2 *Practical Focusing*

CCD cameras represent some pretty fancy technology, but in some ways they are just like ordinary cameras. As with a traditional film camera, the difference between a snapshot and a great photograph lies as much with the photographer as with the equipment.

CCD focusing is done in an iterative fashion, taking test exposures and then examining the results. The various camera control programs allow you to speed up the process so you can get focusing done efficiently.

Section 1: Focusing Fundamentals

FIGURE 2.1.1. AN IMAGE WITH GOOD FOCUS CAN BE STRIKING, SHOWING A HIGH LEVEL OF DETAIL.

You may have heard that focusing is difficult, or time consuming, or just plain annoying. It doesn't have to be that way. You do need to be extremely careful when focusing to get the best possible results. A little extra time spent focusing is well worth the effort. Good focusing is one of the single most important ingredients in taking a good image, and it is totally under the control of the operator.

In this chapter, you will learn everything you need to know to focus effectively. You'll learn:

- Why focusing is critically important.
- How to achieve best focus every time.
- Software aids for achieving best focus.
- Hardware aids for achieving best focus.
- Alternative focusing techniques.

Focusing a CCD Camera

The human eye is a marvelous instrument. It is capable of focusing over a wide range of distances. In addition, because our eyes function cooperatively with our brain, they are capable of accommodating to rapidly changing conditions. When you use your eye to look at a celestial object through a telescope, your eye can adjust to slight focus errors with little or no trouble. It can even adjust to rapid variations in focus caused by turbulence in the atmosphere, if the turbulence isn't too rapid or severe.

A camera, on the other hand, has no ability to accommodate even a slightly out-of-focus image. CCD cameras are no different from film cameras in this regard. If an image is out of focus, the photons are scattered over a wider area, and dim stars and faint details are lost.

Precise, accurate focusing is critical to success. Unfortunately, focusing any astro camera requires a little more work than focusing an ordinary camera. When you are taking a snapshot of the Grand Canyon, you have plenty of light to work with while you focus, and so does the automatic focuser found in most of today's cameras. Professional film cameras allow you to focus by looking at a ground glass screen that is conveniently located exactly the same distance from the camera lens as the film. The scene is bright, and focusing is relatively easy. Your camera might even have some optical tricks installed to make it even easier, such as split-ring focusing.

Working at night under the stars, there's not as much light to work with. The whole idea of using a camera is to take long exposures to capture as many of those scarce photons as possible. Focusing a film camera for astrophotography is a challenging task, quite unlike the daytime equivalent. Automatic focusers don't have enough light to work with, and a ground glass screen is suddenly too dim to focus with easily. Film-based astrophotographers have developed special devices to help them achieve good focus.

Instead of a ground glass screen, a CCD camera displays its results right on your computer screen. This means you aren't limited to the available light. You can collect photons over time while you are focusing, and this is a definite advantage over film. Still, there is significant work to be done in achieving good focus. No matter what type of object you wish to image with a CCD camera, most of the time you use a star for focusing. It is more challenging to focus on extended objects such as nebulae and galaxies because of their lower contrast. Solar system objects are a special case; see chapter 3 for details.

Stars are point sources of light. It would be ideal if stars became true points at perfect focus, but that's not the case. The image of a star on a CCD chip is actually a small disc. A number of factors contribute to this spreading out of the light from distant stars:

- The laws of optics describe how a point source of light gets spread out because of diffraction. See the section Diffraction Effects below for more information about diffraction.

- Turbulence in the atmosphere scatters light. The amount of scattering varies from night to night, even from hour to hour and minute to minute.

- Every telescope has at least some level of optical aberration. This can interfere with achieving perfect focus.

- Many telescopes require user collimation. If collimation isn't perfect, you won't be able to achieve best focus no matter how hard you try. Chapter 3 provides detailed help for collimating the telescopes most commonly used for CCD imaging.

On any given night, one or all of these factors will dominate. So "best focus" becomes an elusive prospect. And because the seeing is always tossing your star image around (a little or a lot), it takes some know-how to tell when you've got best focus. In this section, you will learn what it takes to achieve optimal focus for CCD imaging.

Diffraction Effects

The image of a star in a telescope eyepiece is in no way indicative of its actual diameter. All but a few stars are simply too far away to see as a disk even with fancy professional equipment. Yet if you magnify any star image, you will see a small disk. This is the result of diffraction effects. A photo, on film or with CCD, is a time exposure. That introduces a few other considerations, such as air turbulence, that increase the size of this disk. Those topics are covered elsewhere in this chapter.

Light is made up of photons. They aren't particles in the way we think of particles at our human scale. They also behave like little waves. This dual nature is common to the stuff you find at the subatomic level. It gives rise to phenomena that are sometimes non-intuitive. Diffraction is one of those phenomena. Wrap your mind for a moment around the idea of very small particles moving in a wavelike manner.

Waves are able to reinforce and cancel one another. If the peaks of two waves coincide (called reinforcement), the resulting wave is the combined height of the two peaks. If two troughs meet, the result is an extra-deep trough. Similarly, if a peak and a trough meet, they will cancel each other out, and the result is a flat spot.

These rules about waves also apply to photons. When two photons have waves that reinforce each other, you get a bright spot. When the waves cancel each other out because they coincide peak to trough, you get a dark spot.

When light passes through an aperture, the light waves are diffracted, changing the way the peaks and troughs interact at the focal plane. The net effect of these interacting photons results in a diffraction pattern caused by light waves reinforcing and canceling each other to varying degrees. In the case of the round objective of a telescope, this is a bright center surrounded by alternating dark and bright rings.

Photons have a very small wavelength, and they combine in a variety of ways as they come to focus at the back of the telescope. For a star, most of the light waves will combine to form a central bright spot. There will be some slightly off-axis photons resulting from diffraction, however, and they will travel a slightly different path to the focal plane. These will meet on-axis photons and depending on the distance from the optical axis, they will cancel or reinforce each other. This creates the bright and dark rings around the bright central spot. Each ring is less bright than the previous one because most of the light energy is toward the center of the pattern.

Figure 2.1.2 shows three examples of diffraction rings. The image on the left is an enlarged view of a star in an optically perfect refractor. The image is simulated with Aberrator 3.0, a software program that shows the effects of many types of optical defects on the image of a star or planet. You can download Aberrator from **http://aberrator.astronomy.net**.

The left image shows a bright center disk surrounded by successively dimmer diffraction rings. Most of the rings are too dim to show up clearly. The image in the middle shows the effect of a large central obstruction, such as the secondary mirror of a Schmidt-Cassegrain. The disk is slightly dimmer and the diffraction rings are slightly brighter. This reduces contrast, and explains why high-end refractors are desirable for imaging. The image at right shows what poor optics do to the diffraction pattern. Poor optics put more light into the diffraction rings, and they disturb the even distribution of that light in and around the central disk.

The central disk is called the Airy disk, named after a 19th century mathematician, George Airy, who established the mathematics behind the effect.

With perfect optics, 84% of the light from the star will be in the bright center, another 7% in the first ring, 3% in the second ring, etc. A telescope with a central obstruction, will spread the light out into the diffraction rings as illustrated by figure 2.1.2. Poor optics will cause a similar effect.

When the central spot is not as bright as the diffraction rings, it is because more of the light energy winds up in the rings. This is why a star test is such a useful way to analyze the quality of optics in a telescope: the diffraction rings tell the story of how good or bad the optics are. An experienced observer can often analyze a slightly out of focus diffraction pattern and determine the cause(s) of the non-standard pattern.

Air turbulence will also affect the appearance of the diffraction pattern. Figure 2.1.3 shows in-focus stars with the diffraction rings muddled by various degrees of turbulence. The images at left are the least affected by turbulence, and the images on the right are the most affected. The top images simulate a refractor, and the bottom images simluate an SCT. The obstructed telescope's image (SCT) breaks down with less turbulence. The same is true for optical quality: the poorer the optical quality, the more susceptible the telescope will be to loss of contrast and detail from turbulence.

FIGURE 2.1.2. THEORETICALLY PERFECT DIFFRACTION RINGS (LEFT); DIFFRACTION THROUGH A SCOPE WITH A 35% CENTRAL OBSTRUCTION (CENTER); DIFFRACTION THROUGH POOR OPTICS (RIGHT).

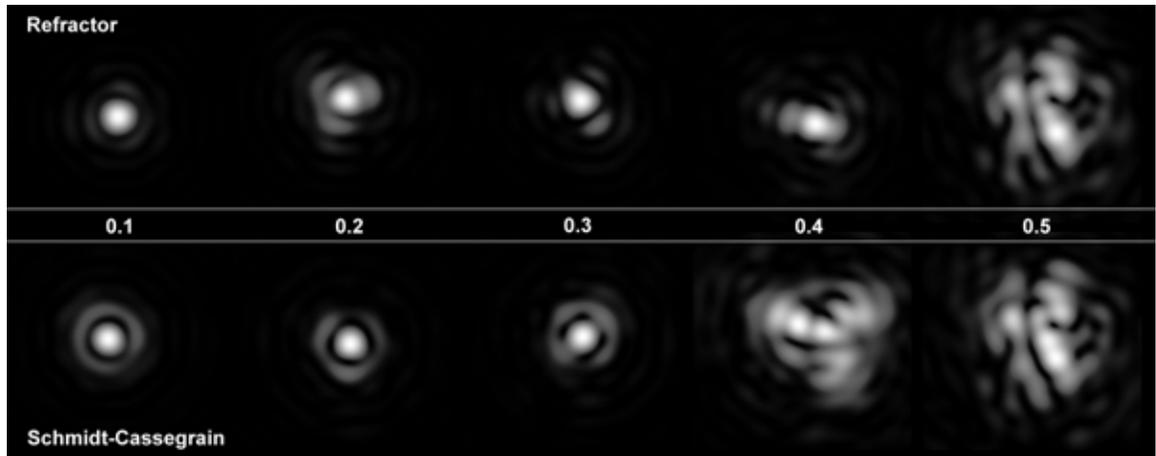Refractor   Schmidt-Cassegrain   Poor Optical Quality

FIGURE 2.1.3. THE EFFECT OF INCREASING TURBULENCE ON DIFFRACTION PATTERNS IN DIFFERENT TELESCOPES.

No optical system, no matter how perfect, can ever do away with diffraction to create point-like images of stars; the wave nature of light won't allow it. Even perfectly focused, there will always be some spreading out of the light into a diffraction pattern. Thanks to turbulence, the image gets spread out even more. On any given night, turbulence (seeing) will limit the potential image quality for both film and CCD imaging. The shorter the focal length of your telescope (or the larger your camera's pixel size), the lower the magnification factor and the less impact turbulence will have.

Figure 2.1.4 shows a small section of an image captured with a CCD camera. You don't see any diffraction rings around the stars because two things conspire to hide them. One, the diffraction rings are very small, and would only show up at very high magnification. Most CCD imaging is not done at such high levels of magnification. Two, turbulence is nearly always the dominant factor, and it smears diffraction rings (and

FIGURE 2.1.4. STARS DON'T SHOW DIFFRACTION RINGS IN IMAGES.

the star's image) into a larger circle. The brighter the star (and the longer the exposure), the larger the circle. Why does brighter equal larger? The longer the exposure or the brighter the star, the larger the number of scattered and diffracted photons that will be recorded.
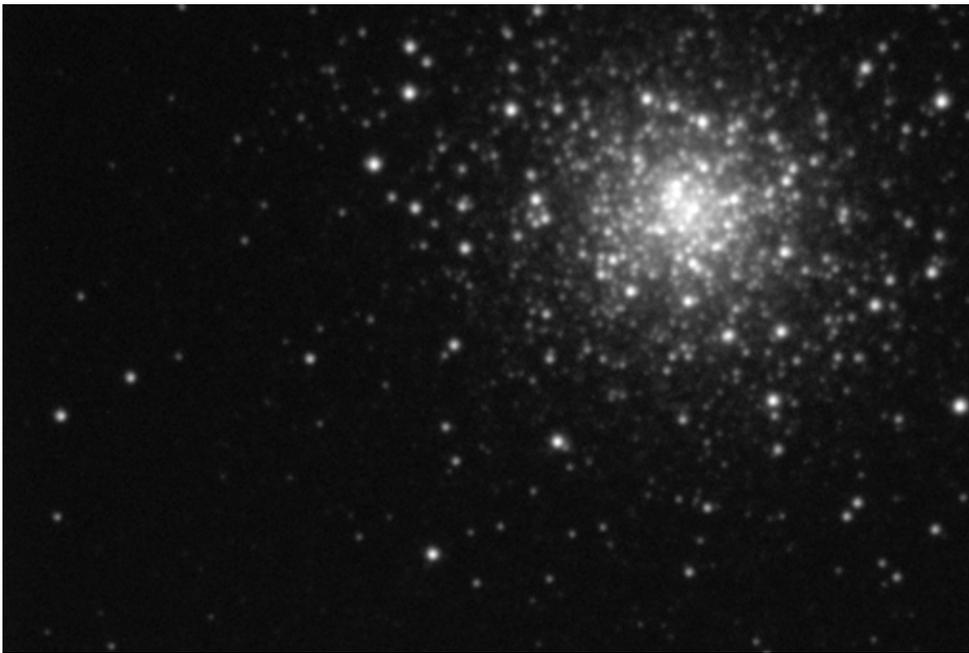
Optimal Focus Position

How important is optimal focus? Figure 2.1.5 shows an image of the globular cluster M13 in excellent focus. Notice how the individual stars are tiny points of light, and you can easily see darker spaces between the stars, even near the core of the cluster. There are large numbers of both bright and dim stars.

FIGURE 2.1.5. THE GLOBULAR CLUSTER M13, SHOWING AN EXAMPLE OF EXCELLENT FOCUS.

Figure 2.1.6, on the other hand, shows a globular cluster with less than perfect focus. Star sizes are larger, and they are not nearly as crisp and attractive. Fewer dim stars are present. Poor focus spreads out the light, and for dim stars this is enough to make them disappear entirely.

The difference between these two images is a very, very tiny amount of focuser movement, yet the difference in appearance in enormous. Nothing you do on any given night will have more impact on the quality of your images than focusing. Taking the time to get perfect focus will make a big difference in the appearance of your images.

The care you must take to achieve perfect focus changes with the

FIGURE 2.1.6. THE GLOBULAR CLUSTER M92 WITH POOR FOCUS.

characteristics of various types of telescopes. The type of focuser in use, the arrangement of mirrors and/or lenses, and the focal ratio of the telescope all affect how hard you will have to work to achieve optimal focus.

One of the difficult challenges in CCD imaging is making very small focus changes. Some focuser designs make this easy, but many do not. For example, refractors typically use rack-and-pinion focusers. These are effective for visual use, but they are often too coarse for CCD imaging. What works well for the eye doesn't necessarily work well with a CCD camera. Schmidt-Cassegrain telescopes present a different kind of focusing problem. They use a moving primary mirror to achieve focus. The mirror can shift after you focus, or when you change the direction of focuser travel. This isn't a big problem for the eye, but it can be frustrating when focusing with a CCD camera.

Figure 2.1.7. Telescope focal ratio determines the length of the critical focus zone.

TIP: CCD imaging requires extremely fine control over focus position. Many telescope designs do not have an optimal focusing mechanism for CCD imaging. In most cases, there are alternative focusing mechanisms or techniques available that will help you achieve perfect focus. The details are covered later in this chapter.

Focusing Explained

The human eye is a marvelous instrument. Not only can it follow rapidly moving objects, but it can also adjust focus in real time, compensating for minor focus drift, curved fields, or minor out of focus conditions. The eye is a very forgiving focuser.

A CCD camera, on the other hand, is very unforgiving. You will need very precise focus to get sharp, detailed images from your CCD camera. Precise focus is also important for research (astrometry and photom-etry) so that you can accurately measure the brightness of objects.
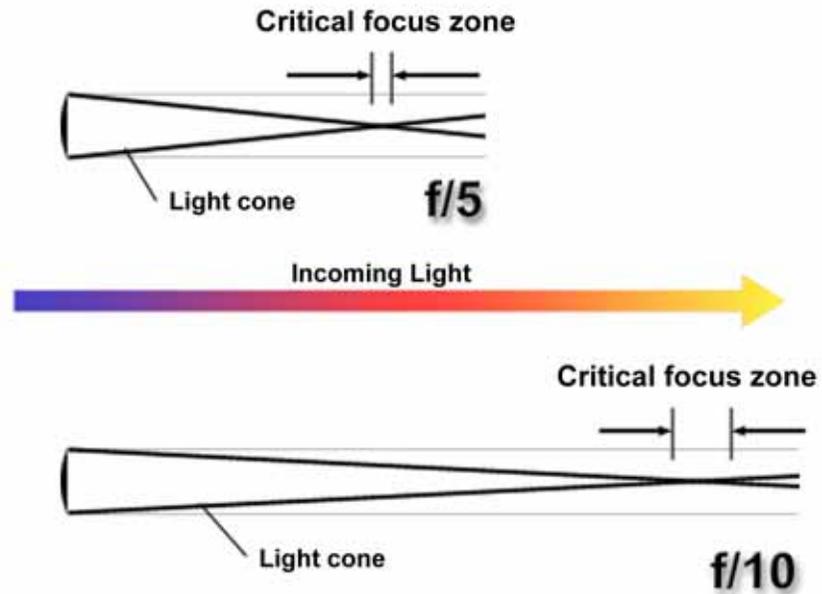
Camera control programs have a variety of built-in features that will allow you to achieve the best possible focus. But there are also mechanical considerations that play a role in how effectively you can achieve focus.

"Critical focus" is actually a range of focuser positions, not just a single, exact spot along the focuser's range of travel. Since turbulence, diffraction, and other factors spread out the star's light into a disk, any focus position that provides the smallest possible disk will suffice. In other words, "critical focus" is actually a range of focus positions. Any position in the critical focus zone provides the best possible focus.

The actual size of this zone is based on the focal ratio of your telescope. The faster your focal ratio, the shorter the zone of critical focus is. For the purposes of focusing, a fast focal ratio is f/5 or lower; a slow focal ratio is greater than f/8. Scopes with a fast focal ratio will be more challenging to focus, and scopes with slow focal ratios will be a little more forgiving.

TIP: The focal ratio is the ratio of the telescope focal length to the aperture. For example, a telescope with an aperture of 100mm and a focal length of 500mm

has a focal ratio of f/5. Lower-numbered focal ratios are said to be "fast" because they require shorter exposure times.

Figure 2.1.7 shows light cones for fast (f/5) and slow (f/10) refracting telescopes. The front of the hypothetical telescopes is on the left. Light enters from the left through the telescope objective, and comes to a focus where the converging lines cross. Other types of telescopes will have similar critical focus zones, but the light path be shaped differently. The f/5 light cone is steep; as you move away from the front of the scope, the light converges to focus very quickly. The f/10 light cone is shallow, and does not converge as rapidly as you move away from the front of the telescope. For all telescopes, the light diverges again past the focal point.

The telescope's focuser, manual or motorized, moves the CCD camera back and forth. The CCD detector inside the camera must sit within the critical focus zone to get a sharp image. To bring the CCD camera to focus, the focuser moves the camera so that the CCD detector is within the critical focus zone, as shown in figure 2.1.8.

Since telescopes with fast focal ratios have a smaller critical focus zone, you can focus more effectively if your focuser allows very small adjustments. You can improve your ability to focus a fast telescope by adding a motorized focuser.

TIP: Not all motorized focusers are ideal for CCD imaging. The best motorized focusers provide very fine control over focus position, sometimes using gears or a Crayford style add-on focuser to give you a high degree of control. Motorized focusers that simply move your existing focuser may or may not have fine enough control to give you an advantage. This is especially true with the rack and pinion focusers of refractors, which are relatively coarse without some kind of reduction gearing.

CCDSoft includes a focusing utility, @Focus, which can use a variety of motorized focusers to automatically find a position in the critical focus zone. The best focusers for use with @Focus are capable of making extremely small movements (the minimum movement is called the step size). Telescopes are susceptible to various kinds of focus drift, from looseness in the focuser to physical shrinking as temperatures fall during the night. A motorized focuser can help you adjust focus during a long imaging session.

When the seeing is very good (i.e., the atmosphere is stable), star images hold steady and are smaller and sharper. As the seeing deteriorates, star images begin to bloat up and lose their hard edge. This makes it more difficult to measure focus. CCDSoft's automatic focusing tool, @Focus, can average multiple images to help it converge on the best focus position even under poor seeing conditions. Manual focusing also becomes harder under poor seeing conditions. You wind up going through focus repeatedly, never quite sure where best focus is.

FIGURE 2.1.8. MOVING THE CAMERA INTO THE CRITICAL FOCUS ZONE.

TIP: If the zone of critical focus is very small, you may find it difficult to achieve critical focus reliably or easily using a manual focuser. There are several different types of motorized focusers available.
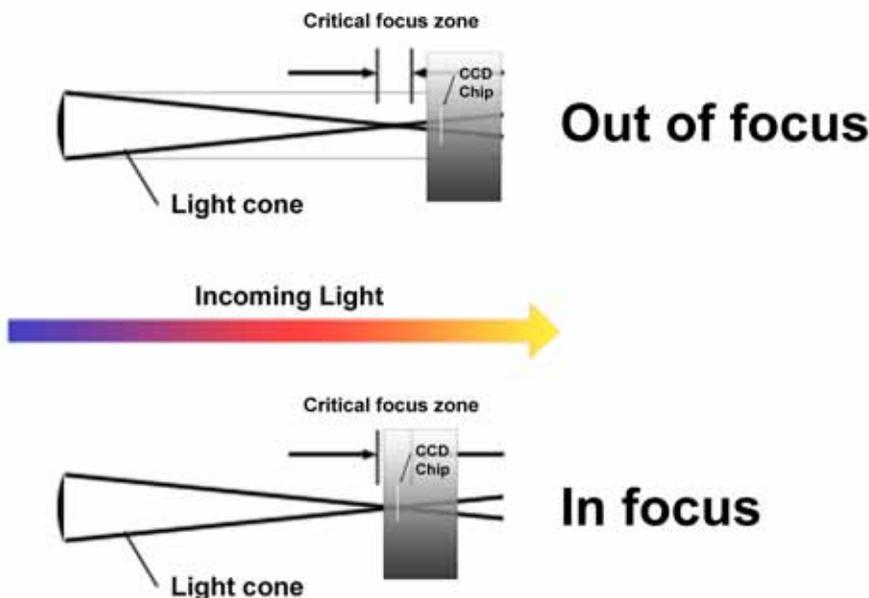
A motorized focuser can provide smaller adjustments in many cases than you can do by hand, and is thus better at making the small adjustments needed to position the CCD detector inside the critical focus zone. To get useful results from a motorized focuser, it should enable you to make movements that are no larger than one-half the size of your zone of critical focus. For optimal focusing, especially on nights of really good seeing, look for a focuser that will move in increments that are one-quarter or less the size of your critical focus zone.

The equation below computes the size of the critical focus zone (CFZ) in microns for a "perfect" optical system that is perfectly collimated:

$$CFZ = focal\_ratio^2 * 2.2$$

So for a C-14 at f/11:

$$CFZ = 11^2 * 2.2 = 266$$

266 microns is 0.266 millimeters or 0.01 inches. Here's an example with an f/5 focal reducer on the C-14, making it effectively an f/5.5 system:

$$CFZ = 5.5^2 * 2.2 = 66.5$$

66.5 microns is 0.0665 millimeters or 0.0026 inches. Note that the critical focus zone of the f/5.5 scope is one quarter that of the f/11 scope. This means that if you reduce the focal ratio by half, you reduce the close focus zone (CFZ) to one quarter.

Note: real world values for the CFZ are approximately 10%-30% greater than the theoretical values above.

Automated Focusing

CCDSoft includes two methods of focusing: automatically using @Focus, and manually using the Sharpness graph on the Focus Tools tab. To use @Focus, you must have a computer-controlled focuser (e.g., Robo-Focus, Optec TCF-S), or a motorized focuser controlled by your mount (e.g., JMI NGF-S or motofocus connected to a Paramount GT-1100s, LX200, or Astro Physics GTO).

To access CCDSoft's focusing features, click on the Focus Tools tab of the Camera Control panel. Figure 2.1.9 shows the layout of the Focus Tools tab.

For a step-by-step example of using @Focus, see the Alternative Focusers section later in this chapter.

The Implications of Focal Ratio

Focal ratio describes the relationship between the aperture of a telescope and the focal length. For example a telescope with an aperture of 100mm and a focal ratio of f/8 would have a focal length of 800mm. The shorter the focal length, the wider the field of view. The longer the focal length, the greater the magnification for prime focus photography.

Telescopes of similar focal ratio have characteristics in common, even if the apertures of the two telescopes are different. For CCD imaging, a fast focal ratio allows you to take shorter exposures. Because a fast

FIGURE 2.1.9. THE FOCUS TOOLS TAB OF THE CAMERA CONTROL PANEL.
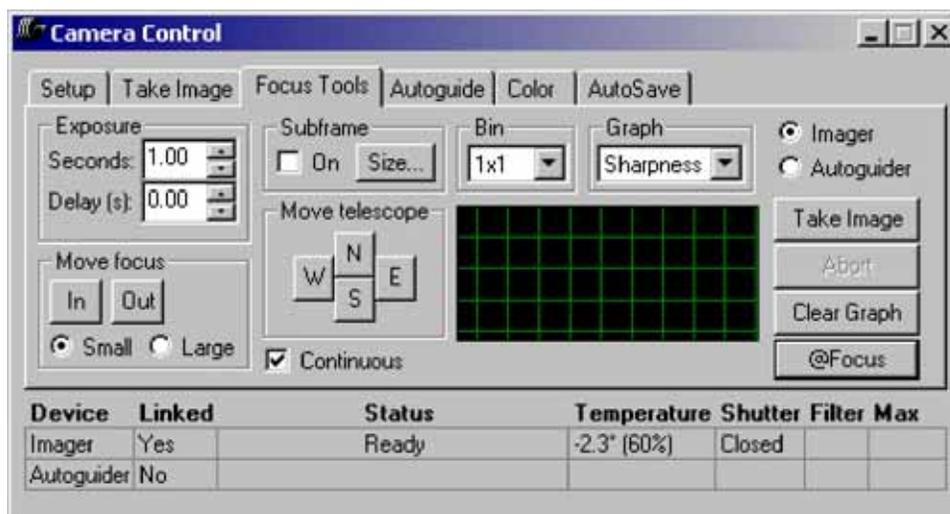
focal ratio also means a wide, diverging light cone, it will provide a wide-angle view of the sky. This allows you to image large objects, such as the moon. Or you can image multiple objects at once, or large nebulae such as the North American Nebula.

To get serious magnification with a fast focal ratio, you will need to use a scope that has a large aperture. For example, a 4" f/5 refractor equipped with an ST-8E camera will provide a field of view that is 1 x 1.5 degrees. A 16" f/5 Newtonian, on the other hand, will provide a field of view that is much smaller: 23.3 x 15.5 arcminutes.

A slow focal ratio telescope, on the other hand, will have a gently sloping light cone, and will cover a small area of sky. Small objects will fill the field of view. This is ideal for close-up images of a galaxy like M51 or a nebula like M16, the Eagle. If you want a wider field of view with a slow focal ratio, you'll need a small aperture. For example, an 8" f/10 SCT with an ST-9E has a field of view that is 17.6 x 17.8 arcminutes. A 3.5" f/10 telescope would have a field of view of 40 x 40 arcminutes with the same camera. Figure 2.1.11 shows some examples of different fields of view.

FIGURE 2.1.10. EXAMPLES OF CELESTIAL OBJECTS WITH DIFFERENT ANGULAR DIAMETERS.