Journal of Quantitative Spectroscopy & Radiative Transfer 181 (2016) 52–66

Contents lists available at ScienceDirect

Journal of Quantitative Spectroscopy & Radiative Transfer

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

Testing sky brightness models against radial dependency: A dense two dimensional survey around the city of Madrid, Spain

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ARTICLE INFO

Article history:
Received 23 November 2015
Received in revised form
18 February 2016
Accepted 21 February 2016
Available online 26 February 2016

Keywords:
Light pollution
Techniques: photometric
Remote sensing
Artificial sky glow

ABSTRACT

We present a study of the night sky brightness around the extended metropolitan area of Madrid using Sky Quality Meter (SQM) photometers. The map is the first to cover the spatial distribution of the sky brightness in the centre of the Iberian peninsula. These surveys are necessary to test the light pollution models that predict night sky brightness as a function of the location and brightness of the sources of light pollution and the scattering of light in the atmosphere. We describe the data-retrieval methodology, which includes an automated procedure to measure from a moving vehicle in order to speed up the data collection, providing a denser and wider survey than previous works with similar time frames. We compare the night sky brightness map to the nocturnal radiance measured from space by the DMSP satellite. We find that (i) a single source model is not enough to explain the radial evolution of the night sky brightness, despite the predominance of Madrid in size and population and (ii) that the orography of the region should be taken into account when deriving geo-specific models from general first-principles models. We show the tight relationship between these two luminance measures. This finding sets up an alternative roadmap to extended studies over the globe that will not require the local deployment of photometers or trained personnel.

1. Introduction

Light pollution (the inappropriate or excessive use of artificial light, as defined by the International Dark Sky Association) is a major issue worldwide, especially in urban areas. It increases the sky glow and prevents us from observing a dark starry sky. This is why astronomers are among the worst affected by urban sky glow [9] and they have been fighting against light pollution since 1950 [51]. One of the key parameters to select a site to build an observatory is the night sky brightness because some astronomical research could not be performed with the required quality if the sky is not dark enough. Thus, it is not a surprise to find that the astronomical observatories are located in remote areas far from light pollution sources.

There are citizen campaigns in defense of the values associated with the night sky and the general right of the citizens to observe the stars. 'Starlight, A Common Heritage' promoted by the IAU and the UNESCO, said: 'An unpolluted night sky that allows the enjoyment and contemplation of the firmament should be considered an inalienable right of humankind equivalent to all other environmental, social, and cultural rights, due to its impact

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http://dx.doi.org/10.1016/j.jqsrt.2016.02.029
0022-4073/

on the development of all peoples and on the conservation of biodiversity' [52].

The main data input for artificial lighting registered from space has been the images obtained with sensors onboard the US Air Force Defense Meteorological Satellite Program (*DMSP*) Operational Linescan System (*OLS*) developed to map human settlements. Using the digital archive for *DMSP/OLS* data (available at the National Geophysical Data Center[1]), that contains annual cloud-free composites of nighttime lights, it is possible to obtain a spatial model of population density [53,54], and economic activity [55]. This archive is a very useful source of data to study the evolution of light emission. An expansion of lighting surrounding urban centres and areas of new lighting are found [17] although a reduction of the sky glow that surrounds some big cities has been also found [49]. This good news may be the result of changes in lighting type or the installation of lighting fixtures to direct light downwards. It is worth mentioning that an application of these data consists in the modeling of artificial night sky brightness and its effect on the visibility of astronomical features [20,9,6,10,11,8].

Urban illumination comes mainly from street lighting, office buildings, and also ornamental and advertising. For Spain the street lighting is mostly public [48,46]. Detecting light pollution is straightforward by visual inspection of the images which speak by themselves and is very useful to draw public attention of the problem [14,28,30]. The intensity of the pixels is related to the amount of light being sent to space and scattered by the atmosphere. The bright spots of light reveal an excess or bad use of lighting. The extension and intensity of this emission put in evidence that light pollution is, besides a concern for astronomers, a global problem that is damaging our environment [35].

In this paper we address the study of light pollution and its effect on the night sky brightness and on the visibility of the stars (see for instance [8]) using night sky brightness data collected from photometers on top of moving vehicles around Madrid. We have used Sky Quality Meter (SQM) devices which are pocket size photometers designed to provide measures of the luminance or surface brightness of the sky (night sky brightness, NSB for short) in astronomical units of magnitude per square arcsecond (mag arcsec^{-2}) [7]. The resulting NSB map (5389 km^2) is compared with calibrated images of radiance as measured from space. Our test has been carried out in a region around the big city of Madrid ($\sim$5.4 millions of inhabitants inside an area of 27 km radius) for a total population in the region of around 6.5 millions of inhabitants.

The first published work [27] on artificial sky glow caused by a city was performed inside and around Cracow (Poland). The measurements within the city were collected in 10 selected fixed monitoring points, whereas the measurements outside the city were spaced by 5 km along different directions and they reached 50 km from the city centre. A similar study was performed by [5] around the city of Perth (Western Australia) with 1.27 millions of inhabitants. Perth is a very isolated city and the NSB measurements were not affected by light from nearby large cities. On the other hand the measurements were made using hand held photometers with a total of 310 useful data points. The observations for the Hong Kong light pollution map [40] were performed by 170 volunteers who acquired 1957 night sky measurements in 199 locations. The map covers an area of 1100 km^2. To speed up the data acquisition, Espey and McCauley [18] used a method based on measurements taken from a vehicle and GPS information. They surveyed rural areas close to Dublin (Ireland) with 1.27 millions of inhabitants.

One of the main motivations of this study has been to quantify the increase of the night sky brightness as a consequence of the artificial lighting present around a big city. The results thus become the reference values to compare with similar studies to be carried out in the future that focus on the evolution of the light pollution in the region around Madrid. The calibration and procedures could be extended to the study of wider areas.

2. Brightness of the night sky

Image observations to measure the magnitude of astronomical objects are performed using standard astronomical photometry methods. The images are taken through a filter and registered by a CCD detector. Its quantum efficiency or spectral response, in conjunction to the filter transmission, determines the photometric band. The most used astronomical bands for light pollution studies are *B*, *V* and *R* of the classical Johnson photometric system centered in 0.44, 0.55 and 0.65 microns respectively.

The contribution of the background sky can be estimated in the nearby field free of objects registered in the image and it should be subtracted to obtain the net flux of the object. When processing astronomical photometry observations the value of the background sky is usually not stored after the analysis of the images. Since the astronomers consider the sky background a subproduct, their values are not published in the scientific papers. To get information on sky background one has to browse archival data, to get the images, and measure each one [37,38,19].

The history of the artificial sky glow measurements has been recently reviewed by [51]. To summarize, there are two most common methods used by people joining citizen-science projects: visual and instrumental. On one hand, the visual observations include (a) the comparison with observational scales, (b) the degree of condensation of a comet on the sky background, and (c) reporting the number of stars that the observer can see after visual observations of selected sky fields. These data inform about the limiting magnitude of the sky, which is closely related to the sky brightness. Although these methods rely on subjective measures, it has been shown that they yield scientific information and their precision increases when the number of observations increases [51,33]. On the other hand, there is the instrumental method where sky brightness can be measured as intensity over an area in astronomical units of mag arcsec^{-2}. These measures are usually referred to an astronomical band, a part of the

[1] http://ngdc.noaa.gov/eog/dmsp.html