Light Pollution in Barcelona: Night Sky Brightness Analysis

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Abstract: We have studied the annual evolution of Night Sky Brightness (NSB) in the urban area of Barcelona using a Sky Quality Meter photometer pointing to the zenith. Annual, monthly and daily moonlight effects have been considered and analysed and we have searched for changes in brightness at zenith due to singular events.

I. INTRODUCTION

In our society, the concept of light pollution seems strange: can light be a source of pollution? For our civilization, having well-illuminated towns is a strong symbol of development and we usually associate a city seen from the *International Space Station* (ISS) at night with beauty (Sánchez de Miguel, 2015). We rarely think about the consequences coming from this over illumination. Light pollution is defined by the *International Dark Sky Association* (IDA) as all adverse effects generated by artificial light, for example: light illuminating non-necessary areas, glare, wrong distribution of illumination, waste of energy for excessive consumption and light scattered to the atmosphere (Skyglow). These phenomena have negative effects on natural environments, human health (both psychological and physiological) and astronomy (Ribas, 2015).

In the last century, light pollution has became a problem for astronomers, and all new observatories have been placed in remote places, far away from big cities and their excessive illumination. Due to this problem, characterizing light pollution and it's effects on NSB became an important field in astronomy.

In 2001, Catalonia approved the first law to protect night environments, with a first campaign of measurements around the territory. Since 2012, measurements have been restarted by the *Universitat de Barcelona* (UB) and *Parc Astronòmic Montsec* (PAM) in natural reserves, specially in Montsec (Spain), that has been declared a Starlight destination. Besides a Network of SQM's (Section II) has been created for monitoring NSB around the territory (Ribas, 2015). It includes a SQM detector in the Faculty of Physics whose results are discussed in this paper, which is fixed while pointing to the zenith. Its measurements are taken automatically using PySQM software (Nievas & Zamorano, 2014), taking a measure of our zenith's brightness approximately every minute. In the rest of Spain we can find other examples of actions focused on preserving dark sky, such as *Ley del Cielo de Canarias* (1998), the Galician NSB Monitoring Network (Bará, 2014), and studies of light pollution in Madrid (Sánchez de Miguel, 2015).

Moreover, the protection of dark sky is not only a scientific problem since the destruction of it implies the destruction of the nocturnal environment and doesn't allow people to enjoy night sky elements -e.g. constellations, planets, the Milky Way,...- despite it is an inalienable right of humanity (Marín & Jafari, 2008).

II. SKY QUALITY METER

Measuring and quantifying NSB is necessary for protecting territories from light pollution and determine the quality of the sky - There are several detectors designed with this purpose (Ribas, 2015). However they are usually expensive, require a heavy transport or have a slow set up. The Sky Quality Meter (SQM) is a solid state TAOS TSL 237S detector (silicon photodiode), and provides a useful, low cost tool to measure NSB, being able to be used for both amateur and professional astronomers. It can be used to obtain spatial NSB maps of some regions (Sánchez de Miguel, 2015), NSB evolution information (Bará, 2014) or to construct all-sky NSB maps (Zamorano et al., 2013).

In astronomy brightness has historically been measured in magnitudes (*mag*), so NSB is given in $mag/arcsec^2$ - i.e. brightness per solid angle - following a logarithmic scale.

$$m = -2.5 \cdot log(Flux) \tag{1}$$

We should remark two facts: First, that because of this logarithmic scale, a difference of 5 *mag* leads to a factor 100 in the photon flux. And second, it is an inverse scale: more magnitude implies darker sky. In this way, a natural sky is near 22 *mag* in new moon nights, whereas polluted skies usually reach 16-17 *mag*. Thus, in order to determine NSB at zenith, we expect SQM to measure brightness in a single direction, so we have to know its angular and spectral response to obtain results in $mag/arcsec^2$. These studies were made carefully by other authors (Ribas, 2015). It may be interesting to remark that a SQM photometer has a spectral response between 320 - 1050 nm, but uses a HOYA CM-500 filter to adapt its range between 320 - 720 nm, i.e. humans'

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night vision. It has been proved that in this regime, an SQM has a similar response to Johnson's V band (Cinzano, 2005).

There are different kinds of SQM photometers designed by Unihedron company and we have used a SQM-LE (lectured by ethernet port). All of these are calibrated by Unihedron with a luxmeter, but they show a systematic uncertainty of 10% (around 0.10 $mag/arcsec^2$) (Kyba et al. 2011) that can be improved with intercalibration between different SQMs. Some campaigns with this purpose have been done in Croatia (2013), Italy (2015) and Spain (2014, 2016) by European project Loss of the Night Network (LoNNe), including SQMs belonging to our project. With the intercalibration, an offset has been obtained for every instrument and is applied to our data (Ribas, 2015).

III. MOONLIGHT EFFECTS ON NSB

NSB is not only due to light pollution, there are some other components apart from skyglow that have importance on it, involving all spectrum, which have been well described previously (Leinert et al., 1998):

1. Moonlight
2. Airglow: Light emission by the atmosphere due to molecular recombination which have been photodissociated by the Sun.
3. Zodiacal Light : Solar light scattered by interplanetary dust.
4. Coronal brightness: Light emitted or scattered by coronal ions.
5. Integrated Starlight: Light from stars which are too weak to be differentiated.
6. Diffused Galactic Light: Light scattered or emitted by our own galaxy dust.
7. Extragalactic Background Light: Contribution from extragalactic sources.

Because these phenomena have weak contributions, in a polluted sky we only expect to notice moonlight and skyglow, and we will focus on them. As we stated in Section I, we have worked on Barcelona - Faculty of Physics station, which belongs to the catalan network. It started running in November 2014 and the data analysed in this work includes a whole year (from November 2014 to November 2015).

A. Annual study

Previous works for Barcelona (Ribas, 2015) and Madrid (Sánchez de Miguel, 2015) are global. In this work we tried to obtain more detailed results.

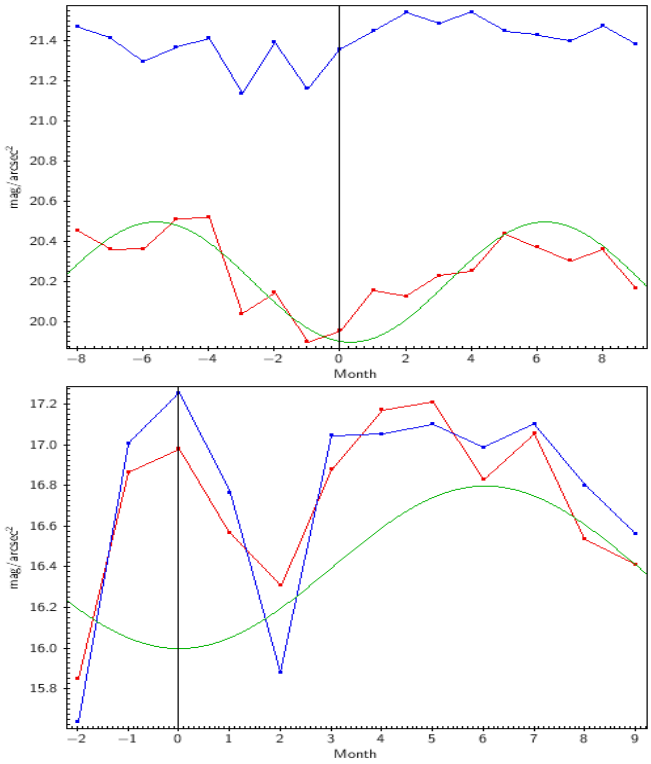

FIG. 1: *Average magnitude vs month plot in Montsec (top) and Barcelona (bottom), with (red) and without (blue) moonlight. Month 0 correspond to January. The green line simulates a linear effect of lunar distance to the zenith on NSB.*

Studying the average magnitude for every month, we expect the zenith magnitude to be brighter in winter than in summer because in this season the moon's height in the sky is higher. This phenomenon can be observed in Montsec (Fig. 1, top). As it is expected for a natural sky, the blue line (data without moon, i.e. data taken after moon setting or before moon rising) has darker values and remains constant, whereas red line (data with moonlight nights) shows a weak sinusoidal behaviour, associated with seasons: higher peaks correspond with summer and valleys with winter.

On the other hand in Barcelona we don't find the same pattern (Fig. 1, bottom). The red and blue lines show the same behaviour and are not related with season, showing non-lunar dependence.

B. Monthly study

In our annual analysis we haven not found any lunar effect on NSB, but now we will focus month by month.

We have done the following steps with all months analysed, but we only show October 2015 as an example. Comparing plots with and without moon data (Fig. 2) we can not distinguish moon's phase cycle, a characteristic trend of very polluted skies (So, 2014).

Another form of showing this loss of moonlight infor-

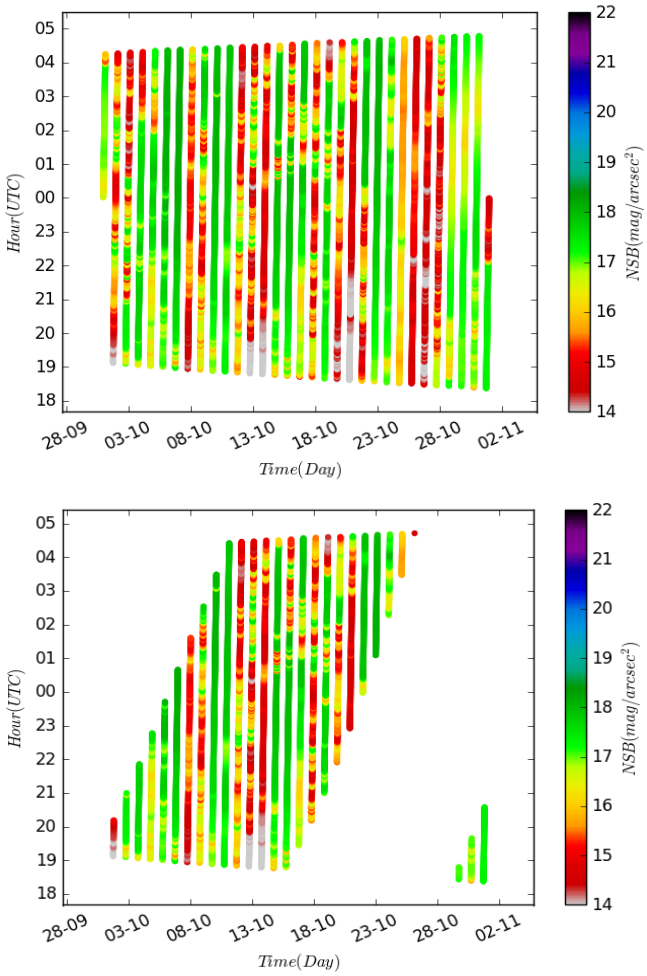

FIG. 2: *NSB evolution in October 2015 with (top) and without (bottom) moonlight data.*

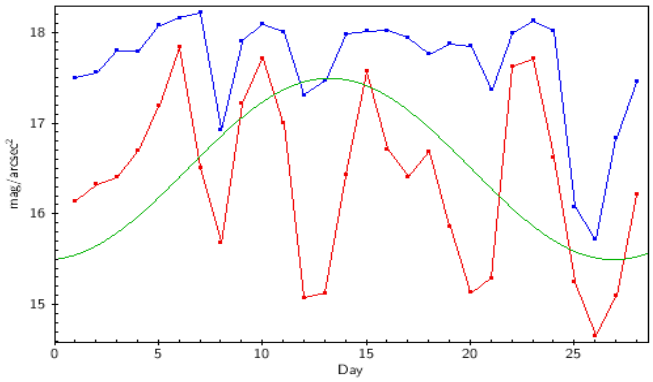

FIG. 3: *Average (red) and highest (blue) magnitude vs day in Barcelona (October 2015). The green line represents lunar phase, where valley corresponds to full moon.*

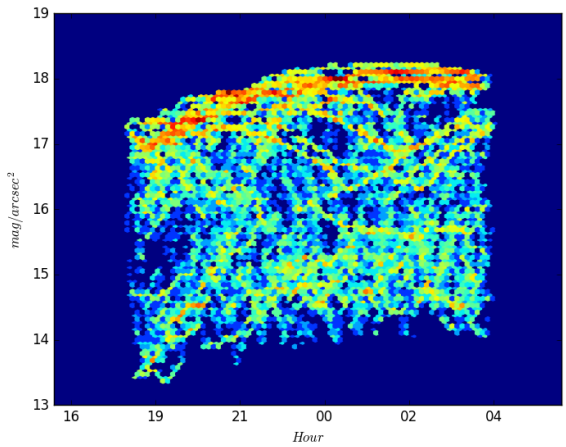

FIG. 4: *NSB density plot in Barcelona from October 2015.*

mation is with Fig. 3, where we can observe how average values of NSB have no correspondence with moon phase. More surprisingly is that the darkest values of every night show the same pattern, confirming a strong light pollution. Only in a few months both profiles have substantial differences. If we compare this behaviour with the presence of clouds measured with a ceilometer installed in the Faculty of Physics since July 2015, we can find how brighter nights correspond to nights with more presence of clouds i.e. cloud coverage acts as an amplifier for light pollution, as it was pointed in previous studies (Kyba et al., 2011).

In addition, we have plotted a density map of frequencies in Fig. 4 for the same data. We can see a similar spread of NSB values and how it is present during all night, with higher frequency around 18 *mag* corresponding sky background measurements, without clouds.

A clear NSB's increase is measured every month at early night, associated with the progressive switch off of commerces, ornamental lights and other human activities (So, 2014). In addition, at the end of the night we suggest that in some months, we can detect the switch on of some urban lights or traffic due to the return of the human activity near 03:00 A.M. (UTC). This phenomenon has not been observed all months in our sample, therefore more data are needed to verify this origin.

To end the subsection, we have tried to recognise from NSB fog's amplification of light pollution as observed in Balaguer and Lleida. A brighter layer in density plots only present during winter months was related to it (Ribas, 2015). This phenomena is not observed in Barcelona globally, but in November 2015 there is a similar pattern. We have tried to recognise fogs with the ceilometer with non-positive results - the behaviour was related with low clouds in our case.

C. Single-night analysis

We have searched for the effect of the moon in a single night due to its height's change. A correlation between lunar topocentric zenith angle and NSB has been observed in clear nights (Fig. 5), where this pattern is

shown clearly.

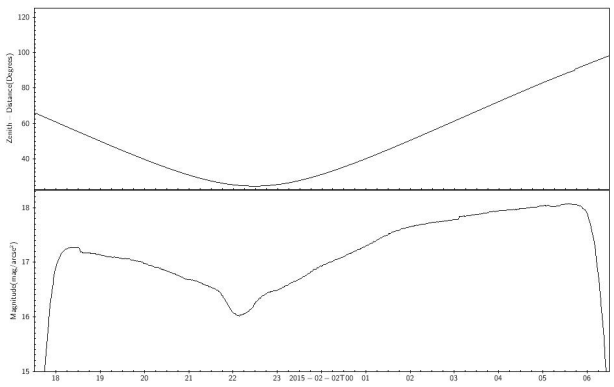

FIG. 5: *Comparison between NSB and zenith angular distance on 01-02-2015 (UTC).*

Here we can identify another interesting phenomenon: we can observe a strange response of the SQM at 22:00 (UTC). It is due the direct entrance of moonlight inside the case, giving values which do not really correspond to NSB (Ribas, 2015).

IV. SINGULAR EVENTS

Now we have a general point of view of Barcelona's NSB. Furthermore, it should be necessary to focus our attention in some events that can affect our measurements and we can characterize and quantify with our SQM.

A. Eclipse

Usually eclipse data are neglected from global studies (So, 2014) but we have used them to characterise light pollution effects in NSB. The night from 27th to 28th of September of 2015 there was a total lunar eclipse observable in Spain which coincided with the moon in the perigee. This night was clear both in Barcelona and Montsec so we can compare their night profiles (Fig. 6) and see that although the maximum magnitude reached is different, the general behaviour is the same in both places.

We can observe how at 02:00 (local time) the magnitude increases reaching a maximum before 04:00, like it was predicted for the eclipse. After a some time with the whole moon darkened, the magnitude raises to its normal values in the same way. This eclipse is more evident in Montsec where the maximum magnitude was close to 22 *mag* during the eclipse, not in Barcelona where its effects are much less pronounced due to light pollution. In Barcelona magnitude variation between the start of the penumbra (00:12 UTC) and the maximum of the eclipse (02:47 UTC) is $\Delta m = 1.35 \pm 0.02\ mag/arcsec^2$, and in Montsec is as high as $\Delta m = 4.95 \pm 0.02\ mag/arcsec^2$.

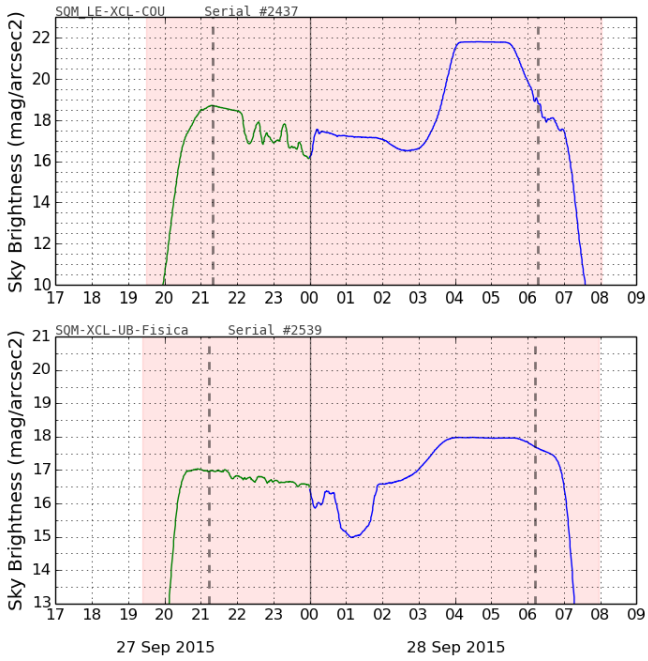

FIG. 6: *Single night of 27-09-2015 (Local Time) during a lunar eclipse in Montsec (top) and Barcelona (bottom).*

B. Camp Nou

Near Faculty of Physics in Barcelona is Camp Nou (F.C. Barcelona's Stadium) and it is a clear focus of light pollution. In a first approach it is not possible to distinguish any effect due to its illumination during a game, but focusing on single-night plots it is possible to observe the switch off (Fig. 7) in all the very clear nights. It usually occurs two and a half hours after starting the match with an average difference of $\Delta m = 0.15 \pm 0.05$ $mag/arcsec^2$ at zenith, and often a weaker second switch off is observed without a regular pattern.

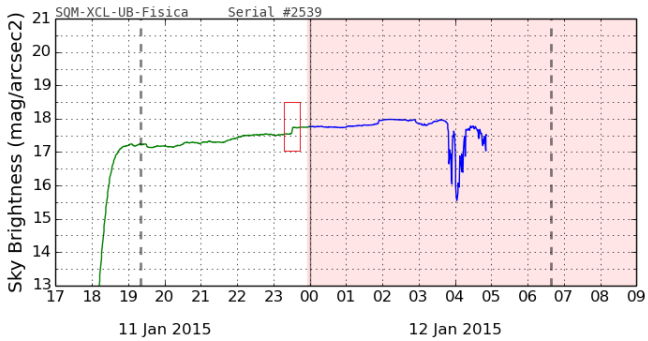

FIG. 7: *Single night of 11-01-2015 during a F.C.B. match, which started at 21:00 (Local Time). We can observe the switch off at 23:30 (squared in red). At the end of the night some clouds are measured.*

Note that we are not observing Camp Nou's illumination: we are looking for the change in zenith's brightness.

C. WWF Earth Hour

We have also looked for changes in NSB during the well known *Earth Hour* promoted by World Wildlife Fund (WWF) on 28th March of 2015, between 20:30 and 21:30 (Fig. 8). As in other previous studies made in Valencia (Marco et al., 2013) there is no decreasing of the NSB and that's because of some factors: the first one and probably the most important is that cloud coverage complicates inspection, making it difficult if not impossible. Also there was a gradual commerce switch off during this hour (Section III-B), making it more hard to distinguish. The same action was done in 2016 with similar results obtained.

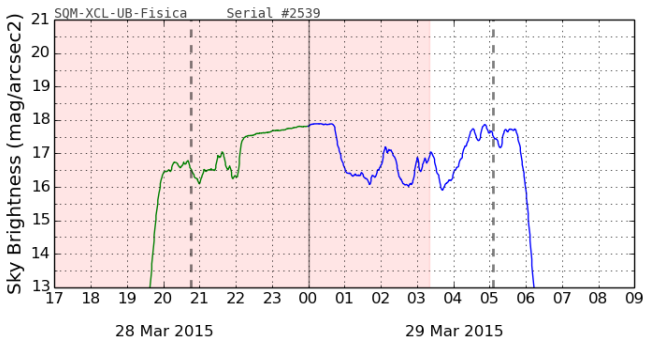

FIG. 8: *Single night of 28-03-2015 (Local Time).*

This kind of actions are great tools to fight against waste of energy, but if we are interested in NSB we should take into account that saving energy does not necessarily lead to reduce light pollution, while reducing light pollution economizes energy. That is because a more efficient luminous system generates light pollution if it is not set up to avoid this effect.

V. CONCLUSIONS

In this work we have seen how our SQM is prepared (Section II) and capable to work characterizing NSB in different regimes: we are able to study natural and artificial affectations on it, both regular (Section III) and singular events (Section IV). In this sense, we can conclude that Barcelona has a large amount of light pollution and an average NSB much more brighter than 22 *mag* corresponding to a natural sky. This leads to a loss of lunar cycles which have been screened (Section III-A and III-B), and moon brightness has been shown to be only detectable at zenith in very clear nights (Section III-C). Furthermore, single natural events have been recognised, as an eclipse (Section IV-A), and Camp Nou's illumination effect at zenith has been detected and quantified (Section IV-B). In order to exemplify the lack of consciousness with light pollution, we have shown how one of the most important actions used to protect the environment has no recognisable effect on NSB (Section IV-C). In the next years, a large amount of data will provide information about the continuity of this patterns and their evolution so it is necessary to remain studying NSB in Barcelona.

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