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1 Despite its importance to biologists studying physiology and behaviour, there is no common reference value for the illuminance of the full Moon. (Ricardoreitmeyer, Dreamstime.com)

How bright is moonlight?

Christopher Kyba, **Andrej Mohar** and **Thomas Posch** seek a standard figure for moonlight illuminance.

Recent years have seen increasing recognition and study of the effect of moonlight on plants and animals. The typical brightness of moonlight is therefore an important parameter for biological laboratory studies, yet incorrect values for the moonlight illuminance are frequently used and cited. We have used the brightness of the "supermoon" of 14 November 2016 to demonstrate that typical lunar illuminance is around 0.05 to 0.1 lux at temperate latitudes during the summer.

The amount of visible light on Earth's surface at night varies by about three orders of magnitude over the course of a month, as a result of the lunar cycle. This change has profound effects on the physiology and behaviour of many plants and animals (Kronfeld-Schor *et al.* 2013, Reinberg *et al.* 2016), especially in tidal environments (e.g. Brady *et al.* 2016). Despite its importance for many organisms, the scientific literature lacks a commonly accepted reference value for the photopic illuminance of full moonlight. As a result, many existing publications report incorrect values of full Moon illuminance, for example 2.2 lux (Marcum *et al.* 2004), 2 lux (Yorzinski *et al.* 2015), and 0.5–1 lux (Bruce-White & Shardlow 2011). Even the Wikipedia page for "Lux" currently reports an incorrect range of up to 1 lux for full moonlight, based on an old citation (Bünning & Moser 1969), which in fact bases the value on an even older German text (Sauberer & Härtel 1959).

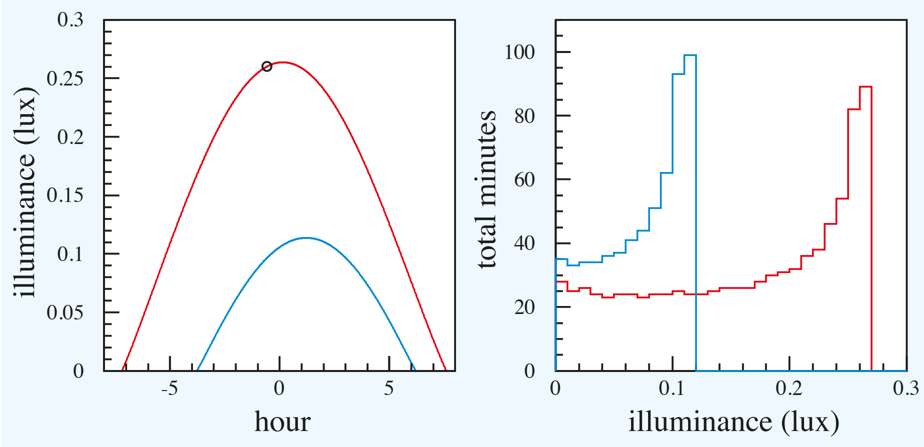
"Exceptionally bright moonlight is not at all representative of 'typical' moonlight"

Maximum value

Biologists have a particular interest in the maximum possible values of moonlight, i.e. for a full Moon at zenith (directly overhead) in a clear atmosphere. Our intentions here are to provide an easy-to-find reference containing a measurement of exceptionally bright moonlight – and to stress that this is not representative of moonlight in general.

We report observations of the supermoon of 14 November 2016, made in an open field 49 km from the centre of Vienna, Austria (47.7956°N, 16.1366°E) at 23:25 local time. The Moon was at 55.5° elevation, 8 hours and 33 minutes after full Moon (99.8% full), and 11 hours 2 minutes after perigee (Espenak 2016). The lunar distances and elevations are based on Meeus (1991), calculated in Perl using Astro::Coord::ECI::Moon by Tom Wyant. Illuminance was measured using a Minolta T-10 illuminance meter. The horizontal photopic illuminance was 0.26 lux. In a second observation, the illuminance meter was tilted in order to measure the illuminance in the plane perpendicular to the Moon, yielding 0.30 lux.

The background from airglow, stars and the Milky Way can be excluded, as it is in the millilux range (Hänel *et al.* in prep.). The influence from the artificial skyglow from Vienna and surrounding communities was



2 Comparison of photopic illuminance from the full Moon according to equation 1 for 14 November 2016 (red) and 7 August 2017 (blue). The left panel shows illuminance against time relative to local midnight, and the histograms at right show the total number of minutes under each illuminance condition. Note that these graphs do not account for atmospheric scattering and absorption, which would further reduce the illuminance when the Moon is at low elevation angles.

negligible for this observation: Falchi *et al.* (2016a,b) estimated the zenith skyglow to be 0.265 mcd m^{-2}, which corresponds to approximately 0.001 lux (using the approximation $I=\pi L$, where I is illuminance and L is zenith luminance, which is probably accurate to within about a factor of 2 [see Kocifaj *et al.* 2015]). For comparison, in central Vienna, Falchi *et al.* (2016a) predict 4.59 mcd m^{-2} (~0.014 lux), and Puschnig *et al.* (2014) reported best sky luminance of 2.15 mcd m^{-2} (~0.007 lux) at 3.5 km from central Vienna. While moonlight dominates over skyglow under clear conditions, this is not the case under overcast conditions. The typical overcast skyglow observed by Puschnig *et al.* (2014) before midnight was about 45 mcd m^{-2}, approximately 0.14 lux, of similar magnitude to full moonlight. Other areas are considerably brighter than Vienna (Pun *et al.* 2014, Kyba *et al.* 2015).

Celestial illuminance

Neglecting atmospheric scattering and absorption, the horizontal illuminance from a celestial source goes as $I=I_o\sin\theta_e$, where θ_e is the elevation angle and I_o is the illuminance from the source when it is at zenith. The observation of 0.26 lux for a Moon at 55.5° elevation (34.5° from zenith) suggests that had the Moon been directly at zenith, the illuminance would have been near 0.32 lux. It is critical to note that 0.3 lux is not "typical" for moonlight, but rather a value that could occur under optimal atmospheric conditions, for a few hours each year, in the tropics. The Moon never reaches zenith at latitudes greater than 28° (all of Europe, most of the USA), and the full Moon rises to lower elevations in summer.

The Earth surface to Moon distance (henceforth Earth–Moon distance) has a minor effect on illuminance, because the Moon is slightly smaller in the sky when it is further away. The Moon illuminance decreases with the square of the Earth–Moon distance, so we can approximately compare full Moon illuminance using

$$I=I_o\sin\theta_e(d_o/d)^2 \qquad (1)$$

where d_o is the Earth–Moon distance when I_o was estimated.

On 14 November 2016, the Earth–Moon distance was about 351 000 km. In contrast, during the full Moon of 7 August 2017, the Earth–Moon distance will be about 391 000 km. This will reduce the expected illuminance by nearly 20%. More importantly, summer full Moons do not rise as high; on 7 August 2017 the Moon will only rise to 26.5° above the horizon near Vienna.

The horizontal photopic illuminance estimated by equation 1 for 14 November 2016 (red) and 7 August 2017 (blue) is shown in figure 2. The time of the observation is shown by the black circle in the left panel. The effect of the higher elevation angle in November is reflected both in the maximum illuminance and in the length of time the Moon is up. Note that the blue curve in the left panel is shifted by one hour due to daylight saving time.

"A definitive publication is needed of long-term 'typical' values of moonlit nights"

Equation 1 and figure 2 neglect atmospheric scattering and absorption. When the Moon is at an elevation of less than 45°, these processes also reduce moonlight illuminance. Even when the Moon reaches its highest elevation, most full Moons at mid-latitudes will produce only 0.05–0.2 lux. Furthermore, the Moon experiences a dramatic increase in brightness when it is completely full (the so-called "opposition surge", see e.g. Buratti *et al.* 1996). This means that on the nights before or after the night of full Moon, direct illuminance cannot reach 0.32 lux, regardless of the Moon's position and atmospheric conditions.

Finally, it is important to return to the effect of atmospheric conditions. The observations reported here were for a clean, clear sky. Increased air pollution can reduce lunar illumination, and overcast skies dramatically reduce it. Moonlit landscapes free of artificial light pollution experienced by wild nocturnal animals will in general be far less bright than the maximum values reported here.

We have shown that in the extremely unusual case of a near-perigee full Moon, near-zenith, under near-ideal atmospheric conditions, the maximum possible horizontal photopic illuminance is approximately 0.3 lux. This value does not represent a typical value of moonlight, but rather the most extreme case possible: a supermoon, near zenith, near perigee, nearly fully illuminated and experiencing the opposition surge. These conditions are not representative of moonlit nights as a whole, and we urge biologists studying the influence of moonlight illumination levels on physiology and behaviour to study lower light levels (e.g. 0.05–0.10 lux). There is a need for a definitive publication, written with biologists in mind, that reports long-term typical values of moonlit nights. These observations must be taken from a location without light pollution, and should cover at least one year of natural variations in lunar elevation and cloud cover. ●

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