Journal of Quantitative Spectroscopy & Radiative Transfer 139 (2014) 21–26

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

journal homepage: www.elsevier.com/locate/jqsrt

The impact of light source spectral power distribution on sky glow

Christian B. Luginbuhl [a,*], Paul A. Boley [b], Donald R. Davis [b]

[a] U.S. Naval Observatory Flagstaff Station, 10391 W Naval Observatory Road, Flagstaff, AZ 86001, United States
[b] Dark Sky Partners LLC, 4825 Camino La Brinca, Tucson, AZ 85718, United States

ARTICLE INFO

Article history:
Received 4 July 2013
Received in revised form
23 September 2013
Accepted 4 December 2013
Available online 12 December 2013

Keywords:
Light pollution
Sky glow
Blue-rich light sources

ABSTRACT

The effect of light source spectral power distribution on the visual brightness of anthropogenic sky glow is described. Under visual adaptation levels relevant to observing the night sky, namely with dark-adapted (scotopic) vision, blue-rich ("white") sources produce a dramatically greater sky brightness than yellow-rich sources. High correlated color temperature LEDs and metal halide sources produce a visual brightness up to 8 × brighter than low-pressure sodium and 3 × brighter than high-pressure sodium when matched lumen-for-lumen and observed nearby. Though the sky brightness arising from blue-rich sources decreases more strongly with distance, the visual sky glow resulting from such sources remains significantly brighter than from yellow sources out to the limits of this study at 300 km.

1. Introduction

Outdoor lighting is an increasingly pervasive aspect of the human nocturnal environment. Yet beyond the intended effects for human vision and information conveyance, a variety of collateral impacts arise from its use – these impacts are often referred to as "light pollution" (e.g. [1] and references therein). Though there are a number of aspects of light pollution such as glare, disturbance to biological systems, and "light trespass," one of the principal impacts is increased night sky brightness ("anthropogenic sky glow") arising from light scattered by atmospheric molecules and aerosols. Beginning as early as the 1930s, when a site was being chosen for the 200 in. Hale telescope, astronomers have been concerned about the impact of this increased sky brightness on the observability of faint astronomical sources. In the past 50 years protection has been sought through civil regulations that require shielding of light fixtures to prevent light emanation above the horizontal plane; in the last 25 years these efforts have extended in some cases to limits on both the total amount of light and the spectral characteristics of the light sources.

Garstang developed the first comprehensive model [2,3] that treats the scattering of light from molecules and aerosols in clear (cloudless) air, and accurately accounts for varying locations of light source and observer, Earth (and atmospheric) curvature, and varying levels of atmospheric aerosol. This model, extended to account for blocking of light rays by objects in the near-ground environment [4] has been successfully used to predict the sky brightness arising from artificial light sources (e.g. [4,5]).

In recent years there has been an increasing interest in the use of solid-state lighting sources (LEDs) with a broad and relatively blue-rich spectral power distribution compared to the previously dominant technology, high-pressure sodium (HPS) (see, for example, discussions of

---

[*] Corresponding author. Tel.: +1 928 779 5132; fax: +1 926 774 3626.
E-mail addresses: cbl@nofs.navy.mil (C.B. Luginbuhl), pboley@gmail.com (P.A. Boley), drd@psi.edu (D.R. Davis).

0022-4073
http://dx.doi.org/10.1016/j.jqsrt.2013.12.004

many LED lighting projects undertaken in collaboration with the US Department of Energy Gateway Program [6]). The question arises as to the impacts on anthropogenic sky glow of such a shift in light source spectrum. In this contribution we present an extension of the Garstang model to include the wavelength dependence of molecular and aerosol scattering, to allow the treatment of light sources with different spectral power distributions. An initial study [7] has examined the impact of a variety of light sources on the radiant sky glow in different parts of the visible spectrum. The goal of this study is to examine the impacts on the visual or luminous sky glow as observed by the human eye under both photopic and, more importantly, scotopic conditions.

2. Model

To examine these effects, an implementation of Garstang's [2,3] monochromatic model has been generalized to allow the calculation of sky brightness arising from polychromatic light sources. Along a given path through the atmosphere, Garstang's model calculates the amount of light removed due to extinction, as well as added due to scattering. Single and double scatterings are treated; higher order scattering is neglected. This is done for a two-component atmosphere consisting of molecules and aerosols. Each of these two components is defined by a number density at height h above ground level and a scattering cross-section. The amount of aerosol is defined through a parameter K (see Eq. (3) below) which sets the ratio of total molecular to aerosol scattering.

Generalization of Garstang's model for wavelength dependence requires specification of the wavelength dependence of the scattering cross-sections. The scattering by molecules is assumed to be Rayleigh scattering, where the cross-section scales with λ^{-4}. The aerosol scattering cross-section, on the other hand, scales with λ^{-1} for aerosol particle sizes most relevant to clear atmospheres (see, for example, [8] for experimental measurements). Referenced to the center of the astronomical Johnson V band at 550 nm, the wavelength-dependent aerosol and molecular scattering cross-sections σ_a and σ_R can be written as

$$\sigma_a(\lambda) = \sigma_a(550\ \text{nm})\left(\frac{550\ \text{nm}}{\lambda}\right) \tag{1}$$

$$\sigma_R(\lambda) = \sigma_R(550\ \text{nm})\left(\frac{550\ \text{nm}}{\lambda}\right)^4 \tag{2}$$

These wavelength-dependent definitions of the scattering cross-sections can then be substituted into the model equations given by Garstang [2,3]. However, it is important to note that particular care needs to be taken with the aerosol component; as in the Garstang approach the aerosol scattering cross-section is defined relative to the amount of molecular scattering at ground level at the center of the V band ([2], Eq. (4)). Consequently, the wavelength-dependent form of this relation is

$$N_a\sigma_a(\lambda) = \left(\frac{550\ \text{nm}}{\lambda}\right)11.11KN_m\sigma_R(550\ \text{nm})\exp(-cH) \tag{3}$$

where c is the reciprocal scale height for the molecular atmosphere and H is the height of the light source above sea level, which is consistent with the original definition when $\lambda = 550$ nm. The rest of the Garstang's model equations can then be generalized for wavelength dependence by replacing σ_a and σ_R with the relations in Eqs. (1) and (2).

To determine the visible sky glow resulting from polychromatic light sources used for outdoor lighting, the spectrum of a light source is first scaled such that the spectrum, multiplied by the CIE $V(\lambda)$ (photopic) response [9] yields a fixed luminous output (in lumens). We next perform the radiometric calculations on the scaled lamp spectrum within 20 nm wide wavelength bins, using the prescription described above, to compute the mean sky radiance $\overline{L_e^{(i)}}$ in each wavelength bin i. The physical quantity calculated is the luminance L_v, which we define in terms of the mean radiance in each wavelength bin as

$$L_v = \sum_i \overline{L_e^{(i)}} \int_{\lambda_i}^{\lambda_{i+1}} V(\lambda)\, d\lambda \tag{4}$$

when the sky brightness evaluation is intended to apply to scotopic vision, we substitute the CIE $V'(\lambda)$ response [10] in place of the $V(\lambda)$ response, and refer to the results as "scotopic" luminance[1] or luminance ratios.

2.1. Light sources

2.1.1. Lamps

Six lamp types were examined in this study: low-pressure sodium (LPS); high-pressure sodium (HPS); two types of white light emitting diodes with correlated color temperature (CCT) of 2400 K (LED2400K) and 5100 K (LED5100K); ceramic metal halide with CCT of 4100 K (MH4100K); a white LED (3000 K CCT) filtered with a 500 nm short cutoff filter (FLED). Spectra for the sources are shown in Fig. 1. In the analysis all light sources were balanced for equal luminous output (measured in lumens).

2.1.2. Uplight angular distribution

Light propagating upward into the atmosphere consists of two components: light emitted directly upward from incompletely shielded fixtures, and light reflected upward from illuminated surfaces. We use the angular descriptions for these components as defined by Garstang ([2], Eq. (1)) assuming direct upward component $F = 0.10$ and a horizontal ground surface with average reflectance $G = 0.15$. To account for blocking of upward rays by objects in the near-ground environment, we follow the treatment of Luginbuhl et al. ([4], Eq. (2)) assuming a vertical "blocking extinction" $E_b = 0.3$ magnitudes, with an overall unblocked fraction $\beta = 0.10$.

2.2. Atmosphere

A "moderately clear" atmosphere characterized by a total aerosol to molecular scattering ratio of 11:1 (following Garstang [2]) is adopted for the majority of the

---

[1] Strictly speaking, the term "luminance" is defined only in terms of photopic vision.