Lowering the Threshold

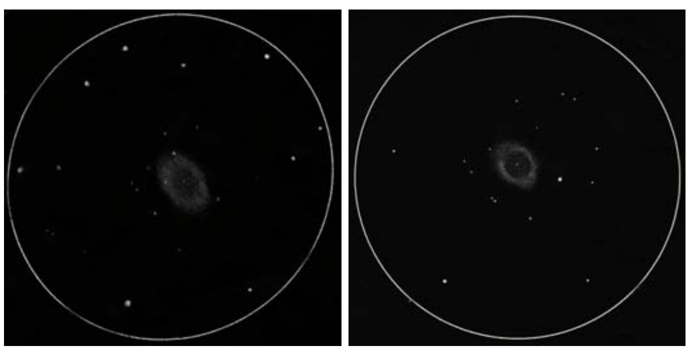
By W. D. Ferris *©2005*

Why do we see more stuff in bigger telescopes? If you think you know the answer, you may be in for a surprise. About ten years ago, I thought I had the answer. It was only after I took a serious look at the question and the pat answers offered by my fellow amateur astronomers that I realized I really didn't have a clue.

Most answers begin with, "Bigger scopes collect more light." That's true enough. The light-gathering power of an aperture depends on its surface area. Simple geometry tells us that the surface area of a circular aperture equals pi (3.1416) times the square of the radius: $\pi \bullet r^2$

If you calculate the surface areas for two apertures, one twice as large as the other, you'll find the larger aperture has four times the light-gathering power of the smaller. And this illustrates a long established relationship between aperture and light-gathering: light-gathering changes according to the square of the change in aperture. Doubling aperture quadruples light-gathering power. Halving the aperture quarters the light collected.

So, yes, bigger scopes do collect more light. But that doesn't answer the question. We still have to connect the increased light-gathering power to the fact that more stars and galaxies can be seen in the larger scope. Why is it that collecting more light translates into seeing more stuff?



M57 as seen in my 10 inch Meade Starfinder (left) and as it appears in my 18 inch Obsession (right).

From, "Bigger scopes collect more light," some amateurs would continue with, "and that makes objects brighter." OK, let's consider that. First, we need to distinguish between point sources and extended objects. Point sources are stars and anything else having brightness but not dimension. Extended objects have brightness *and* dimension. Examples include galaxies, nebulae…any celestial object having measurable size.

Let's begin with stars. Does increasing aperture make stars brighter? One way of approaching this issue is to compare an observer's naked eye limiting magnitude to his limiting magnitude with a telescope. Here's a simplified formula for predicting telescopic limiting magnitude: $NELM+2.5 \bullet \log_{10}(T^2/E^2)$[1], where NELM is the naked eye limiting magnitude, T is the telescope aperture (mm) and E is the eye pupil diameter.

The naked eye limit at the dark sky sites I use is about 7.5 magnitude. And with my 10

[1] Equation 4.1, "Visual Astronomy of the Deep Sky," Roger Clark, Cambridge University Press, 1990

inch Newtonian, I've gone as faint as 15.7 magnitude. If we assume an eye pupil size of 7.5 mm, the above formula predicts that I should be able to see 15.3 magnitude stars with my 10 inch (254 mm) telescope.

Not only is that a reasonable match with my real world experience, it illustrates the role a telescope plays in allowing us to see more stars. Because stars are point sources, all that additional light the telescope collects is focused into a point. Increasing aperture makes stars look brighter. My 10 inch, for instance, makes a 15th magnitude ember appear as bright as a 7th magnitude star appears to the naked eye.

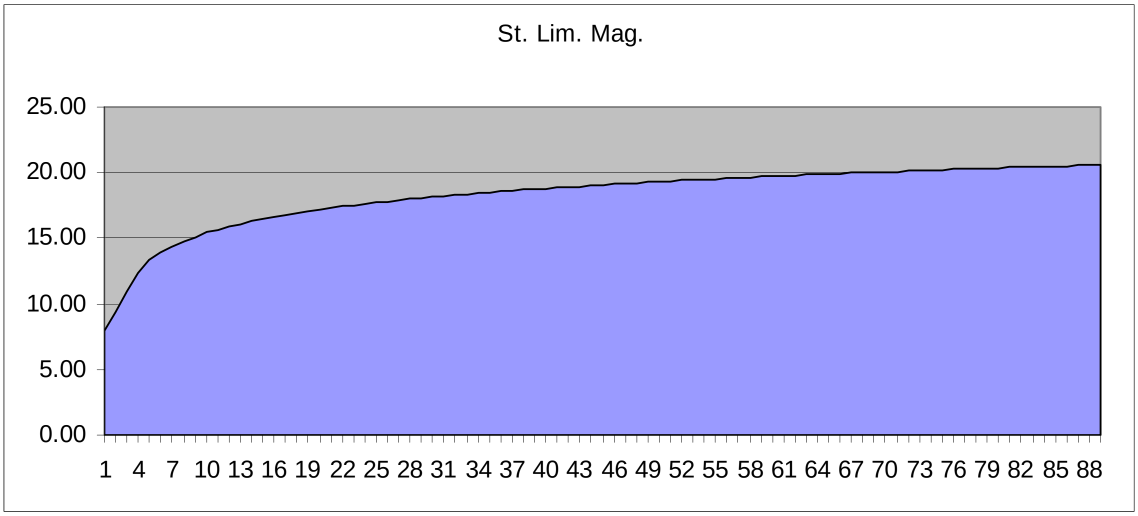


Figure 1: Plot of telescopic limiting magnitudes for apertures from naked eye to 88 inches. Based on equation 4.1 from Clark.

OK, increasing aperture does make point sources brighter. Making stars brighter makes them easier to see and you know the rest of the story.

What about galaxies and other deep-sky objects? Well, because these objects are extended, they have a property called surface brightness. This is an object's brightness per unit area, and it's often expressed in magnitudes per square arc second. A lot of novice observers—and this was me about 15 years ago—think that galaxies are easier to see because more aperture translates to a higher surface brightness. Fair enough; let's check that assumption.

We'll use M33, a galaxy in Triangulum, to explore this question. M33 is a 5.7 magnitude face-on spiral with dimensions of 71' by 42'.[2] Here's a simplified formula for calculating surface brightness: $Mag+2.5 \cdot \log_{10}((A \cdot B) \cdot 2827)$, where Mag is the object's visual magnitude, A is its large dimension in arc minutes, B is the small dimension and 2827 is a conversion factor from square arc minutes to square arc seconds.[3]

[2] M33 data from NASA/IPAC Extragalactic Database: http://nedwww.ipac.caltech.edu/

[3] The formula for the surface area of an ellipse is $\pi/4 \cdot a \cdot b$, or $.7854 \cdot a \cdot b$. $3600 \cdot .7854=2827.44$, which converts the surface area from units of square arc minutes to square arc seconds.

Applying this formula to M33, we get a surface brightness of 23.0 magnitudes per square arc second. That's the brightness per unit area of this galaxy to the naked eye. What's its surface brightness when seen through a telescope?

Well, before going too much farther, we need to talk about the fact that any time you increase aperture you also increase the *minimum useable magnification*. This is the lowest magnification at which you're using the full aperture of the telescope. At any lower magnification, the aperture is effectively reduced. Why?

The diameter of the light cone leaving the eyepiece is called an *exit pupil*. If that light cone is larger than your eye pupil, some of the light collected by the telescope will be lost. It won't make it into your eye. The vignetting produced by an overly large exit pupil effectively reduces the telescope's aperture.

Exit pupil can be calculated by dividing the telescope's aperture by its magnification. The magnification producing an exit pupil equal in size to your eye pupil is the lowest magnification you can use with the telescope's full aperture.

OK, back to M33. Since a telescope magnifies, this galaxy appears larger at the eyepiece. As a result, the telescope spreads all that additional light over a larger surface area. This is true for any extended object. And due to this increase in apparent size, we have to calculate a *surface brightness reduction* for the object. Here's that formula: $5 \bullet \log_{10}(\text{Mag}/\text{Ap} \bullet 3.387)$[4], where Mag is the magnification, Ap is the aperture (inches) and 3.387 is a conversion factor based on eye pupil size and the telescope transmission.[5]

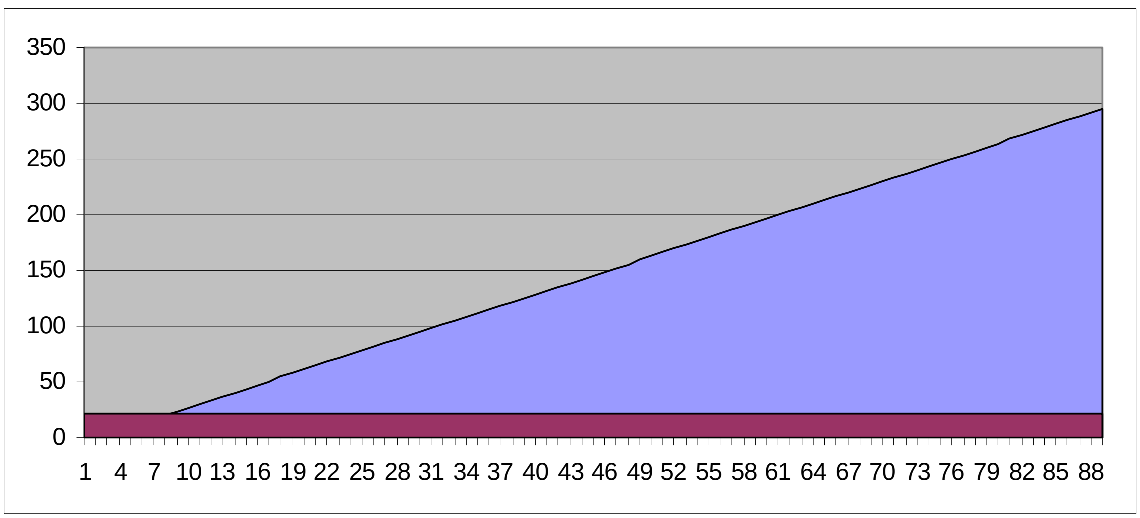


Figure 2: Plot of object surface brightness (purple zone) versus minimum useable magnification for a range of apertures from naked eye to 88 inches. Based on equation 4.3 from Clark.

If we use my 10 inch reflector for this exercise and assume a 7.5 mm eye pupil, the minimum useable magnification will be 33.87X.[6] So the surface brightness reduction for M33 will be $5 \bullet \log_{10}(33.87/10 \bullet 3.387)$ or 0.0 magnitude. In other words, M33's surface brightness stays

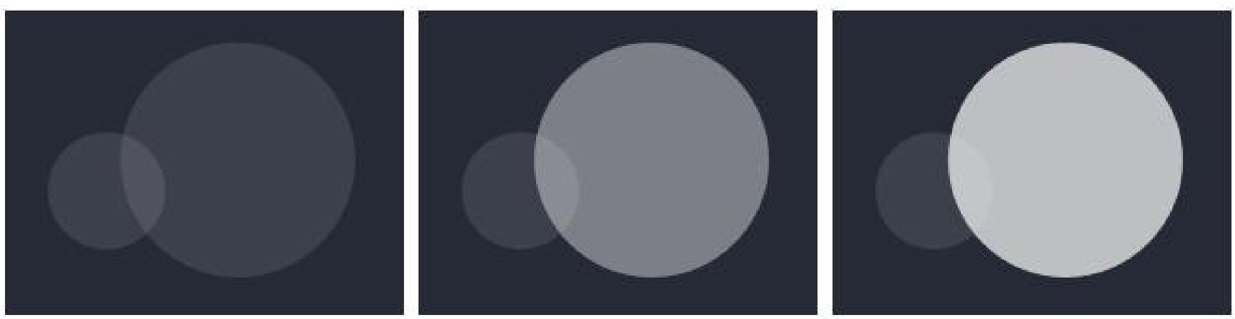
[4] Based on equation 4.3, "Visual Astronomy of the Deep Sky," Roger Clark, Cambridge University Press, 1990
[5] Clark's equation 4.3 uses 2.833, which is based on a 70% transmission for the optical system.
[6] 33.866X rounded up

the same, even when viewed through a telescope that collects far more light than your eye.

But that's in a perfect world where every photon collected by the telescope is delivered to the eye. In reality, no telescope has perfect 100% transmission. Every aperture loses some light due to the imperfections inherent in mirror coatings and glass. So, not only will M33's surface brightness not increase when observed through a telescope, the cold hard reality is that its surface brightness will—at best—be slightly reduced. All extended objects have their greatest apparent surface brightness to the naked eye. When you apply a larger aperture, surface brightness is reduced.

All right, if increased surface brightness isn't the answer, certainly improved contrast must be. As many deep-sky hounds come to appreciate, seeing faint extended objects is principally an exercise in detecting subtle changes in brightness; seeing a faint patch of light against a dark sky background. This is known as contrast detection and contrast is determined by the ratio of object brightness to sky brightness. Something many amateurs don't know, is that a galaxy's surface brightness and the sky's surface brightness are additive. The contrast between the two is determined by adding object surface brightness and sky surface brightness, then comparing that to sky surface brightness, alone.

Since we see the galaxy by looking *through* Earth's atmosphere, the sky and object overlap; the result being that their surface brightnesses combine to produce the final apparent surface brightness of the galaxy. This explains why it's possible to see a galaxy having a lower surface brightness than the sky. Since sky and object surface brightness are additive, the galaxy *always* appears at least a skosh brighter than the surrounding sky. The darker and more transparent your sky is, the greater the contrast.



Figures 3-5: These illustrate the additive nature of object and sky surface brightness. The rectangular background is "space." The smaller circle represents an extended deep sky object. The larger circle represents the sky through which the object is observed. Where the object and sky overlap, their brightnesses are additive and this determines the contrast of the object against the sky. As sky surface brightness increases—from left-to-right—contrast is reduced and the object becomes harder to detect.

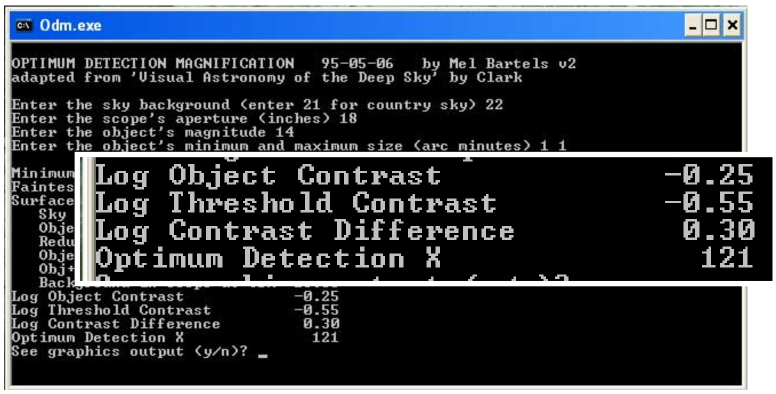
So, does contrast improve as aperture increases? Unfortunately, the answer is no.

The sky is an extended object. As such, it responds to magnification and aperture exactly as M33 or any other extended object would. Whatever combination of aperture and magnification you use, sky surface brightness and object surface brightness will be altered to the same degree. So that ratio of brightnesses that determines contrast remains unchanged. In all apertures at all magnifications, contrast remains constant.

By the time I'd gotten this far in my quest to understand why aperture allows us to see more and fainter galaxies, I was ready to throw up my hands and yield to a higher authority, "I give up! Galaxies aren't any brighter. Contrast is the same. Still, I can see more stuff in my 10 inch than I can in my 60 mm. I'll just accept it and move on."

Then, I found ODM, a great little freeware application created by Mel Bartels.[7] Bartels wrote ODM to explore the concepts developed by Roger Clark in his seminal work, *Visual Astronomy of the Deep Sky*. Ostensibly, ODM calculates the optimum magnification for seeing galaxies and other extended objects. All you do, is input values for sky surface brightness, object brightness and object size, and ODM does the rest.

One of the factors ODM calculates is the *threshold contrast* for a given combination of sky brightness, aperture and magnification. Threshold contrast, it turns out, is the key to understanding why we see more stuff in bigger telescopes.

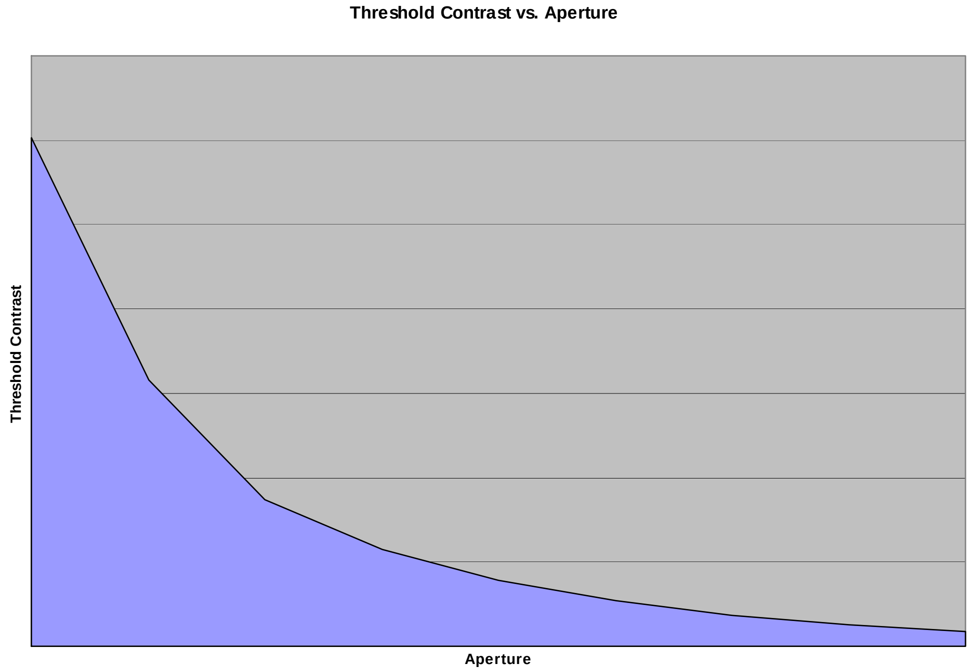


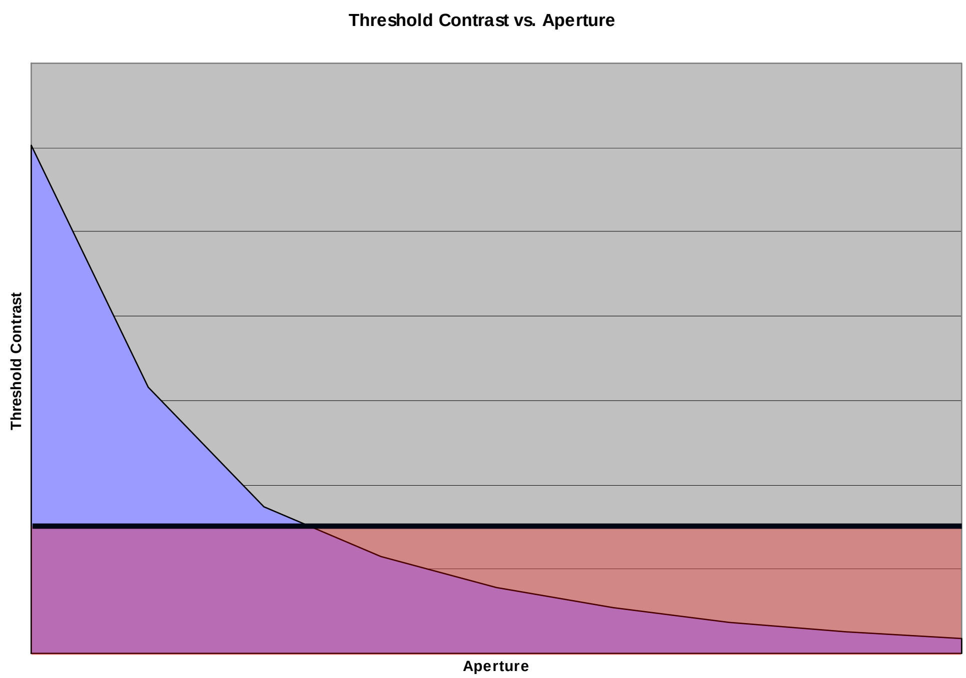
A screen shot of an ODM display with the inset image zoomed in on readouts for Log Object Contrast, Log Threshold Contrast, Log Contrast Difference and the ODM.

Think of threshold contrast as the point at which an object emerges from the surrounding sky. And here's the kicker; threshold contrast changes with aperture. It is reduced as aperture increases and visa versa.

On the following page, the top illustration plots ODM's calculation of the log threshold contrast for a range of apertures from the naked eye to 88 inches. It's assumed the telescopes are at the same location under a pristine sky. The bottom illustration adds an overlay representing some hypothetical object's contrast in those same apertures. Notice that contrast remains constant for all apertures under the same sky conditions. But also notice that the gap between object contrast and threshold contrast gets larger as aperture increases.

[7] ODM can be downloaded here: http://www.bbastrodesigns.com/dnld/odm.zip



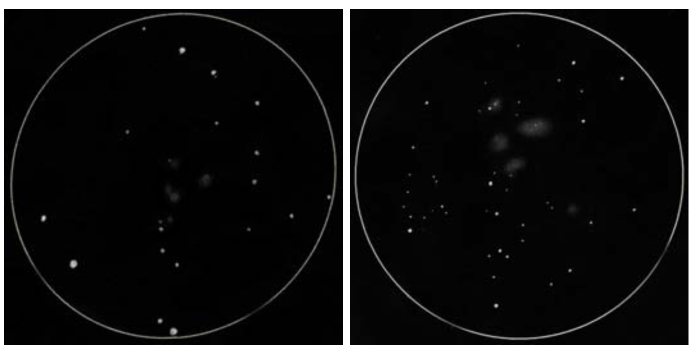


Figures 6-7: Figure 6 (above) plots ODM's predicted *Log Threshold Contrast* for a range of apertures. Figure 7 (below) presents the same plot with some hypothetical "fixed contrast" overlain. This illustrates the impact increasing aperture has of effectively raising objects above the threshold of visibility, despite absolute contrast remaining fixed.

When we increase aperture, the net effect is a lowering of the threshold at which objects become visible. This threshold reduction can be viewed in another way: increasing aperture effectively raises objects like M33 higher above the threshold of visibility. The galaxy becomes easier to detect. Details like spiral arms that fall below the threshold of visibility in smaller apertures, eventually fall at or above this threshold as aperture increases. Finally, lowering threshold contrast brings within reach fainter galaxies that were below the threshold of visibility in smaller scopes.

Threshold contrast is the key to solving the riddle, "Why do we see more stuff in bigger scopes?" The real beauty of this concept, is it explains why observing with large aperture creates the impression that object surface brightness has increased and contrast has improved. Intellectually, we know contrast remains fixed and object surface brightness can't improve from the naked eye view. But as threshold contrast lowers, we *perceive* objects as brighter and contrast as improved.

Admittedly, I don't know *why* threshold contrast is reduced in larger apertures. I suspect this has something to do with the larger light packet delivered to the eye. Perhaps, this moves the eye's performance closer to that of daytime vision. But that's just a hunch. I'm still exploring that question…but not even close to throwing up my hands in despair over the lack—for the moment—of an answer.



Stephan's Quintet as observed with 10 and 18 inch Newtonians. The sketch on the left was made with my 10 inch Meade Starfinder. The sketch on the right presents the view of this galaxy cluster as it appears in my 18 inch Obsession. Notice NGC 7320C, the faint galaxy to the lower-right of the Quintet, in the observation made with the big Dob.