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The emission function of ground-based light sources: State of the art and research challenges

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ABSTRACT

To understand the night sky radiance generated by the light emissions of urbanised areas, different researchers are currently proposing various theoretical approaches. The distribution of the radiant intensity as a function of the zenith angle is one of the most unknown properties on modelling skyglow. This is due to the collective effects of the artificial radiation emitted from the ground-based light sources. The emission function is a key property in characterising the sky brightness under arbitrary conditions, therefore it is required by modellers, environmental engineers, urban planners, light pollution researchers, and experimentalists who study the diffuse light of the night sky. As a matter of course, the emission function considers the public lighting system, which is in fact the main generator of the skyglow. Still, another class of light-emitting devices are gaining importance since their overuse and the urban sprawl of recent years. This paper will address the importance of the emission function in modelling skyglow and the factors involved in its characterization. On this subject, the author's intention is to organise, integrate, and evaluate previously published research in order to state the progress of current research toward clarifying this topic.

1. Introduction

Light pollution is an environmental issue of the new era that has been increasing exponentially in recent years [85,24,77,89,75,97,42]. The night lighting is spreading continuously, which results not only in high amounts of wasted energy but as well in injudicious, harmful over illumination of natural environments [61,40,23,63]. The main representation of light pollution is the skyglow also known as the night sky radiance [5,87,69,35,41]; a global atmospheric problem provoked by an incorrect planning of the artificial night lighting systems that pollute the nocturnal environment [34,65].

To comprehend the optical properties of the troposphere level is essential in modelling the nocturnal radiance in a diverse nocturnal atmosphere [71,15]. For instance, fluctuations on the night sky radiance are resolute, to a large extent, to variability of aerosol particles and air molecules, which are the greatest modulators of skyglow [48,53]. Aerosol microphysical characteristics might undergo substantial changes even under clear sky conditions because of turbulent mixing, raising humidity, and change of wind direction [66,14]; thus resulting in a visible influence of local polluters surrounding a measuring site. Since the scattering efficiency intensifies with the growth in the volume concentration of scatterers, the amount of skyglow increases in the lower troposphere as a result of elevated aerosol content [79,96].

The concentration of aerosol particles peaks in the atmospheric boundary layer while the molecular atmosphere extends to much higher altitudes [82,58]. Despite that fact, both aerosols and air molecules are important components in modelling radiative transfer in the nocturnal atmospheric environment (please see Fig. 1). Along with the importance of the optical properties of the atmosphere, the night sky radiance differs with the so-called emission patterns [49]. This paper has the intention of integrating the current literature dealing with the emission function. In this context, the main subjects to discuss on the manuscript are the analysis and the key factors to consider in the retrieval of this function. The motivation of the manuscript is to evaluate previously published research on the topic of the emission function in order to state the progress of current research toward clarifying this subject.

2. The emission function

The propagation of radiation in a diffuse atmosphere is ruled by scattering and absorption processes [82,2,44]. The single scattering by air molecules and aerosol particles is a contributory influence to the diffuse light in an optically thin cloudless atmosphere. This involves a change of the optical properties of the atmosphere with

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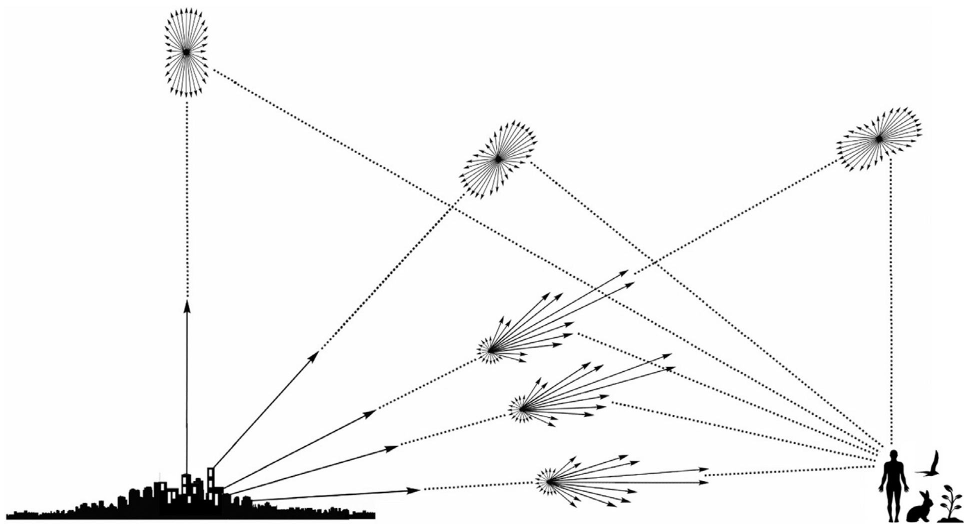

Fig. 1. Schematization of the interaction between the radiance generated by a ground-based light source and the constituents of the atmosphere.

different scattering angles, due to rapid angular variations of the differential scattering cross section of aerosol particles [46,70,38]. Those atmospheric disparities combined with the physical properties of the ground-based light sources appear to be significant factors influencing skyglow. The atmospheric optics rescales the light emissions from ground-based sources that are further suffering a transformation along the beam path in a turbid atmosphere. As a consequence, the sky radiance distributions are distorted in a complex manner depending on many factors. By way of explanation, the temporal and spatial changes of skyglow are determined by both the atmosphere and the emission function of terrestrial light emissions.

While there are different sources of skyglow, including natural radiation, artificial lighting is accepted as the greatest component of skylight during the night [80,68]. The main part of the emission function is a collective effect of the elementary emission functions of both artificial private and public lights that are spatially distributed in the studied space. The spectral radiance and the diverse distributions of the ground-based light sources are indisputable difficulties in this field [7,76,63]. In particular, the emission function is one of the most unknown properties on modelling skyglow. Basically, each light source can be characterised by a different emission and there is not a standard emission function. Therefore, this function must be studied in detail, because of the information required by modellers, environmental engineers, urban planners, and light pollution researchers who study the diffuse light of the night sky. Correspondingly, most mathematical models that are currently dealing with the prediction of the night sky brightness entail the information on this function.

2.1. A brief history of the early modelling of skyglow

To understand the night sky radiance generated by the light emissions of urbanised areas, several approaches that consider the physics of radiative transfer have been developed until now by different researchers. These models have increased in number in recent years. At the beginnings of skyglow modelling, the characterization of upward directed urban beams were performed using semi-empirical approximations. However, it is known that the radiation from the ground-based light sources is subjected to absorption and scattering processes due to the optical properties of atmospheric constituents.

The first model developed for the analysis of light pollution was proposed by Walker [93]. As astronomer, Walker [94] analysed the spectra of stars, nebula, and natural night-sky emissions concluding they were similar. Though, the emission lines of mercury from the artificial lights of California (USA) increased in strength vastly with time. The model from Walker [93] was motivated for the development of an empirical equation to find the better astronomical observation places [93–95]. The main fundaments of the Walker's law are the standardisation of the cities as a source of pollution and the use of the known inverse-square law. It is interesting to note that the exponent of the distance is 2.5 and not 2 as for the inverse square law in Walker's model. One might assume that absorption of light in the atmosphere plays an important role [73]. In this sense, Walker [93] was the primary researcher to relate the population of an urban space with the quantity of skyglow received at nearly distances from the city centre. His model was the first to undertake an empirical analysis of the emission function of ground-based light sources.

Treanor [92] analysed the Walker's law and improved it by introducing different factors related to the scattering of light by suspension of molecules and aerosol particles across a homogeneous atmosphere. The Treanor's approach was a simplified equation for the propagation of artificial radiation through a semi-empirical and hypothetical atmosphere. The light sources, or cities, were considered as point sources. Indeed, the data obtained by the Treanor's model were collected in its origins with the purpose to analyse a calculated map for light pollution in Italy [9].

Later, Berry [8] studied the Treanor's model and proposed different changes in the equation to determine the night sky radiance produced by the zenith's glare from the light of small cities. As a result, Berry obtained valuable empirical data represented by the glare of the sky related with the population of the cities and a distance function considering an average of the atmospheric conditions. These functions were used in a simple mathematical equation for the characterization of the light pollution in Ontario [8]. This model is still seeing the cities as point sources.

One of the most known light pollution models was developed by Garstang [26], who introduced a simulation of the brightness of the nocturnal environment based on the luminance of the night sky. His mathematical approach used an atmospheric scale taking into account aerosols and air molecules suspended in the troposphere. Garstang added a parameter in the formula that represents the aerosol content. The model allowed an angular distribution of light emission, since it considered a lambertian distribution for ground reflection. As well, the Garstang's model defines the specific angular distribution for the light emitted directly up-