Chapter 5

Stops and Pupils

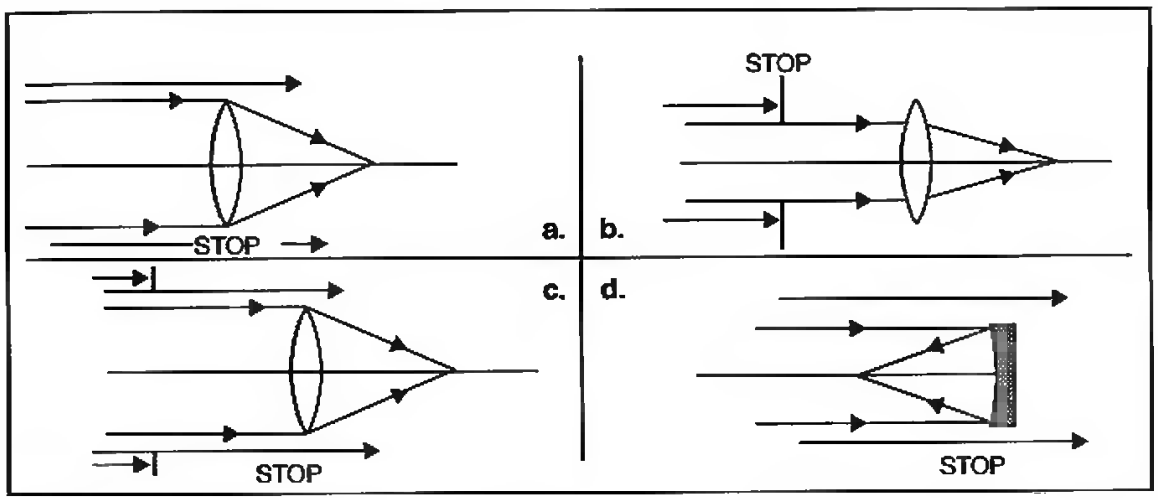

Fig. 5.1 *Examples of stops.*

5.1 Introduction

One of the most important concepts in optical design is that of the *stop* and its associated *pupils*. Most of us have used a stop (whether we knew it or not) when taking photographic pictures. Most good quality camera lenses have an internal adjustable iris by which one can control the exposure. This iris is a stop. It is not only used to change light levels at the image plane; designers use the stop's size and location to help control aberrations. You will see this application when you design a front landscape lens. The stop also defines two of the most important rays in optics: the marginal ray and the chief ray. When you do paraxial ray tracing from now on, these are the only rays that you will need to worry about. The ray heights and angles generated will be used to calculate aberrations.

5.2 Stop and Pupils

The stop is a hard physical aperture in the optical system. It is the *limiting* aperture of the system allowing some rays to pass through to the image, but blocking others. It may be defined by the diameter of an individual optic itself, or by an aperture plate (or iris) residing somewhere in the optical system. This is illustrated in Figure 5.1.

Let's look at Figure 5.1*b* again. Because of the location of the stop in front

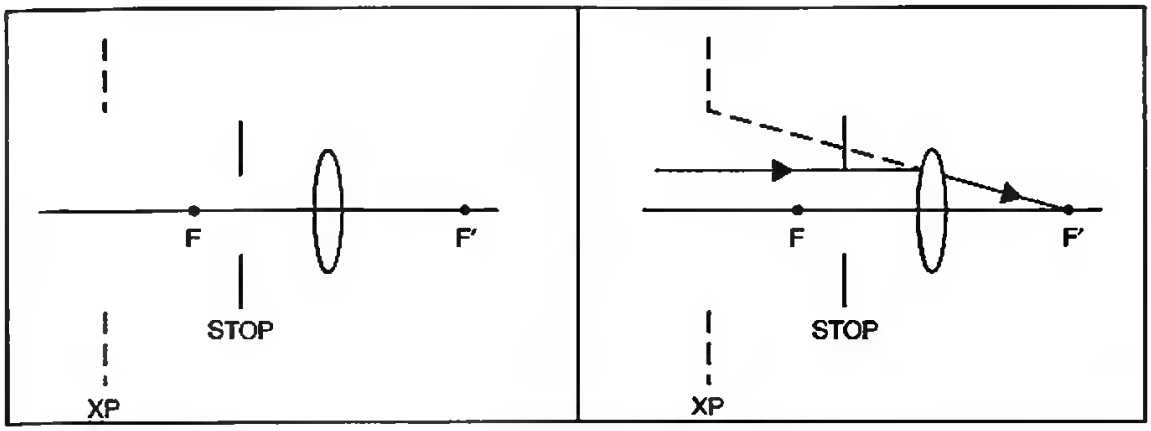

Fig. 5.2 *Image of stop—the exit pupil.*

Fig. 5.3 *In image space, rays appear to be coming from the exit pupil.*

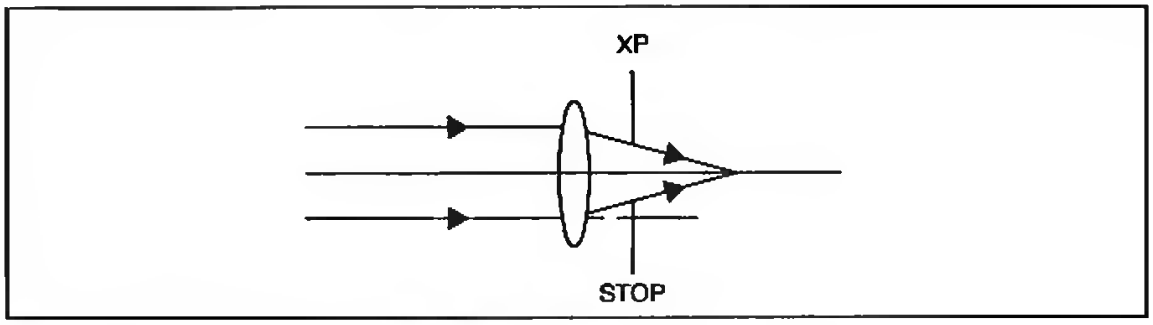

Fig. 5.4 *Stop located after lens.*

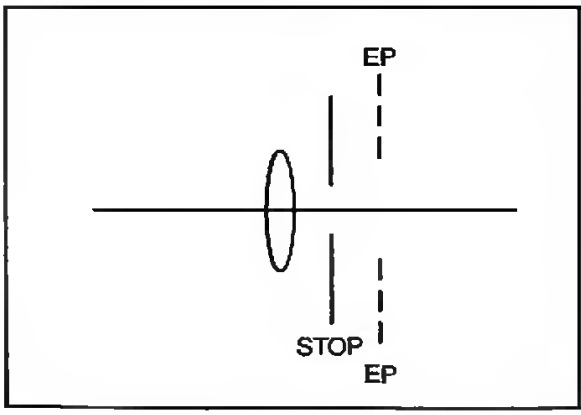

Fig. 5.5 *Image of stop—the entrance pupil.*

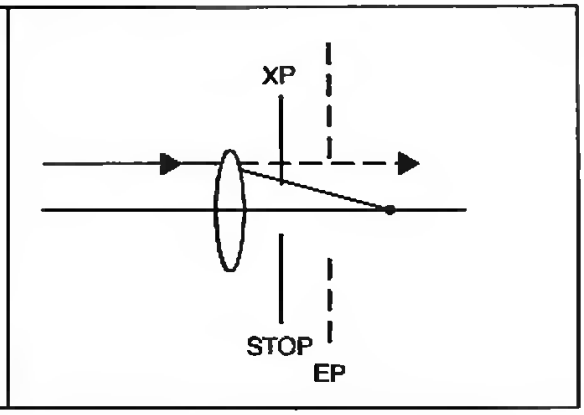

Fig. 5.6 *In object space, rays appear limited by the entrance pupil.*

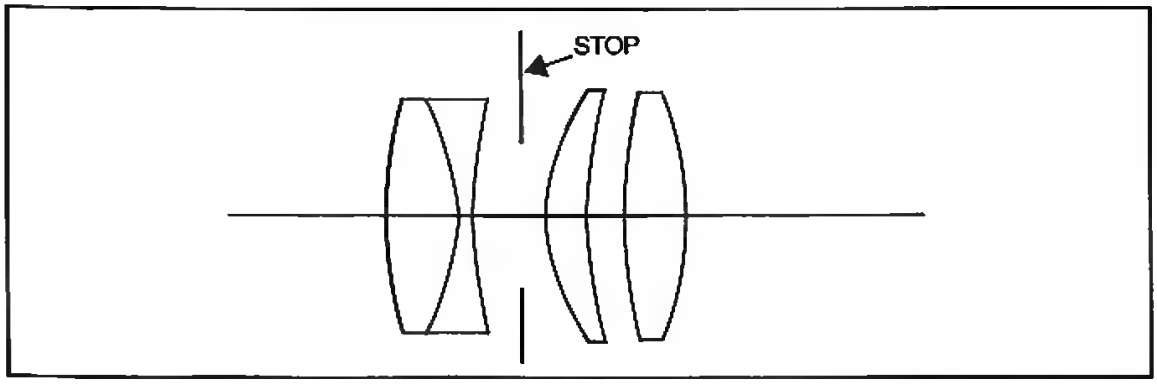

Fig. 5.7 *Buried stop. From M. Klein,* Optics *(John Wiley and Sons). Reprinted with permission of John*

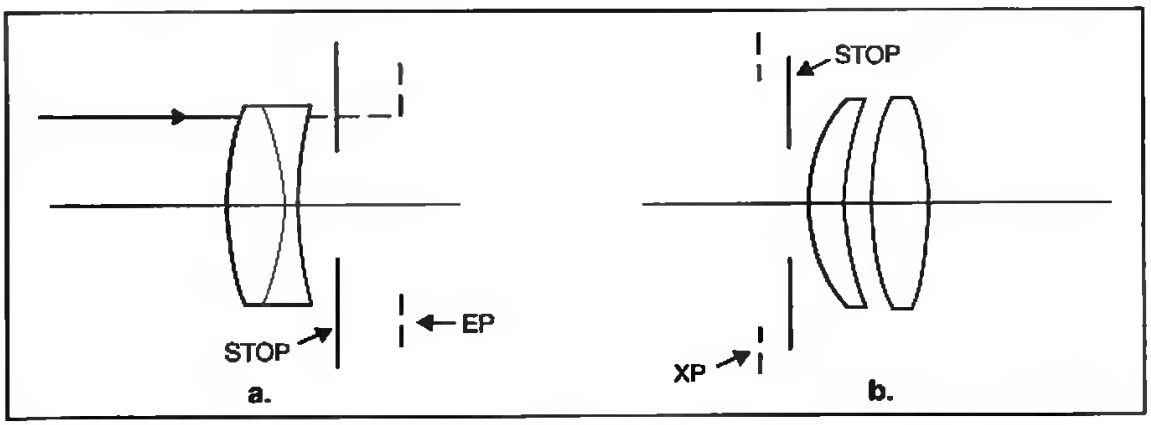

Fig. 5.8 *Images of stop:* **a.** *the entrance pupil;* **b.** *the exit pupil. From M. Klein,* Optics *(John Wiley and Sons). Reprinted with permission of John Wiley and Sons, Inc.*

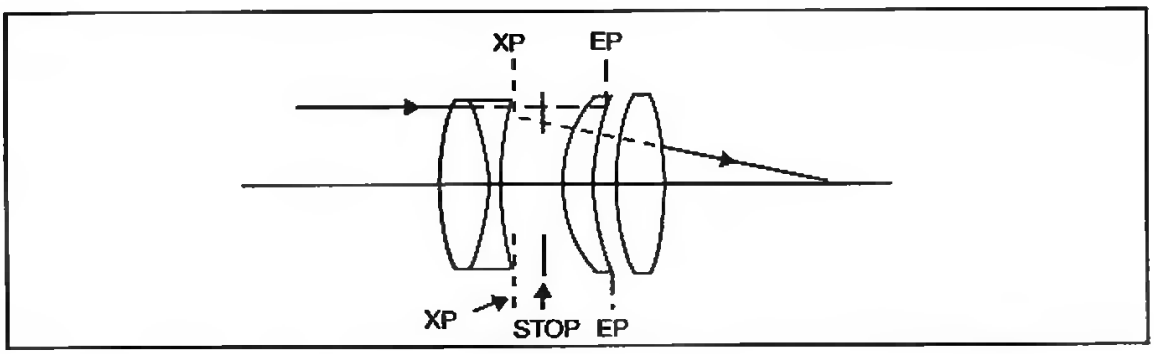

Fig. 5.9 *Real ray bundle appears limited by virtual entrance pupil. From M. Klein,* Optics *(John Wiley and Sons). Reprinted with permission of John Wiley and Sons, Inc.*

of the lens, it is also called the entrance pupil. Now consider the stop as an object to be imaged by the lens. The image of the stop (shown in Figure 5.2) is called the exit pupil. If you trace the real ray converging toward an image (due to an axial object at infinity) backward, it will track to the rim of the exit pupil, as shown in Figure 5.3.

Now consider the stop location shown in Figure 5.4. It comes *after* the lens. In this case, the stop is also the exit pupil. We can still consider the stop as an object to be imaged by the lens (just trace rays right to left this time). The stop image in this case is the entrance pupil (see Figure 5.5). Rays coming from an axial object at infinity will appear to be limited by the entrance pupil as shown in Figure 5.6.

Now consider the stop location in Figure 5.7. It is buried in the middle of the lens system. It is neither the entrance pupil nor exit pupil. However, we can still consider it as an object to be imaged. The stop image formed by all optics to the *left* of the stop is the entrance pupil, while the image of the stop formed by all optics to the *right* of the stop is the exit pupil. This is illustrated in Figure 5.8*a* and *b*.

For an axial object at infinity, the rays are aimed at the rim of the entrance pupil, while the rays appear to leave the rim of the exit pupil in image space as shown in Figure 5.9.

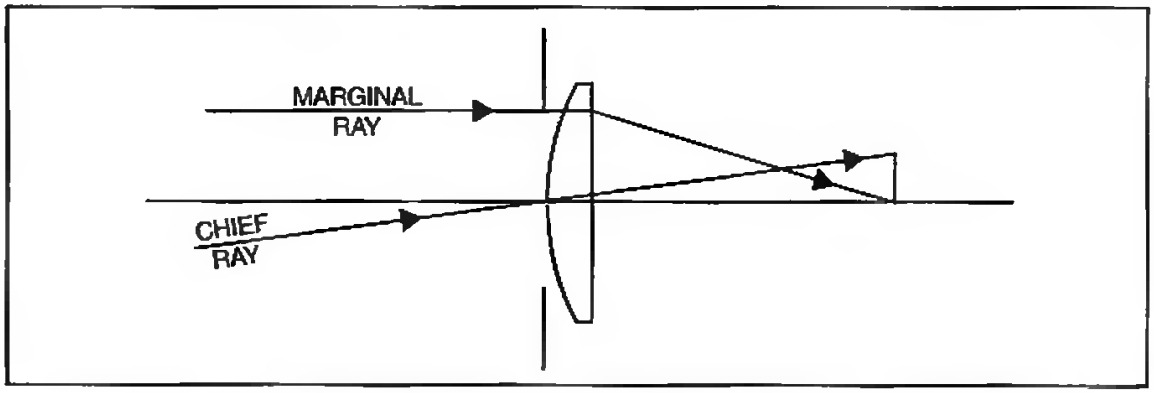

Fig. 5.10 *Simple illustration of the marginal and chief ray.*

5.3 Marginal and Chief Rays

For an axial object point, the ray that just brushes the *edge* or *rim* of the stop (and entrance pupil and exit pupil) is called the marginal ray. Now consider the off-axis point that defines the *maximum* field angle. The ray from this point that passes through the *center* of the stop is called the chief ray.[1] Figure 5.10 illustrates these two rays for a simple system.

By convention, the chief ray is inserted into the system with a positive angle (which implies that the off-axis object point is negative y). Also by convention, when the PRTE (Equations 4.1 and 4.2 on page 33) are applied to the chief ray, a bar is placed over the height and angle variables:

$$n'\bar{u}' = n\bar{u} - \bar{y}\Phi \tag{5.1}$$

$$\bar{y}_{j+1} = \bar{y}_j + \bar{u}'t \tag{5.2}$$

5.4 Locating Buried Stop Entrance and Exit Pupils Using PRTE

Suppose we are given the triplet with a buried stop shown in Figure 5.11. We want to trace the marginal and chief ray through the system. But to do that we need to aim the marginal ray at the edge of the entrance pupil and the chief ray at the center of the entrance pupil. How do we find these aim points? By finding the image of the stop due to all the optics to the left of the stop. We now go to the paraxial representation of the triplet as shown in Figure 5.12. We select two points on the stop: a point at the center and a point on the edge. From each point we launch a ray toward the optics on the left hand side. The launch angle is not critical. (It may also be easier to turn the picture around so that the rays are moving left to right as indicated in Figure 5.13.) Trace the ray from the center of the stop first. Trace it all the way through the truncated system. At the last surface, the ray will emerge at a

[1] Often the chief ray and principal ray are considered interchangeable. In this book, the chief ray will always refer to the *maximum* field angle. The principal ray, on the other hand, will refer to any field angle.

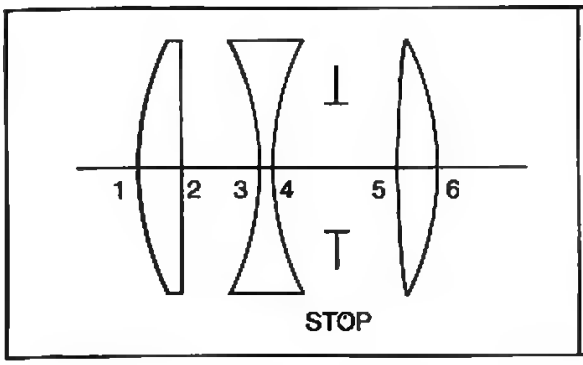

Fig. 5.11 *Triplet with buried stop.*

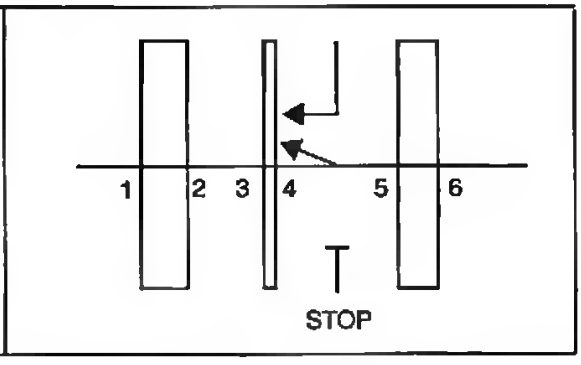

Fig. 5.12 *Paraxial triplet with stop.*

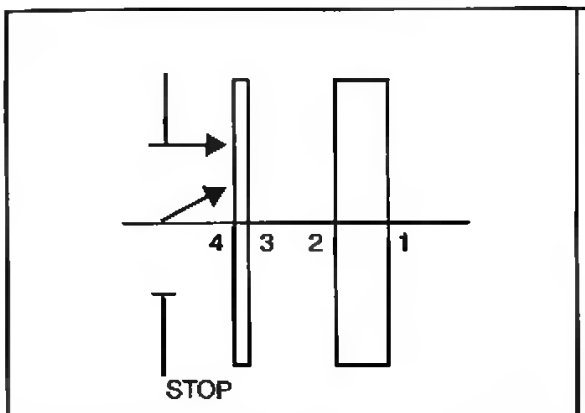

Fig. 5.13 *Front portion of triplet turned around.*

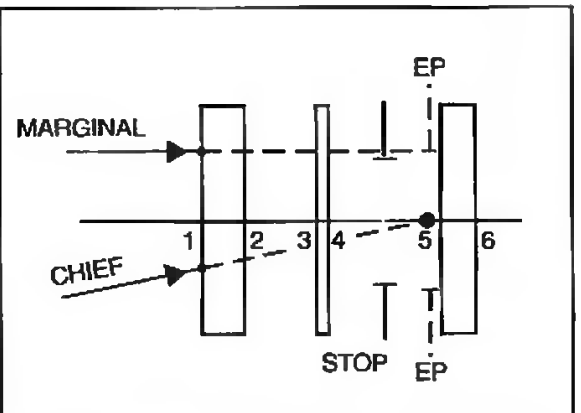

Fig. 5.14 *Triplet with aim points located.*

certain height and angle. Locate the image plane by tracing the ray to the surface where its height will be zero. (Note: This will likely be a virtual ray—or a ray that is backtracked.) This is the point where the ray crosses the optical axis. This will locate the axial position of the entrance pupil. But how big is the entrance pupil? To answer this question, trace the ray from the edge of the stop through the system to where it crosses the image plane defined by the previous ray. It will cross this plane at a certain height. This height defines the radius of the entrance pupil. So now we know the size and location of the entrance pupil. We turn the picture back around and incorporate it into the total system as shown in Figure 5.14. We now have our aim points for marginal and chief rays.

5.5 Pupil Size and F-Number

In Section 2.8.1 we saw how the f-number was related to the marginal ray angle in image space. This was done for a simple thin lens. However, that relationship is true even for complicated systems. Consider the system shown in Figure 5.15 where the stop is buried. Illustrated are the first and last paraxial surfaces, the entrance pupil, and the rear principal plane. The marginal ray is aimed at the entrance pupil. This ray emerges from the last surface at a certain height and angle.

Backtracking the image ray into the system, it crosses the projection of the