THE DANCING SKY
SIX YEARS OF NIGHT SKY OBSERVATIONS
AT ESO PARANAL

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Introduction

The effect of light pollution on optical astronomical observations is devastating (*Fig.1*). Even though the largest observatories are now placed in the most remote corners of our planet, the integrity of these sites (which are becoming also more and more rare) can only be ensured by appropriate regulations accompanied by night sky brightness monitoring campaigns. In this spirit, soon after the beginning of Very Large Telescope (VLT) science operations in Paranal, the European Organization for Astronomical Research in the Southern Hemisphere (ESO) has started an automatic optical sky brightness survey, with the aim of both characterizing the site and studying the long term trend, in order to detect any possible effects of human activity. The results obtained during the first 18 months of operations (April 2000 - September 2001) have been presented and discussed in Patat (2003, hereafter Paper I). This programme, which makes use of all scientific images obtained with FORS1, is building one of the most extensive, accurate and homogeneous optical sky brightness data sets ever studied. As shown in Paper I, these data allow a very detailed analysis, including the study of correlations with other parameters, short, medium and long term variations. The interested reader can find exhaustive reviews on this subject in Roach & Gordon (1973) and in Leinert et al. (1998). Since the publication of the first results, obtained on 174 different nights close to maximum of solar cycle n.23, the data base has been steadily growing and progressively extending towards the solar minimum. Here I will present a global analysis run on the whole data set, which includes broadband observations taken on 668 separate nights between 20 Apr. 2001 and 20 Jan. 2007. Additionally, I present and discuss here for the first time a set of more than 1000 low-resolution long-slit night sky spectra taken with FORS1 between May 1999 and Feb. 2005. In this paper I will only summarize the basic results while a detailed report is given in Patat (2007).

Observations and Data Reduction

The data used in this work were obtained with the FOcal Reducer/low dispersion Spectrograph (hereafter FORS1), mounted at the Cassegrain focus of ESO Antu/Melipal/Kueyen 8.2m telescopes and equipped with a 2048x2048 pixel (px) TK2048EB4-1 backside thinned CCD.

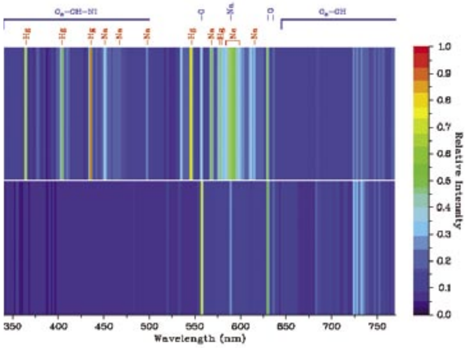

Figure 1. Comparison between a night sky spectrum obtained in an astronomical observatory in northern Italy (upper panel) and at Cerro Paranal (lower panel). The main line/band from artificial (red) and natural (blue) sources are identified on the top.

The photometric data set includes 10,432 images obtained in the UBVRI passbands with both collimators. The reduction procedure is described in Paper I, to which I refer the reader for a more detailed description. Once the instrument signatures are removed from the images, the sky background is estimated using a robust algorithm.

The photometric calibration into the Johnson-Cousins system is then achieved using zeropoints and colour terms derived from the observation of standard star fields, regularly obtained as part of the FORS calibration plan. Finally, the observed values are corrected to zenith using the standard procedure and logged together with a number of relevant parameters.

The spectroscopic data set includes a sub-sample of all long-slit science data present in the ESO archive whose proprietary period has expired by the time this paper has been written. In order to accumulate a wide data sample, I have retrieved from the VLT archive all public spectra taken with the most used spectroscopic setups, for a total of more than 1100 spectra. Exposure times range from a few minutes to one hour.

Dark time night sky brightness

Since the data set includes observations obtained under a wide variety of conditions, in order to estimate the zenith sky brightness during dark time it is necessary to apply some filtering (see Patat 2003, 2007). The results of this selection, which reduced the number of suitable data points to 3736, are summarized in *Table 1*. As one can see, the average values are all within 0.1 mag from those reported in Paper I (see Table 4). In all filters there is a systematic shift towards darker values, with the only exception of the I band. Since the values reported in Paper I were obtained during the sunspot maximum and, given the correlation between solar activity and night sky brightness shown by Walker (1988), Pilachowski et al. (1995) ; Krisciunas (1990) Leinert et al. (1995) and Mattila et al. (1995), Krisciunas (1997), Krisciunas et al. (2007), this behavior was

Table 1. Zenith corrected average sky brightness during dark time at Paranal. Values are expressed in mag arcsec^{-2}. Columns 3 to 8 show the RMS deviation, minimum and maximum brightness, number of dark-time data points, expected average contribution from the zodiacal light, and total number of data points, respectively.

Filter	Sky.Br.	rms	Min	Max	N_{dark}	Δm_{ZL}	N_{tot}
U	22.35	0.19	21.89	22.78	129	0.20	264
B	22.67	0.16	22.19	23.02	493	0.28	1400
V	21.71	0.24	21.02	22.30	692	0.20	1836
R	20.93	0.24	20.42	21.56	1285	0.16	3931
I	19.65	0.28	18.85	20.56	1137	0.07	3001

indeed expected. The values reported in *Table 1* do not reflect the actual change in the night sky brightness, due to the uneven distribution of observations in the covered time interval. In fact, due to a change in the operations schema in Paranal, FORS1 has been sharing the telescope time with other instruments and, as a consequence, this has turned into a smaller data production rate. Moreover, most of the scientific programs scheduled at this instrument are more and more devoted to *target of opportunity* observations of transient objects (like Gamma-ray Bursts and Supernovae), that are performed basically under any condition, hence decreasing the fraction of dark-time data. For this reason, the average values reported in *Table 1* are rather biased towards the sunspot maximum phase.

Sky brightness vs. solar activity

As first pointed out by Rayleigh (1928) and confirmed later on by several other authors (see for instance Rosenberg & Zimmerman 1967; Walker 1988; Krisciunas 1990; Leinert et al. 1995; Mattila et al. 1996; Krisciunas 1997; Krisciunas et al. 2007) many of the emission features in the night sky spectrum show a clear dependency on the sunspot cycle. In particular, B and V present a peak-to-peak variation of ≈0.5 mag arcsec^{-2} during a full solar cycle. Less clear is the behavior at longer wavelengths, which are dominated by the OH emissions, whose intensity is uncorrelated with solar activity.

The data presented here cover the descent from the maximum of sunspot cycle n.23 to the minimum phase. During this interval the Solar Flux Density (hereafter *SFD*) spans from 0.8 to 2.4 MJy, a range which is very close to that of a full cycle (the solar minimum was reached at the beginning 2007). Following what has been done by other authors (see for instance Leinert et al. 1995), I have studied the correlation between the sky brightness nightly averages and the *SFD* monthly averages, computed during the 30 preceding days. The sky brightness measurements have been corrected for the zodiacal light contribution computed for each data point as in Paper I (Sect.4). All passbands show very good linear correlations. In order to give a quantitative representation of the effect, I have fitted a relation of the type $m = m_0 + g\ SFD$ to the data. The results are shown in *Table 2* for all filters. Besides reporting the zeropoint (m_0, mag arcsec^{-2}), the slope (g, mag arcsec^{-2} MJy^{-1}) and their associated statistical errors, the Table includes also the estimated full solar cycle variation ($\Delta m = g|(2.4-0.8)|$), the value attained at solar minimum, evaluated *SFD*=0.8 MJy (m_{min}), the value corresponding to the average *SFD* level <*SFD*>=1.6 MJy (m_{ave}), the *RMS* deviation from the best fit relation (rms), the linear correlation factor (r) and the number of nights used for each filter (N). As one can

Table 2 - Linear least squares fit parameters for the sky brightness vs. solar activity relation. Input data have been corrected for the differential zodiacal light contribution.

Filter	m_{min}	m_{ave}	Δm	m_0	*g*	*rms*	*r*	*N*
U	22.86	22.58	0.61	23.15	-0.36	0.15	0.47	32
B	23.11	22.98	0.29	23.25	-0.17	0.12	0.40	127
V	21.99	21.86	0.30	22.13	-0.17	0.14	0.42	148
R	21.26	21.09	0.37	21.33	-0.22	0.15	0.44	202
I	19.81	19.72	0.20	19.90	-0.11	0.18	0.28	144

see, the values of Δm are smaller than those reported by other authors: with the only exception of *U*, which reaches about 0.6 mag arcsec^{-2}, all the others show values that are smaller than 0.4 mag arcsec^{-2}. Walker (1988) quoted maximum ranges of ΔV≈1.0 and ΔB≈0.8 mag arcsec^{-2} for solar cycle n.21, while Krisciunas (1997) reports ΔV=0.6 for solar cycle n.22, and similar values are reported by Leinert et al. (1995) and Mattila et al. (1996). On the other hand, Liu et al. (2001) quote an increase of the V sky brightness of ≈0.2 mag arcsec^{-2} from 1995 to 2001. This value is consistent with the measures discussed here, especially taking into account that cycle n.23 had a second maximum, which occurred after the observations presented by Liu et al. (2003).

These facts seem to suggest that not all solar cycles have identical effects on the night glow. As a matter of fact, Walker (1998), while revising the result of previous works, had suggested that the relation between intensity of the [OI]5577Å line and the solar activity might vary from cycle to cycle, within a given cycle and possibly with geographical location. Unfortunately, the number of sunspot cycles covered by the observations is still too small to allow a firm conclusion, but the very recent results discussed by Krisciunas et al. (2007), which cover two full solar cycles, seem indeed to confirm this finding.

Seasonal Variations

In the previous work I had attempted to detect night sky brightness seasonal variations but, due to insufficient number of data points, I could not draw any firm conclusion (see Fig.14 in Paper I). Thanks to the much larger sample now available, this analysis becomes feasible, as it is clearly shown in shown in *Fig.2* where, besides reporting the single dark time measurements, I have also plotted the monthly averages. The input data have been corrected for differential zodiacal light contribution and the solar flux dependency derived in the previous section has been removed using the parameters presented in *Table 2*. This semi-annual oscillation (hereafter SAO) is definitely present in V, R and I, while its presence in B is more questionable (U data were not included since the sample in this passband is too poor for this purpose). The modulation amplitude grows at longer wavelengths, shows two maxima around April-May and October, and two minima around July-August and December-January. In general, the variation is more pronounced in Winter-Spring than in Summer-Fall. For example, in I it reaches a peak-to-peak value of about 0.5 mag arcsec^{-2}.

As pointed out by Benn & Ellison (1998), the variable contribution of zodiacal light can mimic a seasonal variation. In order to exclude a possible contribution by this source to the observed behavior, I have analyzed the expected enhancement of brightness due to the zodiacal light for each data point. The conclusion is that the observed SAO is not due to the periodic apparent variation of the ecliptic height above Paranal's horizon.

An interesting thing to be noticed, is that the minima and maxima of the SAO occur out of phase with respect to the Equinoxes and Solstices (see *Fig.2*, vertical dotted lines). While seasonal variations of emission lines and/or bands have been studied by several authors in the past (see for example Chamberlain 1961 and Roach & Gordon 1973 and references therein), broad band measurements are much more scanty and the results not always in agreement. For instance, Schneeberger, Worden & Beckers (1979) report particularly bright values obtained in June at the Sacramento Peak Observatory and they find them to be "marginally correlated with the strong seasonal trend evident in the record of daytime sky brightness observations". In their survey run at the Lowell Observatory, Lockwood, Floyd & Thompson (1990) discuss the seasonal variation, concluding that "neither winter enhancements [...] nor springtime rise [...] is indicated [...]". Benn & Ellison (1998) reach the same result from the analysis of the data obtained on La Palma, concluding that "dark-of-moon sky brightness does not vary significantly (<0.1 mag) with season [...]". Finally, Liu et al. (2003), analyzing data taken at the Xinglong Station between 1995 and 2001, find that "the sky is darker in the fall and winter than in the spring and summer [...]". While part of the discrepancies can be due to latitude effects (see for example Chamberlain 1961), some of the negative detections are probably to be ascribed to non sufficient time sampling and coverage. In fact, the SAO amplitude is at most comparable with the night-to-night fluctuations and hence large and well sampled data sets are required. The observed behavior might indicate that whatever the reason for the periodic variation is, it is not directly related to the amount of sun radiation received by a given patch of the atmosphere during the day. In fact, one might think that since during the austral summer days are much longer than nights, this could result into a brighter nightglow. The data show actually the opposite behavior, since during austral summer the night sky reaches its lowest average value. Moreover, this appears to be in phase with what is observed in the northern hemisphere, where the sky is darker in winter than is summer (see for example Liu et al. 2003). This seems to indicate that the SAO is more related to atmospheric circulation. Remarkably, but after all not surprisingly, polar auroral activity shows a similar temporal fluctuation, with maxima in spring and autumn (see for example Meinel, Neighed & Chamberlain 1954).

Spectroscopic analysis

The [OI]5577Å is generally the most prominent feature in the optical night sky spectrum. It falls right in the center of the V passband, giving a typical contribution of 20% to the global surface brightness in this filter. It has a typical intensity of 250 R, it arises in layers placed at about 90 km (Roach & Gordon 1973) and it displays a marked dependency from solar activity (Rayleigh 1928). This is clearly shown also by the data presented here (*Fig.3*, lower panel), which indicate also the presence of pronounced fluctuations (40 to 750 R peak-to-peak) around the average level (230 R). To quantify the correlation with solar activity and following the procedure that has been applied to the broad band data, I have fitted to the data a law of the type $\log F = \log F_0 + g\ SFD$. The results for this and other lines are presented in Patat (2007). What is interesting to note is that, once the solar dependency is removed from the data, the flux of this line displays a marked SAO (see *Fig.3*, upper panel), similar to that seen in the broad band data (*Fig.2*).

This fact has been already noticed by Buriti et al. (2001), who found that this line and other mesospheric features all show a SAO. The same behavior is, in fact, shown by the [OI]6300,6364Å doublet, which is produced at 250-300 km (Roach & Gordon 1973) and it is known to undergo abrupt intensity changes on two active regions about 20º on either side of the geomagnetic equator (Barbier 1957), hence marginally including the Paranal site. Indeed, the [OI]6300Å measured fluxes show very strong variations (10 to 950 R) around the average level (≈150 R), with spikes reaching 1 kR, so that

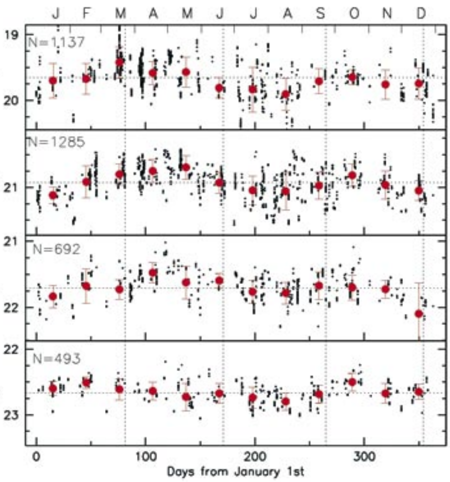

Figure 2. Seasonal variation of dark time sky brightness with respect to the average value. Small symbols are the single measurements while large symbols mark the monthly averages, computed in bins of 30 days each. The error bars indicate the RMS deviations from the average within each bin, while the vertical dotted lines mark equinoxes and solstices. Data have been corrected for differential zodiacal light contribution and solar flux dependency.

the line fluxes span almost a factor 100 (to be compared with the factor 25 measured for the [OI]5577Å). In this respect, the behavior of the [OI]6300,6364 Å doublet is different from that of the [OI]5577Å line, since in a significant number of cases its flux is very small and the line is practically invisible, lost in the OH(9-3) molecular band. In fact, its flux is less than 80 R for more than 50% of the cases considered in this work, the minimum recorded value being 10 R. The range of variability observed for the [OI]5577Å line can produce a maximum variation of about 0.5 mag arcsec^{-2} in the V band, while a similar effect is produced by the [OI] doublet in the R passband. Given the fact that the RMS variation in the V and R passbands is about 0.25 mag arcsec^{-2} (see *Table 1*), this implies that the fluctuations seen in these passbands are not completely accounted by the changes in the atomic O line fluxes.

The two lines appear to show a very weak correlation: the average ratio F(6300)/F(5577) is 0.64, but in a significant number of cases (25%) this ratio is larger than 1. In those circumstances, the [OI]6364Å line becomes the most prominent nightglow atomic feature in the optical domain.

The OH bands show a very tight mutual correlation, in the sense that they appear to vary in unison. Moreover, they do not show any correlation with solar activity (r<0.1 for all bands), while they show a SAO, even though not as pronounced as for the other features. All bands shows the same range of variation, which is close to a factor 2 around the mean value. Given the intensity of these features (especially OH(8-3) and OH(6-2)), their variability is certainly the dominating source of sky brightness fluctuations in the I passband.

The spectral database allowed me to study many other aspects. While I refer the interested reader to Patat (2007) for a thorough discussion, I like to conclude this paper mentioning one final fact, which regards the nitrogen line at 5200Å and, to the best of my knowledge, was never noticed before. This feature is supposed to originate at about 260 km and has a typical intensity of 1 R (Roach & Gordon 1973). As I have shown in Paper I, this line shows abrupt changes, possibly following the behavior of the [OI]6300 Å line. The data discussed here show that the flux of this line ranges from practically zero (the line is not detected) to about 30 R; moreover, the flux distribution is rather similar to that of [OI]6300Å, strengthening the impression that these two lines are related. In fact, the linear correlation factor in the log-log plane is r=0.95 and this appears to be one of the strongest correlation between airglow features found in the dataset presented here, surpassed only by that shown by the OH bands. This line displays also the strongest dependency on solar activity.

The vast majority of astronomers (including myself) spend most of their time trying to get rid out of the sky background, either of natural or artificial origin. Nevertheless, when the human made night light is silent, a whole series of interesting and not yet fully understood phenomena is disclosed. And this makes the night sky itself a beautiful object of research.

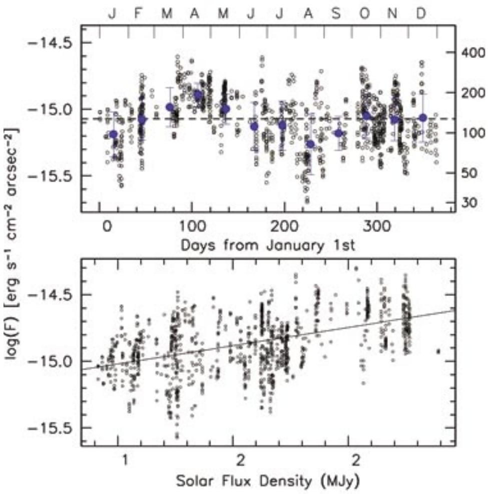

Figure 3. Lower panel: dark time, zenith corrected [OI]5577Å line flux as a function of SFD. The solid line traces a linear least-squares fit to the data. Upper panel: line fluxes as a function of time from the beginning of the year. The data have been corrected to solar minimum (SDF=0.8 MJy) using the relation shown in the lower panel. The large points mark monthly averages and the right vertical scale is expressed in Rayleigh.

Notes and References

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