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Light pollution at the Roque de los Muchachos Observatory

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Abstract

Sky spectra were obtained from archival science frames taken with DoLoRes at the 3.58 m Telescopio Nazionale Galileo with a wavelength range ~3800–8000 Å and resolution of 2.8 and 3.6 Å/pix. Our spectra include all the important sodium and mercury light pollution lines and span a wide interval of azimuth and observing conditions, essential to disentangle environmental and seasonal effects. New sodium and mercury lines were also detected for the first time at the observatory. Light pollution from NaD_{5892-8} emitted by the LPS lamps increased by a factor of 1.5–2 with respect to the average values of 1998. At the same time, light pollution from Hg lines decreased by ~40% and reaches the 1998 levels only when observing toward the towns. The contribution of NaD_{5892-8} from LPS lamps to sky background is 0.05–0.10 mag at V-band and 0.07–0.12 mag at R-band. Synthetic sky brightness measures calculated from our spectra at V, B and R bands are in good agreement with those of [Benn, C.R., Ellison, S.L., 1998. La Palma Technical Note, p. 115] if we take into account that our observations were done during 2003, 7 years after the last sunspot minimum. The effects of the application of the Canary Sky Law are directly visible in the spectra as a 50% dimming of the Hg light-polluting lines in the spectra taken after local midnight.

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1. Introduction

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, and a high fractions of clear (~70%) and photometric nights (~60%) and a mean seeing of 0.76″ (Munoz-Tunon et al., 1997). The ORM is located at ~2300 m altitude, close to the summit of a 2426 m volcanic peak at longitude 17.9°W and latitude +28.7° and very close to the rim of a caldera. An inversion layer

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in the 1300–1700 m height range, guarantees (though with many exception in winter) stable observing conditions during 3/4 of the year. The relative proximity (~200 km Eastward) of the Moroccan coast makes it possible that, especially during the summer, dust from the Sahara desert blows over the island, increasing atmospheric extinction (typically ~0.09 mag at r′-band). To our knowledge, after Benn and Ellison (1998, hereinafter BE98), who presented a low-resolution night-sky spectrum taken at WHT in 1991 (see their Fig. 1), no other works have been published on light pollution at ORM. Our spectra have about three times greater resolution than that of BE98; they span a wide range of environmental parameters and observing conditions and show all the important light pollution lines. During recent years the island of La Palma underwent a strong development of turistic resources with the construction of new hotels, roads and urban areas. Though a special Sky Law exists which establishes the general rules for public and private illumination, this growth inevitably led to an increase of the outdoor lighting with negative consequences for the light pollution at the observatory. The aim of this paper, is to give a comprehensive and up-dated view of the light pollution at ORM during 2003.

The organization of the paper is as follows: the sources of light pollution in La Palma are described in Section 2; the observational data are summarized in Section 3 and the analysis of the night-sky spectra is described in Section 4. Spectrophotometric data are described in Section 5 and conclusions are summarized in Section 6.

2. Light pollution at ORM

About 85,000 people live in La Palma, mainly concentrated in eight 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. During summer, the presence of the anticyclone of Azores causes the clouds to be dispersed, so that outdoor lighting can easily escape upward. The most important sources of light pollution in La Palma are listed in Table 1. Though the study of the sky brightness is not the aim of this paper, their contribution to the zenith sky brightness at V-band has been calculated using the model of Garstang (1989). This model (tested with some US cities) is based on a series of assumptions which do not translate entirely to La Palma.

Though the ground reflectivity and the fraction of aerosols in the atmosphere can be those of a typical high-altitude site in the US (e.g., Mount Graham), the fraction of outdoor lighting escaping upward is much less in La Palma. The relative fraction of lamps installed on La Palma (LPS lamps are much preferred here) is also different from other cities, so that light pollution preferentially arises toward red wavelengths, with different impact on the sky brightness with respect to a site where mercury lamps are predominant. On the other hand, the above model assumes 1000 Lumens/head which approximately agrees with the typical values of La Palma (~1850 Lumens/head before local midnight and ~1000 Lumens/head after).

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, 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 (see Table 2).

LPS lamps are the best choice for astronomy because their emission is almost exclusively concentrated in the NaD_{5890-6} doublet, which simply

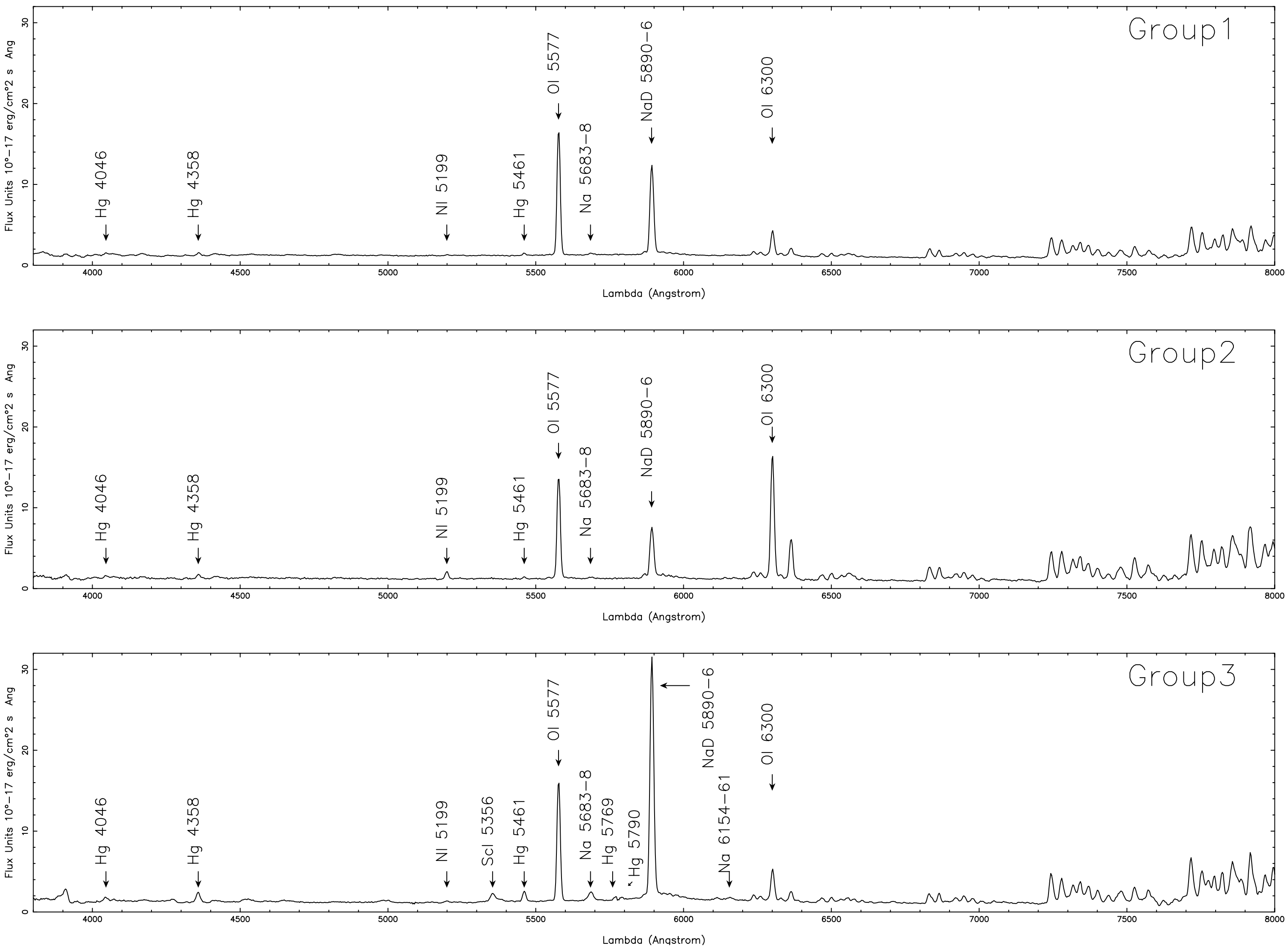

Fig. 1. The night-sky spectra (see Table 3). The Group 1 (4 h total exposure) is the average of eight spectra and best represents the average observing conditions at ORM; the Group 2 spectrum was taken towards the NW, the least light-polluted zone at ORM. The Group 3 spectrum was taken towards the most 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 (see Section 4.1).

Table 1
Sources of light pollution at the ORM at different azimuths (North through East)

Town	Azimuth (°)	Population (2003)	Distance (km)	Δ_{mag} (V)
Barlovento	50	2400	10	0.03
San Andres y Sauces	110	5100	12	0.05
Santa Cruz	125	18,200	15	0.13
Brena Alta/Baja	140	10,800	15	0.07
El Paso	180	7500	12	0.08
Los Llanos + Tazacorte	200	26,100	12	0.32
Puntagorda	280	1800	9	0.03
Garafia	325	2000	9	0.03

The contributions are calculated according to the model of Garstang (1989) and should be considered as upper limits (see Section 2).

Table 2
Type and number of lamps installed at La Palma at the end of year 2000 (Francisco Javier Diaz Castro – private communication)

Type of lamp	Number	MLumens	Fraction of total Flux
LPS	11,086	72,000	0.45
HPS	1350	35,000	0.22
Mercury	1040	14,800	0.09
Incandescent	1026	30,150	0.19
Fluorescent compact	560	670	<0.01
Tube-discharge	2104	6312	0.04

Column 3 gives the total amount of light produced by each class; Column 4 gives the fractional contribution of each class to the total luminic flux of the island.

adds to the natural sky glow at these wavelength. No continuum emission arises from these lamps. Other emission lines are Na_{5683-8} and $Na_{6154-61}$, the latter about four 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 (see Section 4.1). Up to now, the only way to measure the natural NaD skyglow at ORM was during an artificial 1 h blackout on the night 24–25 June 1995 to celebrate the 10th anniversary of the inauguration of the ORM (see BE98 for details).

The HPS lamps are the second contributor in terms of light output on La Palma (see Table 2). Their emission is characterized by a smooth continuum in the ~5500–7000 Å range. The NaD_{5890-6} line, is now replaced by a deep void. Other narrow emission line are: Na_{4665-9}, $Na_{4979-83}$, $Na_{5149-53}$, Na_{5683-8} and $Na_{6154-61}$.

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: Hg_{4046}, Hg_{4358}, Hg_{5461}, Hg_{5769} and Hg_{5790} (see Section 4.2).

Incandescent lamps are a significant source of light pollution before midnight (see Table 2), 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.

3. 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 Optimized for Low Resolution), equipped with a 2048×2048 pixel thinned back-illuminated CCD with 15 μpixels. 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 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_{5892} line fluxes differed by no more than 30%. In particular, the spectra with the highest Na line fluxes (less cloud cover) were considered. Our data were reduced using standard IRAF tasks for long-slit spectra. The final wavelength calibration is accurate to ~0.8 Å r.m.s. Flux calibration was performed by observing spectrophotometric standard stars (typically one per night); within each group, the individual response functions were averaged to reduce errors introduced by slit losses and the variability of the photometric quality of the nights. The final flux calibration is accurate to ~15%.

4. Analysis of the night-sky spectra

4.1. Na Lines – natural and artificial contributions

Given the population of lamps at La Palma, the NaI lines are by far the most important sources of light pollution at ORM. BE98 reported a median equivalent width of NaD_{5892} of ~100 Å (~100 R) 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 and 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 (see Section 2). To disentangle the natural and artificial contributions to the $NaD_{5892–6}$ emission we used our Groups 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 $Na_{5683–8}$ 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 $Na_{5683–8}$ emission of Group 5 is 3.6/11.4 = 0.32 and that of HPS is 0.68. From the Philips catalog of lamps we derived the ratio $NaD_{5892–6}/Na_{5683–8}$ = 44.6 for the SOX LPS 35W lamps mostly used at La Palma. For Group 6 we calculate that light pollution from LPS lamps contributes $\sim 3.6 \times 44.6 = 161$ R to the $NaD_{5890–6}$ 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 $NaD_{5892–6}$ skyglow at ORM was ~90–100 R.

We also tried another approach to verify our assumptions about the fluxes of $Na_{5683–8}$ for Groups 5 and 6. From Table 2 the ratio of the illumination contribution of HPS vs. LPS lighting in La Palma is ~0.48. From the Philips catalog of lamps, as most of the HPS lamps at La Palma are SON-T 70W, we calculate that the flux of $Na_{5683–8}$ emitted by a LPS lamp is 0.38 times that emitted by a HPS lamp. Thus, for $Na_{5683–8}$ 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 $Na_{5683–8}$ in Group 6 (3.6 R) comes from LPS lamps.

Group 1 (see Fig. 1) is our longest exposure spectrum and well represents the average observing conditions at ORM after midnight when looking at ±5 h from the meridian. The first important difference from BE98 is that we now clearly detect $Na_{5683–8}$ emission, while $Na_{6154–61}$ is still undetected. Moreover, the Group 1 spectrum shows that the average contribution of light pollution to the $NaD_{5892–8}$ flux in the southern regions of sky after midnight is ~150 R, about twice the value measured in 1998.

Group 2 (see Fig. 1) is interesting because it was taken towards the NW, a zone with relatively low light pollution (see Table 1) as confirmed by the lowest contribution of artificial $NaD_{5892–8}$ detected in our spectra (89 R). With respect to Group 1, the higher flux of $Na_{5683–8}$ is due to the fact that Group 2 was taken before local midnight.

Group 3 has light pollution lines with abnormally high fluxes (see Fig. 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 $NaD_{5892–8}$ 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 region of sky, ~2 h before meridian. Here, the effects of the two urban areas of Brena Alta/Brena Baja and partly of Santa Cruz de La Palma (see Table 1) are evident. The higher-than-average levels of the Na lines (note the $Na_{5683–8}$ 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 $NaD_{5892–8}$ to be 134 R.

The above discussed Groups 5 and 6 are typical spectra taken at the meridian where the line of sight intercepts the town of El Paso (see Table 1). The decrease of the Na lines fluxes is evident in Group 6, taken after midnight. The contribution of light pollution to the $NaD_{5892–8}$ is ~160 R, similar to that of Groups 4 and 1.

From Table 4 it is evident that in all our spectra, the fluxes of the $NaD_{5892–6}$ 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.

4.2. HgI lines

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

Although the Group 2 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 (see Tables 3 and 4). 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.

Table 3
Overall properties of the night-sky spectra

Name	Exposure time (h)	Slit width (arcsec)	Azimuth (°)	Airmass	Extinction r-band (mag)	Date and time
Group1	4.0	1.0	+90–250	1.19	0.1	July–August 2003; after 24 h
Group 2	2.0	1.0	+265	1.25	0.11	29/08/03; Before 24 h
Group 3	1.0	1.0	+215	1.30	n.a.	29/10/03; Before 24 h + thin clouds
Group 4	1.0	1.3	+154	1.21	0.12	27/12/03; Before 24 h
Group 5	1.5	1.3	+170	1.30	0.12	27/09/03; Before 24 h
Group 6	2.0	1.3	+181	1.15	0.14	27/09/03; After 24 h

Last column reports when the exposures were taken (either before or after local midnight, when restrictions to the outdoor lighting of La Palma are applied; see Section 2).

Table 4
Fluxes of the most important emission lines as measured in our spectra

Line	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6
Hg_{4046}	3.4	5.2	9.5	6.1	10.2	6.3
Hg_{4358}	5.6	7.9	22.0	17.6	14.2	4.5
NI_{5199}	1.5	15.4	3.2	11.2	5.1	3.1
Hg_{5461}	4.4	5.5	25.7	10.9	8.6	4.7
OI_{5577}	310	256	303	234	447	504
$Na_{5683–8}$	3.5	6.3	30.6	9.5	11.4	3.6
Hg_{5769}	n.d.	n.d.	7.2	n.d.	1.9	1.4
Hg_{5790}	n.d.	n.d.	4.7	n.d.	1.7	0.7
$NaD_{5890–6}$	189(156)	148(89)	658(431)	284(134)	251(162)	270(161)
$Na_{6154–61}$	n.a.	n.d.	9.5	n.a.	9.6	n.a.

Values are in 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 $NaD_{5890–6}$ from light pollution is shown in parentheses (see Section 4.1).

The most striking feature in our spectra is the line detected in Group 3 (see Fig. 1) at 5355.5 Å which we identified as ScI (tabulated lambda is 5356.09 Å, see Table 6 of Slanger et al., 2003). Scandium 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 Fig. 2) can also be identified as ScI emission (tabulated lambda 5349.71 Å). The Group 3 shows other two lines never detected before at ORM: Hg_{5769} and Hg_{5790}, only observed 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 (see Table 4).

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 the effect of the application of the Sky Law after midnight but it is evident that mercury 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 Group 5–6), we infer that only half of the mercury lamps are extinguished after midnight.

5. Spectrophotometry

Synthetic night-sky brightness measures at B, V and R bands were also calculated from our spectra. The advantage of using spectra is that both natural airglow (OI_{5577}) and artificial ($NaD_{5892–8}$) lines can be eliminated by replacing them with the average continuum. It is noteworthy that the OI_{5577} line typically contributes 0.16 mag/arcsec^2 to the broadband V (Massey and Foltz, 2000). The values presented in Table 5 were obtained as in Massey and Foltz (2000) and reported to zenith as in BE98. The contribution (in mag/arcsec^2) of the $NaD_{5892–8}$ emitted by LPS lamps to the V and R magnitudes is also reported in Table 5.

The sky brightness values in Table 5 are consistent with those of BE98 if we take into account that our observations were made about 7 years after the 1996.5 solar minimum (sky is ~0.4 mag darker at solar minimum). From Table 5 it is evident a significant increase of light pollution from the $NaD_{5892–8}$ line emitted by LPS lamps in La Palma (BE98 reported a 0.05 mag contribution).

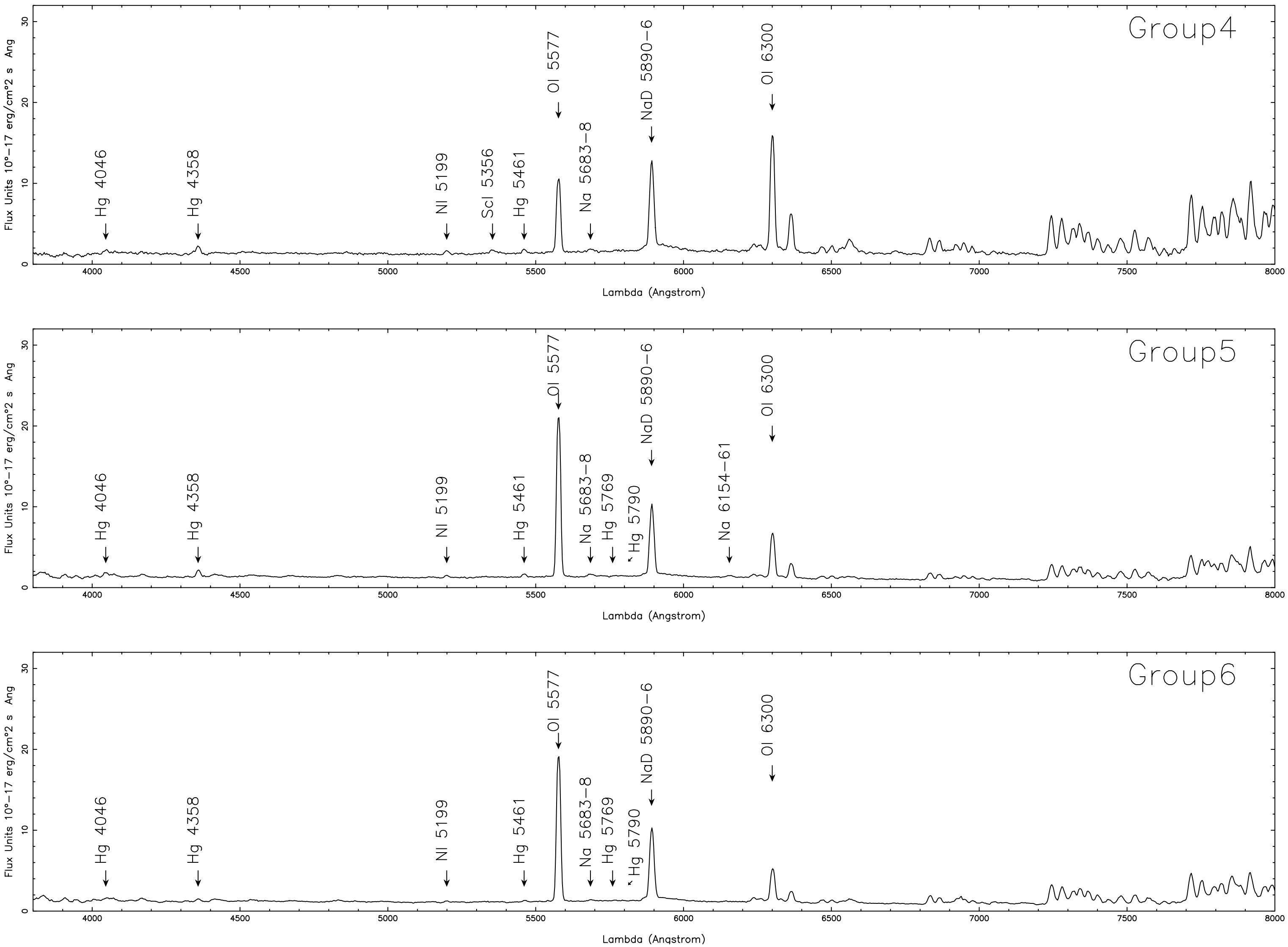

Fig. 2. The night-sky spectra (see Table 3). The Group 4 spectrum was taken toward a moderately polluted region (see Table 1) before midnight; the Group 5 spectrum was taken toward the meridian before midnight; the Group 6 spectrum was taken toward the meridian after midnight.

Table 5
Synthetic sky brightness measures (mag/arcsec^2) as obtained from our spectra (see Section 5)

Spectrum	B	V	R	LPS-V	LPS-R
Group 1	22.48	21.66	20.74	0.09	0.11
Group 2	22.46	21.74	20.79	0.05	0.07
Group 3	22.34	21.48	20.47	0.26	0.31
Group 4	22.40	21.58	20.69	0.08	0.10
Group 5	22.40	21.64	20.72	0.10	0.12
Group 6	22.42	21.67	20.77	0.10	0.12

The natural OI_{5577} and artificial NaD_{5892-8} emission were replaced by the average continuum. LPS-V and LPS-R indicate the contribution of NaD_{5892-8} (in mag/arcsec^2) emitted by low-pressure sodium lamps to the V and R magnitudes, respectively.

6. Conclusions

Light pollution lines at the Roque de los Muchachos Observatory (ORM) – La Palma were studied with archive low-resolution spectra taken with DoLoRes at the 3.58 m Telescopio Nazionale Galileo during 2003. Our spectra cover the wavelength range ~3800–8000 Å, and have resolution of 2.8 and 3.6 Å/pix (slit width 1.0″ and 1.3″, respectively). Only deep exposures taken with airmass <1.3 during photometric, moonless nights with low extinction were selected, resulting in six deep spectra which span a wide range in azimuth, epoch and observing conditions. We showed in Section 4.1 how the detection of Na_{5683-8} permits the artificial and the natural contributions to the NaD_{5892-8} line to be disentangled. The average intensity of the NaD_{5892-8} line emitted by LPS lamps increased by a factor of 1.5–2 over the last 5 years on La Palma 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 IAUs recommendation that NaD_{5892-8} emission should not exceed in intensity the natural background, is definitely no longer met in La Palma. Sodium lines such as Na_{5683-8} and $Na_{6154-61}$ were also detected in our spectra for the first time. Light pollution from mercury 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. Our spectra also show the Hg_{4046} and, in two cases, the Hg_{5769} and Hg_{5790} lines, never detected before at ORM. Though in non-optimal atmospheric conditions, we detected in Group 3 one strong line which was identified as Scandium (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 ScI emission. Synthetic sky brightness measures were derived from our spectra at V, B and R bands (see Section 5). Our values are in good agreement with those of BE98 if we take into account that our observations were done at 2003, about 7 years after the last sunspot minimum (sky is ~0.4 mag darker at solar minimum).

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