Seeking the (very) elusive

Keith Venables FRAS

ABSTRACT

The various factors affecting our ability to see astronomical targets at the very limit of our telescope and visual capabilities are explored. Helped by an informal survey of around 100 amateur visual astronomers, the key factors are identified. To frame the impact of the factors, the performance of the telescope is modelled using the analysis presented by Crumey (2014) and the model validated against some specific recent observations. Using the validated model, the impact that various factors have on the visibility of low contrast targets are considered. It is shown perhaps unsurprisingly that the aperture and magnification dominate equipment factors, but the model allows the impact to be quantified in practical terms. For the observer it is dark adaptation that is most important, and some evidence is presented in how to maximise this in practice. The vision of the specific observer is also critical, and the model indicates ways the individual's vision can be quantified and included in subsequent projections of performance at the telescope eyepiece. The need to use averted vision to exploit dark adaptation is considered, and the requirements this places on initial location of the target position.

1. INTRODUCTION

1.1 Background

The author usually doesn't follow any specific long-term observing program, concentrating instead on what advances can be made through equipment enhancements. More recently it was clear that the observer was now perhaps too often the 'weakest link'. This led to a new program of research, trials and modelling.

This paper presents the results of this program with the overall conclusion that adoption of better observing regime can produce up to a 1.8 improvement in minimum observable magnitudes.

1.2 The Survey

An informal survey of around 100 visual observers was undertaken. They were asked to rank various aspects of the visual observing process in importance. These aspects had been selected from a breakdown of the factors which is described in figure 1.

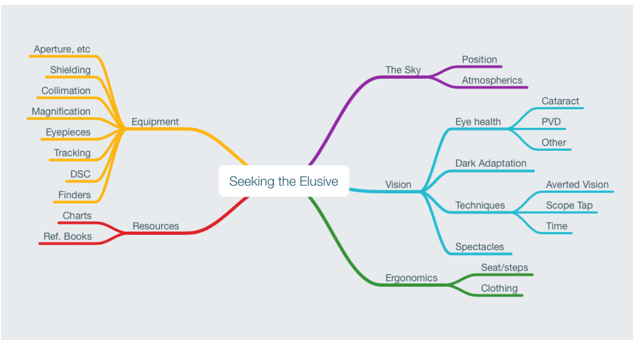

Figure1. Key factors affecting visual observations.

The responses are presented in figure 2 as 'reward' versus 'difficulty'. This is a form of the BCG Matrix that is widely used to determine business improvement decisions. The factors near the top of the chart are clearly thought to give most benefit and should be adopted, although towards the right they become increasingly difficult to achieve. For instance, dealing with atmospherics requires observing from a mountain top!

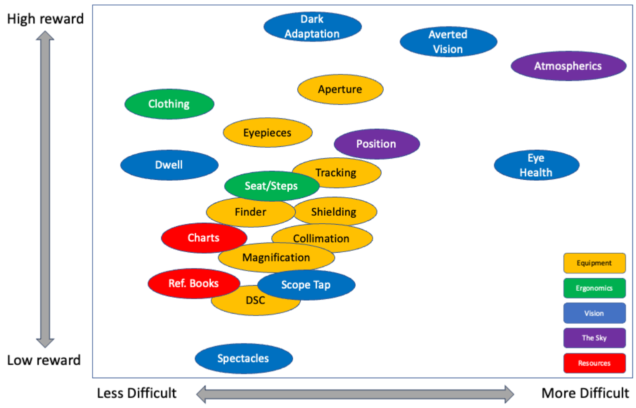

Figure 2. Survey results on modified BCG Matrix chart.

Factors near the bottom of the chart produce small benefits and hence could be ignored or dealt with later. But some have impact on the higher reward factors. An example being the use of charts and reference books, which although in themselves are considered of low reward, if done poorly could seriously impair dark adaptation, which is of very high importance.

Plotting the factors along the path of a photon on its way from a distant object to the retina and visual perception, highlights that loss of performance by any one factor, cannot be recovered by improving others. Once a photon is lost, it is lost. The impact from most factors is cumulative. Figure 3 depicts this path.

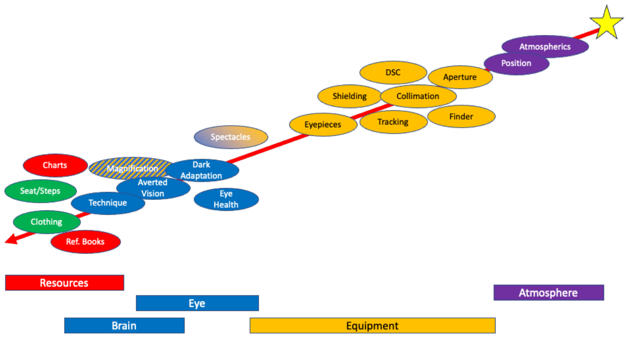

Figure 3. Path of a photon through the factors.

1.3 Key Factors

Five top factors influencing observing performance were derived. These are based on the survey results, the author's observing experience and reviews of contributions to the internet hosted observing sub-forums on CloudyNights and StarGazersLounge.

These are,

- Achieving maximum Dark Adaptation
- Observing Technique, including averted vision
- Magnification & exit pupil
- Eye condition and health
- Use of finders and charts

Apart from the eye, these factors are considered in the rest of this paper. The eye is excluded as the observer should consult with an ophthalmologist, although section 4.2 covers how an individual's visual threshold can be assessed.

First the subject of human visual threshold detection is considered as it is fundamental to understanding the interrelationship between many of the factors.

2 Threshold Detection

2.1 Introduction to contrast threshold detection

The principles of observer contrast threshold detection have been well covered. A popular book is by Clark (1990), and although out of print is commonly referenced. More recently Crumey (2014) has comprehensively reviewed the principal works bringing much better thoroughness and accuracy. His new models form the basis for the threshold calculations in this paper.

For visual astronomers the factors can be conveniently grouped into three areas: the contrast of the target against the background sky, the modification by the telescope, and finally the performance of the eye and brain.

Usually, approximations will be necessary due to the non-uniformity of targets in both surface brightness and shape. Crumey (2014) also considered the varying colour temperatures of the sky, stars and extended sources. Often, data on the colour temperature of the target and background will be lacking and so further approximations will be necessary. Overall, considering the difference between average colour temperature for ngc's versus typical stars, we might expect an error of up to 0.2 mag in some model outputs.

The impact of the telescope is usually much easier to model, although in practice factors such as transmission for a particular instrument may not be known.

The performance of the individual observer is by far the most complex to model and quantify. Some factors such as eye pupil diameter can be established and some factors are well established, such as Ricco's Area (1877). Ricco's Area is the minimum size whereby an extended object can be differentiated from a point source. The introduction of a field factor **F** is used to cover the various human vision effects, so that although the details may not be known or understood, their overall impact is quantifiable.

2.2 Introduction to the models

Crumey (2014) extensively reviews previous models. Many are built upon others, and some weaknesses have propagated. Crumey then proceeds to build a new model based on the empirical relationship between contrast threshold and adaptation luminance. He demonstrates that his model for both point sources and extended targets work on all reliable historical datasets, in particular that by Blackwell(1946). The detail within the models is significant and could not be done justice here. It is recommended that if desired, reference is made directly to Crumey (2014).

The models essentially cover the two cases of point sources, and area sources. The models includes a number of parameters derived empirically from previous work and data. Input variables are: sky background brightness at the target area, target size and surface brightness, telescope aperture, magnification and transmission, observer NELM and eye pupil diameter.

3. The Threshold Model

3.1 Validation of the model

In his 2014 paper, Crumey showed how his models aligned well with previous observations.

The models are quite complex and after writing a Python implementation of it, the author first ensured that the results shown by Crumey were reproduceable. The next stage was to apply the models to some observations recorded fairly recently by the author.

Point-source model validation

In September 2022 the author undertook measurements of the faintest star visible in his telescope, while attempting to improve his dark adaptation. The environment was the Kelling Heath astrocamp. Whilst the sky was quite dark, it was possible to move around without a torch indicating a significant amount of ambient light. Results were,

15 mag initially after an hour of observing and taking no special action.
16.8 mag immediately after 1 hour pre-adaptation in total darkness
This degraded to 16.1 mag which was then maintained by using red goggles.

The telescope was an 18" (457mm) f4.5 Dobsonian and an applied magnification of x515. Additional variables as input to the model were: Telescope transmission = 70%, sky background 21.6 mpsas (Unihedron SQM-L meter), eye pupil 6.5mm. Cinzano (2005) showed the meter to be a good tool for sky photometric measurements, although care needs to be taken to exclude bright stars and planets.

Figure 4 shows the models output of minimum detectable telescopic magnitude m0 as a function of NELM. We can see what the model requires for NELM to achieve the measured telescopic minimum magnitudes.

For the final measurement of 16.1 with 'protected dark adaptation', the author's estimate of NELM was 6.3. The model predicts 6.2, very close and the difference could well be due to the measured telescopic value of 16.1 being driven by the available sequence of field stars in the eyepiece, (Schaefer 1990). Probably a 16.2 not being available in the field. These results and the impact of dark adaptation will be discussed further in section 3.1.

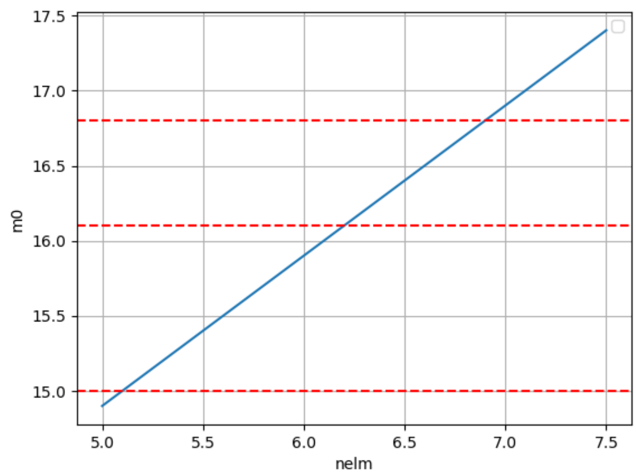

Figure 4. Magnitude limit as a NELM, calculated from equation (68) Crumey 2014. Aperture = 457mm, ρ=6.5mm, µsky = 21.6. the three horizontal red lines correspond to the measured telescopic minimum magnitude detectable with varying degrees of dark adaptation.

Area-source model validation

In October 2022 the author and 3 others observed the planetary nebula BV 5-3. This can be a challenging object with a visual magnitude of 15, surface brightness 21.2 and a diameter of 24arcsec. Again, using the 18" the author was able to just see BV 5-3 at x254. With the same telescope and magnification, two of the other observers could just see it only when told exactly where it was in the field, the fourth observer could not see it all. Thus the observation is a useful tool for validation as it is close to the observed threshold of detection. Additionally, BV 5-3 has relatively uniform surface brightness across its whole area.

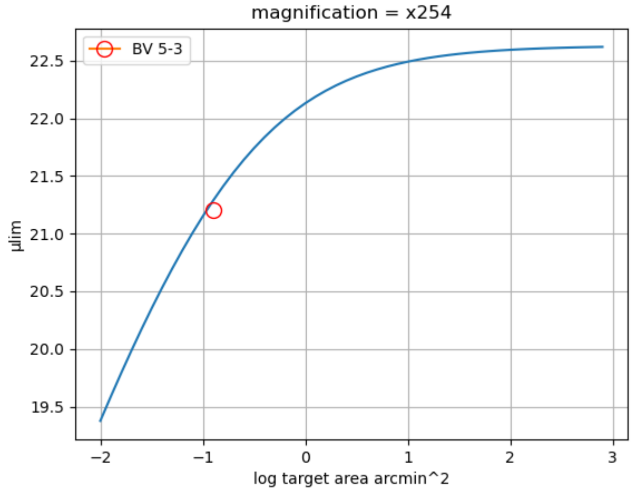

Figure 5. Detection threshold μ lim as a function of object size. Aperture = 18", μ sky = 21.5 mpsas, NELM = 6.2. BV5-3 plotted for comparison.

The model results for the observation are shown in figure 5. The position of BV 5-3 is shown on the plot, from which it can be seen that it is indeed right on the threshold given the conditions and equipment. A very good match with the actual observations.

Based on these observations (stellar and PN) it is considered that the model provides a fairly accurate description of threshold detection in a practical observing session.

3.2 More insights from the models

Unless otherwise specified, the parameters for the following analyses were: Aperture 18", eye pupil 6.5mm, NELM 6.1, background sky brightness 21.5 mpsas, magnification x300. Where appropriate BV 5-3 is plotted to aid interpretation.

This section is quite wide ranging, but it serves to help the relationships between the key factors.

Point-sources

Figure 6 shows how the minimum magnitude detectable varies with sky brightness, for various telescope magnifications. For the authors 18" we can see that for every improvement of 1 magnitude in sky background brightness, the minimum detectable stellar magnitude falls by about 0.4 mag. This confirms the generally held figure.

An obvious feature is the minimum magnitude of 16 regardless of magnification and sky. Crumey (2014) describes this as m_cut, occurring when the magnified background is effectively zero to the observer.

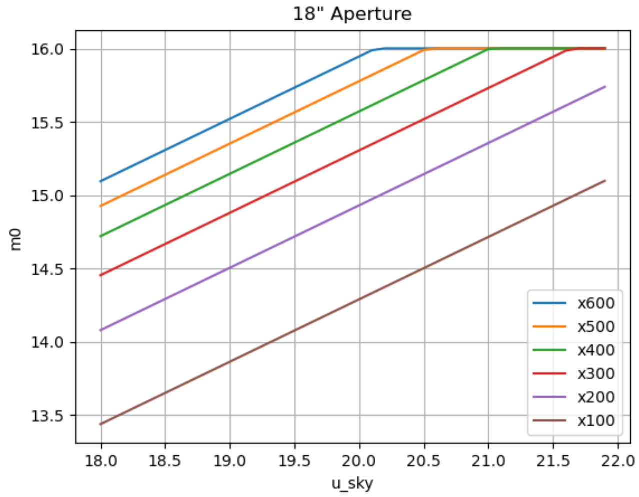

Figure 6. Minimum point source detectable magnitude m0 as a function of background brightness μ sky mpsas, and telescope magnification.

An alternative view is shown in figure 7, whereby the minimum point source magnitude is shown as a function of magnification, for various telescope apertures. We can again see the cut-off kicking in. With this information we can now see that the x525 magnification used for the field tests, was excessive and beyond x300 no fainter stars would have been seen. It is possible that beyond cut-off point, excessive magnification will lead to a poorer threshold due to the star being 'nebulous'. Exploring this is left as a future project. The steep change in slope at low magnifications is due to the telescope exit pupil becoming larger than the eye pupil.

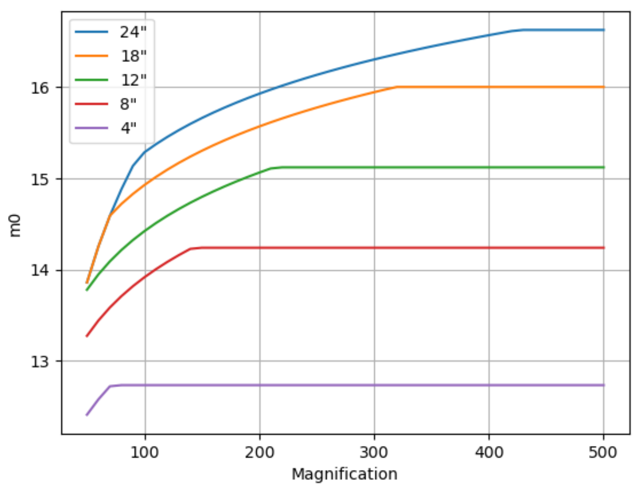

Figure 7. Minimum point source detectable magnitude m0 as a function of magnification, for a number of common telescope apertures. Sky brightness = 21.5 mpsas.

Area Sources

For any particular instrument and observer, perhaps the most interesting model output is shown in figure 8. This plots the threshold magnitude for seeing a target of a given surface area. As expected, larger targets can be seen at a fainter surface brightness. When we consider the effect of telescope magnification we see that for the relatively small object BV 5-3 (24" in diameter), a minimum magnification of about x200 is required. The reverse is true for objects larger than 34" in diameter, where reducing magnification may be necessary.

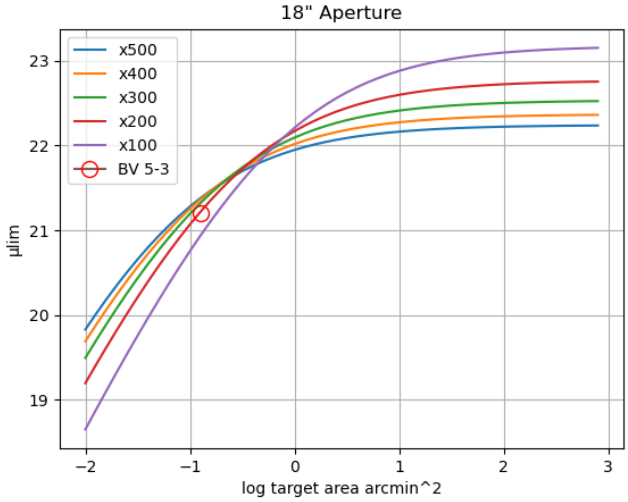

Figure 8. Thresholds for detection of non-point sources, as a function of target size, and telescope magnification.

This raises the issue of the optimum detection magnification for any given object. Clark (1990) places emphasis on deriving this number (ODM), but it is also derived for other conditions by Lewis (1913) and Garstang (1999). Figure 9 describes the new model's results as the threshold for detection as a function of magnification, for various object sizes (log10 area arcmin^2). The model predicts that for large area objects there is an optimum magnification, illustrated by the top 4 lines in the figure. But that this optimum increases rapidly as target size falls and for targets smaller than about the size of BV 5-3 (24" diameter) the optimum magnification becomes larger than is practical given telescope performance and sky seeing conditions.

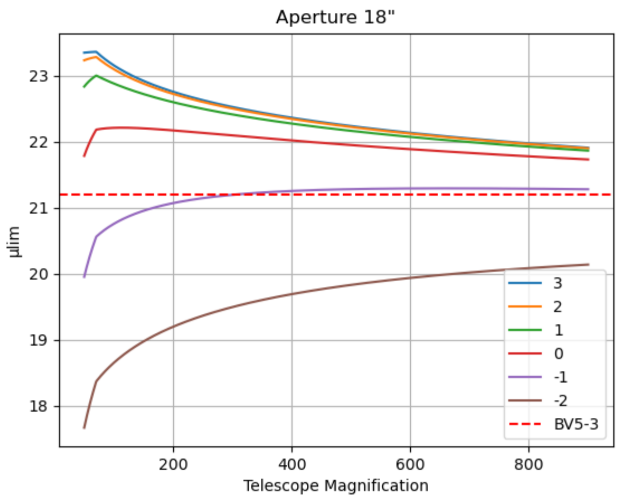

Figure 9. Threshold for detection as a function of telescope magnification, for a range of object sizes, log target area arcmin^2. Sky background = 21.5 mpsas.

Clark presents his analysis with respect to apparent background sky brightness, which in a telescope is itself a function of magnification. Interpretation of his results is not as obvious as with the new model, but he lists ODM for many of the NGC objects. Comparison with the new model suggests Clark's values are in broad agreement for objects around log area arcmin^2 greater than 1, but significantly lower as object size decreases. This matches the author's personal experience in finding benefit with higher magnifications.

Before we leave the influence of target area, let us look at the impact of the background sky. Figure 10 shows the threshold as a function of target area, plotted for four sky background brightness levels. Again BV 5-3 is plotted and we can immediately see the sky quality needed to observe the object. The observer may try increasing magnification to overcome such conditions, but figure 11 shows that only a small gain can be won. The graph implies that the successful observation of BV 5-3 under 21.5 skies could be repeated down to about a 21.3 sky by doubling the magnification. For skies worse than that the target is lost.

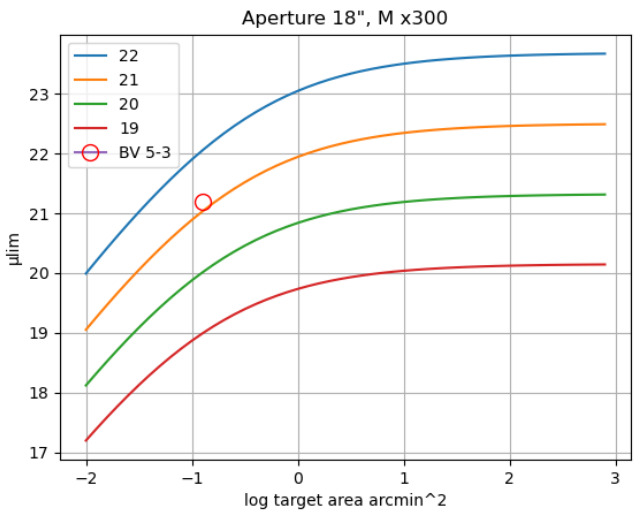

Figure 10. Threshold for detection as a function of target size, for a range of background sky brightness, mpsas.

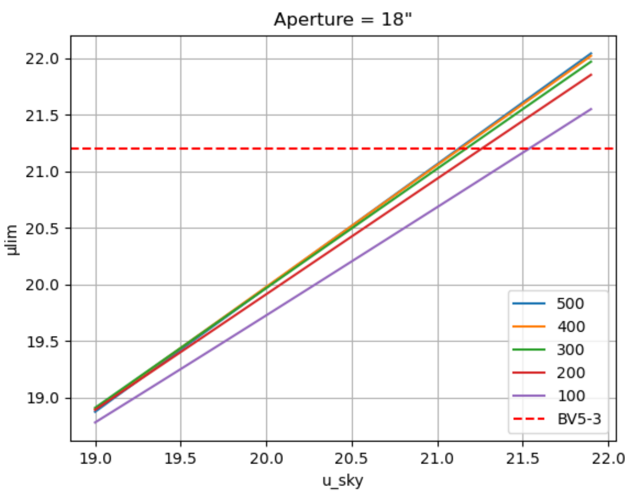

Figure 11. Threshold for detection as a function of background sky brightness [mpsas], for a range of magnifications.

The author's field work to measure the effect of dark adaption on minimum stellar magnitude, points us to considering the threshold for area sources as a function of NELM too. Figure 12 confirms the linear relationship between NELM (ref figure 1), minimum telescopic stellar magnitude, and minimum telescopic area source threshold.

Finally for completeness, figure 13 shows the threshold for detection as a function of NELM, for a range of telescope apertures. The four individuals in the BV 5-3 observation would be expected to have varying NELM, and the impact is shown. Given the telescope (18", transmission 70%) and 21.5 sky we can see that a minimum NELM of around 6 is required to have seen the planetary nebula. Factors affecting and individual's NELM are considered in section 4.2.

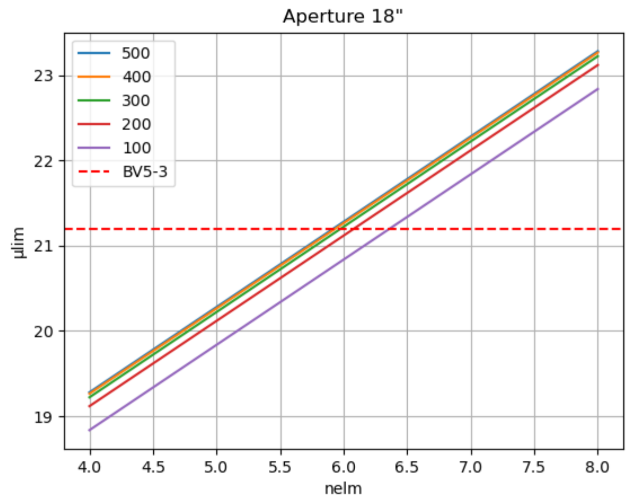

Figure 12. Threshold for detection as a function of NELM, for a range of magnifications.

One of the key findings from the using the model, is the impact of NELM and magnification as being the only variables available to an observer, without purchasing a larger aperture telescope or moving to a better observing site.

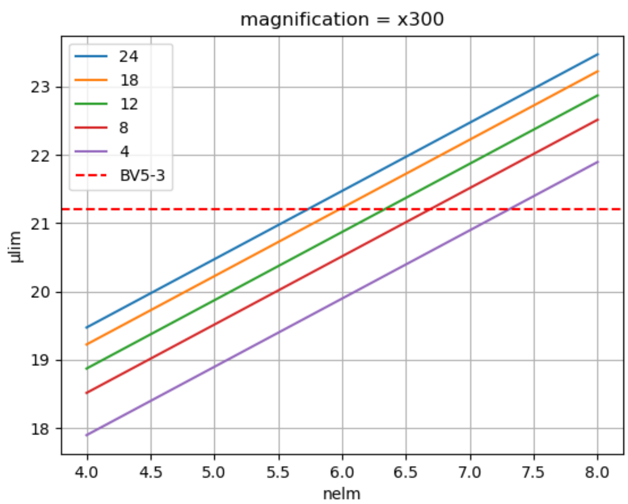

Figure 13. Threshold for detection as a function of NELM, for a range of apertures.

An observer's NELM is a characteristic of the human vision system and determined by a number of factors, with dark adaptation perhaps being the most variable. The next section considers some of these visual factors.

4. Maximising personal vision

4.1 Dark Adaptation

The observer's level of dark adaptation is one of the most fundamental factors in seeing challenging objects. It is certainly one that the observer has some degree of control over.

During the field trials briefly outlined in section 3.1, the author achieved three levels of dark adaptation. In each case the level achieved was measured by examining a high magnification field in his 18" telescope and recording the minimum brightness star visible.

The first measurement was made after about one hour of typical observing. The site, at Kelling Heath astrocamp was not particularly dark although the sky SQM was 21.6 within 20 degrees of the zenith. It was possible to walk around without a torch and the author had made occasional trips into his caravan, which had red LED lighting and a dim computer screen. The minimum star brightness detectable was mag 15.0.

One hour was then spent in the caravan, in complete darkness. The observation was then repeated, using a hood to completely block views other than in the eyepiece. The new minimum stellar magnitude was 16.8.

The hood was then removed but red goggles worn for the rest of the session. The minimum stellar magnitude was seen to plateau out at 16.1.

From figure 4 we can see that these telescopic minimum magnitudes, translate to NELM as follows, 15 = 5.1, 16.1 = 6.2 and 16.8 = 6.9, for the given parameters.

Thus, the author was able to improve his measured NELM by up to 1.8 mag. This figure was achieved with possibly extreme measures, but the 1.1 mag improvement using red goggles was readily attained and maintained. The action of putting the goggles on and experiencing a new much darker environment, underwrites just how well lit the observing site was with stray white light. The goggles are the type sold for builders to better see their laser levels in daylight and cost around £12.

The impact of red and white light on dark adaptation is often debated. Deep dark adaptation uses the rods in the retina. The rods lose their dark adaptation when exposed to light, although this effect is minimal if the wavelength is longer than 630nm. The problem with red is that it is inefficient, for both routine tasks and in particular reading charts etc. This leads to observers, or others around them, using very bright red lighting, or resorting to dim white light. It is also to be noted that the author has yet to find a red LED torch with a wavelength longer than 620nm.

To assess the impact of such lighting on dark adaptation, the author organised some field trials at the Texas Star Party in 2007, (Venables 2007). Around 10 volunteers used a lightbox to view a fairly detailed chart. The chart could be illuminated with white or red (620nm) light, of varying degrees of brightness. Unsurprisingly, everyone preferred the white light for reading, achieving good legibility even when very dim. The volunteers looked into the box for periods of about 10 seconds, and then assessed how long it took for their dark adaptation to return. The site was dark with an author's NELM estimate of 6.8.

After looking at the very dim white illuminated chart for 10 seconds, full recovery generally took only about 30 seconds. If the chart was observed for much longer, then recovery time quickly extended into many minutes.

The dim red light had almost no recovery time, and a brighter red light still only required about 15-20 seconds to recover full dark adaptation.

The Kelling Heath trial shows the 'floor' of dark adaptation being influenced by the general ambient level of mostly white light. Figure 14 describes the classic dark adaptation curve with time, for three final achieved levels, or 'floors', This light can come from the sky or local environment. This floor is hard won and needs care to maintain it. The Texas results show that the effect on dark adaptation of short-term use of dim white or red light can be managed. However, is a shared environment this management requires much more consideration and cooperation.

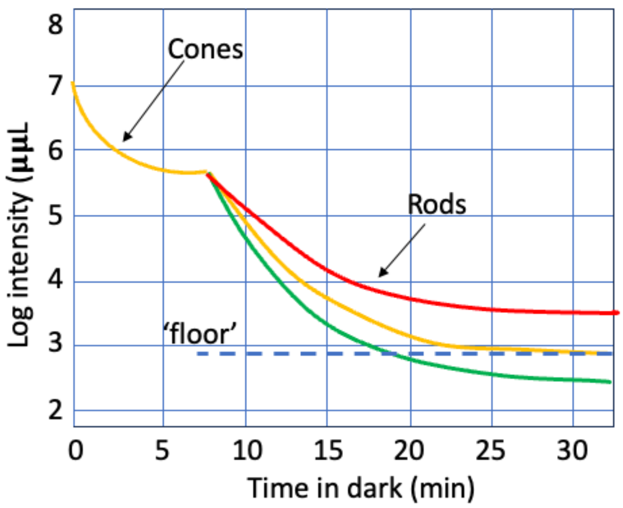

Figure 14. Dark Adaptation over time for three final levels or 'floors',

4.2 NELM and Observer variability

Crumey (2014) covers a number of field factors (Taylor 1964) to describe telescope and observer influences on the threshold. Three of these he is able to attribute empirical but fixed values to, but the fourth **F** concerns the observer's vision. Observer variability is obvious, even if the causes cannot be defined. Eye health, age, observer dark adaptation, skill and experience are probably the main contributors. Stephen O'Meera is known for his low visual threshold and the author was able to observe next to him in Texas and experienced a 1.5 mag difference in NELM.

Crumey presents a convenient approximation that relates an observer's NELM to their personal **F**.
For dark sites, 20 < μ sky < 22 mpsas,
m0 (NELM) = 0.4260 μ sky – 2.365 – 2.5log10**F**
This factor is key as Crumey reviews previous work and derives **F** for the observers. He notes a typical spread of 2.4 to 1.4 for **F**, equivalent to an NELM range of 6 - 6.6.

Blackwell and Blackwell (1971) undertook a study of visual performance against observer age. Their results show a very significant reduction in contrast sensitivity with age. The contrast reduction factor varies greatly between individuals, but compared with the mean average of 20 year olds, at age 65 an observer's contrast multiplier can range from 2.66 (50 % mean) to 6.92 (95^{th} percentile).

4.3 Averted Vision and finding the target.

Averted Vision

The model of threshold for detection is almost entirely concerned with scotopic vision, using the rods in the retina.

When fully dark adapted, the rods provide up to 4 magnitude improvement in sensitivity compared to the cones. Within the area of rods on the retina, there can also be a large factor in sensitivity. This variation has not been well established, and in itself varies between individuals, Sidgwick(1971).

The author has broadly 'mapped' the area of maximum sensitivity across his retina. This was accomplished again using BV5-3, which being on the threshold of detection provided a useful tool. The object was centred in the eyepiece field (100° AFOV). The eye's centre was then directed to dwell at various points in the field, thus placing the object in the corresponding opposite position on the retina. An area was found that was significantly more sensitive than the rest of the retina. BV 5-3 could be seen steadily only if placed in this 'zone', otherwise it could be either just glimpsed or not seen at all. Figure 15 describes approximately the size and position. The distance of the zone from the centre was estimated to be around 15°.

Applying averted vision is not easy but can be mastered for most with practice. The visual observer is strongly encouraged to discover their own optimum zone.

Finding the Object

Having located our zone of maximum sensitivity, the target object must be placed in that zone for the best result. Indeed, the target may not even be detected if not well placed in the eye's field of view.

Searching a field of view for a threshold object requires scanning the whole view, only using the optimum averted vision zone, with a dwell period at each stage. The optimum length needed for the dwell isn't clear, ranging from 1 second (Bishop & Lane, 2004) to 6 seconds (Clarke, 1990).

Figure 15. Location of the author's area of maximum rod sensitivity within the overall distribution of rods. Right eye in object space.

A practical demonstration of this difficulty is the previously described group observation of BV5-3, whereby 2 observers initially failed to see it, despite being told it was definitely visible. When told exactly where it was, they immediately could see it. This phenomenon is often seen when observing with a 'buddy'. After an object is found by one observer and position and appearance described, the second observer usually rapidly acquires the object.

The author was a frequent participant in the Advanced Observers Programme at the Texas Star Party. Each year a list of very challenging objects was attempted, most requiring a bespoke printed finder chart. Experience showed that after each examination of the chart, trying to memorise the orientation of field stars, some minutes were required to re-acquire field stars and attempt the observation. Trying a higher magnification usually led to disorientation with further time required to get back on course. Some objects would take an hour to find.

Some amateur visual astronomers find the 'hunt' the most interesting part, happy to then move on fairly soon. For others, minimising the time to hunt and improve success rate, allows more time 'on target' making observations.

Applications like SkySafari can assist greatly with the flexibility to match image scale and orientation, and the range of magnitudes being displayed. However very few tablets or computers will go dim enough to preserve dark adaptation, and most 'leak' light. Screen filters can help but often are a compromise. A device with an OLED or AMOLED technology screen can overcome most of these disadvantages as they have no backlight. However, be aware that the red is still around 620nm or less and prolonged exposure will degrade dark adaptation.

The author has recently finished the development of a digital finder system, eFinder (2023), Venables (2023), which can place the eyepiece centre within about 15 arcsec of any required RA & Dec. The telescope position is measured by image plate-solving and hence any mount or encoder errors are eliminated. Such systems have long been used by astrophotographers, who need to place objects on small camera sensors. Celestron are the first to offer this technology for visual observers, which has proved very popular. The author's system is available for diy build.

5. Conclusions

This paper presented three key tools in the visual astronomers' quest to see the most elusive objects.

First, validation of the Crumey threshold model in both quantifying the observer's visual performance, and reviewing candidate objects before planning and attempting an observation.

Secondly, a demonstration of how an observer's dark adaptation can be extended by relatively large amounts. Even adoption of the simple expedient of wearing red goggles during the session can produce more than a magnitude improvement in NELM and telescopic detection threshold.

Finally, exploiting acquired dark adaptation through the use of averted vision, is greatly benefitted by placing the eye's most sensitive zone over the object. Use of finder charts whilst protecting dark adaptation is problematic. The more recent emergence of digital finders for visual observers can provide great benefits.

Through a combination of the above, the author is now regularly observing and enjoying objects up to two magnitudes fainter than previously attempted.

My thanks to Andrew Crumey for reviewing this article and suggesting some valued changes.

References

Bishop R., Lane D., (2004) J. R. Astron. Soc. Can., 98, 78
Blackwell, O. M., Blackwell H. R. (1971) Visual Performance Data for 156 Normal Observers of Various Ages. J. IES. Oct 1971
Blackwell, H. R. (1946). Contrast Thresholds of the Human Eye. *J. Opt Soc Amer.* ***36*** *624-643*
Cinzano P., 2005, ISTIL Int. Rep. 9, Night Sky Photometry with Sky Quality Meter. ISTIL, Thiene
Clark, R. N. (1990). Visual Astronomy of the Deep Sky. *Cambridge University Press*
Crumey, A (2014). Human contrast threshold and astronomical visibility. *MNRAS 442, 2600-2619*
eFinder (2023) https://www.astrokeith.com/equipment/efinder/
Garstang R. H., 1999, J. R. Astron. Soc. Can., 93, 80
Lewis T., 1913, The Observatory, 36, 423
Schaefer B. E., 1990, PASP, 102, 212
Sidgwick, J. B. (1971). Amateur Astronomer's Handbook. *Faber & Faber*
Taylor J. H., 1964, Appl. Opt., 3, 562
Venables, K. (2007). Preserving Dark Adaptation. *Texas Star Party*
Venables, K. (2022). Update: Electronic Finder for a Dobsonian. *Astronomy Technology Today,* ***15*** *iss4, 63-68*

www.cloudynights .com Deep Sky Observing Forum
www.stargazerslounge.com Observing – Deep Sky Forum