MOONLIGHT WITHOUT THE MOON

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Abstract. Light pollution, the alteration of the natural light levels in the night environment produced by man-made light, is one of the most rapidly increasing threats to the natural environment. The fast growth of the night sky brightness due to light pollution not only is damaging the perception of the starry sky but it is silently altering even the perception of the moonlight nights by mankind. The cyclic alternation between the new Moon's dark sky with thousand of stars and the moonlight sky, less dark but always full of stars among which our satellite moves, is rapidly changing toward a perennial artificial moonlight due to the man-made light wasted in the atmosphere. The Moon periodically will appear inside the same perennially luminous sky from which stars will have almost disappeared. Here we present a map showing "artificial moonlight" levels in North America and some statistical results.

1. Introduction

Many adverse effects of light pollution are reported on the animal kingdom, the vegetable kingdom and mankind (e.g., Cinzano, 1994). One of the more impressive effect of the growth of light pollution is the increase of the night sky brightness which is damaging mankind's perception of the night sky, the panorama on the Universe where we live (Crawford, 1991; McNally, 1994; Isobe and Hirayama, 1998; Cinzano, 2000; Cohen and Sullivan, 2000). It is commonly believed that this problem does not affect moonlight nights because the Moon itself already provides light to the sky background. However light pollution is silently changing even the perception of the moonlight nights by mankind. The cyclic alternation between the new Moon's dark sky with thousand of stars and the moonlight sky, less dark but always full of stars among which our satellite moves, is rapidly changing towards a perennial moonlight. The Moon periodically will appear inside the same perennially luminous sky from which stars will have almost disappeared. Due to light pollution propagation, this photon smog will spread from the more populated areas to the rest of the territory. The majestic spectacle that for millennia followed mankind and the development of its culture, is being broken in few decades. Moreover this alteration could affect other animals whose life cycles depend on the Moon phases as reported elsewhere in this book.

Our research group is mapping many effects of light pollution in the World based on measurements of upward light flux obtained with the Defense Meteor-

Earth, Moon and Planets **85–86:** 517–522, 2001.

ological Satellite Program (DMSP), like, e.g., the artificial night sky brightness accounting for the elevation, the total night sky brightness, accounting for the natural sky brightness and the mountain screening, the naked eye star visibility, accounting for eye capability and stellar extinction, the number of visible stars (Cinzano et al., 2000, 2001a, b; Falchi et al., 2000). Here we present a map showing "artificial moonlight" levels in North America and some statistical results.

2. Method

High resolution data on the upward light flux emitted by sources on the Earth surface have been obtained from the Operational Linescan System (OLS) carried by the DMSP satellites, an oscillating scan radiometer with low-light visible and thermal infrared (TIR) imaging capabilities. At night the OLS uses a Photo Multiplier Tube (PMT), attached to a 20 cm reflector telescope, to intensify the visible band signals which have a broad spectral response from 440 to 940 nm with highest sensitivity in the 500 to 650 nm region. This covers the range for primary emissions from the most widely used lamps for external lighting. Satellite images were obtained in darkest nights of lunar cycles in March 1996 and January and February 1997 after special requests to the Air Force made by the US Department of Commerce, NOAA National Geophysical Data Centre. Cloud free sections of each orbit based on OLS-TIR data have been identified and cleaned. Many data with different instrumental gains have been combined with advantages in the removal of ephemeral lights sources, such as fire and lightning, and in the retrieval of lights from small towns that are near the detection limits of the sensor and processing algorithms (Elvidge et al., 1999, 2000). Calibrated upward fluxes per unit solid angle toward the satellite have been obtained from radiance data based on pre-fly irradiance calibration of OLS-PMT, accounting for differences between the spectral sensitivity band of the PMT detector and the photometric V astronomical band, for extinction of the light in the atmosphere and for the surface of each land area covered by a pixel in the final image. The calibration has been checked by Earth based measurements of sky brightness giving a good agreement. For other directions upward fluxes have been obtained based on an average normalized emission function in agreement with a study of the upward flux per unit solid angle per inhabitant of a large number of cities at different distances from the satellite nadir (Cinzano et al., 2000).

Maps of artificial sky brightness with a resolution of about one kilometer have been obtained from the upward flux data, taking into account Rayleigh scattering by molecules, Mie scattering by aerosols, atmospheric extinction along light paths and Earth curvature (Garstang, 1986, 1989, 1991a, b, 2000; Cinzano, 2000a, b). We neglected third and higher order scattering which can be significant only for optical thickness higher than ours. The artificial night sky brightness in a given direction of the sky in (x', y') can be obtained from upward flux measurements:

$$b(x', y') = \int\int e(x, y) f((x, y), (x', y'))\, dx\, dy, \tag{1}$$

where $e(x, y)$ is the upward emission per unit area in (x, y), $f((x, y), (x', y'))$ is the light pollution propagation function, i.e., the artificial sky brightness per unit of upward light emission produced by the unitary area in (x, y) at the site in (x', y'). The propagation function f, expressed as total flux per unit area of the telescope per unit solid angle per unit total upward light emission, is obtained integrating along the line of sight the fraction of light scattered toward the observer from atmospheric molecules and aerosols:

$$f = \int_{u_0}^{\infty} (\beta_m(h) f_m(\omega) + \beta_a(h) f_a(\omega))(1 + D_S) i(\varphi, s) \xi_1(u)\, du, \tag{2}$$

where $\beta_m(h)$ and $\beta_a(h)$ are respectively the scattering cross sections of molecules and aerosols per unit volume at the distance u along the line of sight, $f_m(\omega)$ is the normalized Rayleigh angular scattering function for molecules, $f_a(\omega)$ is the normalized angular scattering function for aerosols, $\xi_1(u)$ is the extinction of the light along its path from the considered scattering volume to the telescope and $i(\varphi, s)$ is the direct illuminance per unit flux produced by each source on each infinitesimal volume of atmosphere along the line-of-sight of an observer. The scattering angle ω, the emission angle φ, the distance s of the section from the source and the elevation h of it, depend on the elevations of the site and the source, their distance, the zenith distance and the azimuth of the line-of-sight and the distance u along the line of sight, through some geometry which must take into account Earth curvature. D_S is a correction factor which takes into account the illuminance due to light already scattered once from molecules and aerosols and which can be evaluated as Garstang (1989). The direct illuminance per unit flux on each infinitesimal volume of atmosphere along the line of sight is:

$$i(\varphi, s) = I(\varphi)\xi_2/s^2 \tag{3}$$

in the range where there is no shielding by Earth curvature and zero elsewhere. Here $I(\varphi)$ is the normalized emission function giving the relative light flux per unit solid angle emitted by each land area at the zenith distance φ, s is the distance between the source and the considered infinitesimal volume of atmosphere and ξ_2 is the extinction along this path. We neglected screening by mountains in this paper.

We associated the predictions with well-defined parameters related to the aerosol content, so the atmospheric conditions, which predictions involve, are well known. Atmospheric conditions are variable and a careful evaluation of the "typical" atmospheric condition in the local "typical" clean night of each area is quite difficult, so we used the same atmospheric model everywhere, corresponding to standard clean atmosphere (Garstang, 1986). This avoids confusion between effects due to light pollution and effects due to geographic gradients of atmospheric conditions in "typical" nights. Being more interested in understanding and comparing light pollution distributions rather than in predicting the effective sky brightness for observational purposes, we computed the artificial sky brightness at sea level, in order to avoid introduction of altitude effects. More details are available in Cinzano et al. (2000, 2001a, b).

The total night sky brightness has been obtained assuming an average natural night sky brightness of 8.614×10^7 V ph cm^{-2} s^{-1} sr^{-1} under the atmosphere corresponding approximately to 21.6 V mag/arcsec^2.

3. Results and Conclusions

We compared the night sky brightness maps (Cinzano et al. 2001b; see *www.pd.astro.it/cinzano/dmsp/*) with the DOE population density database (Dobson et al., 2000), to determine the fraction of population in the United States (excluding Alaska and Hawaii) and in the World, who are living under a sky of typical "moonlight" brightness. Our data refers to 1996–1997 so the situation today could be still worse. We found that in the areas where the 98% of US population and half of the World population live, the night sky in standard clean atmospheric conditions is brighter than astronomers measured with the first quarter Moon in the best astronomical sites (Walker 1987). The 93% of US population and 40% of the World population, live under a night sky brighter than they could have in the same place with first quarter Moon at 15 degrees elevation (Krisciunas and Schaefer, 1991) if light pollution would be zero. So they live in a perennial moonlight. They rarely realize it because, the Moon light sums to the artificial light so that they still perceive an increase of the brightness which seems normal. We also found that for 80% of US population and about one fourth of the World population the sky brightness is even greater than what astronomers measured close to the days of full Moon in best astronomical sites (Walker, 1987). The "night" never really come for them even because this sky brightness is approximately the typical zenith brightness at nautical twilight (Schaefer, 1993). Figure 1 shows the "artificial moonlight" at sea level in North America under standard clean atmosphere. Levels from white (red in color image) to gray indicates respectively the typical brightness: (i) When less than $\sim$100 stars are visible even at new Moon, (ii) close to the days of full Moon in best astronomical sites or at nautical twilight, (iii) with first quarter Moon at 15° above horizon, (iv) with first quarter Moon at best astronomical sites, (v) as before but in year 2050 assuming typically a 7% yearly growth rate.

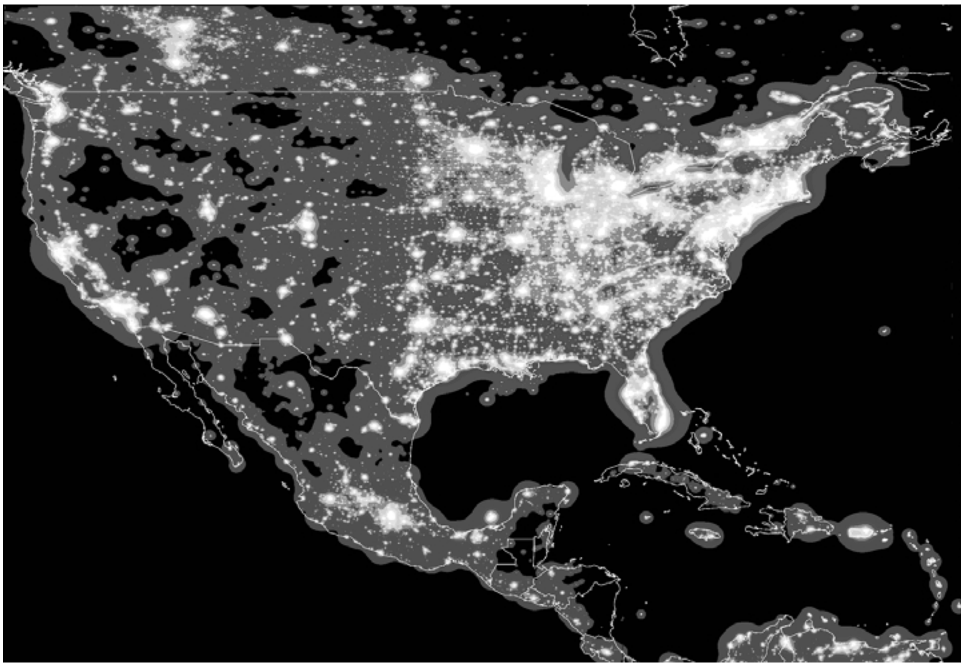

Figure 1. Artificial moonlight levels in North America in 1996–97 for standard clean atmosphere. Levels indicates respectively the typical brightness: When less than ∼100 stars are visible even at new Moon (red); close to the days of full Moon in best astronomical sites or at nautical twilight (orange); with first quarter Moon at 15° above horizon (yellow); with first quarter Moon at best astronomical sites (azure); as before but in year 2050 assuming typically a 7% yearly growth rate (gray).

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