NIGHT SKY BRIGHTNESS DURING SUNSPOT MAXIMUM AT PARANAL

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IN THIS PAPER WE PRESENT AND DISCUSS A LARGE DATA SET OF UBVRI NIGHT SKY BRIGHTNESS MEASUREMENTS COLLECTED AT PARANAL FROM APRIL 2000 TO SEPTEMBER 2001. THIS UNPRECEDENTED DATABASE ALLOWED US TO STUDY IN DETAIL A NUMBER OF EFFECTS INCLUDING DIFFERENTIAL ZODIACAL LIGHT CONTAMINATION, AIRMASS DEPENDENCY, DAILY SOLAR ACTIVITY AND MICRO-AURORAL EVENTS.

CERRO PARANAL IS ABOUT 108 km S of the nearest town (Antofagasta, 225,000 inhabitants), 23 km NNW from a small mining plant (Yumbes) and 12 km inland from the Pacific Coast. This ensures that the astronomical observations to be carried out there are not disturbed by adverse human activities such as dust and light from cities and roads. Nevertheless, a systematic monitoring of the sky conditions is mandatory in order to preserve the high site quality and to take appropriate action, if the conditions are shown to deteriorate. Besides this, it also sets the stage for the study of natural sky brightness oscillations, both on short and long time scales, such as micro-auroral activity, seasonal and sunspot cycle effects. For this purpose, we have started an automatic survey of the *UBVRI* night sky brightness at Paranal with the aim of both getting, for the first time, values for this site and building a large database (Patat 2003a).

The night sky radiation has been studied by several authors, starting with the pioneering work by Lord Rayleigh in the 1920s. The interested reader can find very good reviews on this subject in the classical textbook by Roach & Gordon (1973) and the more recent work by Leinert et al. (1998).

The optical night sky radiation, as seen from the ground, is generated by several sources, some of which are of extra-terrestrial nature (e.g. unresolved stars/galaxies, galactic background, zodiacal light) and others are due to atmospheric phenomena (airglow and auroral activity). In addition to these *natural* components, human activity has added an extra source, namely the artificial light scattered by the troposphere, mostly in the form of Hg-Na emission lines. While the extra-terrestrial components vary only with position on the sky and are therefore predictable, the terrestrial ones are known to depend on a large number of parameters such as season, geographical position, solar cycle and so on.

In fact, airglow contributes a significant fraction (up to 50%) of the optical global night sky emission and hence its variations have a strong effect on the overall brightness. To illustrate the various processes which contribute to the airglow at different wavelengths, in Figure 1 we have plotted a high signal-to-noise night sky spectrum obtained at Paranal on a moonless night.

In the *B* band the spectrum is rather featureless and it is characterised by the so-called airglow pseudo-continuum, which arises in layers at a height of about 90–100 km. All visible emission features, which become particularly marked below 400 nm and largely dominate the *U* passband (not included in the plots), are due to molecular Oxygen bands.

The *V* passband is chiefly dominated by [OI]557.7 and to a lesser extent by NaID and [OI]630.0,636.4nm doublet. Besides the aforementioned pseudo-continuum, several OH Meinel bands are also present in this spectral window.

All these features are known to be strongly variable and show independent behaviour, probably due to the fact that they are generated in different atmospheric layers. In fact, [OI]557.7 nm, which is generally the brightest emission line in the optical sky spectrum, arises in layers at an altitude of 90 km, while [OI]630.0,636.4 nm is produced at 250–300 km. The OH bands are emitted by a layer at about 85 km, while the NaID is generated at about 92 km, in the so-called Sodium-layer, which is used by laser guide star adaptive optic systems.

In the *R* passband, besides the contribution of NaID and [OI]630.0, 636.4 nm, strong OH Meinel bands begin to appear, while the pseudo-continuum contribution remains constant. Finally, the I passband is dominated by Meinel bands and a broad feature at 860-870nm, due to O_2.

Several sky brightness surveys carried out in *B* and *V* passbands have demonstrated that the dark time sky shows strong variations within the same night on time scales of tens of minutes to hours, and this is commonly attributed to airglow fluctuations. Moreover, as first pointed out by Lord Rayleigh, the intensity of the [OI]557.7 nm line depends on solar activity. Later on, similar results were found for other emission lines like NaID and OH. Walker (1988) found that *B* and *V* sky brightness is well correlated with the 10.7 cm solar radio flux and reported a range of about 0.5 mag in *B* and *V* during a full sunspot cycle; analogous values were published by other authors, so that the effect of solar activity is now commonly accepted (Leinert et al. 1998).

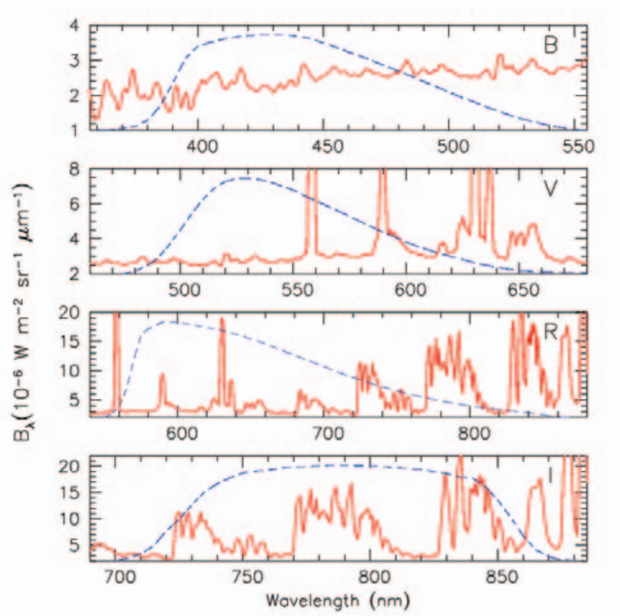

Figure 1 : Night sky spectrum obtained at Paranal in the spectral region covered by *B, V, R* and *I* passbands, whose response curves are indicated by the dashed lines.

Table 1: Zenith corrected average sky brightness during dark time at Paranal. Values are expressed in mag arcsec^{-2}. Columns 3 to 7 show the root mean square (RMS) deviation, minimum and maximum brightness, number of data points and expected average contribution from the zodiacal light, respectively.

Filter	Sky Brightness	σ	Min	Max	N	Δm_{ZL}
U	22.28	0.22	21.89	22.61	39	0.18
B	22.64	0.18	22.19	23.02	180	0.28
V	21.61	0.20	20.99	22.10	296	0.18
R	20.87	0.19	20.38	21.45	463	0.16
I	19.71	0.25	19.08	20.53	580	0.07

ESO-Paranal night sky brightness survey

The observations were carried out in Service Mode with FORS1 between April 1, 2000 and September 30, 2001 and include data obtained on 174 different nights. During these first eighteen months of activity, 4439 images taken in the *UBVRI* passbands and processed by the FORS pipeline were analysed and 3883 of them were judged to be suitable for automatic sky brightness measurements (Patat 2003b).

Due to the kind of scientific programmes which are usually carried out with FORS1, most of the observations were performed at high galactic latitude, and therefore the region close to the galactic plane is not well enough sampled to allow for a good study of the sky brightness behaviour in that area. The scenario is different if we consider the helio-ecliptic coordinate system: due to the geographical position of Paranal, the large majority of the observations have been carried out in the range -30°≤ β≤+30°, where the zodiacal light is rather important at all helio-ecliptic longitudes. As far as the solar activity is concerned, all measurements were taken very close to the maximum of sunspot cycle no. 23, and thus we do not expect to see any clear trend. The dark time values, presented in Table 1, show quite a strong dispersion, which is typically of the order of 0.2 mag RMS. Peak to peak variations in the *V* band are as large as 0.8 mag, while this excursion reaches 1.5 mag in the I band.

As we anticipated, these estimates are certainly influenced by zodiacal light effects. To give an idea of the amplitude of this bias, in the last column of Table 1 we have reported the expected contribution Δm_{ZL} which, in the *B* passband, is as large as 0.3 mag. The sky brightness dependency on the ecliptic latitude is clearly displayed in Figure 2, where we have plotted the deviations from the average sky brightness for *B*, *V* and *R* passbands. For comparison, in the same figure we have superimposed the behaviour expected on the basis of the Levasseur-Regourd & Dumont (1980) data. As one can see, there is a rough agreement, the overall spread being quite large, probably due to the night-to-night fluctuations in the airglow contribution.

As a matter of fact, if the same sky patch is monitored for a sufficiently long time, it clearly displays smooth variations (see Figure 3). In general, the behaviour shown during single nights covers a wide variety of cases and there is no clear average trend. Of course, mild and steady time-dependent effects cannot be ruled out; they are probably masked by the much wider night-to-night fluctuations and possibly by the patchy nature of the night sky even during the same night.

The results we have obtained are compared with those of other dark astronomical sites in Table 2. The first thing one notices is that the values for Paranal are very similar to those reported for La Silla, which were also obtained during a maximum of solar activity. They are also not very different from those of Calar Alto, acquired in a similar solar cycle phase, even though Paranal and La Silla are clearly darker in *R* and definitely in *I*.

All other sites presented in Table 2 have data which were obtained during solar minima and are therefore expected to show systematically lower sky brightness values. This is indeed the case. For example, the *V* values measured at Paranal are about 0.3 mag brighter then those obtained at other sites at minimum solar activity (Kitt Peak, Cerro Tololo, La Palma and Mauna Kea).

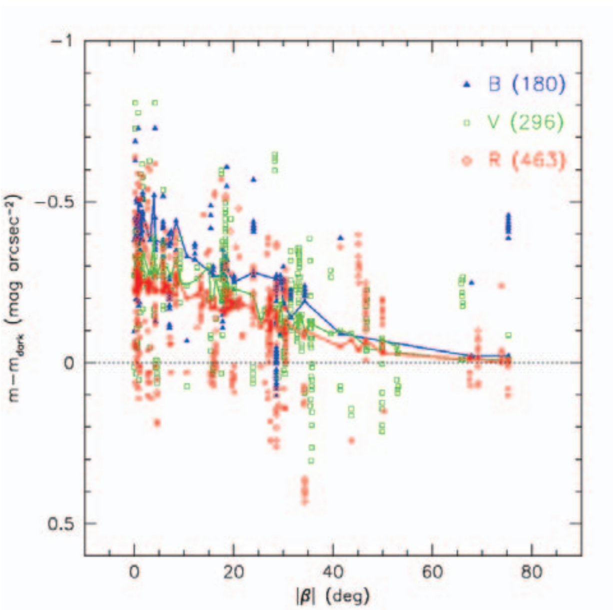

Figure 2 : *B*, *V* and *R* dark time sky brightness variations as a function of ecliptic latitude. The solid lines trace the behaviour expected from the Levasseur-Regourd & Dumont (1980) data for the different passbands.

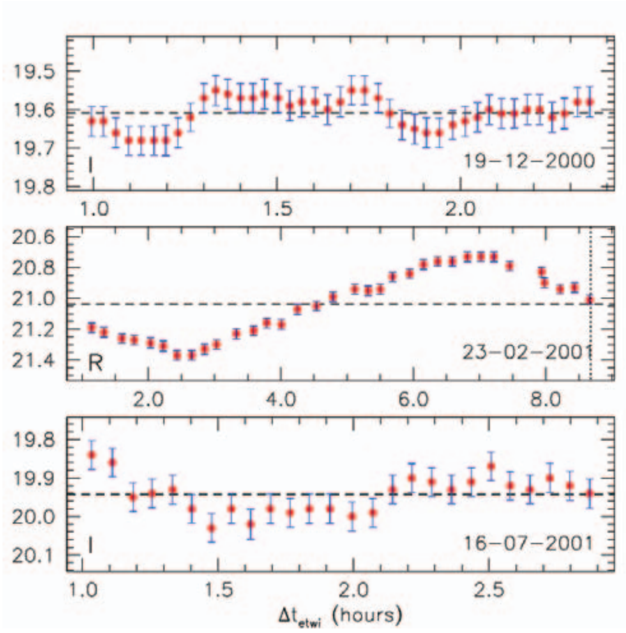

Figure 3 : Time sequences collected on 19-12-2000 (*I*), 23-02-2001 (*R*) and 16-07-2001 (*I*). The data have been corrected for airmass and differential zodiacal light contribution. The vertical dotted line is placed at the beginning of morning astronomical twilight.

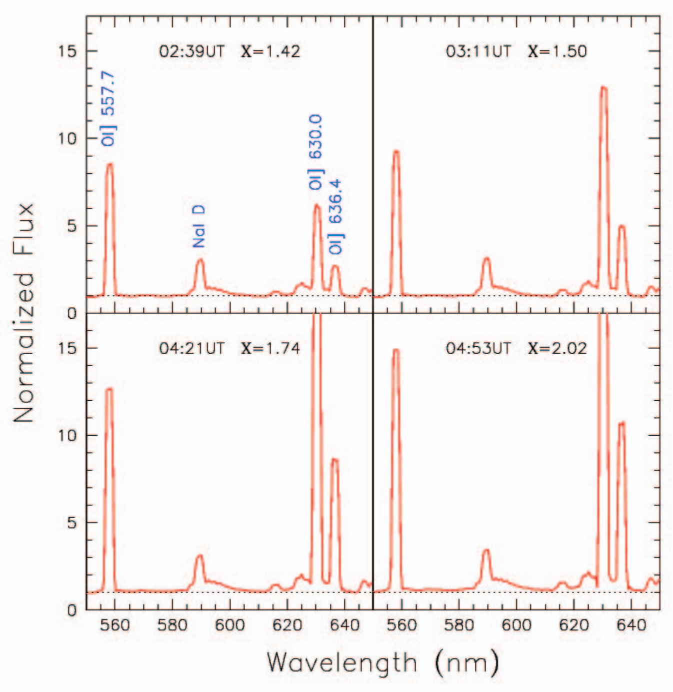

Figure 4 : Evolution of the night sky spectrum on February 25, 2001 in the wavelength range 550-650 nm. In each panel the starting UT time and airmass X are given. For presentation the four spectra have been normalised to the continuum of the first one in the region 560-580 nm.

The overall *BVRI* Paranal sky brightness will probably decrease in the next 5–6 years, to reach its natural minimum around 2007. The expected darkening is of the order of 0.4–0.5 mag arcsec^{-2} (Walker 1988) but the direct measurements which will be provided over the coming years by this survey, currently operated and maintained by the Quality Control Group, will give the exact values for this particular site.

Solar activity

As we have mentioned, during the time covered by the data here presented, the solar activity has reached its maximum. To be more precise, since the current solar cycle has shown a double peak structure, our measurements cover the descent from the first maximum and the abrupt increase to the second maximum. Mainly due to the latter transition, the solar density flux at 10.7 cm in our data set ranges from 1.2 MJy to 2.4 MJy.

Even though this is almost half of the full range expected on a typical complete 11 years solar cycle (0.8–2.5 MJy), a clear variation is seen in the same solar density flux range from similar analyses performed by other authors.

The extrapolation of our *R* nightly average sky brightness turns into an expected variation of 0.24±0.11 mag arcsec^{-2} during a full solar cycle. This value is smaller by a factor of two than that which has been reported by other authors for *B, V* and *uvgyr* for yearly averages (0.4–0.5 mag arcsec^{-2}) and it is consistent with a null variation at the 2σ level. Similar results are obtained for *B, V* and *I* passbands, thus indicating no short-term dependency from the solar activity. As a consequence, it would seem that no firm prediction on the night sky brightness can be made on the basis of the solar flux measured during the day preceeding the observations, as it was initially suggested by Walker (1988).

Sky brightness fluctuations

The night sky can vary significantly over different time scales, following physical processes that are not completely understood. The observed scatter is certainly not produced by the measurement accuracy and can be as large as 0.25 mag (RMS) in the *I* passband; this means that, in this filter, the sky brightness can range over about 1.4 mag, even after removing the effects of airmass and zodiacal light contribution.

To illustrate how complex the night sky variations can be, in Figure 4 we present a sequence of four spectra taken at Paranal during a moonless night, starting more than two hours after evening twilight. For the sake of simplicity we concentrate on the spectral region 550–650 nm, right at the intersection between *V* and *R* passbands, which contains the brightest optical emission lines. Due to the increasing airmass, the overall sky brightness is expected to grow by about a factor 1.2 in *V* and *R*, in very good agreement with what is actually measured. But something very different happens to the [OI]630.0,636.4 nm doublet: the integrated flux changes by a factor 5.2 in about two hours, causing a sensible brightening in the *R* passband. This is easily visible in Figure 4, where the [OI]630.0 nm component surpasses the [OI]557.7 nm in the transition from the first to the second spectrum and keeps growing in intensity in the subsequent two spectra.

The existence of these abrupt changes has been known since the pioneering work by D. Barbier, who showed that the [OI]630.0,636.4 nm doublet can undergo strong brightness enhancements over a couple of hours on two active regions about 20° on either side of the geomagnetic equator, which roughly corresponds to tropical sites. With Cerro Paranal included in one of these active areas, such events are therefore not unexpected.

The case of NaI D lines is slightly different, since these features follow a strong seasonal variation (more than a factor 6!) which makes them brighter in winter and fainter in summer. This fluctuation is expected to produce a seasonal variation with an amplitude of about 0.1 mag in the *R* passband, and therefore very difficult to detect due to the strong night-to-night fluctuations.

To search for possible signs of light pollution, we have examined the last spectrum presented in Figure 4 in the wavelength range 350–550 nm, where a number of Hg and Na lines produced by street lamps fall. As expected, there is no clear trace of such features; in particular, the strongest among these lines, HgI 435.8, is definitely absent. This appears clearly in Figure 5, where we have plotted the relevant spectral region and the expected positions for the brightest Hg and Na lines. In the same figure we have also marked the positions of O_2 and OH main bands: almost all features can be confidently identified with natural transitions of molecular oxygen and hydroxyl. There are probably only two exceptions, which are in any case very weak. Nevertheless, if real, they could

Table 2: Dark time zenith night sky brightness measured at various observatories (adapted from Benn & Ellison 1998). S10.7cm is the Penticton-Ottawa solar density flux at 2800 MHz [2]. Source references are given in Patat (2003a).

Site	Year	$S_{10.7cm}$ MJy	U	B	V	R	I
				mag arcsec^{-2}			
La Silla	1978	1.5	-	22.8	21.7	20.8	19.5
Kitt Peak	1987	0.9	-	22.9	21.9	-	-
Cerro Tololo	1987-8	0.9	22.0	22.7	21.8	20.9	19.9
Calar Alto	1990	2.0	22.2	22.6	21.5	20.6	18.7
La Palma	1994-6	0.8	22.0	22.7	21.9	21.0	20.0
Mauna Kea	1995-6	0.8	-	22.8	21.9	-	-
Paranal	2000-1	1.8	22.3	22.6	21.6	20.9	19.7

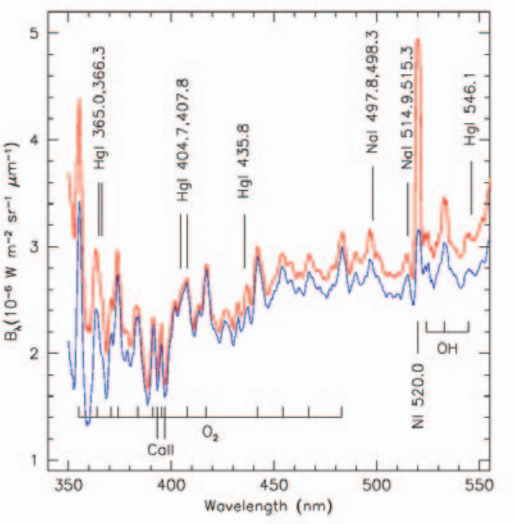

Figure 5 : Night sky spectrum obtained at Paranal on February 25, 2002 at 04:53 UT (blue line). Marked are the expected positions for the most common lines produced by artificial scattered light (upper ticks) and natural atmospheric features (lower ticks). The blue line traces part of the spectrum taken during the same night at 02:39 UT.

indicate the possible presence of some artificial NaI. If this contamination is really present, it should show up with broad NaI D features, which are a clear signature of high pressure sodium lamps. However, the inspection of a low airmass and high signal-to-noise UVES spectrum (Hanuschik 2003) has shown no traces of either such broad components or of other NaI and HgI lines.

There are finally two interesting features shown in Figure 5 which deserve a short discussion. The first is the presence of CaII H&K absorption lines, which are the probable result of sunlight scattered by interplanetary dust.

The other interesting aspect concerns the emission at about 520 nm. This unresolved feature, identified as a NI lines blend, is usually extremely weak. On the contrary, in our first spectrum (blue line in Figure 5) it is very clearly detected and steadily grows until it becomes the brightest feature in this wavelength range. This blend is commonly seen in the Aurora spectrum with intensities from 100 to 1000 times larger and it is supposed to originate in a layer at 258 km. The fact that its observed growth (by a factor 4.3) closely follows the one we have discussed for [OI]630.0,636.4 nm, suggests that the two regions probably undergo the same micro-auroral processes.

Such abrupt phenomena, which make the sky brightness variations during a given night rather unpredictable, are accompanied by more steady and well-behaved variations, the most clear of them being the inherent brightening one faces going from small to large zenith distances. In fact, the sky brightness increases at higher airmasses (see Figure 6), especially in the red passbands, where it can change by 0.4 mag going from zenith to airmass X=2. As a result of the photon shot noise increase, this turns into a degradation of the signal-to-noise ratio by a factor 1.6. Unfortunately, there are two other effects which work in the same direction, i.e. the increase of atmospheric extinction and seeing degradation. Combining the three mechanisms one can verify that the average signal-to-noise ratio decreases by about a factor of 2 passing from airmass 1.1 to airmass 1.6 (see Patat 2003a). Such a degradation is not negligible, specially when one is working with targets close to the detection limit.

The Future

The automatic sky brightness survey we have presented here continues to run. Since its start, it processes all Service Mode imaging frames obtained with FORS1 at a current average rate of more than 2600 measurements per year. This, coupled with the high accuracy one can achieve with an 8m telescope, has already given the unprecedented chance of investigating in detail a number of effects and of getting, for the first time, the optical night sky brightness for Paranal. These values are fully consistent with those of other dark sites monitored during maximum solar activity and no signs of light pollution have been detected, neither in the photometry nor in the spectroscopy we have analysed. In particular, there is no indication of a sky brightness enhancement in the critical directions of Antofagasta and Yumbes mining plant, at least not in the zenith distance range covered by the data.

In the next 2–3 years, the night sky is expected to get 0.4–0.5 mag fainter. If this is true, it will have quite a strong impact on the limiting magnitudes one will achieve, especially in the red passbands, allowing the community to push the instrumental limits a bit further. The data collected by the survey will tell us whether this is indeed the case.

As a by product, this project will also allow us to investigate a number of related issues, like the correlation with other ambient conditions, seasonal variations and moon contribution to the global background at a given position. The latter is a particularly important aspect, since it could allow the user to specify less stringent constraints, enlarging the chance that the scientific observations are executed and thus improving the observing efficiency.

In conclusion, we think that this first analysis has shown how useful and interesting these studies are, even if they could be referred to as "the art of getting rid of astronomical objects" which, admittedly, is quite an unusual activity for an astronomer.

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Figure 6 : Paranal's southern horizon as seen from the platform. The original photo was taken by Leonardo Vanzi on October 6, 2002 at 08:33 UT. The Southern Cross is just rising above the Yumbes mining plant; its brightest star, α Cru, is at an elevation of 6°, while α Cru is at only 2°. The sky re-darkening can be seen very close to the horizon.