Which Eyepiece Focal Length?

A telescope alone will show an image of the skies, but the image is too small for our eyes to fully enjoy, so we make it bigger by using an eyepiece. A previous article ("Average Eyepiece Choices") also discussed an eyepiece's field of view and eye relief; this article addresses focal length and exit pupil. Choosing eyepiece focal lengths is complicated, not only because of optical physics and eyeball biology, but also because of the different objects to view and personal preferences. Moreover, there are many ways to select eyepiece focal lengths, with different individuals preferring different methods. Since there's no quick answer, let's just dive into this complexity.

The magnification provided by an eyepiece is calculated as the telescope focal length divided by eyepiece focal length. Magnification is good because bigger images of objects activate more of the retina, making it easier to see details. But as magnification increases, views of extended objects (not pinpoint stars, but nebulae, galaxies, Moon/planets, and even the background sky brightness) become dimmer because the light is more spread out. Additionally, the size of the view going into the eyeball (exit pupil) shrinks with more magnification (i.e., exit pupil = telescope aperture divided by magnification). If views using the same magnification in different telescopes are compared, the exit pupil is larger as the telescope aperture gets larger, which means that the overall view seems brighter (and this is a basis of the phrase "Aperture rules!"). Instead of specific magnification values, which vary between different telescopes, exit pupil sizes make guidelines easier to discuss and are readily applicable to different equipment setups.

Focal Length Limits

When the exit pupil is larger than the iris opening into the eyeball (typically 5 to 7 mm), then one is reducing the aperture of the telescope itself (thus stopping it down, to use a photography term). Additionally, if looking at a large object such as the Moon when the exit pupil is very large, the secondary mirror (in Newtonians, SCTs, Maks, etc.) casts a dark shadow in the middle of the view.

As the exit pupil drops to about 1 mm, the wave properties of light become more visible because stars begin to show as a dot of light (Airy disk) surrounded by a "Bull's Eye" pattern (diffraction rings), assuming that the atmosphere is stable (i.e., good seeing exists). Below ~1 mm, smaller exit pupils cause the Airy disk and diffraction rings of stars to act as extended objects, by appearing larger and dimmer when using higher magnification. If the exit pupil is very small (below about 0.6 mm), then not only is the overall image very dim, but "floaters" (small solid debris in the eyeball fluid) are usually seen drifting across views of the Moon or Jupiter, etc.

Therefore, one generally strives to keep the exit pupil of an eyepiece between a maximum of about 6 or 7 mm (depending on eyeball age and general area background lighting) and a minimum of more than about 0.5 mm (except, perhaps, when splitting/separating very close double stars, where floaters and diffraction rings don't seem to interfere very much). Another way of relating to the exit pupil concept is to determine the corresponding magnification per inch of telescope aperture (also calculated as mag/in = 25.4 / exit pupil), so that one strives for a range of about 4x/inch (low power) to about 50x/inch (high power).

Viewing Guidelines

So far, only the upper and lower bounds of choosing eyepieces have been mentioned, however one observes infrequently at these extremes – intermediate focal lengths are used most often, where the choice depends on the particular object being viewed. Even **for the same object, different magnifications bring out different details**, which is another reason to observe with more than one eyepiece, and why a range of parameters is mentioned for each class of astronomical objects.

These very general guidelines on exit pupils {or magnifications per inch} provide good hints for choosing eyepiece focal lengths:

- Open Clusters & Diffuse Nebulae = 2 to 7 mm {12.5 to 3.6x/inch}
- Globular Clusters & Galaxies = 1 to 2 mm {25 to 12.5x/inch}
- Planetary Nebulae = 0.5 to 1 mm {50 to 25x/inch}
- Double Stars = 0.3 to 1 mm {85 to 25x/inch}
- Sun (with proper filtration) = 1 to 3.6 mm {25 to 7x/inch}
- Luna = 0.5 to 3 mm {50 to 8.5x/inch}
- Planets = 0.5 to 1.7 mm {50 to 15x/inch}

Focal Length Spacing

Unless one opts for using variable focal length eyepieces (also known as zoom eyepieces), the next looming decisions are: how many different focal lengths are needed/desired, and what should be their spacing (or progression). Some of these decisions are governed by available funds (or places to put the eyepieces), some by the available focal lengths, and some by personal observing preferences. General technical approaches include spacing by magnification, or by exit pupil, or by field of view — each has its proponents and all are somewhat similar.

If spacing by magnification, one may consider a minimalist approach of only low, medium, and high power, based on eyepiece focal lengths that provide magnifications of less than 10x/inch, about 15 to 20x/inch, and about 25 to 35x/inch of aperture. Another minimalist magnification spacing approach is 1x-2x-3x, where x is 35 power for 4" telescopes, 50 for 8", 60 for 10", and 70 power for 12" telescopes. Still another magnification spacing approach uses focal length intervals of 1.4x (a difference of 40%, adjusted +/-10% in practice), because the surface brightness of extended objects varies with the square of eyepiece focal length. Some observers have simply decided to space their magnifications evenly (50x, 100x, 150x, 200x, etc.).

Mr. Al Nagler of Televue often recommended using a spacing of specific exit pupils when building an eyepiece collection: 7, 4, 2, 1, and 0.5 mm. Not too excessive in number, but enough to provide useful viewing options. Of course, these are only approximate values because the corresponding eyepiece focal lengths may not be available in the marketplace.

Especially with the current availability of wide field eyepieces, some observers have recommended an eyepiece spacing that results in views of 1.0 degree, 0.75 degree, 0.5 degree, and 0.25 degree (also known as the true field of view [TFOV], which is very roughly calculated as the eyepiece apparent field of view [AFOV] divided by magnification). Similarly, if one's collection includes eyepieces of different AFOVs, then one should also check the TFOV parameter when spacing by magnification or exit pupil.

Other Considerations

A very low power, maximum field of view (for the barrel size, 1.25 or 2 inches) eyepiece is very useful when locating objects using charts and manual star-hopping/navigation techniques.

For the "best" low power view of star clusters and diffuse nebulae against a darker sky, consider using an eyepiece providing an exit pupil of ~4 mm {about 6.3x/inch}.

For the "best" visual acuity of individual stars, consider using an eyepiece providing an exit pupil of ~1.7 to ~3.2 mm {about 15 to 8x/inch}. Some observers refer to an optimum exit pupil of exactly 2 mm, so that the eyeball's resolution matches that of the telescope, but there are far too many variables in the optical train (telescope-eyepiece-eyeball-brain) for this to be a exact value to match.

For the "best" rendition of star colors and for seeing the closest yet still "crisp" double star split that can be delivered by your telescope's aperture, consider using an eyepiece providing an exit pupil of ~1 mm {about 25x/inch}. Also, an eyepiece with an AFOV of 60-70 degrees often provides a good overall context of the double star's neighborhood when at this corresponding magnification.

When trying to split very, very close double stars, don't be afraid to use extremely high magnification. Clarity will be lacking, but the split may be visible, with practice, similar to one's ability to see vehicle headlights through heavy rain.

Large aperture/long focal length telescopes theoretically are able to produce high power views, and on some special nights they may be able to perform quite well. However, only 200-300 power is a practical upper limit based on typical atmospheric conditions. Similarly, moderate aperture telescopes may be limited to about 25x/inch, while small apertures should reach 65x/inch more frequently.

A Barlow (or telecentric) lens accessory may be placed before an eyepiece to increase the magnification. A typical change factor is 2x, meaning that if the telescope and eyepiece alone magnified by 50x, then adding the Barlow would make the net magnification 100x. Using a Barlow to attain higher magnifications will retain the decent eye relief (distance between the eyepiece and eyeball) of a low power eyepiece. Using a Barlow on a high power eyepiece may provide the extreme magnification needed to split very, very close double stars. And if a 2x Barlow were added to a pair of eyepieces with focal lengths separated by 1.4x, then the result would be four effective focal lengths, also spaced by factors of 1.4x (i.e., without duplicate focal lengths). A disadvantage of using a Barlow is the effort of inserting and removing it from the optical train of equipment, possibly with a significant adjustment of focus. It should be noted that if a Televue Paracorr (Newtonian coma corrector) is used, then that accessory also acts as a 1.15x Barlow lens.

For those with astigmatism in their observing eye(s), low magnification views may not provide a crisp focus, whereas high powers (small exit pupils) are generally better because they use only the small central (undistorted) portion of the eye lens. Buchroeder's Rule (from Dr. Richard A. Buchroeder, master optician) provides guidance as to when the astigmatism may not be noticeable while observing:

$$1 / \sqrt{(\text{diopter})} = \text{maximum mm of exit pupil}$$

(alternatively ==> $25.4 \times \sqrt{(\text{diopter})} = \text{minimum magnification/inch}$ *)*

where diopter is the astigmatism cylinder correction for eyeglasses and √ is the square root math function.
(Ref: Sky & Telescope, September 2004, page 132)

Similar information in a graph format may be found on the Televue website (ref: www.televue.com/engine/TV3b_page.asp?id=54&Tab=_Choose). For "average" astigmatism, some observers just use an exit pupil of ~1.3 mm, or about 20x/inch, as a general cutoff value.

Bottom Line

Whether pursuing a minimalist 3-eyepiece approach or obtaining a full eyepiece set/series from a particular vendor, one's astronomizing efforts should produce enjoyable views. There is no single "best" eyepiece or set of eyepieces that will work for every observer. In many situations, an eyepiece collection represents an assortment of tools that was gradually assembled to suit the individual observer. The selection process involves both technical learning and observing experience; in other words, it's a journey. Besides, managing our eyepiece collection gives us something to do on those cloudy nights!

Many Calculations

This whole topic is very complicated for me, especially when I am thinking of getting another eyepiece, with far too many numbers to calculate and review. Therefore, a few years back I made a detailed 2-page Excel spreadsheet that calculates the numerous parameters associated with different telescope and eyepiece options, using some drop-down menus, table look-ups, and common optical cautions. This complex spreadsheet requires only very basic information about the telescope (aperture, focal length, and opening size for eyepieces) and about the eyepieces themselves.

Since I use my eyepieces with more than one telescope, the spreadsheet allows me to quickly see how a particular eyepiece fits into my gear collection. A handy printout reflecting my eyepiece assortment for a telescope also satisfies any technical curiosity during observing sessions.

I have included my spreadsheet with this discussion – it could facilitate your efforts to quickly evaluate lots of numbers, but it is NOT REQUIRED to implement the concepts discussed above. I have also included a separate PDF file with a few examples of how the spreadsheet might be used for different telescopes: a small 80 mm f/6 refractor, a common 8-inch f/10 SCT, and a larger 12-inch f/5 reflector with a Paracorr and Nagler/Ethos eyepieces. Enjoy! Or not.

Source: Jim Kaminski, April 2016