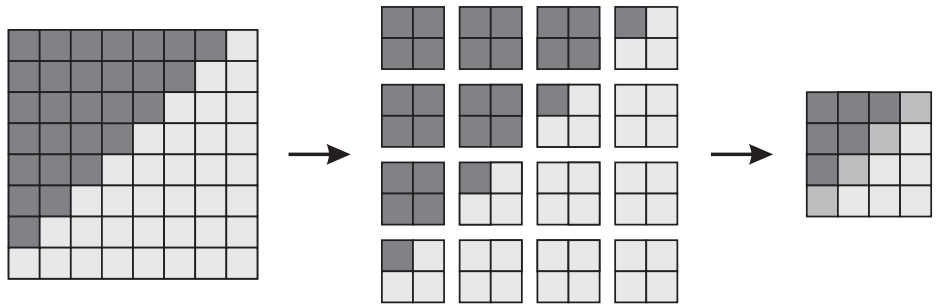


Figure 13.2. Resampling an image to shrink it. The pixels that are to be combined are averaged together. (From *Astrophotography for the Amateur*.)

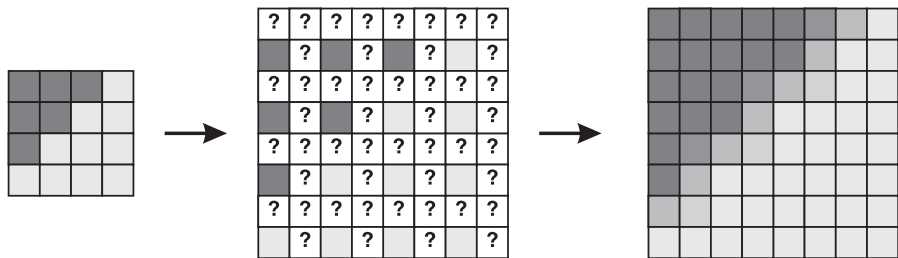


Figure 13.3. Resampling an image to enlarge it. The computer must fill in the missing pixels by averaging their neighbors. (From *Astrophotography for the Amateur*.)

considered the minimum for a full-page print. Clearly, with DSLRs we have plenty of pixels to work with.

### 13.3.2 Resampling

To save file space, or to make the picture fit on a Web page, you may wish to reduce the actual number of pixels in the image. This reduction should be done as the last step in processing because it throws away information. Once you shrink an image, you cannot enlarge it back to its original size with full sharpness.

Changing the number of pixels is called *resampling*, and Figures 13.2 and 13.3 show how it is done.

### 13.3.3 The Drizzle algorithm

The technique in Figure 13.3 assumes that every pixel covers a square area. In reality, pixels are spots; on the image sensor, pixels do not fill the squares allocated to them. Particularly when an image is to be rotated, it is unrealistic to

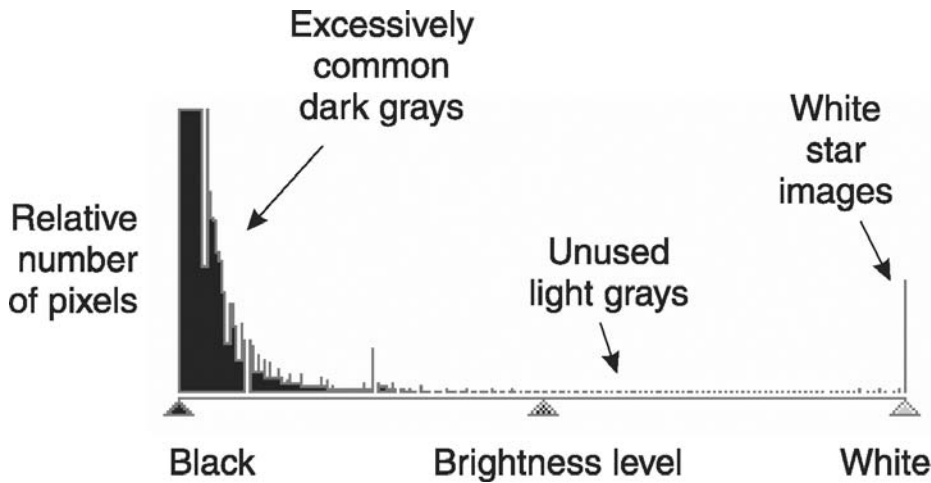


Figure 13.4. Histogram shows how many pixels are at each level of brightness.

treat a pixel as a square segment of the image. That is the key idea behind the Drizzle algorithm of Fruchter and Hook.<sup>1</sup>

To enlarge an image, the Drizzle algorithm takes only the central area of each input pixel and “drops” it (like a drop of rain) onto the output image. This reduces the effect of the square shape and large size of the input pixels. Missing pixels can be filled in by adding additional images or by interpolating.

## 13.4 Histograms, brightness, and contrast

### 13.4.1 Histograms

A histogram is a chart showing how many of the pixels are at each brightness level. You’ve already seen histograms on pp. 36 and 149; Figure 13.4 shows another. The histogram of a daytime picture is normally a hump filling the whole brightness range; astronomical images often leave much of the mid-gray range unused.

### 13.4.2 Histogram equalization

A common task is to equalize the histogram, i.e., spread out the pixel values so that more of the range is used. This can be done with the *Levels* adjustment in *Photoshop* (which looks like Figure 13.4) or the corresponding adjustment in *MaxDSLR* or other software.

<sup>1</sup> A. S. Fruchter and R. N. Hook (2002). Drizzle: a method for the linear reconstruction of undersampled images. *Publications of the Astronomical Society of the Pacific* 114: 144–152.

Under the histogram are three sliders. Do the following:

- If the whole brightness range is not used, move the left and right sliders in so that they just span the range of the histogram that is non-zero.
- If you want to treat the stars as overexposed, move the right slider farther leftward, toward the middle of the range.
- Move the middle slider toward the most heavily populated part of the histogram.

This should generally be done in several small steps, and if you are working with 8-bit pixels, you should convert the image to 16-bit before equalizing it, even if you're going to convert it back to 8 bits for output.

### 13.4.3 Curve shape

The *characteristic curve* of any imaging system is the relationship between input brightness and output brightness. Perfectly faithful reproduction is a straight line (after gamma correction and the effect of the screen or printer).

Almost all image processing software lets you adjust curves. For one example, see p. 158, and for a whole gallery of curve adjustments with their effects, see *Astrophotography for the Amateur* (1999), pp. 226–228.

Left to themselves, when producing JPEG images for output, most digital cameras reduce the contrast of the shadows; that is, they darken the shadows, both to reduce noise and because this is generally considered a pleasing photographic effect. Canon DSLRs, but not Nikons, also compress the highlights so that most of the contrast is in the midtones. You can bypass these effects by working from camera raw images.

### 13.4.4 Gamma correction

When your camera saves a picture as JPEG, or when you decode a raw image file with ordinary (non-astronomical) software, the image undergoes gamma correction, which is needed because pixel values do not mean the same thing in a raw image that they do on a computer screen or printer.

In the raw image, the pixel values are proportional to the number of photons that reached the sensor. But the brightness of a computer screen follows a power law that approximates the eye's logarithmic response to light. Specifically:

$$\text{Brightness (as fraction of maximum)} = \left( \frac{\text{Pixel value}}{\text{Maximum pixel value}} \right)^\gamma$$

where  $\gamma \approx 2.2$ .

Here  $\gamma$  (gamma) is a measure of the nonlinearity of the response. Printers, in turn, mimic the response of the screen. Some printers and Macintosh displays are calibrated for  $\gamma \approx 1.8$  instead of 2.2.

Figure 13.5 shows how this works. A pixel that displays on the screen at 50% of full brightness will have a pixel value, not 50%, but about 73% of the

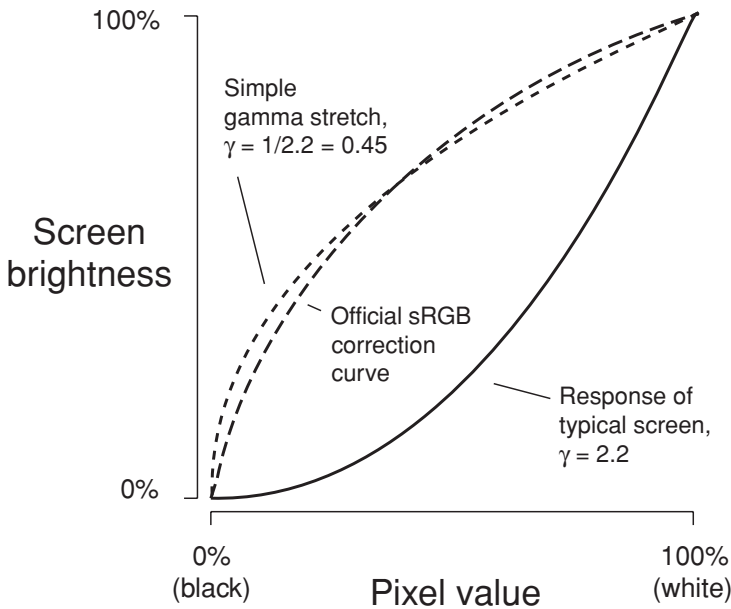


Figure 13.5. Gamma ( $\gamma$ ) measures the nonlinear relation between pixel values and brightness. Upper curves show the correction applied to compensate for screen response.

maximum value because  $0.5^{1/2.2} = 0.73$ . For example, if the pixel values are 0 to 255, a half-brightness pixel will have a value of 186. Monitor calibration test patterns test the gamma of your display by having you compare a patch of pixels at level 186 to a patch of alternating rows of 0 and 255 which blend together as you view the screen from far away.

That's why images taken straight from DSLR raw files generally have the midtones too dark. The upper curves in Figure 13.5 show how this is corrected. The simplest correction is a gamma stretch, defined as follows:

$$\text{Output pixel value} = \text{Max. output pixel value} \times \left( \frac{\text{Input pixel value}}{\text{Max. input pixel value}} \right)^{1/\gamma}$$

For example, if the input and output pixel values both range from 0 to 255, and  $\gamma = 2.2$ , then a pixel whose value was originally 127 (midway up the scale) will become

$$255 \times (127/255)^{1/2.2} = 255 \times (127/255)^{0.45} = 255 \times 0.73 = 186.$$

If  $\gamma = 1$ , this becomes the equation for a linear stretch.

The official correction curve for the sRGB color space is slightly different from a pure gamma stretch. As Figure 13.5 shows, it has slightly less contrast in the shadows (to keep from amplifying noise) and makes up for it in the midtones. Since astronomical images do not strive for portrait-like realism in the first place, there is no need to follow a specific method of gamma correction; just raise the midtones until the image looks right.

## 13.5 Sharpening

One of the wonders of digital image processing is the ability to sharpen a blurry image. This is done in several ways, and of course it cannot bring out detail that is not present in the original image at all. What it can do is reverse some of the effects of blurring, provided enough of the original information is still present.

### 13.5.1 Edge enhancement

The simplest way to sharpen an image is to look for places where adjacent pixels are different, and increase the difference. For example, if the values of a row of pixels were originally

20 20 20 20 30 30 30 30 20 20 20 20

they might become:

20 20 20 15 35 30 30 35 15 20 20 20

(changes underlined). This gives the image a crisp, sparkling quality, but it is most useful with relatively small images. DSLR images have so many pixels that single-adjacent-pixel operations like this often do little but bring out grain.

### 13.5.2 Unsharp masking

A more versatile sharpening operation is *unsharp masking* (Figure 13.6). This is derived from an old photographic technique: make a blurry negative (unsharp mask) from the original image, sandwich it with the original, and rephotograph the combination to raise the contrast. Originally, the unsharp mask was made by contact-printing a color slide onto a piece of black-and-white film with a spacer separating them so that the image would not be sharp.

The effect of unsharp masking is to reduce the contrast of large features while leaving small features unchanged. Then, when the contrast of the whole image is brought back up to normal, the small features are much more prominent than before. What is important about unsharp masking is that, by varying the amount of blur, you can choose the size of the fine detail that you want to bring out.

Today, unsharp masking is performed digitally, and there's no need to create the mask as a separate step; the entire process can be done in a single matrix convolution (*Astrophotography for the Amateur*, 1999, p. 237).

Note that *Photoshop* has a considerable advantage over most astronomical software packages when you want to perform unsharp masking – *Photoshop* can use a much larger blur radius, and a large radius (like 50 to 100 pixels) is often needed with large DSLR images.

## 13.5 Sharpening

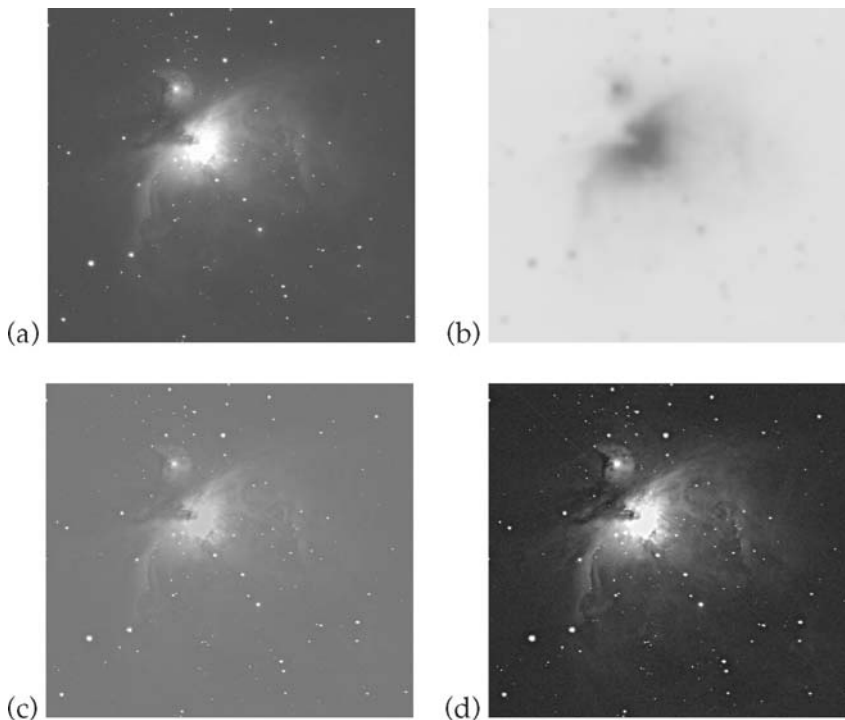


Figure 13.6. The concept of unsharp masking: (a) original image; (b) unsharp mask; (c) result of stacking them; (d) contrast stretched to full range.

### 13.5.3 Digital development

Digital development processing (DDP) is an algorithm invented by astrophotographer Kunihiko Okano that combines gamma stretching with unsharp masking.<sup>2</sup> It is particularly good at preserving the visibility of stars against bright nebulae. Many astrophotographers like the way it combines several steps of processing into one (Figure 13.7).

Some care is needed setting the parameters because implementations of digital development that are optimized for smaller CCDs will bring out grain in DSLR images. The unsharp masking radius needs to be much larger.

In *MaxDSLR*, the unsharp masking part of digital development can be turned off by setting a filter matrix that is all zeroes except for a 1 in the center; digital development then becomes a kind of gamma stretch.

### 13.5.4 Spatial frequency and wavelet transforms

Another way to sharpen an image is to analyze it into frequency components and strengthen the high frequencies.

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<sup>2</sup> Web: <http://www.asahi-net.or.jp/~rt6k-okn>.



Figure 13.7. Digital development processing (DDP) turns the first picture into the second in one step.

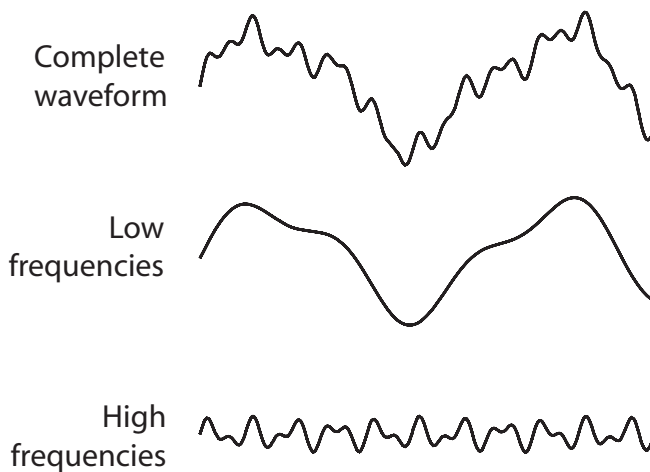


Figure 13.8. Sound waves can be separated into low- and high-frequency components. So can images. (From *Astrophotography for the Amateur*.)

To understand how this works, consider Figure 13.8, which shows the analysis of a sound wave into low- and high-frequency components. An image is like a waveform except that it is two-dimensional; every position on it has a brightness value.

It follows that we can speak of *spatial frequency*, the frequency or size of features in the image. For example, details 10 pixels wide have a spatial frequency of 0.1. High frequencies represent fine details; low frequencies represent large features. If you run a *low-pass filter*, you cut out the high frequencies and blur the image. If you emphasize the high frequencies, you sharpen the image.

## 13.5 Sharpening



Figure 13.9. A wavelet (one of many types). A complex signal can be described as the sum of wavelets.

Any complex waveform can be subjected to *Fourier analysis* or *wavelet analysis* to express it as the sum of a number of sine waves or wavelets respectively. (A wavelet is the shape shown in Figure 13.9.) Sine waves are more appropriate for long-lasting waveforms, such as sound waves; wavelets are more appropriate for nonrepetitive waveforms, such as images.

After analyzing an image into wavelets, you can selectively strengthen the wavelets of a particular width, thereby strengthening details of a particular size but not those that are larger or smaller. This is how *RegiStax* brings out fine detail on planets without strengthening the film grain, which is even finer (see p. 206).

Image processing that involves separating the image into different frequency components is often called *multiscale* processing.

### 13.5.5 Deconvolution

Suppose you have a blurred image, and you know the exact nature of the blur, and the effects of the blur have been preserved in full. Then it ought to be possible to undo the blur by computer, right?

Indeed it is, but the process is tricky. It's called *deconvolution* and has two pitfalls. First, you never have a perfectly accurate copy of the blurred image to work with; there is always some noise, and if there were no noise there would still be the inherent imprecision caused by quantization.

Second, deconvolution is what mathematicians call an *ill-posed problem* – it does not have a unique solution. There is always the possibility that the image contained even more fine detail which was completely hidden from view.

For both of these reasons, deconvolution has to be guided by some criterion of what the finished image ought to look like. The most popular criterion is *maximum entropy*, which means maximum simplicity and smoothness. (Never reconstruct two stars if one will do; never reconstruct low-level fluctuation if a smooth surface will do; and so on.) Variations include the Richardson–Lucy and van Cittert algorithms.

Deconvolution has long been a specialty of *MaxIm DL* (not *MaxDSLR*), although several other software packages now offer it. In Figure 13.10 you see the result of doing it. Fine detail pops into view. The star images shrink and become rounder; even irregular star images (from bad tracking or miscollimation) can be restored to their proper round shape. Unfortunately, if the parameters are not set exactly right, stars are often surrounded by dark doughnut shapes.

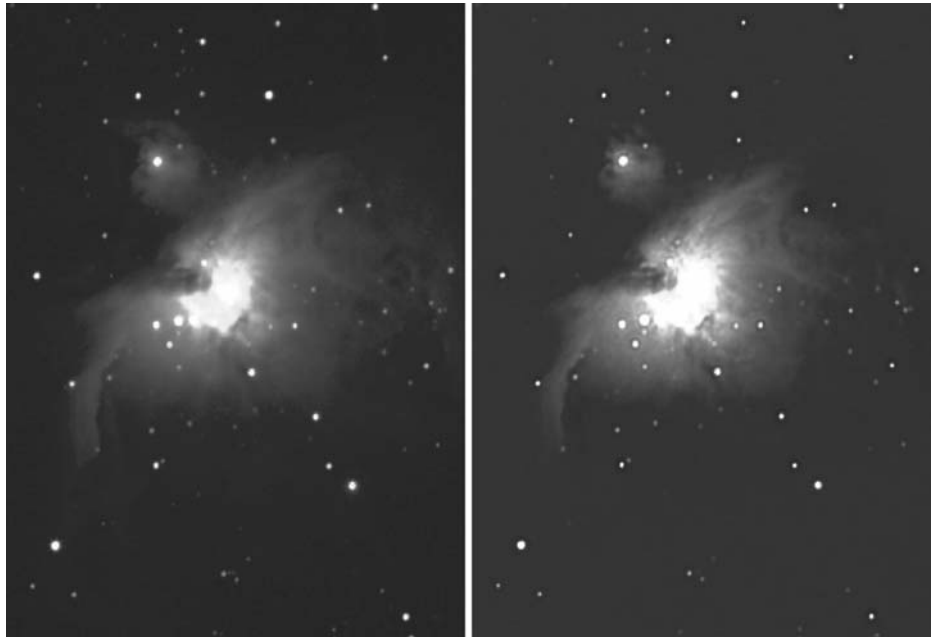


Figure 13.10. Deconvolution shrinks star images and brings out fine detail. This example is slightly overdone, as shown by dark doughnuts around stars in front of the nebula.

Because deconvolution is tricky to set up and requires lots of CPU time, I seldom use it. My preferred methods of bringing out fine detail are unsharp masking and wavelet-based filtering.

## 13.6 Color control

### 13.6.1 Gamut

Like film, computer monitors and printers reproduce colors, not by regenerating the spectrum of the original light source, but simply by mixing three primary colors. This works only because the human eye has three types of color receptors. Creatures could exist – and indeed some human beings *do* exist – for whom the three-primary-color system does not work.<sup>3</sup>

By mixing primaries, your computer screen can stimulate the eye's color receptors in any combination, but not at full strength. That is, it has a limited *color gamut*. Colors outside the gamut can only be reproduced at lower saturation, as if they were mixed with white or gray. Nothing on your computer screen will ever look quite as red as a ruby or as green as an emerald.

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<sup>3</sup> Severely color-blind people have only two primary colors. There are also humans with normal color vision whose primary red is not at the usual wavelength, and it is speculated that a person who inherits that system from one parent and the normal system from the other parent could end up with a working four-color system.

## 13.6 Color control

The gamut of an inkjet printer is also limited, more so than the screen (especially in the deep blue), and the whole art of color management revolves around trying to get them to match each other and the camera.

### 13.6.2 Color space

To account for their limited gamut, digital image files are often tagged with a particular *color space* in which they are meant to be reproduced. The most common color spaces are *sRGB*, or standard red-green-blue, which describes the normal color gamut of a CRT or LCD display, and *Adobe RGB*, a broader gamut for high-quality printers. *Photoshop* can shift an image from one color space to another, with obvious changes in its appearance.

### 13.6.3 Color management

Fortunately, color in astrophotography is not as critical as in studio portraiture, and astrophotographers generally don't need elaborate color management systems. To avoid unpleasant surprises, it is generally sufficient to do the following:

- Install correct drivers for the video card and monitor.
- Adjust the monitor and video card driver using a test pattern such as the one at this book's web site ([www.dslrbook.com/cal](http://www.dslrbook.com/cal)) or those provided by the manufacturer.
- Use your printer with the right kind of paper, or at least try a different kind if you're not getting good results. Different inks soak into glossy paper at different rates, and this affects color rendition.
- Recognize that vivid colors are often out-of-gamut and will look different on the print than on the screen.

When in doubt, make a small test print before committing a lot of paper and ink to a picture.

# Chapter 14

## Techniques specific to astronomy

This chapter presents a selection of image processing techniques that are more specific to astronomy. Again, *vita brevis, ars longa* – more techniques have been invented than any individual can master, and I make no attempt to be exhaustive.

You do not have to master every known technique in order to get good pictures. Keep in mind that there are many ways to achieve almost identical results. Indeed, in the next few years I expect a shakedown and simplification as astrophotographers unclutter their digital toolboxes.

### 14.1 Combining images

Why do we combine images? To build up the signal while rejecting the noise. The key idea is that the random noise is different in each image and therefore will partly cancel out when they are stacked (Figure 14.1). To be precise, the signal-to-noise ratio in the sum or average of  $N$  images is  $\sqrt{N}$  times as good as in one image by itself.<sup>1</sup>

#### 14.1.1 How images are combined

##### Sum

The most obvious way to combine corresponding pixel values is to add them. This is like making a multiple exposure in a camera; every image contributes something to the finished product.

The problem with adding (summing) is that the resulting pixel values may be too high. If you are working with 16-bit pixels, then the maximum pixel value is 65 535; clearly, if you add two images that have 40 000 in the same pixel, the result, 80 000, will be out of range.

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<sup>1</sup> This follows from the root-sum-square law of addition for Gaussian noise sources. If noise sources  $N_1, N_2, \dots, N_n$  are uncorrelated, then the resulting noise amplitude of their sum is not  $N_1 + N_2 + \dots + N_n$  but rather  $\sqrt{N_1^2 + N_2^2 + \dots + N_n^2}$ .

## 14.1 Combining images

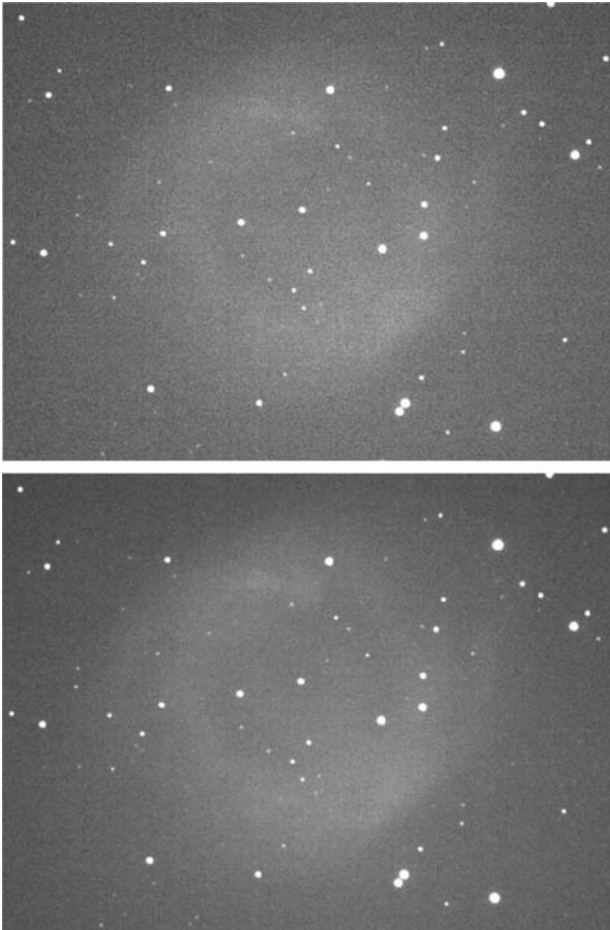


Figure 14.1. Combining images reduces noise. *Left:* Single 6-minute exposure of the Helix Nebula (NGC 7293) through an 8-inch (20-cm) telescope with  $f/6.3$  compressor, with Canon Digital Rebel (300D) at ISO 400. *Right:* Average of three such exposures. Random noise is reduced by a factor of  $\sqrt{3} = 1.7$ .

That may not matter if the only bright spots in the image are star images and you don't mind having them all end up maximum white. In that situation, summing is a good way to strengthen faint objects such as nebulosity.

### **Average (mean)**

The average (the mean) is the sum divided by the number of images. The resulting pixel values are always in the same range as the originals. This is actually the most common way of combining images. As with summing, every image contributes equally to the finished product. In fact, taking the average is exactly equivalent to summing the images and then scaling the pixel values back to the original range.

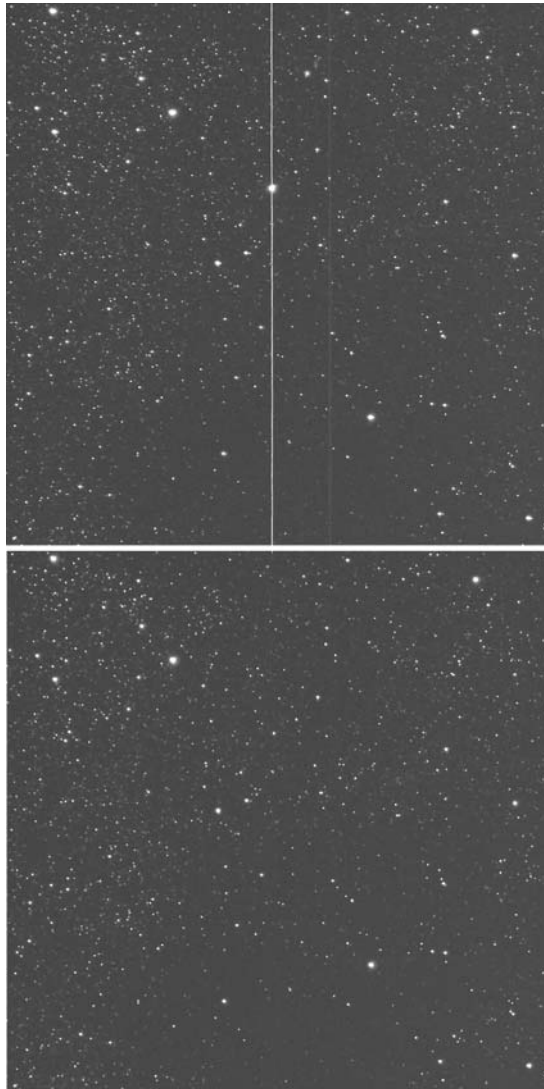


Figure 14.2. Airplane trail disappears when image is median-combined with two more images. If the images had been averaged, the trail would have remained visible at reduced contrast.

### Median

The median of a set of numbers is the one that is in the middle when they are lined up in order. For example, if a particular pixel in five images has pixel values of, respectively, 40, 50, 53, 72, and 80, then the median is 53.

Unlike the mean, the median is not thrown off if one of the numbers is excessively large or small. As we just saw, the median of 40, 50, 53, 72, and 80 is 53. If you change the lowest number to 0, or change the highest number to 400, the median will still be 53 because it is still the one in the middle.

## 14.1 Combining images

When you use it to combine images, the median automatically throws away defective pixels, cosmic ray spots, and even airplane and satellite trails, because each of these produces an excessively high value in one image but does not alter the order of the others. If you take the median of several images, one of which has an airplane trail in it, the airplane will not show in the median *at all* (Figure 14.2). Median combining is especially useful with images of the Orion Nebula (M42), which, when photographed from the latitude of the United States, is often crisscrossed by geosynchronous satellites.

Bear in mind that the median is undefined if there are not at least three images. Also, do not confuse median combining with *median filtering*, which is a way of blurring images by replacing each pixel with the median of a group of pixels.

### Sigma clipping

The average gives the best smoothing, but the median has the ability to reject abnormal pixels. Is there a way to combine the two?

That is the idea behind *sigma clipping* – averaging with abnormal values excluded from the mix. To judge which values are abnormal, the program computes the average and standard deviation ( $\sigma$ , sigma), then rejects any pixels that differ from the mean by more than  $k\sigma$  where  $k$  is a factor you specify, and computes a new average omitting the rejected pixels.

### 14.1.2 Stacking images in *Photoshop*

So far we have only discussed image stacking done automatically by astronomical software. Sometimes you'll want to stack images under full manual control using *Photoshop* or *Photoshop Elements*. Here is the procedure. It introduces an important concept, *layers*.

1. Open both images in *Photoshop*.
2. In the toolbar, choose the Marquee Tool (dotted box).
3. Right-click on one of the images and press Ctrl-A to select the entire image.
4. In the main menu, choose *Edit, Copy*.
5. Click on the title bar of the other image.
6. In the main menu, choose *Edit, Paste*.

You have now pasted the second image on top of the first one. However, your goal was to mix them 50–50, so you're not finished yet. Proceed as follows.

7. In the main menu, choose *Window, Layers* to make the *Layers* window visible.
8. In the *Layers* window, set the opacity of Layer 1 (the added image) to 50% (Figure 14.3).
9. Hit Ctrl-+ several times to magnify the image so that you can see single pixels.

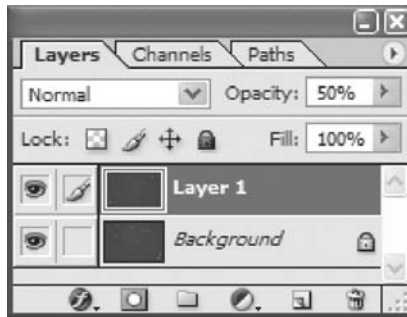


Figure 14.3. In *Photoshop*, the *Layers* window controls the way images are superimposed. Set opacity of Layer 1 (the added image) to 50% to mix two images equally.

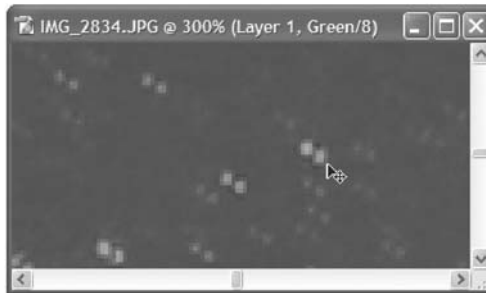


Figure 14.4. Using the Move tool to align images manually. After setting opacity to 50%, move one image, relative to the other, with mouse or arrow keys.

10. Choose the Move tool, and use the mouse or the arrow keys to move one image relative to the other (Figure 14.4) until they are perfectly aligned.
11. In the main menu, choose *Layer, Flatten Image*. This combines the layers into one.

Your image is now ready for further processing.

While aligning the images, you may want to set the blending mode (*Normal* in Figure 14.3) temporarily to *Difference*. Then, when the images are perfectly aligned, the picture will disappear. Set the blending mode back to *Normal* before flattening the layers and saving the results.

If you want to combine more than two images equally, a moment's thought will show that you don't want the opacity of each of them to be 50%. (They can't all be 50% of the total.) Instead, combine the first two with opacity 50%; flatten; combine the next one with opacity 33%; flatten; combine the next with opacity 25%; flatten again; and so on. The sequence of percentages, 50%, 33%, 25%, 20%, 17%..., corresponds to the fractions  $\frac{1}{2}$ ,  $\frac{1}{3}$ ,  $\frac{1}{4}$ ,  $\frac{1}{5}$ ,  $\frac{1}{6}$ , and so on.

### 14.1.3 *Who moved?* Comparing two images

If you align two images and subtract rather than add them, you'll see what is different about them. This is a good way to detect the movement of asteroids or satellites in a star field, or to check for novae or variable stars.

Strictly speaking, if you subtract one image from the other, you'll see *nothing* but the difference, and objects may be hard to identify. Figure 14.5 shows a more practical alternative. In *Photoshop*, convert one of the two images into a negative (on the main menu, *Image, Adjustments, Invert*). Then paste it onto the other one with about 30% opacity. If the opacity were 50%, the background stars would be invisible. As it is, the stars and sky background are visible with reduced contrast, and the two positions of the asteroid are obvious (white in the first image and black in the second).

Besides patrolling for novae and variable stars, you can also use this method to compare the results of image processing techniques – to find out, for example, exactly what details were brought out by deconvolution, or what details were lost by JPEG compression.

## 14.2 Calibration frames

Calibration frames are recordings of the camera's errors, made so that the errors can be corrected (Table 12.1, p. 147). One form of calibration, dark-frame subtraction, was introduced in the previous chapter; here we deal with the rest.

### 14.2.1 Dark-frame subtraction

As you already know, a *dark frame* is an image taken with the lens cap on, so that no light reaches the sensor. Its purpose is to match the hot pixels (and partly hot pixels) of an image of a celestial object, so that they can be subtracted out. The two must match in exposure time, ISO setting, and camera temperature.

### 14.2.2 Bias frames and scaling the dark frame

A *bias frame* is a zero-length exposure, or, with a DSLR, a dark frame with the shortest possible exposure time (1/1000 second or less). Its purpose is to record the pixel value for minimum black, even without leakage. Many pixels have small errors that cause them to start at a value higher than 0.

If you are going to subtract a matching dark frame from an image, you do not need a bias frame because the dark frame contains the bias information.

Bias frames are needed if your software is going to scale the dark frame to match a different exposure time. Suppose, for example, you have a 2-minute exposure of a celestial object but only a 1-minute dark frame. You might think you could use the dark frame by doubling all the pixel values in it. But that wouldn't be quite right, because the dark frame is the sum of two things – dark

Techniques specific to astronomy

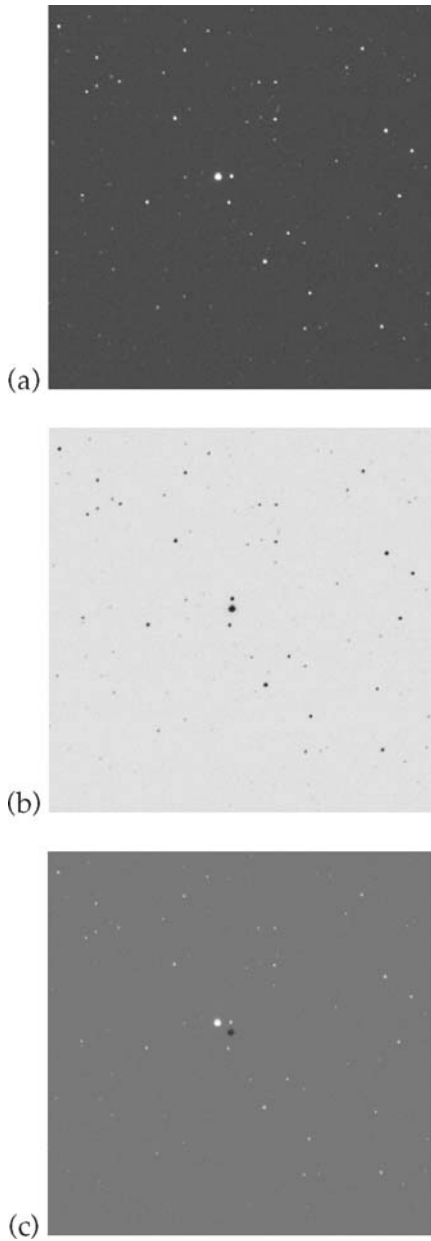


Figure 14.5. Detecting an asteroid by its movement. (a) 3-minute exposure of asteroid Iris with Canon XTi (400D) and 300-mm lens at  $f/5.6$ . (b) Identical exposure 90 minutes later, converted to negative image. (c) Result of pasting (b) onto (a) with 30% opacity.

current and bias – and the bias doesn't need to be doubled. That's why additional information from the bias frame is needed.

### 14.2.3 Flat-fielding

#### The concept

A *flat field* is an image taken with a plain white light source in front of the camera and lens. Its purpose is to record any variations of light intensity across the field – especially vignetting and the effect of dust specks. Figure 14.6 shows what flat-field correction accomplishes.

#### Acquiring flat-field frames

There are many ways to take flat fields. What you need is a uniform light source in front of the telescope or lens. Some possibilities include:

- Hand-holding a light box in front of the camera. That's what I do, with a 10-cm-square battery-powered fluorescent panel originally made for viewing 35-mm slides.
- Putting wax paper across the front of the telescope and then holding the light box about an arm's length in front of it. That's what I do when the telescope is larger in diameter than the light box.
- Illuminating the inside of the observatory dome (if you have one) and taking a picture of it through the telescope.
- Photographing the sky in twilight.
- Photographing several sparse star fields, then median-filtering them to remove the stars and retouching to remove any star images that are left.

What is important is that the telescope or lens must be set up *exactly* the same as for the celestial images, down to the setting of the focus and the positions of any dust specks that may be on the optics or the sensor.

The flat field should match the ISO setting of the celestial images, and the camera should be at the same temperature. However, the exposure time obviously will not match.

Fortunately, if you have a relatively bright light source, exposing a flat field is easy. Just set the camera to auto exposure (*A* or *Av*) and take a picture. Better yet, take several so they can be averaged for more accurate corrections. The flat field will automatically be placed right in the middle of the camera's brightness range.

#### Making the correction successfully

Actually performing flat-field correction can be tricky. Each pixel is corrected as follows:

$$\text{New pixel value} = \text{Old pixel value} \times \frac{\text{Average pixel value in flat field}}{\text{Flat-field pixel value in this position}}$$

Techniques specific to astronomy

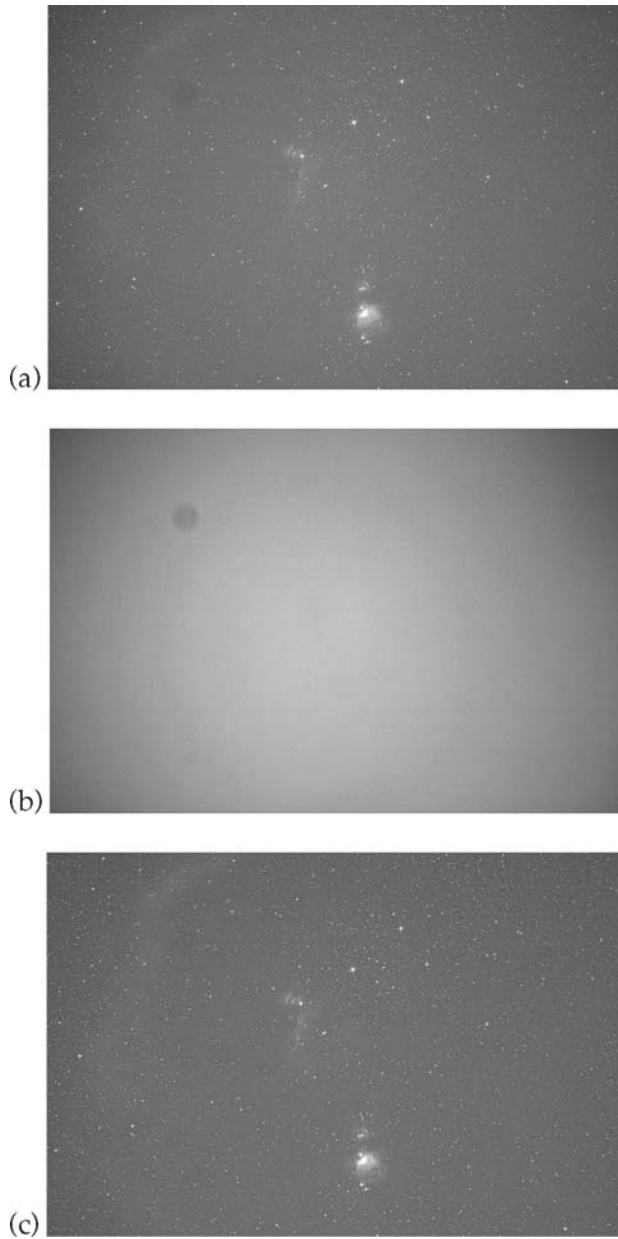


Figure 14.6. The effect of flat-fielding on a wide-field view of Orion with a Canon EOS 20Da and H $\alpha$  filter. (a) Image calibrated with dark frames but not flat fields. (b) A flat field taken through the same lens on the same evening. Note the slight vignetting and prominent dust spot. (c) Image calibrated with dark frames and flat fields. (Slightly undercorrected; see text.)

## 14.2 Calibration frames

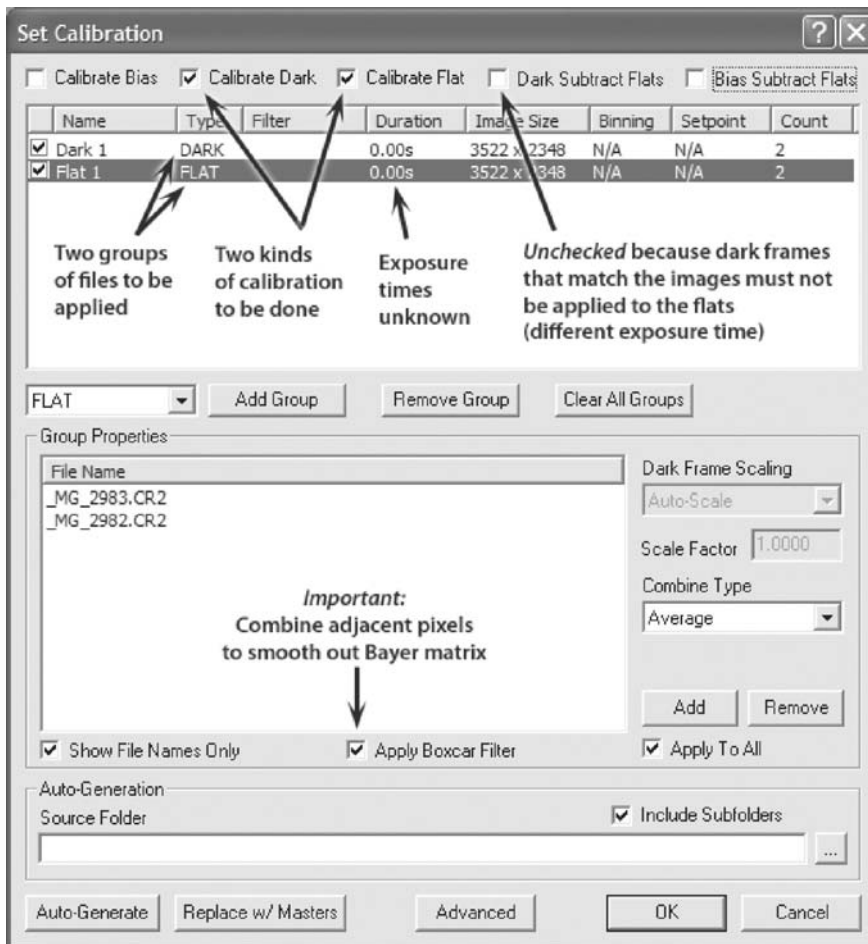


Figure 14.7. Flat-field and dark-frame calibration can be done in a single step in *MaxDSLR*.

The computation is very sensitive to errors. That's why it's so important to match the original ISO setting and optical conditions.

Better yet, make a *calibrated flat field*. That is, along with your flat fields, take some dark frames that match them. Subtract the dark frames from the flat fields, then average the flat fields (*without* aligning or de-Bayerizing them). Save the calibrated flat field and use it to calibrate your astronomical images.

Another reason for making a calibrated flat field is that you can adjust it. If your images come out undercorrected (with vignetting and dust spots still visible), scale up the contrast of the corrected flat field just a bit, and try again. If they are overcorrected, with reverse vignetting (edges brighter than the center), do the opposite.

Figure 14.7 shows the *Set Calibration* window in *MaxDSLR* when both darks and flats are to be applied. Don't make the mistake of subtracting, from your flats, the dark frames that go with the images; the exposure times are very

different and you'll end up brightening the hot pixels instead of removing them. If *MaxDSLR* knew the exposure times, it could keep track of which dark frames go with which images and flats – but if you're working from DSLR raw files, it doesn't know. That's why I recommend keeping things simple.

The results of flat-fielding are often less accurate than we might like. Perfect correction would require infinite bit depth in both the images and the calibration frames, as well as a perfect match between the flat-fielding light source and the effects of collimated starlight. Besides, the vignetted edges of the image, and also the areas blocked by dust specks, really *are* underexposed and will not look exactly like normal exposures no matter what you do. I generally prefer slight undercorrection, as in Figure 14.6, rather than overcorrection.

### 14.3 Removing gradients and vignetting

A *gradient* is a difference in brightness from one side of the picture to the other; it generally occurs when you're photographing close to the horizon or the Moon is in the sky. *Vignetting* is underexposure at the edges of the picture, usually caused by the limited diameter of the light path. Both of these can be corrected by software; in fact, *MaxDSLR* and similar packages can usually correct them automatically (Figure 14.8). Of course, if the vignetting originates in the camera, flat-fielding is a potentially more accurate way to correct it.

You can also correct vignetting manually in *Photoshop*. Briefly, the technique is:

- Learn to use the gradient tool in *Photoshop* to draw gradients, both linear and circular.
- On top of your image, draw a gradient of the same shape and position as the one you want to correct, using *Color Burn* rather than *Normal* as the blending mode.
- Then, on the main menu, choose *Edit, Fade Gradient*, and reduce the opacity of your gradient until it makes the desired correction.

When in doubt, undercorrect.

An impressive *Photoshop* plug-in for semi-automatic correction of gradients and vignetting is Russell Croman's *GradientXTerminator* ([www.rc-astro.com](http://www.rc-astro.com)). It corrects color shifts as well as differences in brightness.

There is an important mathematical difference between the usual gradient (from moonlight or skyglow) and the usual vignetting (from tube obstruction). Vignetting is multiplicative; that is, vignetting reduces the light intensity to a fraction of what it would otherwise have been. Gradients are additive; that is, they consist of extra light added to the original image. The optimal algorithms for correcting them are different, although, in practice, you can usually get away with using the same techniques on both.

#### 14.4 Removing grain and low-level noise

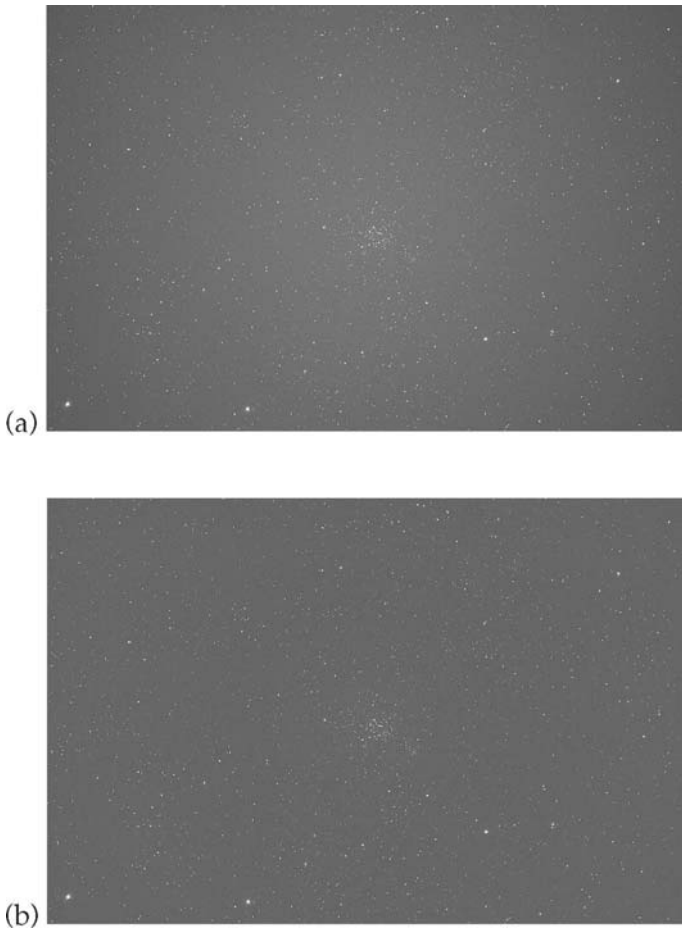


Figure 14.8. Removal of vignetting. (a) Mildly vignetted wide-field view of star cluster M35 (single 2-minute exposure, Nikon 200-mm  $f/4$  lens wide open, unmodified Nikon D50 at ISO 400 in Mode 2). (b) After applying *Auto Flatten Background* in *MaxDSLR*.

#### 14.4 Removing grain and low-level noise

Because no two pixels are alike, and because photons and electrons are discrete particles, digital images of faint objects are grainy. To a considerable extent, grain can be removed by software without obscuring the desired detail in the image. After all, if you can tell the difference between the grain and the image, then, in principle, so can the computer.

All computer graphics textbooks say that you can reduce noise by blurring the image – that is, by averaging each pixel with some of its neighbors. That is true but unsatisfying for two reasons. First, blurring the image makes stars disappear. Second, if you blur a random grain pattern without reducing the contrast, often what you end up with is just a bigger random pattern.

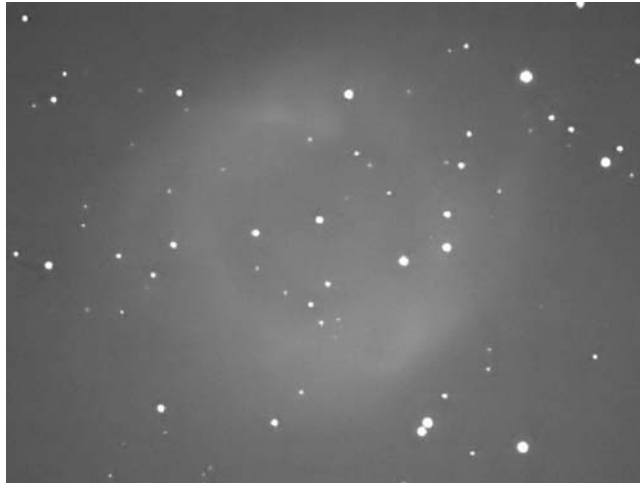


Figure 14.9. *Neat Image* removes virtually all the grain from the stacked image in Figure 14.1 (p. 179) without blurring stars.

A better approach is to try to distinguish intelligently between grain and signal. One piece of software that does an impressive job of this is *Neat Image* ([www.neatimage.com](http://www.neatimage.com)), available both as a standalone package and as a *Photoshop* plug-in. As Figure 14.9 shows, *Neat Image* can almost work magic. The noise reduction filter in *Photoshop CS2* is much less potent.

In operation, *Neat Image* attempts to find a  $128 \times 128$ -pixel area of the image that is free of stars or other detail. From this, it constructs a mathematical model of the grain. If the reference area *does* contain stars, you're likely to end up with excessively aggressive despeckling; *Neat Image* will turn into a star eater.

Because of the Bayer matrix, much of the grain in a DSLR image is actually "color noise" ("chrominance noise"), variation in color rather than in brightness. *Neat Image* recognizes this and lets you adjust the levels of luminance and chrominance noise correction separately.

The algorithms used in *Neat Image* are not made public, but the key idea has to be that each pixel is averaged, not with all of its neighbors, but only with those that are not too different from it in the first place. In this way, low-level noise is removed but star images remain sharp. It also appears that *Neat Image* tries to find and follow straight edges; this is a wise policy in daytime photography, but if an astronomical image is overprocessed in *Neat Image*, nebulae and even stars begin to turn into linear streaks.

## 14.5 The extreme brightness range of nebulae

### 14.5.1 Simple techniques

One of the challenges of deep-sky photography is that nebulae and galaxies are typically much brighter in the center than at the edges. Careful adjustment of

levels or curve shape helps bring out the faint regions without turning the bright regions into featureless white. A good tactic in *Photoshop* is to adjust the *Levels* slider several times in small, careful steps.

If that's not enough, you can stack exposures of different lengths, thereby combining their dynamic range. For scientific work, this is the best way to cover an extreme brightness range because all parts of the image are processed alike. If your goal is only to bring out detail, though, read on.

### 14.5.2 Layer masking (Lodriguss' method)

A very powerful way to combine different exposures is to use layer masking in *Photoshop*. This technique has been perfected and popularized by Jerry Lodriguss ([www.astropix.com](http://www.astropix.com)). Figure 14.10 shows what it accomplishes. The key idea is that the shorter exposure replaces the longer one in the parts of the latter that are overexposed.

I'm going to give quick instructions for this technique here, but if you are not very familiar with *Photoshop*, you may also need to consult additional documentation.

(1) Start with two differently exposed images of the same deep-sky object, one with appreciably more exposure than the other.

(2) Align them, preferably using astronomical software (see p. 154), but do not stack them. Instead, save the aligned images in a form that you can open in *Photoshop*.

(3) Make an extra copy of the image with the longer exposure. This is the one you will edit.

(4) Open all three in *Photoshop*. The image you are going to edit contains a copy of the longer exposure.

(5) Working as described on p. 181, paste a copy of the shorter exposure on top of the image you are editing, in a new layer. Do not merge it down or flatten the image, nor adjust its opacity.

(6) Now you are going to create a *layer mask*, also known as an *alpha channel*. That is an invisible layer containing a black-and-white image whose only function is to control the opacity of a visible layer.

To do this, see Figure 14.11. With Layer 1 (the pasted image) selected, click to create a mask. Then hold down Alt and click on the mask itself (currently an empty white box). Now you are editing the mask instead of the image.

(7) Copy the shorter exposure and paste it into the mask. It will appear in black and white.

(8) Blur and darken the mask so that it looks something like Figure 14.12. The light areas are those where the shorter exposure will predominate in the finished product.

(9) By clicking and Alt-clicking as shown in Figure 14.11, you can switch back and forth between editing the image and the mask. Adjust the mask until its effect suits you.

Techniques specific to astronomy

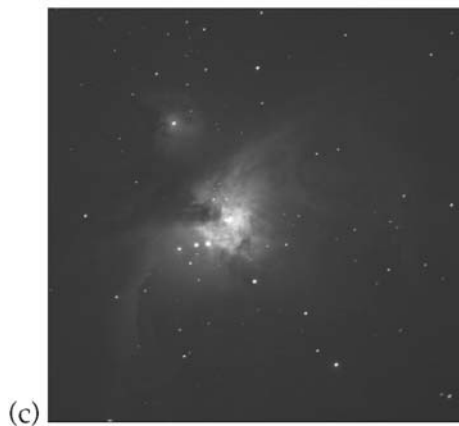
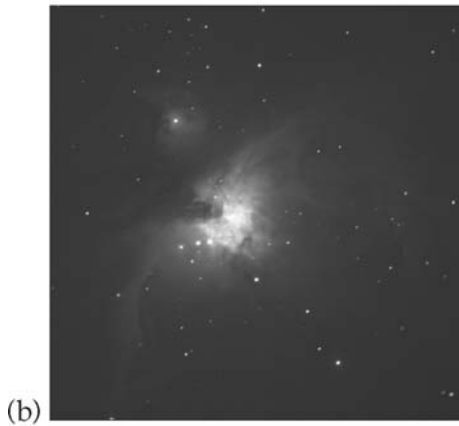
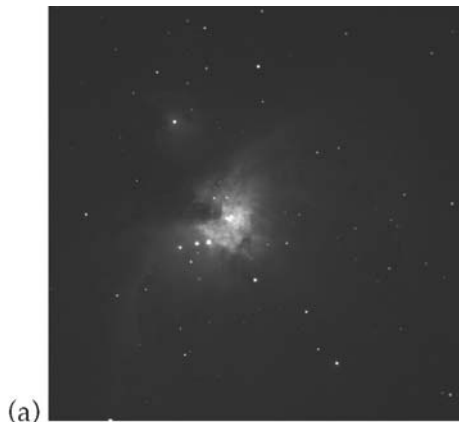


Figure 14.10. Combining different exposures with layer masking. (a) Orion Nebula, 1 minute, 8-inch telescope at  $f/6.3$ , Canon XTi, ISO 400. (b) Same, 2 minutes. (c) Combined, using a layer mask to take the central region from the shorter exposure.

## 14.6 Other *Photoshop* techniques

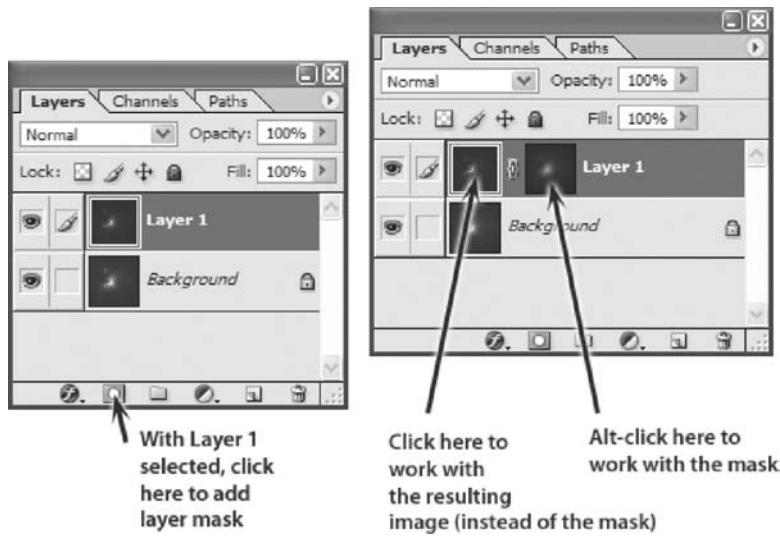


Figure 14.11. How to add a mask to a layer in *Photoshop* and how to work with it.



Figure 14.12. The layer mask used in Figure 14.10.

(10) Finally, flatten the image and make other adjustments, such as levels and unsharp masking.

You can combine any number of images in this way, and the results can be impressive (Figure 14.13).

## 14.6 Other *Photoshop* techniques

In the *Photoshop* main menu, *Image, Adjustments, Auto Levels* will automatically stretch the image, in each of three colors, so that it uses the full brightness range.

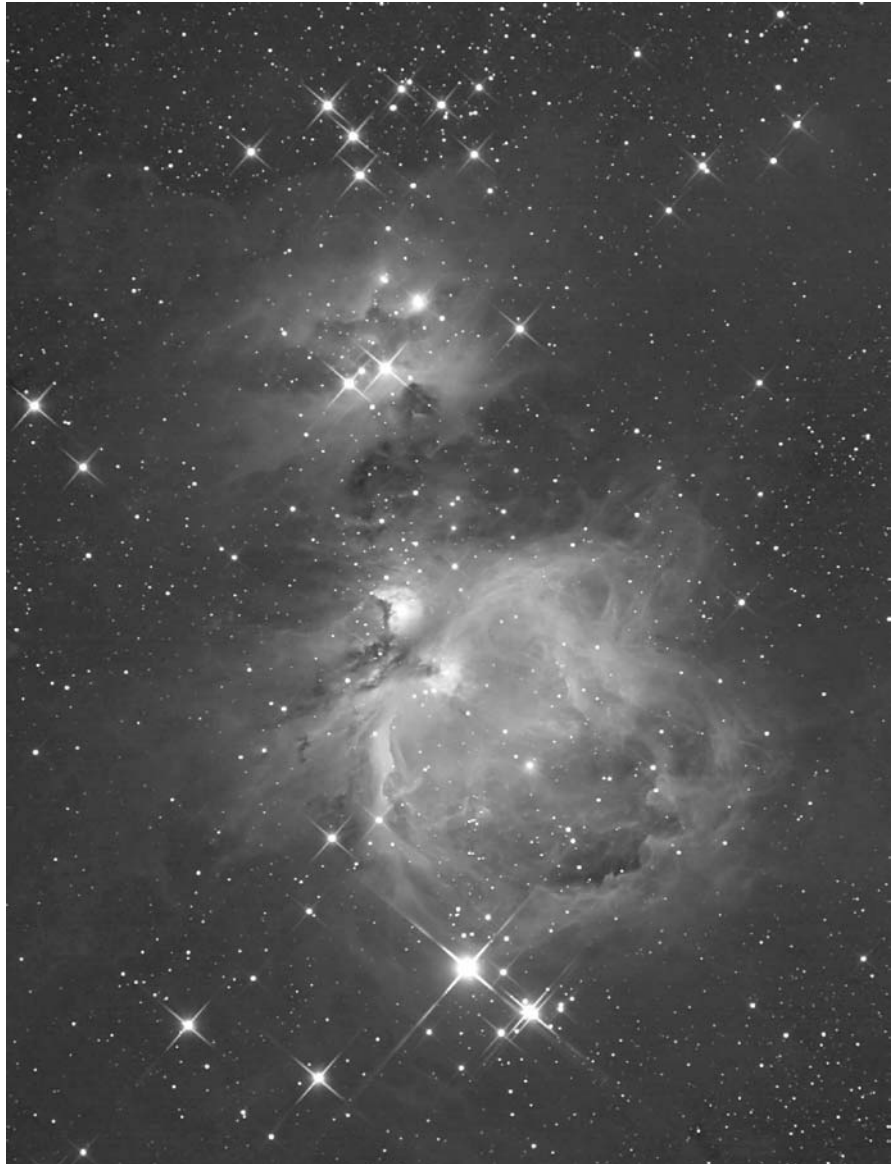


Figure 14.13. The Orion Nebula (M42) in exquisite detail – a combination of 29 5-minute, five 1-minute, and five 10-second exposures at ISO 800 using a Canon XT (350D) and an Orion ED80 8-cm telescope with a focal reducer giving  $f/4.7$ . Wire crosshairs in front of the telescope produced diffraction. Processing included layer masking, Richardson–Lucy deconvolution, and noise removal with *Neat Image*. (Hap Griffin.)

## 14.7 Where to learn more

This or almost any other image alteration can be “faded” by choosing *Edit, Fade*. What this does is mix the altered image with the previous, unaltered version of the same image, thus reducing the effect.

A large number of astronomically useful *Photoshop* operations, including quite complex ones, have been scripted as macros in Noel Carboni’s *Astronomy Tools Action Set* (<http://actions.home.att.net>). These include unobvious procedures such as “make stars smaller” and “add diffraction spikes.” They come highly recommended.

## 14.7 Where to learn more

Astronomical image processing has been a thriving art for over a quarter century now. The best general handbook I know of is *The Handbook of Astronomical Image Processing*, by Richard Berry and James Burnell (2nd ed., 2005), published by Willmann–Bell ([www.willbell.com](http://www.willbell.com)); it comes with an excellent software package, *AIP4WIN*.

For general principles of digital image processing, see Scott E. Umbaugh, *Computer Imaging* (Taylor & Francis, 2005). Other useful handbooks include R. Scott Ireland, *Photoshop Astronomy* (Willmann–Bell, 2005), and Ron Wodaski, *The New CCD Astronomy* (New Astronomy Press, 2002, [www.newastro.com](http://www.newastro.com)).

Two useful books-on-CD, *Photoshop for Astrophotographers* and *A Guide to Astrophotography with DSLR Cameras*, have been authored and published by Jerry Lodriguss ([www.astropix.com](http://www.astropix.com)). I also highly recommend Robert Reeves’ pioneering *Introduction to Digital Astrophotography* (Willmann–Bell, 2005); it may seem odd to describe a book only two years older than this one as a pioneer, but that’s how fast the field is changing!



## **Part IV**

### Appendices



## Appendix A

# Astrophotography with non-SLR digital cameras

If your digital camera is not a DSLR, it has a smaller sensor with a higher noise level, making it unsuitable for deep-sky work. More importantly, it doesn't have interchangeable lenses.

Those facts don't make it useless. Non-SLR digital cameras have one great advantage – their shutters are almost totally vibration-free. This enables them to get sharp images of the sun, moon, and planets (Figures A.1–A.3). In fact, a Nikon Coolpix 990 is my usual camera for photographing lunar eclipses.

The coupling of camera to telescope has to be afocal; that is, the camera is aimed into the telescope's eyepiece. Numerous adapters to hold the camera in place are available; my favorite, which only works with older Nikon cameras, is a ScopeTronix eyepiece that threads directly into the filter threads of the camera. With a bright image of the Moon, the camera can be hand-held.

Set the camera to infinity focus (the mountain symbol), turn off the flash, and focus the telescope while viewing the display on the camera. If the Moon fills the field, the camera can autoexpose; otherwise, you'll have to set the exposure manually by trial and error. Set the self-timer (delayed shutter release) so that the picture will not be taken until you have let go of the camera and it has stopped vibrating.

The examples shown here are single images, but you can of course take many exposures of the same object and combine them with *RegiStax* (p. 206).

If you'd like to photograph the stars, try the same fixed-tripod or piggybacking techniques as with a DSLR (p. 40), but expect a lot of hot pixels, so take dark frames too. See p. 163 for how to process the images. You have one advantage over DSLR users – you don't have to hunt for infinity focus; just turn off autofocus and lock your camera to the mountain symbol.



Figure A.1. Partially eclipsed Moon on 2004 October 27. 5-inch (12.5-cm)  $f/10$  Schmidt-Cassegrain telescope, 25-mm eyepiece, and Nikon Coolpix 990 camera, autoexposed.

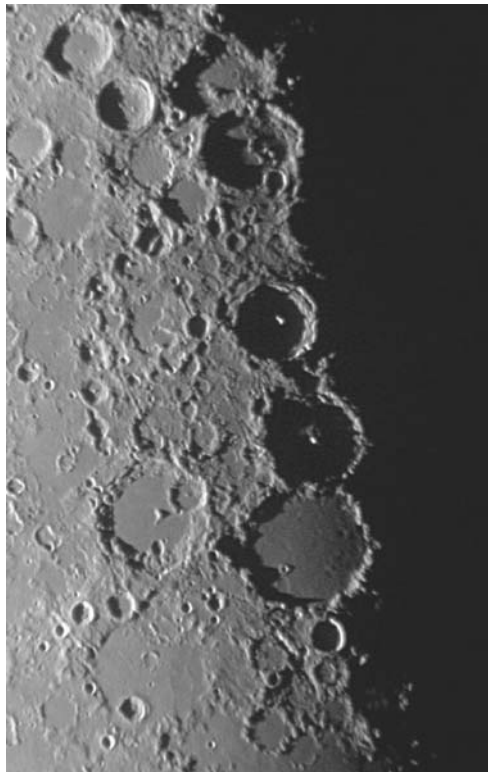


Figure A.2. Lunar craters. Same telescope, camera, and technique as Figure A.1; 18-mm eyepiece.

Astrophotography with non-SLR digital cameras

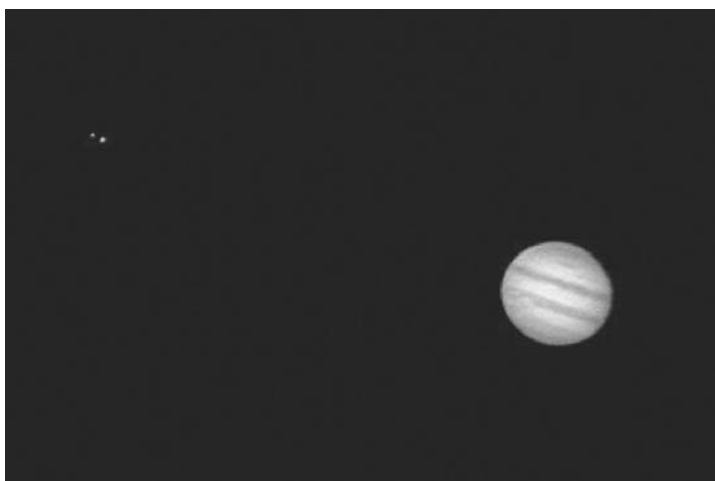


Figure A.3. Jupiter and satellites Ganymede (larger) and Europa. Nikon Coolpix 990 camera, 18-mm eyepiece, and 8-inch (20-cm)  $f/10$  Schmidt-Cassegrain telescope.

## Appendix B

# Webcam and video planetary imaging

### B.1 The video astronomy revolution

The reason DSLRs are not used for high-resolution lunar and planetary work is that another, much cheaper, instrument works much better. Just before the DSLR revolution came the video astronomy revolution. By aligning the best frames from a video recording, it suddenly became possible for amateurs with modest telescopes to take pictures like Figure B.1, which were, until then, almost beyond the reach of any earth-based telescope.

The resolution of planetary images is limited by the turbulence of the atmosphere. By aligning hundreds or thousands of images, the video astronomer can see right through the turbulence. Air movements that are different in every frame cancel each other out, and what's left is what all the frames have in common, namely the true appearance of the planet.

What's more, imperfect tracking is actually an advantage. If the planet image moves all over the sensor during the recording, no single pixel or dust speck will have much of an effect.

### B.2 Using a webcam or video imager

A *webcam* is a cheap CCD camera that delivers a continuous stream of video to the computer by USB or FireWire connection. These are commonly used for low-cost videoconferencing. For astronomy, the lens is unscrewed and replaced with an eyepiece tube adapter (Figure B.2). Because the IR-blocking filter is in the lens, which was removed, it is desirable to add a UV/IR-blocking filter at the end of the eyepiece tube.

Webcam adapters are sold by many telescope dealers. You can also buy them directly from independent machinists who make them, such as Pete Albrecht ([www.petealbrecht.com](http://www.petealbrecht.com)).

Alternatively, you can also buy your video camera ready made. The Meade Lunar/Planetary Imager (LPI) and the Celestron NexImage are basically

## B.2 Using a webcam or video imager

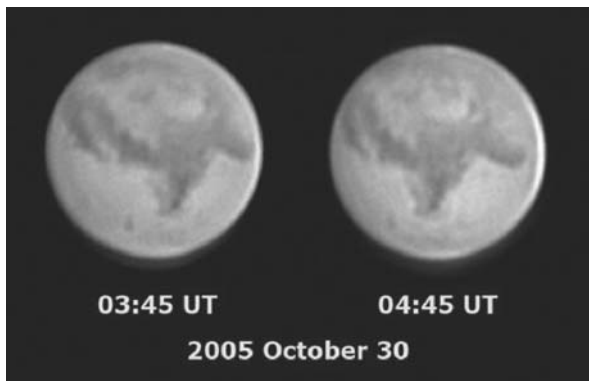


Figure B.1. Rotation of Mars in 1 hour. Each image is a stack of frames selected from a 3000-frame video sequence taken with an 8-inch (20-cm) telescope with negative projection giving  $f/30$ .



Figure B.2. A webcam modified for astronomy (my Philips ToUCam Pro, vintage 2003). *Top*: Assembled and ready for use. *Bottom*: The components: webcam with lens removed, eyepiece tube adapter, and UV/IR blocking filter. Parafocalizing ring around adapter is optional.

## Webcam and video planetary imaging

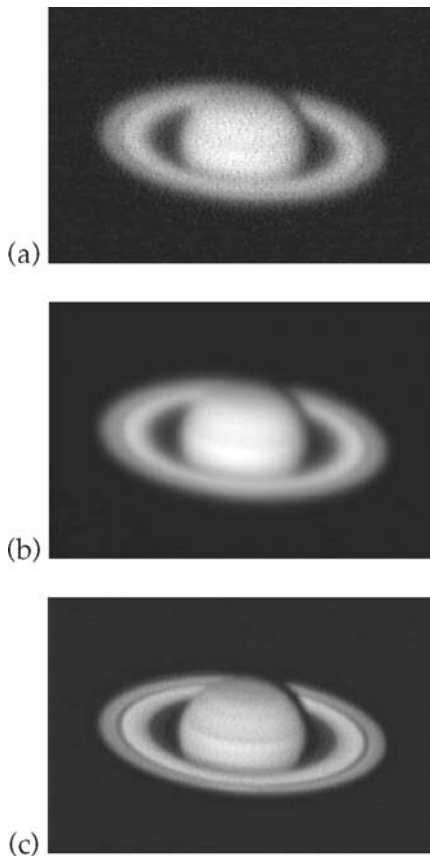
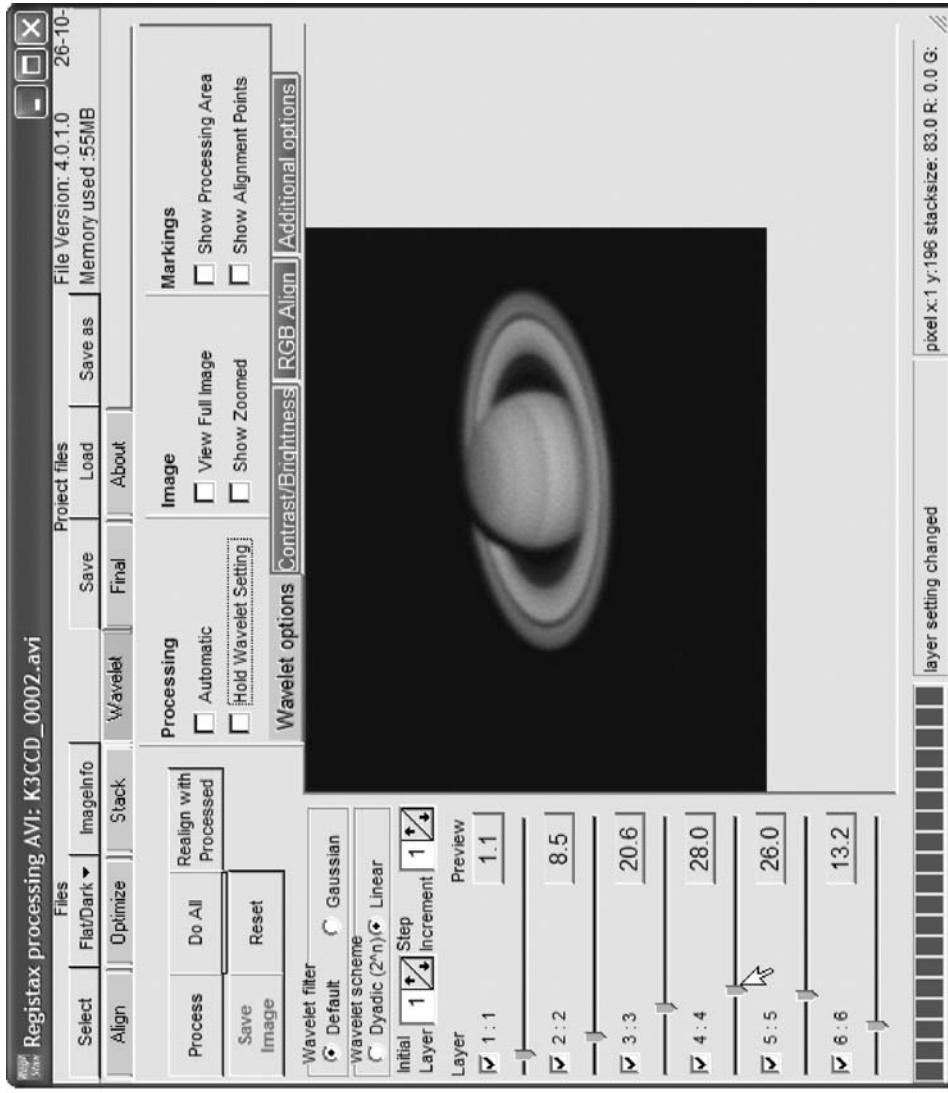


Figure B.3. Video astronomy. (a) Single frame of a video recording of Saturn made with an 8-inch (20-cm) telescope at  $f/20$ . (b) The best 500 frames (out of 805), aligned and stacked. (c) After wavelet filtering.

webcams. Any astronomical CCD camera, cooled or not, will work if it has a continuous live video output to the computer.

The camera goes in place of the eyepiece of a telescope working at  $f/10$  to  $f/30$ ; I use an 8-inch (20-cm) Schmidt–Cassegrain with a Barlow lens. For easy focusing, I suggest using the Moon as your first target. To further speed focusing, I've put parfocalizing rings on my webcam and an eyepiece so that they match; I do rough focusing with the eyepiece, center the object in the field, and then switch to the webcam. The field of the webcam is very small, so centering is important.

To record video, you can use the software that came with the camera or any number of astronomical software packages. Create a file in AVI format. The camera controls will be much the same no matter what software you use, since they are provided by the manufacturer's drivers. Turn auto exposure off, set the speed to 15 frames per second, set the exposure to 1/25 second and the gain to medium, use the full resolution of the camera, and see what you get. Adjust



**Choose  
size of  
details to  
emphasize**

Figure B.4. Wavelet filtering in *RegiStax*. Sliders allow selective enhancement of details of different sizes.

exposure and gain as needed. Err on the side of underexposure, since images tend to gain a little brightness during wavelet processing.

I usually record about 1000–3000 frames (1–3 minutes). The rapid rotation of Jupiter will start to blur detail if you record for more than about a minute (this is a very rough guideline); with Mars, you have more time.

### B.3 Using *RegiStax*

The software that makes video astronomy possible is Cor Berrevoets' *RegiStax* (<http://registax.astronomy.net>). By now, several other software packages have developed similar capabilities, but *RegiStax* is the gold standard, and it's free.

*RegiStax* includes clear instructions which I shall not repeat here. You give it an AVI video file, and it aligns the images, sorts them in order of decreasing quality, suggests a cutoff point for discarding the bad ones, and then stacks them carefully, iterating to improve the match. Then you get to perform wavelet-based sharpening as shown in Figure B.4. Each slider controls wavelets of a particular frequency and hence details of a particular size. The first slider generally affects only grain; the second and third begin to bring out image detail. When the image looks the way you want, you can save it and do further processing, if needed, with *Photoshop*.

*Registax* isn't just for videos. You can use it to stack and enhance images from any source; newer versions are becoming increasingly suitable for deep-sky work.

## Appendix C

# Digital processing of film images

You can, of course, process film images with the same software that you use for DSLR images. The grain in each image is different; there is no fixed-pattern noise. Stacking multiple images builds contrast and reduces grain.

First you have to get the film images into digital form. There are many methods. The best is a film scanner with a resolution of at least 2400 dpi (about 100 pixels/mm). This scans each 35-mm slide or negative into a file containing eight or more megapixels, comparable to the resolution of a good DSLR. I use a Nikon Coolscan III (LS-30) and get excellent results. It even has the ability to detect and electronically remove dust and scratches, which, unlike film, are opaque to infrared light.

I have not had good results with flatbed scanners that claim to scan film. In my experience, the flatbed scanner acquires a rather blurred image and then applies a strong sharpening filter to it. It's much better to scan the image faithfully in the first place.

You can use your DSLR to digitize film images. Any slide duplicator attachment that fits a film SLR will also work with a DSLR, except that it may not cover the whole slide because the DSLR sensor is smaller than a film frame. The alternative is to use the DSLR with a macro lens and light box, and simply photograph the slide or negative (Figure C.1). To get the camera perpendicular to the slide, put a mirror where the slide is going to be, and aim the camera at its own reflection.

Once the images are digitized, proceed as with DSLR or CCD images, except that gamma correction is not needed. Figure C.2 shows an example. Three Ektachrome slides were scanned, the images were stacked, vignetting was removed, the contrast was adjusted (separately for green and red), and unsharp masking was done.

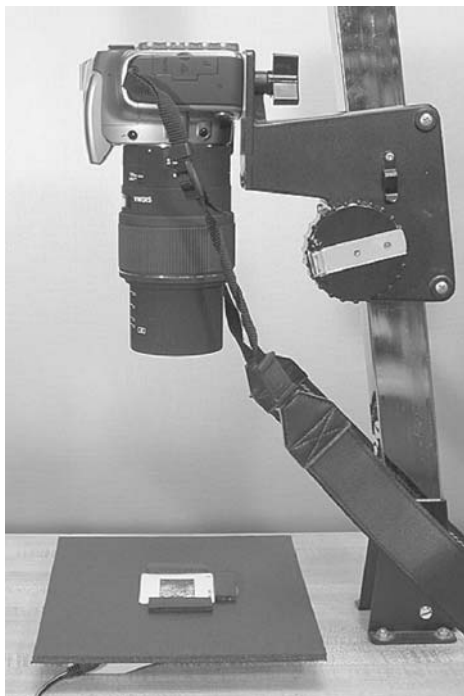


Figure C.1. One good way to digitize color slides is to use a DSLR with a macro lens and light box. Work in a darkened room.



Figure C.2. Effect of stacking and processing film images. *Left*: Nebula IC 4628 in Scorpius; central part of single 7-minute exposure on Kodak E100GX film with Nikon 300-mm  $f/4$  lens. *Right*: Result of stacking three exposures and processing in *MaxDSLRL* and *Photoshop*.

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