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How can we tell if light pollution is getting better or worse?

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For more than a century, each time the standard outdoor lighting technology has changed, visible band astronomy has become more challenging due to increased skyglow (light pollution). The world is once again in the midst of a complete change in lighting technology, from gas discharge lamps (mainly High Pressure Sodium, HPS) to LEDs. It is therefore incumbent on astronomers to ask: is light pollution continuing to get worse, or is the flexibility of LED lighting finally leading to improvement? The question is simple to ask, but surprisingly tricky to answer. In this letter, I will demonstrate the difficulty of answering this question with instrumental observations, and show that the best results will actually come from amateur estimations of limiting magnitude.

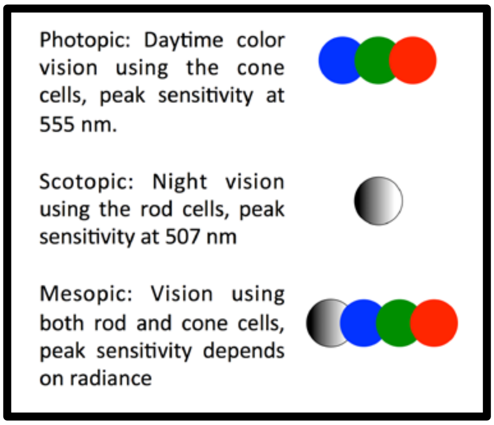
Before getting into details, it is important to address the scope of this discussion. While light pollution is a critical factor for professional observatories, there is already widespread public agreement about the importance of minimizing light pollution in adjacent areas. For example, municipalities near observatories often already follow best practice lighting guidelines (e.g. "full cutoff" lighting that does not emit any light above the horizontal, and narrow band sources such as low pressure sodium or amber LED lamps). Unfortunately, away from observatories, these guidelines are still mostly not followed. As a result, an estimated 36% of the World's population could not see the Milky Way from their home in 2014, including 60% of Europeans and 78% of the US population (Falchi et al 2016a). Furthermore, short distance travel is usually not sufficient to reach a really dark sky. The land area of 49% of the EU and 23% of the USA experience skies at least 50% brighter than natural at the zenith, and skyglow is generally considerably brighter near the horizon. The focus of this letter is therefore on public access to starry skies worldwide, and how this is changing with the transition to LED lights.

One thing is certain: the night sky is going to change dramatically in the coming decade, due to changes in the spectrum, direction, and total flux of lamps. Light from so-called "white" LEDs has a broad spectrum, rather than narrow emission lines. Most LEDs currently used in outdoor lighting are rich in blue light, with a peak around 450-480 nm. Since Rayleigh scattering probability increases at shorter wavelengths, the greater the blue component, the more light will be returned to Earth as skyglow on clear nights (Kolláth et al. 2016). This clear astronomical downside of white LEDs will be offset to some extent by the fact that many LEDs used in street lighting use a full cutoff design, whereas most legacy streetlights do not (Kinzey et al. 2017). The most pernicious effect of white LEDs may however turn out to be their high luminous efficiency. This effectively makes light cheaper, which could lead to increased light use rather than energy or monetary savings. This is called a "rebound effect" in energy economics, and has been observed in historical lighting trends (Tsao et al. 2010) and more recently via satellite observations (Kyba et al. 2017).

Lighting change, however, isn't just driven by technology. Individual activists and organizations such as the International Dark-Sky Association (IDA) aim to reduce skyglow through improved awareness, design, and lighting ordinances. Taking a broad view, the light pollution activist community has had some tremendous successes since Riegel (1973) sounded the alarm over vapor discharge lamps. Full cutoff design for street and area lighting is increasingly frequently used, and variations of the old activist slogan "the right lamp shining in the right place at the right time" are now actually used in lighting industry advertising (Philips 2017). An advertisement by Cree (2017) even emphasized the importance of proper design, by showing an angry resident sawing down a glaring lamp. While this represents a victory of sorts, the uncomfortable fact remains that urban skies are perhaps an order of magnitude brighter than they were in 1973. Will better design lead to a reemergence of the Milky Way over the suburbs?

Consider the case of a large city such as Chicago undergoing a complete streetlighting transition to LEDs. The city is using a full cutoff design, and warm white (3000 K) LEDs that satisfy the current recommendations of the IDA and the American Medical Association (Rogers 2017). How could we test the extent to which the skyglow over Chicago gets worse or better?

At first glance, the solution seems obvious: go outside with a radiometer before and after the transition, and measure the change in skyglow. Many amateur astronomers own relatively low-cost "Sky Quality Meters" that are specifically designed for this purpose, so where is the problem? They say the devil is in the details, and in this case the detail is the spectral shift. Sanchez de Miguel et al. (2017) have used synthetic photometry to examine the change in the night sky that would be observed by a viewer 3 km outside of a large city. A transition from 5% uplight HPS lamps to 0% uplight 3000 k LED that preserved photopic luminance on the street would lead to more than a doubling of scotopic (night vision) band radiance (see Box 1). However, the radiance observed in the SQM band would in fact decrease by 6%, leading to a completely incorrect conclusion. Kolláth et al. (2016) provide a real-world demonstration of band-dependent changes in skyglow. Using color photographs of a small city's skyglow near the horizon, they showed that while radiance in the camera's red band decreased greatly after a transition to zero-uplight LEDs, radiance in the blue band decreased only slightly.



Photopic: Daytime color vision using the cone cells, peak sensitivity at 555 nm.

Scotopic: Night vision using the rod cells, peak sensitivity at 507 nm

Mesopic: Vision using both rod and cone cells, peak sensitivity depends on radiance

Box 1: Spectral bands for human vision

Complicating matters further, humans do not use scotopic vision to view the sky near a big city light Chicago. Instead, we use "mesopic" vision, a transition zone between the photopic and scotopic bands. The mesopic spectral response is dependent on radiance, so the "appropriate" radiometric band for human vision depends not only on where you make the observation, but in some cases may not even be the same in the before and after condition, due to the change in radiance. If the problem still doesn't seem hopeless, consider the additional fact that ambient light affects dark adaptation and pupil dilation. Any amateur astronomer worth her salt knows that these have a strong spectral dependence, and therefore carries a red flashlight.

If quantitative observations with radiometers can't tell us if skyglow is getting worse or better, what can be done? The solution is simple: ask people how many stars they can see. At first glance, this proposal might sound even more problematic than using a radiometer. After all, observer experience can affect limiting magnitude determination by up to a full magnitude (Schaefer 1990). But while individual observations are indeed highly uncertain, when a great number of observations are available, the uncertainty on the mean is greatly reduced. When naked eye limiting magnitude (NELM) estimates from the Globe at Night project are binned according to the Falchi et al. (2016a) global skyglow model, the mean observed NELM is strongly correlated with the skyglow luminance prediction (Figure 1). Despite this result, we cannot count on using models to track how skyglow is changing in the near future for two reasons. First, global skyglow models are based on a satellite radiometer that is completely blind to blue light, with a spectral response from 500-900 nm (Miller et al. 2013). Second, most LED streetlight transitions eliminate the direct emissions slightly above the horizon that are most likely to produce skyglow, and this change cannot be directly observed by satellite.

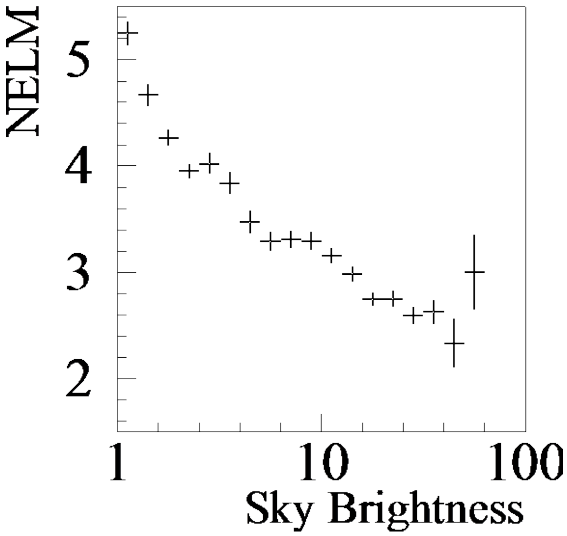


Figure 1: Comparison of naked eye observations in 2015 from Globe at Night to sky brightness predictions from Falchi et al. (2016b). Data processed using the methods reported in Kyba et al. (2013). Zenith sky brightness is relative to an assumed natural sky of 0.236 cd/m^2. Data points are mean value in each bin of predicted sky brightness, and error bars show the standard deviation of the mean.

There are several projects to crowdsource estimations of NELM; I will present two of them. The Globe at Night project (www.globeatnight.org) started in 2006, and has produced the largest dataset to date. Globe at Night asks participants to evaluate which of a series of 8 star charts best matches the sky where they are observing, in integer steps of NELM from 0 to 7. The integer steps limit the possible precision, and therefore the data are best suited for examining global or regional changes, rather than changes at an individual site.

The Loss of the Night app was designed to complement Globe at Night, by allowing dedicated participants to make more precise NELM observations. The app directs participants to a sequence of individual stars, and asks them to report whether they are visible (directly or with averted vision), not visible, or if the participant is either unsure or cannot observe in that direction. The accuracy of the observation can be evaluated by checking whether the decisions are self-consistent. Experienced participants can make precise observations (within about 0.1 magnitudes) in a period of 5-20 minutes (Figure 2). This precision will allow them to observe changes in NELM at their observing location, but it should be noted that most participants do not tend to make such precise measurements.

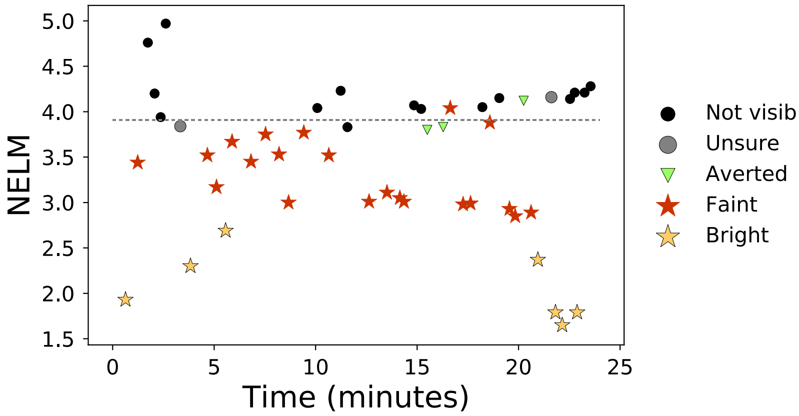


Figure 2: Estimation of the naked eye limiting magnitude using the Loss of the Night app by a project participant from Portugal. The grey line shows the fit limiting magnitude of 3.91.

The main limitation of tracking skyglow change with these projects is the relatively low level of participation. For example, in the last three years, only a handful of cloud-free observations have been submitted from Manhattan and downtown Chicago. In contrast, the widespread and numerous annual observations in specific countries (e.g. Poland) and cities (e.g. Denver) demonstrate that there is room for greatly increased participation. If the majority of professional and amateur astronomers were to make just a single observation each year, spatial coverage would increase extraordinarily. Furthermore, the impact of astronomers can easily be multiplied, either by promoting skyglow observations on social media, or as part of standard astronomy outreach. Another possibility within the educational setting would be assigning introductory astronomy students the task of making a NELM observation as homework.

We are currently at a moment when two possible futures lay before us. In one future, inexpensive light leads to ever-greater usage, and skyglow growth continues apace. In the second, the transformative potential of LEDs is used to cut total light emissions dramatically while improving visibility (see e.g. Narendran et al. 2016), leading to a reduction in skyglow. At the moment, we do not yet know which trajectory we are following, and naked eye observations are the key to discovering the answer. Chicago is spending $160 million on its lighting transition (Rogers 2017), and the annual global spending on outdoor light globally likely measures in the tens of billions of dollars. Surely it must be worth it for professionals and amateurs alike to spend a few minutes each year gazing at the stars, in order to help understand what all of that spending means for the future of visual astronomy.

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