Night Sky Brightness at Cerro Pachon

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Executive Summary

Cerro Pachon is presently a dark site. The massive change in lighting fixtures taking place at present throughout the II, III and IV regions of Chile as a consequence of the "lighting law" will reverse the tendency for the Cerro Pachon sky to become ever-brighter as the population increases in the surrounding urban areas. Under conservative assumptions, population and night sky brightness models predict that the light contamination should remain below the pre-changeover (2003) level for some decades into the future. Continued strong involvement of the optical observatories in the control of light pollution is needed to ensure that northern Chile remains a pristine environment for existing and new facilities.

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1. Introduction

The growth of the population centers in the vicinity of Cerro Tololo and Cerro Pachon (La Serena-Coquimbo, Vicuña, Andacollo, Ovalle), together with the development of tourism in the region, has caused concern that this population increase, coupled with poor lighting-control practices, could threaten the present dark skies at the observatories in the decades to come.

We begin in section 2 by discussing the nature of the night sky background, and describe how it naturally varies on a variety of timescales. We follow by describing the artificial light environment in Section 3, and continue in Section 4 by modeling the contribution of the closese urban areas near Cerro Pachon to the sky background, and then extrapolate to the future assuming various growth models. This is followed by Section 5 which discusses some recent measurements of the night sky brightness made on Cerro Tololo, and makes comparisons between measurements made on Tololo and some other dark sites. We list some final conclusions in Section 6.

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2. A Sky Brightness Primer

The natural night-sky brightness is made up from several components. From Benn & Ellison, La Palma Technical Note 115 (1998), and for the V band at zenith:

Zodiacal light (mean value):	34 nL

Airglow (varies around the solar cycle):	11-50 nL
Background stars (V>20 + interstellar scattering):	13 nL
Galaxies:	0.1 nL
Aurorae (for latitude <40 degrees):	0 nL
TOTAL:	**58-97 nL**

The natural brightness of the airglow component of the night sky varies on timescales ranging from a few minutes to several years, with longer timescales coupled to the 11-year period of the solar cycle. From the table above the amplitude difference from solar maximum to minimum corresponds to about 0.55 mag. in the V band. The behavior in the shorter term also depends on the passband used, since in general for the optical region of the spectrum the brightness is dominated by emissions from different atomic and molecular species. The modulation with time is a function of the exciting mechanism and its strength, and transition(s) decay time. There is a large literature on the topic, the seminal work is by Chamberlain (Physics of the Aurora and Airglow; International Geophysics Series Volume 2, Academic press, NY, 1961). An excellent astronomically-orientated discussion is that by Ferdinando Patat (ESO Messenger, p115, March 2004) with an in-depth treatment in AA, 400, 1183, 2003. Two figures are reproduced from the ESO Messenger article, the first showing night-sky spectra in the B,V,R,I photometric passbands, and the second shows variations over a few hours for the R and I passbands. These two bands are dominated by OH Meinel band emission, this is very variable, and TASCA (Tololo All Sky CAmera) sequences clearly show the large temporal and spatial variations in timescales from minutes upwards and on spatial scales of a few square degrees.

Figure 1

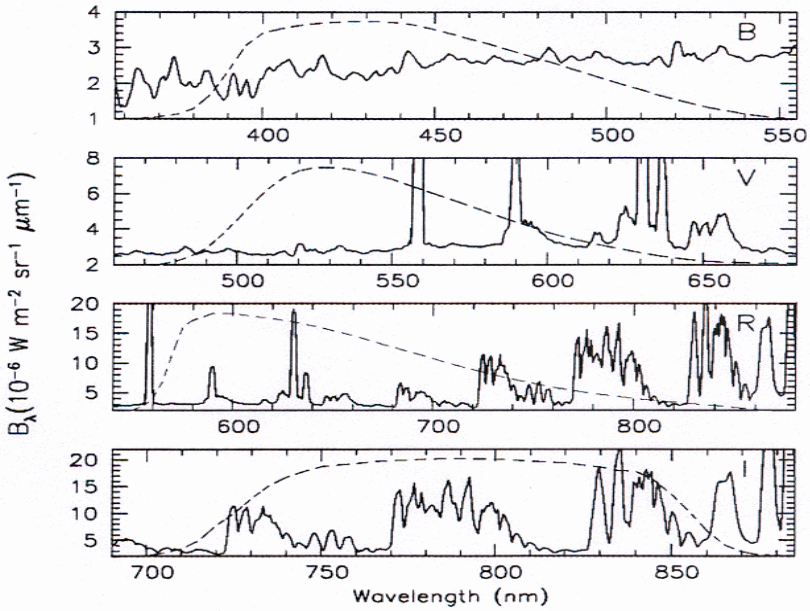


Figure 1 : Night sky spectrum obtained at Paranal in the spectral region covered by *B, V, R* and *I* passbands, whose response curves are indicated by the dashed lines.

Figure 2

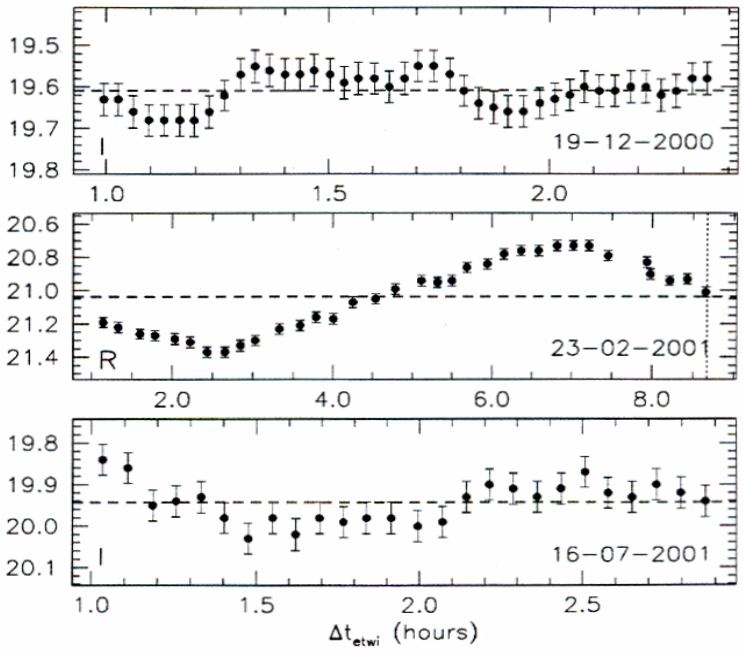
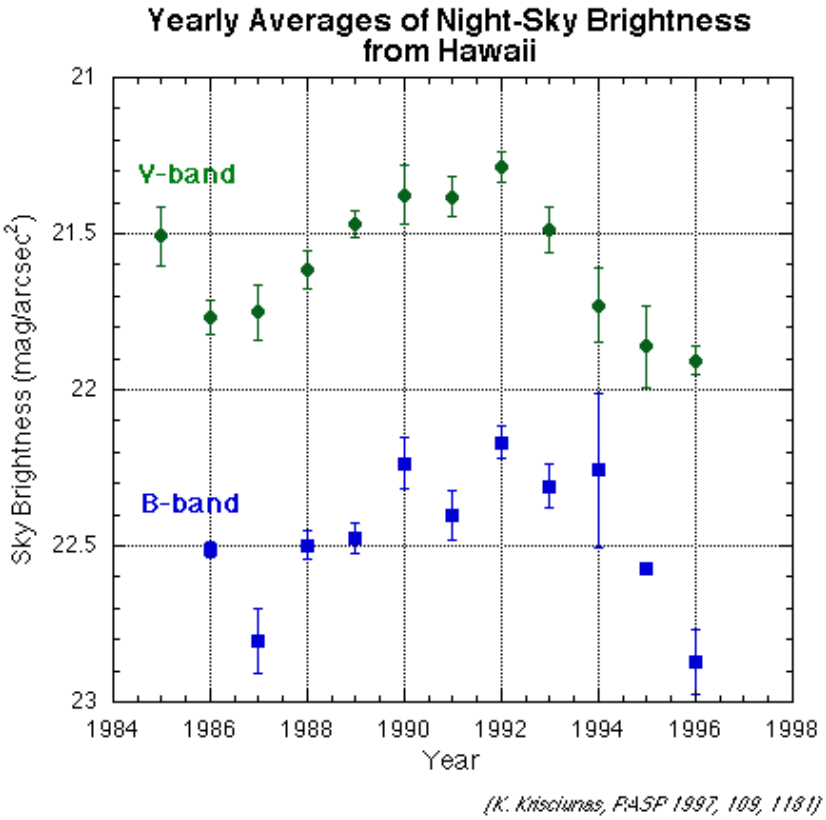


Figure 3 : Time sequences collected on 19-12-2000 (*I*), 23-02-2001 (*R*) and 16-07-2001 (*I*). The data have been corrected for air-mass and differential zodiacal light contribution. The vertical dotted line is placed at the beginning of morning astronomical twilight.

Here we shall concentrate on the V passband measurements, since it is in the V passband that the artificial lines (Na and Hg lines) are most prominent and the natural night sky brightness is lower than in the red. Mercury lines also contaminate the B band. Even for these bluer passbands the short-term natural variation is high, the strong [OI] line at 557.7 nm decays over the first two hours of the night by a factor 2, and there is the "midnight maximum" phenomenon when it brightens for a couple of hours around local midnight, also by up to a factor 2. The conclusion is that significantly sized data sets need to be taken in order to characterize the minutes - to - hours variations in the natural sky background.

Astronomers often do not appreciate that the brightness of the night sky varies around the solar cycle, with a B or V-band peak-peak range of about half a magnitude, this is well shown in Figure 3, from Krisciunas (PASP, 109, 1181, 1997) for Mauna Kea. The data from Patat (2003,2004) would suggest that the amplitude, at least for Chilean sites, is not quite so large shown by Krisciunas (Patat states 0.4-0.5 mag. amplitude in B and V, from several studies).

Figure 3



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3. The Artificial Light Environment

The majority of the Cerro Tololo and Cerro Pachon artificial light contamination originates from urban residential and business sources (street lights, shopping areas, houses, etc.) with a minority component being from industrial lighting, advertising, sports grounds, the mine at Andacollo, etc. The former is almost all high-pressure sodium, most industrial lighting is a mixture of low-pressure sodium and mercury. After five years of effort, spear-headed by the Observatories, a strong "lighting law"(DS686) was promulgated by the Chilean Government in December 1998, ordering that all lighting fixtures in the II, III and IV regions of Chile (which includes all the present and potential astronomical sites) be changed for fixtures which prevent light from shining directly into the sky. The changeover process is underway (all of Vicuna and most of Ovalle are compliant, and at present 30% of all fixtures have been changed) and will be completed by October 2005, The changeover of industrial and private outdoor light fittings should be completed a year earlier, by October 2004. An excellent example is given by before and after pictures of Monte Patria, near Ovalle.

The Chilean environmental protection agency CONAMA, in conjunction with the international optical observatories in Chile, has established a La Serena office (OPCC) specifically to advocate the light control program, by a process of providing technical information and educating local authorities, businesses, and the public, together with monitoring the situation and identifying non-compliance with the program. The OPCC is financially supported by all the observatories, and day-day contact is kept with the AURA Observatory. Additional outreach on this theme is provided by the AURA-supported traveling planetarium

program, and by outreach by AURA staff. There are also links to world-wide efforts via the International Dark Sky Association IDA and the International Astronomical Union Commission 50 (Protection of Existing and Potential Observing Sites).

Another important factor in increasing public and official awareness of the importance in controlling light pollution has been the rapid growth of astro-tourism. CTIO played an important role in the development of the public Mamalluca Observatory near Vicuna, which has spawned similar activities in other municipalities, and an awareness of the importance of dark skies throughout the local communities.

In summary, there is now growing general awareness in Chile of the importance of dark skies, to the benefit of the professional observatories (who are investing in Chile at the rate of $1 billion per decade), to the local tourism industry, and to the populace in general in their appreciation of an unspoiled environment. This is being backed up by a strong law, which is over a short period of time making a radical change to the fraction of energy uselessly radiated into the sky. Chilean law established that all "normas" such as the light pollution law have to be revised every 5 years; this is now happening for the DS686, which will be tightened up and improved to guarantee a continued "dark" future for Chiles northern skies.

We turn now to details of the demography and light output of the region. There is little industry in the IV Region of Chile, and that is not expected to change. The port facilities at Coquimbo, and the mining activities at Andacollo, are the two main examples in the region near Cerros Tololo and Pachon. We thus assume that the light output scales with population, and that street lighting dominates. For this part of Chile, this appears to be a reasonable approximation.

The population statistics from the 1992 and 2002 census records show a 32% growth over the decade for the La Serena-Coquimbo conurbation. This rapid increase is likely not sustainable in the longer term, since as countries become more developed the tendency for the population to concentrate in larger cities tends to go down, together with a declining birthrate. As stated above, there is little industrial growth that would serve to sustain or even increase this growth rate. Therefore we will show two sets of population predictions, one where the growth continues at this extremely high rate, and another where the rate of increase declines from 32% per decade to 15% per decade by 2042. It is evident from the numbers in the below table that La Serena and Coquimbo dominate in terms of population. Of the other nearby towns, Andacollo is a small mining center with little growth potential for both the mining and the population, and indeed the census results show a declining population. Ovalle is an agricultural service center (note we have added in the population of the adjacent Monte Patria). The Limari valley, containing Ovalle, is well-developed, and the population is only likely to grow at a modest rate, the census shows an increase of 13% over the last decade, but even if the increase is much higher than assumed here, the greater distance and intervening hills make this region a less important contributor to the integrated light pollution. Official figures show Vicuna as having an 11% growth rate over the past decade. This town is very important, due to its proximity (light pollution scales as R**-2.5) and the models (see below) show that it terms of the effect on the overhead sky at Cerro Pachon, Vicuna is at present almost as important as La Serena + Coquimbo. In future years as the population of the latter cities increase, they become relatively greater contributors. For all the smaller cities we have assumed that the growth rates measured over 1992-2002 will be applicable for the next few decades.

Population Growth Estimates Based on 1992 and 2002 Census Results:

City/Year	Pachon distance km	1992	2002	2012	2022	2032	2042
LaS-Coq constant growth	66	245K	322K	425K	561K	741K	978K
LaS-Coq declining growth	66	245K	322K	425K	531K	637K	733K

Andacollo	39	12K	10K	10K	10K	10K	10K
Vicuña	24	22K	24K	26K	29K	32K	35K
Ovalle	59	113K	128K	145K	164K	184K	207K

The table below shows the dramatic effect of the implementation of the Lighting Law. We illustrate three cases calculated for the system of street lights in La Serena + Coquimbo, and compare with the unrestricted (i.e. pre-changeover) situation:

Unrestricted : The "pre-change" figures are 312 Mlm total, of which an estimated 47 Mlm goes up directly, and 40 Mlm is reflected up. We apply a factor of 1.5 to the "direct up" light since that does more damage, so the total effective uplight is 111 Mlm.

Case A: All lighting is changed to comply with the law, but the installed power stays the same. The upward light decreases by a factor of about 19, so becomes 3.8 Mlm effectively, plus 40 Mlm reflected makes 43.8 Mlm total.

Case B: All lighting is changed to comply with the law, and installed power is decreased by 30%. The motivation for this is energy savings, since with more efficient fittings the amount of light directed towards the ground will be the same as prior to the change. As an example, the city of Calama in II Region made such a reduction is lamp power when renewing their fittings, locally it is taking an education effort to make the authorities aware of this apparently simple fact, and at time of writing there seems to be lack of political will to reduce lamp power. Thus we have 111 Mlm before change as in Case A, and now only 2.7 Mlm directly up and 28 Mlm reflected up, so a total of 31 Mlm.

Case C: This is as for Case B, but with double ballasts installed which automatically reduce the power by 40% at a certain time of the night (e.g. midnight). This would reduce the power directed upwards to 18 Mlm. We should point out that such an arrangement is already mandatory for industrial lighting, and has already be implemented in Huasco (3rd region).

Effective Energy Delivered to the Sky:

	Direct	**Reflected**	**Total**
Unrestricted (no control)	71Mlm	40Mlm	111Mlm
Case A	3.8Mlm	40Mlm	44Mlm
Case B	2.7Mlm	28Mlm	31Mlm
Case C	1.6Mlm	20Mlm	22Mlm

Thus the effect of the lighting law will be to reduce the upward light by a factor of between 2.5 to 6 depending on the model applied. In the case of authorities wishing to increase lamp power, or increase lamp

density in newly built suburbs, the overall reduction will be approximately a factor two. In our modeling below, *we will conservatively assume we will achieve a factor two reduction (i.e. 55 Mlm in the above table) compared i to pre-changeover of the lighting fixtures. We will call this the* ***Modest Control*** *case below.*

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4. Model Calculations

Note that:

- The models do not take account of intervening terrain. Since direct light escaping at angles close to the horizontal has the most polluting effect at a distance site (Garstang PASP, 101, 306, 1989a) we note that parts of La Serena and Coquimbo, most of Ovalle, and much of the Elqui valley are directly shielded from view. Thus the models will over-estimate the light pollution.

- The models assume an aerosol content of the air "similar to that in the western USA". In hindsight, making this assumption was an error, while it is usually true for the elevated inland towns Vicuna and Andacollo, and often true for Ovalle, it is hardly ever true for La Serena and Coquimbo. These coastal cities almost always have a high humidity environment, and indeed for about 50% of nights there is no light pollution since they are covered in thick fog! Even when not, it is very noticeable that the sky below 10 degrees altitude in the direction of La Serena and Coquimbo is bright due to illumination of the humid air. This same air will attenuate any direct light that would otherwise be responsible for brightening the overhead night sky at Cerro Pachon. Thus although the low altitude glow from La Serena and Coquimbo obviously renders the sky to an altitude of a few degrees quite bright, it has less effect on the overhead sky of interest at Cerro Pachon than if the air was dry, under which circumstances the low altitude glow would be less intense.

- The models assume an output of 300 lumens/ person for 1992, and 1000 lumens/person at later epochs. Garstang (1989a) states that between 500-1000 lumens/person is the standard figure for "an uncontrolled US city".

- The calculations are strictly for the zenith, but are expected to be applicable for a wide area of sky centered on the zenith. The natural sky brightness increases with zenith distance, see Garstang (1989a) and Patat (2003).

The calculation of the amount of light pollution at a given site has been treated by Garstang (1989a) and the evolution with time discussed by Garstang (ARAA, 27,19, 1989b). Here we show as an example how the contributions from direct light, scattering by aerosols, and Rayleigh scattering by molecules vary as a function of zenith distance, calculated by Garstang (1989a) for Mt. Graham.

Figure 4

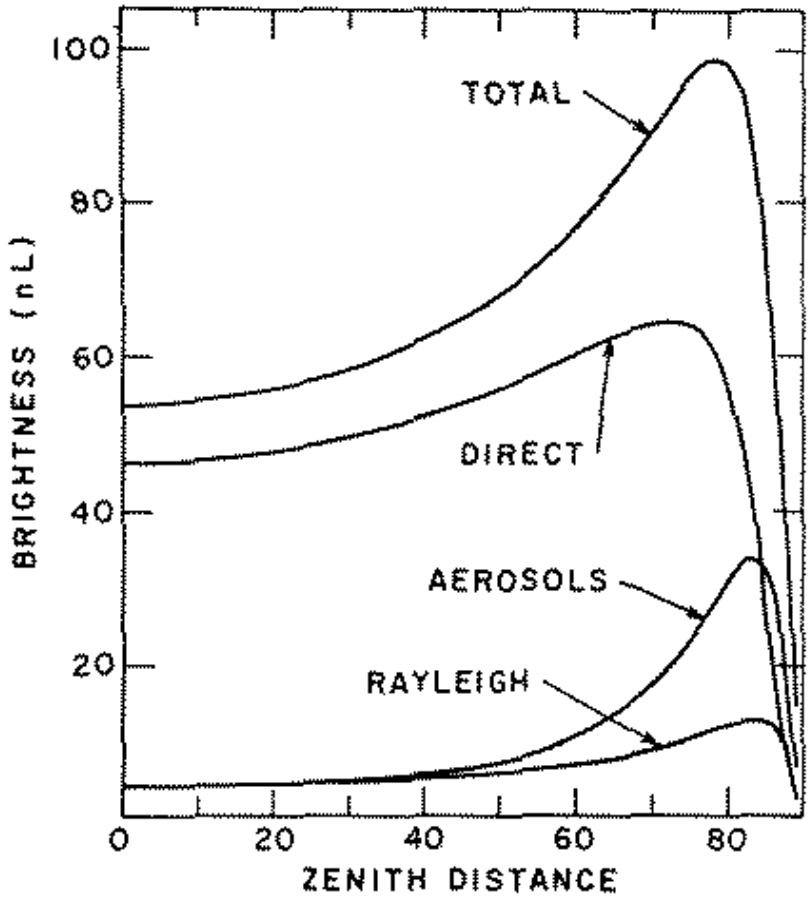

FIG. 4—Contributions to the night-sky brightness by directly transmitted light, by Rayleigh scattering, and by aerosol scattering, calculated for Mount Graham.

Predicted man-made contributions for several observatories that have strong light pollution are shown below, from Garstang (1989b). Note that the solar cycle modulation of 0.4-0.6 mag amplitude has been removed. The pollution growth models are based on population estimates and assume that no attempts are made to reduce the light output per person by installation of environmentally friendly light fixtures, etc. The following calculations will show that Cerro Pachon will remain much darker than all these sites.

Figure 5

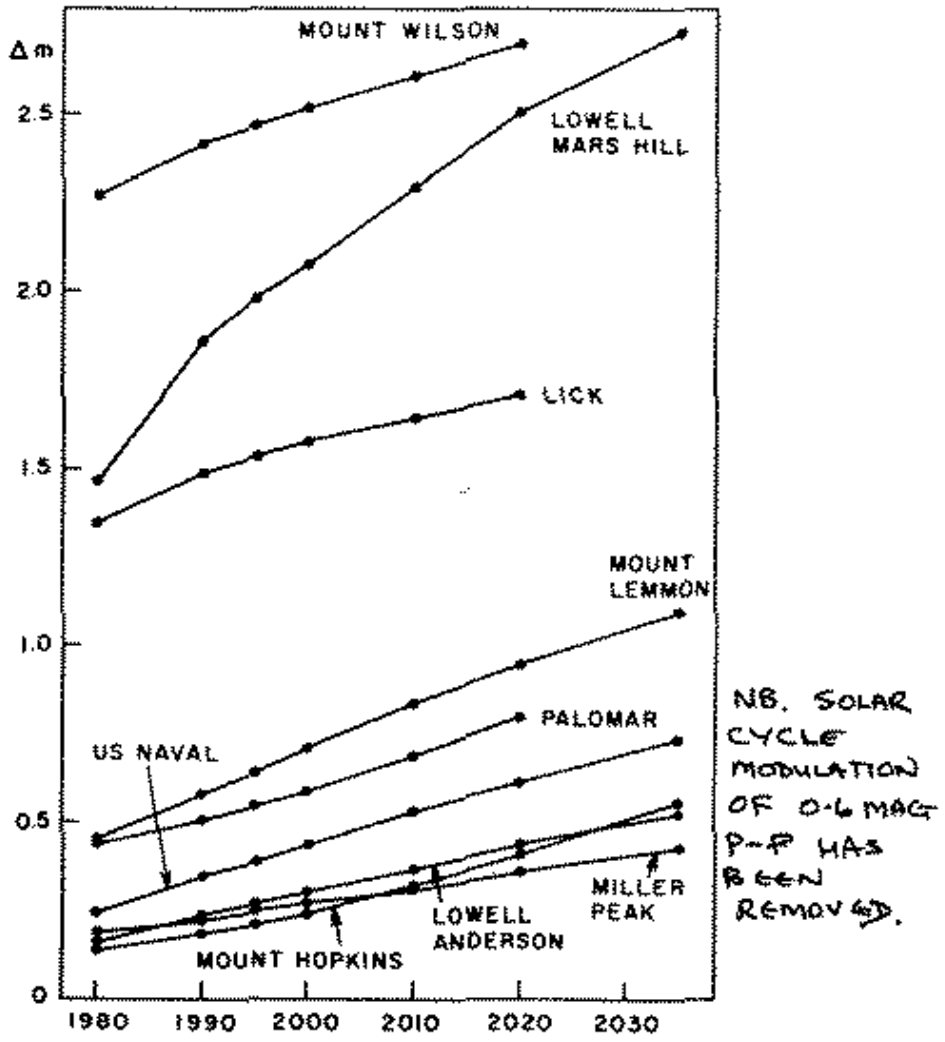

Figure 1 Predicted growth in man-made contributions to the night sky brightness. Δ*m* is in *V* magnitudes per square arcsecond relative to the natural night sky background brightness at sunspot minimum.

The model input parameters are:

- Latitude, longitude and elevation of Cerro Pachon.
- Latitude, longitude and elevations for La Serena-Coquimbo, Vicuña, Andacollo and Ovalle.The cities are treated as point sources.
- Population estimates for each center (1992, 2002, 2012, 2022, 2032, 2042), as given in the table below.
- Light output per person of 300L (1992) and 1000L (others).

Another caveat: These models follow precepts originally described by Merle Walker (PASP, 82, 672, 1973) and developed in several papers by R. Garstang. Garstang showed that an empirical relation given by Walker appeared to be a good approximation for many applications: that the increase in illumination at an angle of 45 degrees from the zenith in the direction of a city was proportional to the population of the city times the distance to the power -2.5, and the average lumens per person was in the range 500 - 1000. See the

discussion by Crawford (Mem. Soc. Astron, Ital. 71, no. 1, 11, 2000). More recent work (see Cinzano et al. MNRAS 323, 34, 2001 and MNRAS 328, 689, 2001; also papers in Mem. Soc.Astron. Ital. 71, no. 1, 2000) shows that there is NOT strong coupling between population growth and lighting contamination in high population-density developed countries, for instance in Europe rapid increase in light output continues despite near-zero population growth. This is of course very worrying. However the R**-2.5 law is not applicable when the contaminating sources are close to a continuum over the landscape, as is often the case in Europe, where overall population density is far higher than in the Chilean desert regions. But it does point to a certain caution needed in interpreting and extrapolating the models.

Model Results

The V-magnitude per arcsec**2 above the natural background (assuming solar minimum sky, of 21.9 mag/arcsec**2 in the V band)) is predicted to be:

Year	1992	2002	2012	2022	2032	2042
Model 1 - Modest Growth of LaS-Coq., Modest Control	0.024	0.092	0.054	0.063	0.072	0.081
Model 2 - High Growth of LaS-Coq., Modest Control	0.024	0.092	0.054	0.065	0.078	0.094
Model 3 - Modest Growth of LaS-Coq., No Control	0.024	0.092	0.106	0.123	0.140	0.156
Model 4 - High Growth of LaS-Coq., No Control	0.024	0.092	0.106	0.126	0.150	0.180

We show in the below table the relative importance of the polluting cities, for **the Model 1 - Moderate Growth, Modest Control** case, as a function of time. As a reminder, for the smaller cities the population model is a linear extrapolation of the 1992-2002 growth, except for Andacollo where we assume the declining population will level off. The *moderate growth* refers to La Serena and Coquimbo, where we assume the present very high growth will decline. *Modest control* is slightly more conservative than the *Case A* defined above.

The tabulated quantities are the zenith increase in background from each city, in nL. Note the natural brightness of the night sky is taken as 54.5 nL:

Year	1992	2002	2012	2022	2032	2042
La Serena + Coquimbo	0.41nL	1.87nL	1.20nL	1.50nL	1.80nL	2.07nL
Vicuna	0.48nL	1.73nL	0.94nL	1.05nL	1.15nL	1.26nL
Andacollo	0.08nL	0.22nL	0.11nL	0.11nL	0.11nL	0.11nL
Ovalle	0.26nL	0.96nL	0.55nL	0.62nL	0.70nL	0.78nL

What conclusions can we draw from these results, remembering that the modeling has uncertainties and we are extrapolating population growth?

- The present effect of the light pollution on the sky brightness is small, but not negligible.
- The solar cycle is still much the dominant effect, with amplitude 0.6 mag. the natural sky brightness at solar maximum is much brighter than the worst case (Model 4) increase over solar minimum brightness, even in 2042.
- The on-going introduction of lighting controls should mean that we do at least as well as the "modest control" used in calculating the corresponding values in the table above.
- It is likely that the very rapid population growth seen for La Serena and Coquimbo over the past decade is not sustainable, and the "modest population increase" values are more realistic. This is not provable, of course.
- The lighting controls now being introduced buy us ~30 years compared to having non-compliant fixtures. In other words, the sky in the decade 2030-2040 is no brighter than it is at present if we can preserve the lighting controls now being installed. Remember that Vicuna is a substantial contributor, so the effect of the rapid population increase of La Serena and Coquimbo is somewhat diluted. However continuing vigilance is necessary. The desire for local authorities not to squander energy may help us to do better than the "modest control" assumed.
- We reiterate that the model assumptions are such that the light pollution from La Serena and Coquimbo is likely to be somewhat over-estimated, and that of course on many nights coastal fog means that there is no pollution at all from these cities.

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5. Measurements at Cerro Tololo

Measuring the night sky brightness in order to quantify contamination in the directions in which we are interested (e.g. zenith distances less than 60 degrees) is difficult due to the necessity of measuring an effect that may be only 1-2 % of the sky brightness. Additionally, interpretation of the results may not be straightforward. We have already shown in Section 2 that the natural brightness varies on timescale of minutes to years with amplitudes of several tenths of a magnitude. The choice of sky position is important, Lavasseur-Regourd and Dumont (AA 84, 277, 1980) model the increase in background as the ecliptic plane is approached, in the V band the effect is 0.3 magnitudes at latitude 0 and falls by roughly 0.05 mag for each 10 degree increase in ecliptic latitude. Thus the measurements below need to be interpreted with care, for example almost all the CTIO 2003 and 2004 results were at the South Galactic Gap with an ecliptic latitude of only 20 degrees.

Night Sky Brightness Estimates from Various Sites (some results from Patat (2003, 2004)

Site	Date	S10.7	U	B	V	R	I	Comments
La Silla	1978	1.5	-	22.8	21.7	20.8	19.5	
Kitt	1987	0.9		22.9	21.9			

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	22.0	22.7	21.8	20.9	19.9	
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	-	-	
Cerro Tololo	1997	1.0	-	22.7	22.0	-	-	
Paranal	2000-1	1.8	22.3	22.6	21.6	20.9	19.7	
Cerro Tololo	2003.0	1.1	-	22.44	21.35	-	19.6	
Cerro Tololo	2003.80	1.3	-	-	21.48	-	20.3	
Cerro Tololo	2003.82	3.0	-	22.67	21.58	-	20.3	
Cerro Tololo	2003.90	1.7	-	22.78	21.73	-	20.1	
Cerro Tololo	2003.97	1.3	-	-	21.1	-	-	
Cerro Tololo	2004.057	1.3	-	22.70	21.86	-	19.7	I airmass 2.0
Cerro Tololo	2004.06	1.3	-	22.68	21.77	-	-	
Cerro Tololo	2004.077	0.9	-	22.61	21.61	-	-	
Cerro Tololo	2005.99		22.1	22.43	21.63	-	20.3	B contaminated by Moon phase 0.22
Cerro Tololo	1992-2006		22.08 (0.03)	22.81 (0.01)	21.79 (0.01)	21.19 (0.01)	19.85 (0.03)	from between 71 (U) and 329 (V) measurements at the 0.9m

The final table line are unpublished data analysed by K. Krisciumas et al.

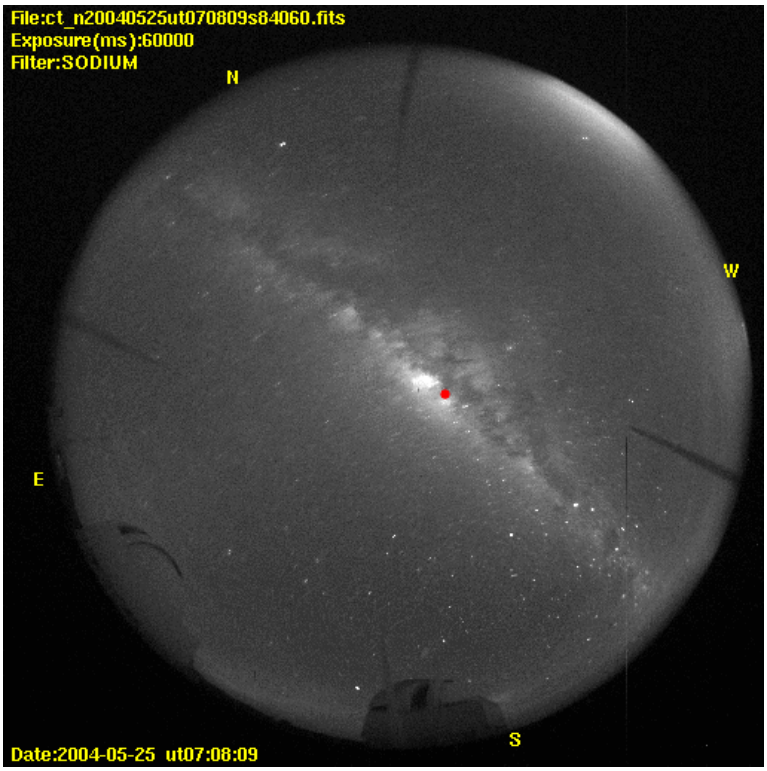
Conclusions and notes from the above table:

- The Tololo sky is still very dark. *We will fill in data for other epochs and filter passbands as they become available*.
- The 2003-2004 CTIO results are values from a few images on single nights and well-illustrate natural variability of the night sky, as discussed in section 2. There is not a 1-1 correspondence between solar radio flux and sky brightness, on a night-night basis, Patat (2003) Figure 13 shows a trend, but with large scatter.

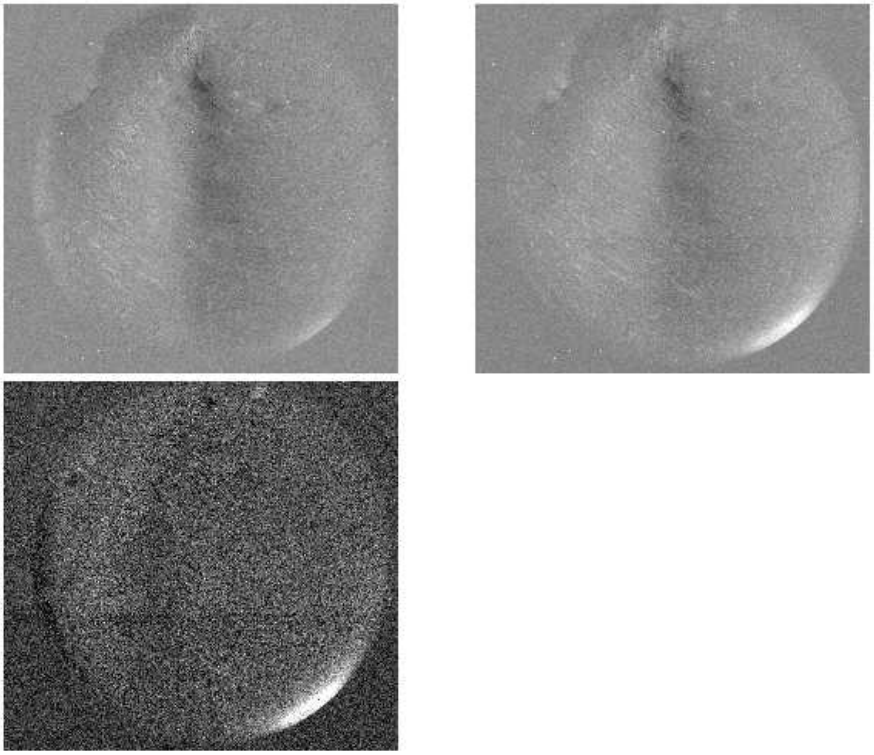
- Cerro Tololo is closer to La Serena-Coquimbo and Vicuña than Cerro Pachon and is roughly estimated to suffer 65% more light contamination than Cerro Pachon. We'll need to analyze a lot more data before we have any hope of seeing long term trends. In addition, it is important to support efforts led by IAU Commission 50 to fund a second epoch of World Atlas of the Artificial Night Sky Brightness.

We now turn to a quick-look at some images taken with the all-sky camera, TASCA. TASCA takes images throughout the night, alternatively through blue and red filters. Pairs of narrow-band Hg and Na images are taken before and after 1 am local time, which is when industries are required by law to turn off Hg lamps.

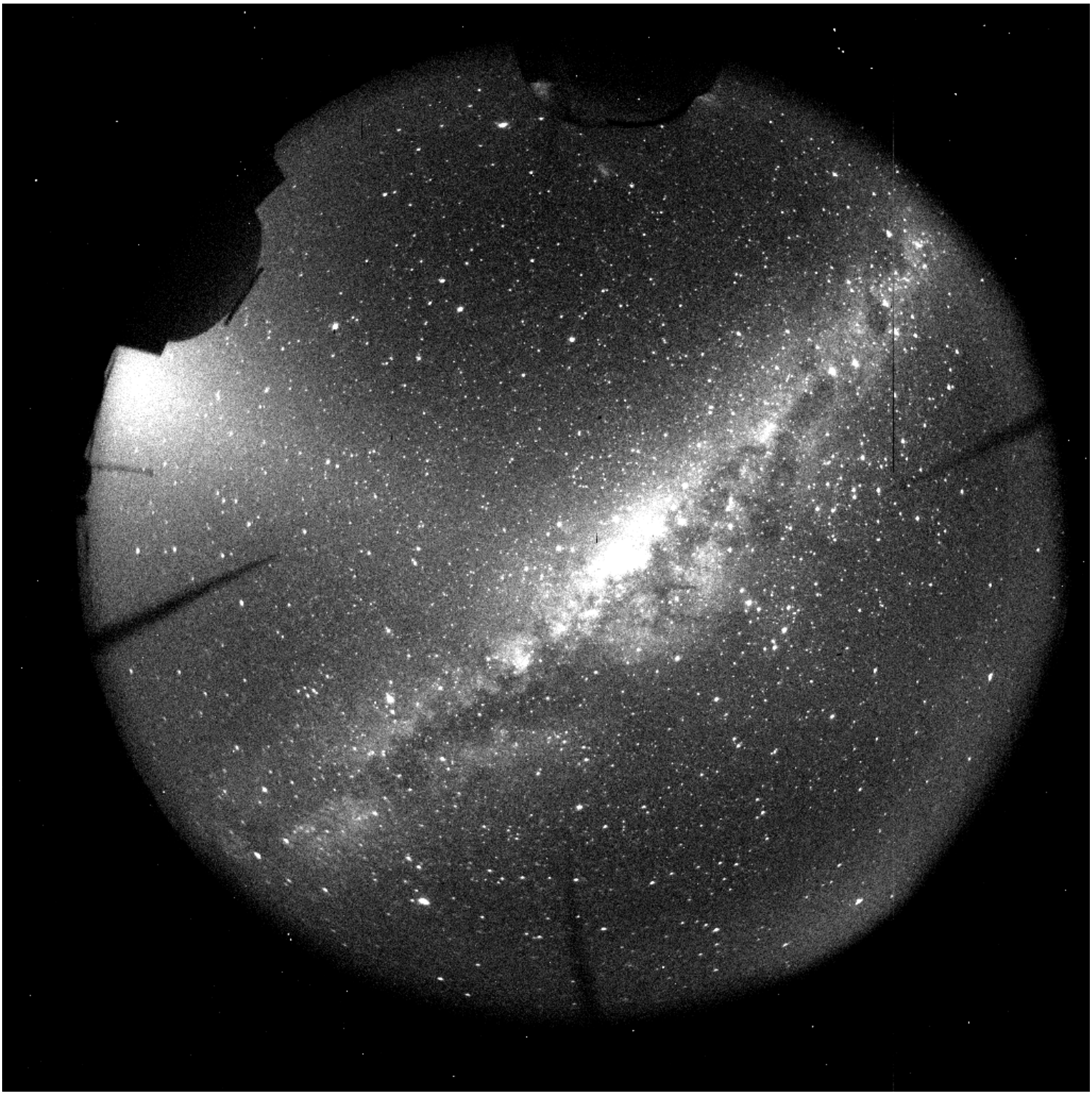
The below image is through a Sodium filter. The glow on the horizon is the emission from La Serena and Coquimbo. The Milky Way is overhead.



The three images below illustrate how the relative strengths of Sodium and Mercury emission change after the 1 am "curfew", when industrial Mercury lamps are meant to be turned off. Top left is an image ratio Mercury-before divided by Mercury-after; top right is Sodium-before divided by Sodium-after, while below is the ratio of the top two images. The glow on the bottom-right horizon is due to light from La Serena and Coquimbo (note the orientation is flipped wrt the previous picture). It can be seen that Mercury weakens relative to Sodium after 1 am, confirming that these lights are indeed being switched off. Note that the Milky Way does not divide out since the images making up the top two pictures are taken at different times. Since cloud cover above the cities has a strong effect on the brightness of the light pollution, images from more than 50 nights were used to make the median images from which these ratio images were generated.



Finally, we show an image taken just before dawn. The bright source on the horizon, almost behind the 0.9-m telescope dome, is not light pollution. It is the Zodiacal light, which can be traced in this image until it merges overhead with the Milky Way. Lights from La Serena and Coquimbo produce the faint glow in the bottom right of the picture.



6. Conclusions

- Cerro Pachon is a dark site.
- The changes to light fittings taking place now and due to be completed by October 2005 will keep it

that way, compensating for population growth at least until the decade 2030-2040. That is, the light pollution will not reach the 2002-2003 pre-changeover levels until that decade, at least.

- Even with an aggressive population growth, and complete failure of the new lighting ordinance, the zenith natural sky brightness at solar *maximum* of a completely non-polluted site would be a factor three brighter than Cerro Pachon would be during solar *minimum* in 2042. This is not a desirable situation of course, and under such circumstances the north-west sky in the direction of La Serena and Coquimbo would be uncomfortably bright, in the case of clear conditions along the coast.

- The Observatories should continue to advocate "dark skies". The above conclusions should not mean we should become complacent, we need to preserve Cerros Tololo and Pachon as pristine observing sites for decades to come.
