An Updated View of the Light Pollution at the Roque de Los Muchachos Observatory

M. Pedani (Fundación Galileo Galilei)

The Sources of Light Pollution at La Palma

The Observatorio del Roque de Los Muchachos (ORM), located at La Palma in the Canary Islands is actually the largest European Observatory in the northern hemisphere. The site benefits from good sky transparency, high fractions of clear (~70%) and photometric nights (~60%) and a mean seeing of 0.76" (Muñoz-Tuñón et al., 1997). An inversion layer in the 1300–1700 m height range, guarantees (though with many exceptions in winter) stable observing conditions during 3/4 of the year. About 85,000 people live in La Palma, mainly concentrated in 8 small towns within 15 km of the ORM. Given the altitude of the ORM, the line-of-sight over the sea has a radius of ~180 km, enough to intercept the lighting of the major Canary island Tenerife (800,000 people and 120 km distant) whose coast is visible to the naked eye on very clear nights. Nevertheless, its contribution to the sky brightness, as well as that of two small islands, (El Hierro and La Gomera, 29,000 people and 40 km distant) is negligible. In many cases, the presence of the so called "sea of clouds" below the thermal inversion layer, greatly reduces outdoor lighting, especially during the coldest months.

The Canary Sky Law, introduced in 1992 (McNally, 1994) put strict limits on the type of lamps which can be used for outdoor lighting, on their power, and on orientation with respect to the ground and implied that, after local midnight, most of the high-pressure sodium (HPS) and mercury lamps must be extinguished, as well as all the discharge-tube illumination. In general, low-pressure sodium (LPS) lamps should be used except in the urban areas where HPS lamps are admitted and a non-negligible fraction of mercury and incandescent lamps still exist.

LPS lamps are the best choice for astronomy because their emission is almost exclusively concentrated in the NaD $\lambda\lambda$ 5890–6 doublet, which simply adds to the natural sky glow at these wavelength. No continuum emission arises from these lamps. Other emission lines are Na I $\lambda\lambda$ 5683–8 and Na I $\lambda\lambda$ 6154–61, the latter about 4 times weaker than the former. Detecting the above lines in the sky spectra permits the contributions to the NaD 5890–6 emission from light pollution and the natural sky glow to be disentangled. Up to now, the only way to measure the natural NaD skyglow at ORM was during an artificial 1 hour blackout on the night 24–25 June 1995 to celebrate the 10th anniversary of the inauguration of the ORM (see Benn & Ellison, 1998 for details).

The HPS lamps are the second contributor in terms of light output on La Palma. Their emission is characterised by a smooth continuum in the ~5500 to 7000 Å range. The NaD $\lambda\lambda$ 5890–6 line, is now replaced by a deep void. Other narrow emission lines are: NaI $\lambda\lambda$ 4665–9, NaI $\lambda\lambda$ 4979–83, NaI $\lambda\lambda$ 5149–53, NaI $\lambda\lambda$ 5683–8 and NaI $\lambda\lambda$ 6154–61.

Mercury lamps, though they contribute with a mere 9% to the total luminous flux of the island are another important source of light-polluting lines, especially in the violet/blue region of the spectrum. There is also a weak continuum emission in the 3200–7800 Å range. The most important lines observed in our spectra are: HgI λ 4046, HgI λ 4358, HgI λ 5461, HgI λ 5769 and HgI λ 5790.

Incandescent lamps are a significant source of light pollution before midnight, though their solely continuum emission is not considered in the present work. Nevertheless, BE98 estimated their contribution to zenith sky brightness at *V*-band to be 0.01 mag.

At La Palma, light pollution originates from 17,166 street lamps (end of year 2000, 23% more than reported in BE98) emitting a total of 1.56×10^5 klumens before midnight, reduced to 1.0×10^5 klumens after that hour. If we consider that about 50% of the light is emitted by the fixtures and the ground reflectivity is assumed 10%, we calculate that the amount of power emitted upward by the outdoor lighting is ~16 W/km^2 before midnight and ~11 W/km^2 after. It is noteworthy that the typical sky background of $V = 21.9$ mag/arcsec^2 corresponds to ~9.2 W/km^2.

Observational Data

Our sky spectra were obtained from archival science frames taken in the period August-December 2003 with the 3.58 m Telescopio Nazionale Galileo at La Palma using DoLoRes (Device Optimised for Low Resolution), equipped with a 2048×2048 pixel thinned back-illuminated CCD with 15 µm pixels. Only spectra taken with the LR-B Grism were considered, with a final wavelength coverage of ~3800–8000 Å. The slit widths used were 1.0" and 1.3", yielding a resolution of 2.8 Å/pix and 3.6 Å/pix respectively. Wavelength comparison lines were obtained with a Helium lamp at the beginning of each night. For the present study, only deep exposures taken with airmass < 1.3 during photometric, moonless nights with low extinction were selected. After a careful visual inspection, those spectra showing very similar content of light pollution lines were aligned and co-added to build six template spectra (hereinafter groups). These groups span a wide range in azimuth, epoch of the year and observing conditions, crucial to disentangle environmental and seasonal effects. As reported by BE98, we also found noticeable night-to-night variations in the intensity of the light pollution lines; this could be due to the presence of clouds below the ORM, blocking most of the outdoor lighting. To reduce the errors on the final line fluxes, we decided to include in the same group only those spectra whose NaD λ 5892 line fluxes differed by no more than 30 %. In particular, the spectra with the highest Na line fluxes (less cloud cover) were considered.

Line	Group1	Group 2	Group 3	Group 4	Group 5	Group 6
Hg I λ4046	3.4	5.2	9.5	6.1	10.2	6.3
Hg I λ4358	5.6	7.9	22.0	17.6	14.2	4.5
N I λ5199	1.5	15.4	3.2	11.2	5.1	3.1
Hg I λ5461	4.4	5.5	25.7	10.9	8.6	4.7
O I λ5577	310	256	303	234	447	504
Na I λ5683–8	3.5	6.3	30.6	9.5	11.4	3.6
Hg I λ5769	*n.d.*	*n.d.*	7.2	*n.d.*	1.9	1.4
Hg I λ5790	*n.d.*	*n.d.*	4.7	*n.d.*	1.7	0.7
NaD λλ5890–6	189(156)	148(89)	658(431)	284(134)	251(162)	270(161)
Na I λλ6154–61	*n.a.*	*n.d.*	9.5	*n.a.*	9.6	*n.a.*

Table 1. Fluxes of the most important emission lines as measured in our spectra. Values are in R (rayleigh, see BE98 for some useful conversion formulas). When not detected, a line is labeled with "n.d."; if the line was too noisy/faint or either blended with another line, it is labeled with "n.a.". Contribution to NaD λλ5890–6 from light pollution is shown in parentheses.

NaI Lines – Natural and Artificial Contributions

Given the population of lamps at La Palma, the Na I lines are by far the most important sources of light pollution at ORM. BE98 reported a median equivalent width of NaD λ 5892 of ~100 Å (~100 R, $1\,R \equiv 10^{10}/(4\pi)$ photons s^{-1} m^{-2} $ster^{-1}$) during summer, of which ~70 R due to outdoor lighting and ~30 R due to the natural skyglow. The natural NaD skyglow is known to have a strong seasonal variation, going from ~30 R in summer to ~200 R in winter (Schubert & Walterscheid, 2000). A noticeable effect we found in our spectra is the decrease of the Na and Hg lines in the spectra taken after local midnight, when most of the HPS and mercury lamps are switched off, according to the Canary Sky Law.

To disentangle the natural and artificial contributions to the NaD λλ 5892–6 emission we used our Group 5 and 6 spectra taken respectively before and after midnight. Note that no seasonal effect is present since both of them were taken at the end of September 2003. We assumed that all the Na λλ 5683–8 flux of Group 6 is due to LPS lamps while that of Group 5 is the sum of LPS and HPS contributions. Thus the fractional contribution of LPS to NaI λλ 5683–8 emission of Group 5 is 3.6/11.4 = 0.32 and that of HPS is 0.68. From the Philips catalogue of lamps we derived the ratio NaD λλ 5892–6 / NaI λλ5683–8 = 44.6 for the SOX LPS 35 W lamps mostly used at La Palma. For Group 6 we calculate that light pollution from LPS lamps contributes ~3.6×44.6 = 161 R to the NaD λλ5890–6 flux; Group 5 has an identical value since LPS lamps are never switched off during the night. We deduce that at the end of September 2003 the natural NaD λλ5892–6 skyglow at ORM was ~90–100 R.

We also tried another approach to verify our assumptions about the fluxes of Na I λλ5683–8 for Groups 5 and 6. The ratio of the illumination contribution of HPS vs. LPS lighting in La Palma is ~0.48. From the Philips catalogue of lamps, as most of the HPS lamps at La Palma are SON-T 70 W, we calculate that the flux of NaI λλ5683–8 emitted by a LPS lamp is 0.38 times that emitted by a HPS lamp. Thus, for Na I λλ5683–8 of Group 5 we obtain that 3.4 R are from LPS lamps and 8.0 R are from HPS lamps. These values are in very good agreement with those obtained above by simply assuming that all the flux of NaI λλ5683–8 in Group 6 (3.6 R) comes from LPS lamps.

Group 1 (see Figure 1) is our longest exposure spectrum and well represents the average observing conditions at ORM after midnight when looking at ±5 hrs from the meridian. The first important difference from BE98 is that we now clearly detect NaI λλ5683–8 emission, while Na I λλ6154–61 is still undetected. Moreover, the Group 1 spectrum shows that the average contribution of light pollution to the NaD λλ5892–8 flux in the southern regions of sky after midnight is ~150 R, about twice the value measured in 1998.

Group 2 (see Figure 1) is interesting because it was taken towards the NW, a zone with relatively low light pollution as confirmed by the lowest contribution of artificial NaD λλ5892–8 detected in our spectra (89 R). With respect to Group 1, the higher flux of NaI λλ5683–8 is due to the fact that Group 2 was taken before local midnight.

Group 3 has light pollution lines with abnormally high fluxes (see Figure 1). It was taken looking in the direction of the most polluting towns of the island, before midnight and with thin clouds above the ORM (no data are available for the atmospheric extinction). A direct estimate with the above explained procedure of the artificial contribution to the NaD λλ5892–8 gives 431 R, which would result in a natural NaD background of 227 R, somewhat higher than expected at the end of October. In this case, the presence of high clouds could have played a role in reflecting back light pollution to the observatory.

Group 4 is a typical spectrum taken looking toward a moderately polluted

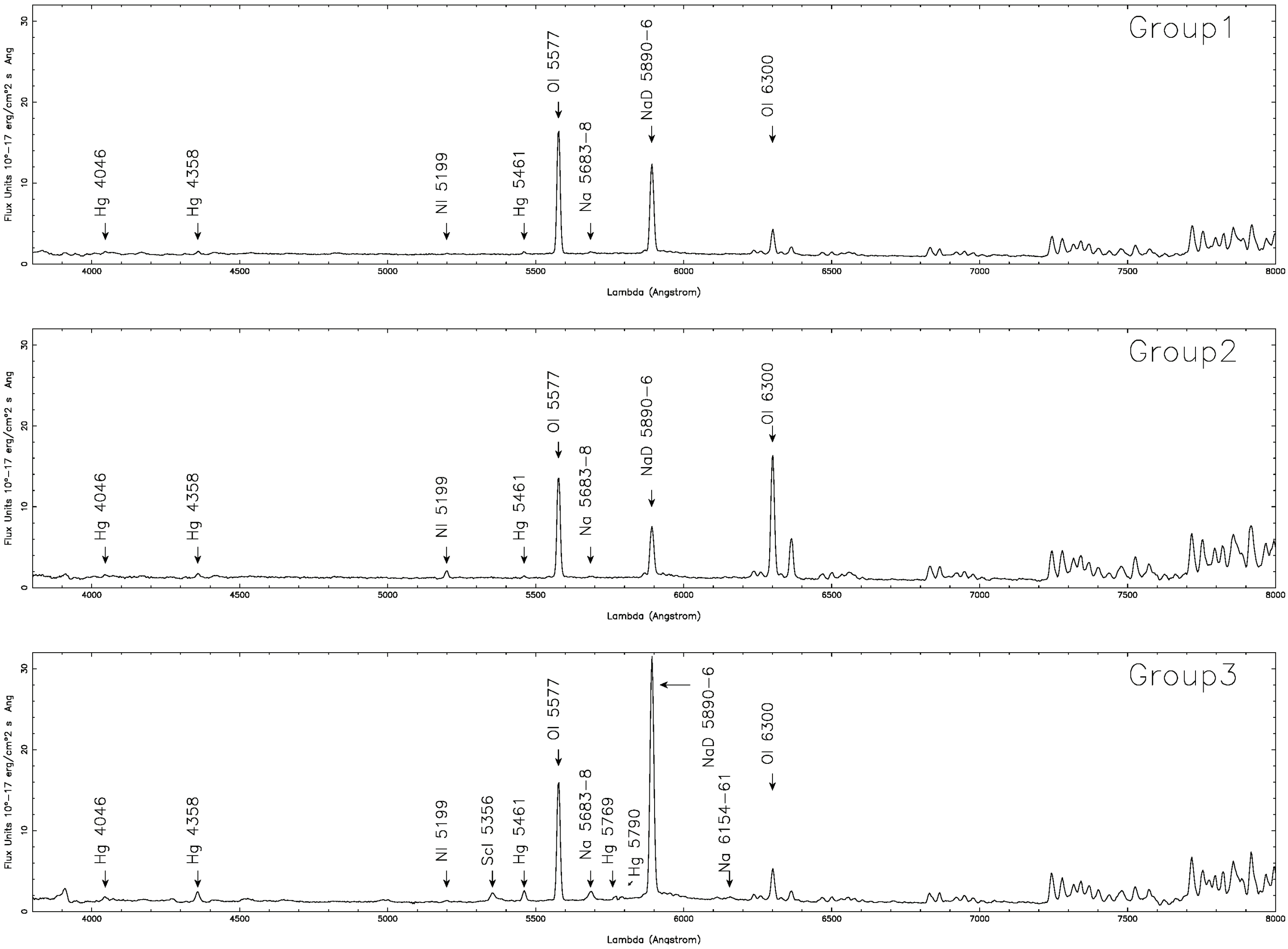

Figure 1. The night-sky spectra. The Group 1 (4 hrs total exposure) is the average of 8 spectra and best represents the average observing conditions at ORM. The Group 2 spectrum was taken towards the NW, the least light-polluted zone at ORM. The Group 3 spectrum was taken towards the most light-polluted region of sky at ORM, before midnight. The presence of thin clouds could explain the abnormally high fluxes of the light polluting lines.

region of sky, ~ 2 hrs before meridian. Here, the effects of the two urban areas of Breña Alta/Breña Baja and partly of Santa Cruz de La Palma are evident. The higher-than-average levels of the Na lines (note the NaI λλ 5683–8 flux of 9.5 R) are also due to the fact that it was taken before midnight. We estimate the contribution of light pollution to the NaD λλ 5892–8 to be 134 R.

The above discussed Group 5 and Group 6 are typical spectra taken at the meridian where the line of sight intercepts the town of El Paso. The decrease of the Na lines fluxes is evident in Group 6, taken after midnight. The contribution of light pollution to the NaD λλ 5892–8 is ~ 160 R, similar to that of Group 4 and Group 1. In all our spectra, the fluxes of the NaD λλ 5892–6 line are always 1.5–2.5 times higher than those of BE98. In principle this indicates that light pollution due to LPS and HPS lamps considerably increased in the last 5 years at La Palma, despite the efforts made to control it.

HgI Lines

If we consider Group 1, the emission of the lines HgI λ 4358 and HgI λ 5461 is about half that reported in BE98 but our spectrum also shows the line HgI λ 4046 detected for the first time at ORM and with intensity comparable to HgI λ 5461.

Although the Group2 spectrum was taken in a less polluted region of sky, it has ~ 40 % more Hg emission than Group 1 and half the Hg emission of Groups 4 and 5 taken toward two towns before midnight. This demonstrates the benefits of the Canary Sky Law; observations made in the less polluted region of sky before midnight imply higher fluxes of Hg lines than those made toward a more polluted region but after midnight.

The most striking feature in our spectra is the line detected in Group 3 (see Figure 1) at 5355.5 Å which we identified as Sc I (tabulated λ is 5356.09 Å, see Table 6 of Slanger et al., 2003). Sc is used as an additive to high-pressure metal halide lamps. Since on La Palma these are used only in the soccer stadiums (to be extinguished after 23:00), our detection could have coincided with some nocturnal sporting activity. The line at 5351.1 Å detected in Group 4 (see Figure 2) can also be identified as ScI emission (tabulated λ at 5349.71 Å). The Group 3 shows other two lines never detected before at ORM: HgI λ 5769 and HgI λ 5790, only observed

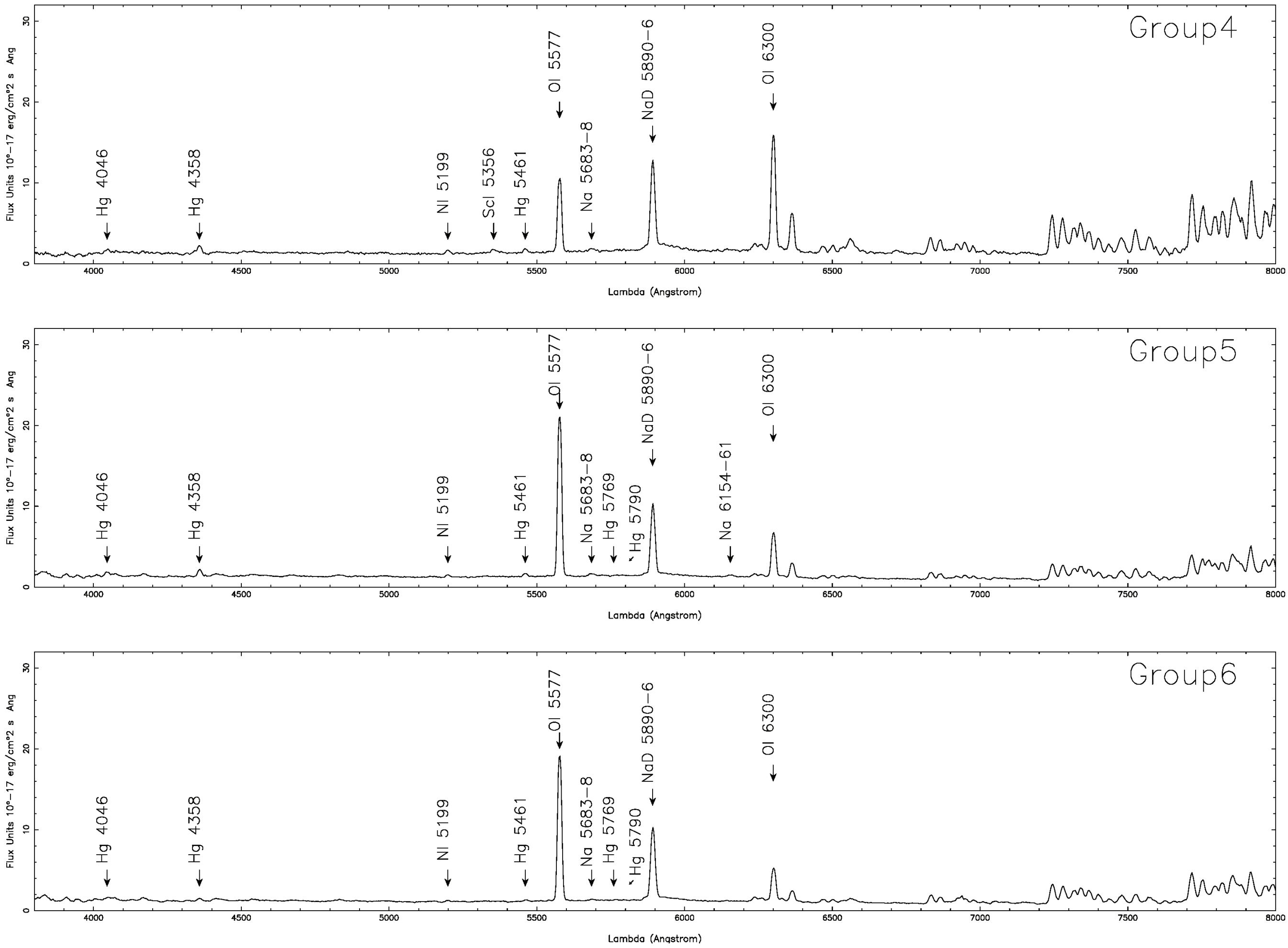

Figure 2. The night-sky spectra. The Group 4 spectrum was taken toward a moderately polluted region before midnight. The Group 5 spectrum was taken toward the meridian before midnight. The Group 6 spectrum was taken toward the meridian after midnight.

at Mount Hamilton (Slanger et al., 2003) and Kitt Peak (Massey et al., 1990). Though very faint, these lines also appear in our Groups 5 and 6, with a clear dimming after midnight evident in the latter spectrum.

To conclude, the average fluxes of the Hg lines detected in our spectra are ~50% fainter than those reported in BE98. When observing toward a town, the Hg lines have about the same intensities as in 1998. Our directional spectra show for the first time the effect of the application of the Sky Law after midnight but it is evident that Hg lamps are never completely extinguished after that hour, since Hg lines are present in all our spectra. For a typical town like El Paso (see Groups 5 and 6), we infer that only half of the mercury lamps are extinguished after midnight. At La Palma, the average intensity of the NaD λλ5892–8 line emitted by LPS lamps increased by a factor of 1.5−2 over the last 5 years and its contribution to the sky background is 0.05–0.10 mag at *V*-band and 0.07–0.12 mag at *R*-band, depending on the region of sky and the time when observations are made. The IAU's recommendation that NaD λλ5892–8 emission should not exceed in intensity the natural background, is definitely no longer met. Na lines such as NaI λλ5683–8 and NaI λλ6154–61 were also detected in our spectra for the first time. Light pollution from Hg lamps is ~50% lower than in 1998, except when observations are made looking toward the towns, before midnight; in this case we found very similar levels. Though in non-optimal atmospheric conditions, we detected in Group 3 one strong line which was identified as ScI. This element is used as an additive in high-pressure metal halide lamps which, to our knowledge, are only used in the soccer stadiums on La Palma. The presence of this type of lamp on La Palma is confirmed by another line at 5351.1 Å detected in the Group 4 spectrum which can also be identified as Sc I emission. ¤

References:

Benn, C. R., Ellison, S. L., 1998, *La Palma Technical Note*, **115**. (BE98)

Massey, P., Gronwall, C., Pilachowsky, C. A., 1990, *PASP*, **102**, 1046.

McNally, D. (ed.), 1994, "The Vanishing Universe – Adverse Environmental Impacts on Astronomy", Cambridge University Press.

Muñoz-Tuñón, C., Vernin, J., Varela, A. M., 1997, *A&AS*, **125**, 183.

Schubert, G., Waltersheid, R. L., 2000, in Allen's Astrophysical Quantities, ed. A. N. Cox (New York: AIP Press; Springer), 4th edition.

Slanger, T. G., Cosby, P. C., Osterbrock, D. E. et al., 2003, *PASP*, **115**, 869.

Marco Pedani (pedani@tng.iac.es)