LIGHTING AND ASTRONOMY

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ABSTRACT

This paper discusses the impact of light from cities on observatory sites, how "skyglow" affects astronomical observations, how it is measured, and how far it reaches, including examples from specific observatories around the world. While both the astronomy and lighting professions have significant expertise in measuring light, our terminology, methods, and needs differ. Background on astronomical observations that is relevant to the lighting community is included.

All light is not created equal. When considering the effects of artificial light escaping from an urban environment, the direction into which the light is propagating is very important. When a town is seen from the vantage point of a distant observatory, important considerations include:

1. The atmosphere is a relatively thin layer, with air density decreasing exponentially with altitude. Every 4 km in altitude corresponds to a decrease by a factor of 0.6 in density and pressure. This means that light that goes nearly straight up has a relatively good chance (about 85%) of leaving the Earth's atmosphere without scattering and contributing to skyglow.
2. Light that is emitted in nearly horizontal directions can propagate for enormous distances through the atmosphere. Because it passes through so much air, it has a much greater likelihood of scattering, and therefore contributing to skyglow. Furthermore, it can produce skyglow at great distances from the light source.
3. Light emitted upward from fixtures, and light reflected off the ground, is blocked to varying degrees by buildings and vegetation. Though this blocking will in general increase for directions near horizontal, light propagating near horizontal still dominates skyglow impacts at distant sites.

For the case of La Serena, located about 90 km from Cerro Tololo Inter-American Observatory in Chile, any light that reflects off the ground has to first find its way "around" obstructions before propagating upwards. If we look from the observatory over La Serena at an angle of 30° from horizontal, the air that the telescope beam passes through over La Serena is 45 km above the Earth, and so has an atmospheric pressure of about 0.003 atm. There is essentially no air there, and so very little light from La Serena scatters into the telescope. The principal way for this light to enter the telescope is for it to scatter twice: once at lower altitude, changing the direction, then a second time closer to Cerro Tololo. This situation should be contrasted to the case of a partially shielded fixture that can emit light directly in the direction of the observatory. Light from such a partially shielded fixture only has to scatter once to enter the telescope. The likelihood of scattering for green light in one thickness of atmosphere is approximately 15%. The difference in impact on observatories between double scattering (required for fully shielded fixtures) compared to single scattering (partially shielded fixtures) is therefore approximately 1/0.15, or a factor of approximately 6.

Not only professional observatories, but many national parks, wilderness areas, rural communities, and other locations that are away from cities around the world are affected at significant distances by skyglow from cities. Simple models have been developed that equate the amount of upward light to skyglow. These can give a reasonable prediction for skyglow above the city or source of light; however, this approach cannot properly predict skyglow at a distance from the city, because the angular dependence of the emitted light is critically important. More robust modelling that includes the angular distribution of light has recently been developed and applied to the case of Flagstaff, Arizona. These results confirm that the angle of emission is critical.

Keywords: astronomy, skyglow, scattered light, light pollution, dark skies

1. INTRODUCTION

2008 marked the first year in which half of the world's population lived in cities where skyglow commonly obscures their view of the stars above. Humankind's access to the universe, that beautiful vista that has inspired people to create beauty in the arts and advances in the sciences, is disappearing. There is no doubt this natural heritage is worth preserving for future generations. The key is finding a practical solution everyone can accept. Minimizing this negative effect of skyglow through smart, ecologically sensitive uses of our resources is a mindful approach many people, groups, and institutions are choosing to take.

Skyglow is increasing exponentially due to population growth and increasing amounts of light per capita; it threatens all of the world's major observatories. Ground-based observatories will not be replaced by observatories in space. Ground-based telescopes produce the vast majority of astronomical observation-based research. We must address the skyglow problem at all levels, from local to international, to prevent the loss of the dark sky resource on which observational astronomy depends.

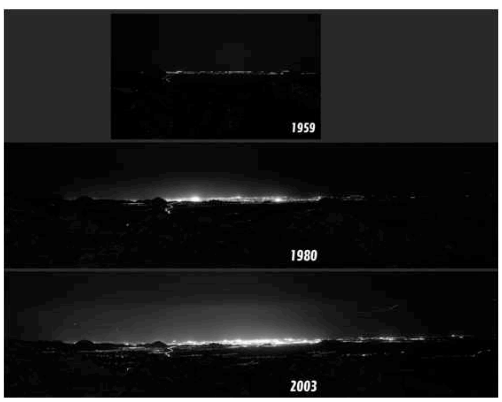

Figure 1. Growth of Tucson from 1959 to 2003 seen from Kitt Peak National Observatory, USA. While, light emission has grown, it has lagged the explosive growth in Tucson's population during this period. Light pollution control ordinances and outstanding public cooperation have limited stray light to the extent that Kitt Peak remains a world-class astronomical site. Credit: Bill Schoening, J.C.Golson, Mark Hanna and NOAO/AURA/NSF.

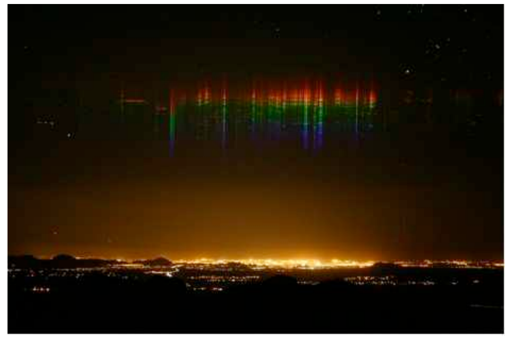

Figure 2. Spectra of the lights of Tucson, AZ. The downtown area lies only 90 km from Kitt Peak National Observatory. Photo courtesy of J. Glaspey.

2. MODELLING SCATTERED LIGHT

When considering the impact of direct and reflected light from cities on observatory sites, the angle at which the light propagates is important. The atmosphere is a relatively thin layer with air density decreasing exponentially. Every 4 km in altitude corresponds to a decrease by a factor of 0.6 in density and pressure. Light travelling upwards in a direction near the zenith has an 85% chance of leaving the atmosphere without scattering; 15% is scattered. Light emitted in nearly horizontal directions can propagate for enormous distances before leaving the atmosphere, leading to nearly a 100% chance of scattering. Some major observatories contend with skyglow from cities even 300 km away. Light emitted upward from fixtures and reflected off the ground is blocked to varying degrees by buildings and vegetation, particularly in directions near horizontal. Nonetheless, we shall see that light emitted near horizontal still dominates skyglow impacts at distant sites.

To explore these effects, the work for this paper uses the models of Garstang (1986, 1989, 1991) and Luginbuhl et al. (2009a). Nine light sources were constructed, each emitting a constant flux (in lumens) into a 10° zenith angle zone, as illustrated in Figure 3.

The model introduces a "weighting factor," for the impact of upward-directed light emissions, based on the sky brightness increases caused by the upward emission relative to the same luminous flux directed downward onto a Lambertian ground surface with 15% reflectance. The 5-point skyglow impact factor (*G*) is defined as

$$G = \langle R(\text{Zenith Angle Zone})\rangle / \langle R(\text{Fully Shielded})\rangle$$

where

$$\langle R\rangle = \{2[Z]+[0°]+[90°]+[180°]+[270°]\} / 6$$

and *[Z]* is the brightness ratio relative to the natural condition (no artificial lighting) at the zenith, *[0°]* the ratio at azimuth 0° and zenith angle 60°, *[90°]* the ratio at azimuth 90° and zenith angle 60°, etc. (Figure 4). Twice the weight is assigned to the point at zenith due to the relative astronomical importance of this area of least atmosphere.

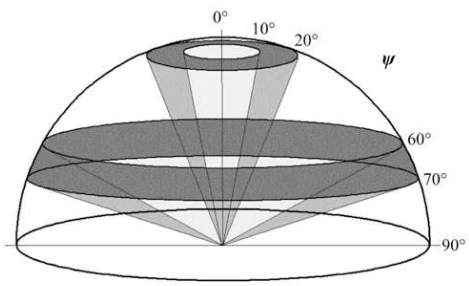

Figure 3. Illustration of representative zenith-angle zones 10°-20° and 60°-70°. The light source is at the bottom, center point.

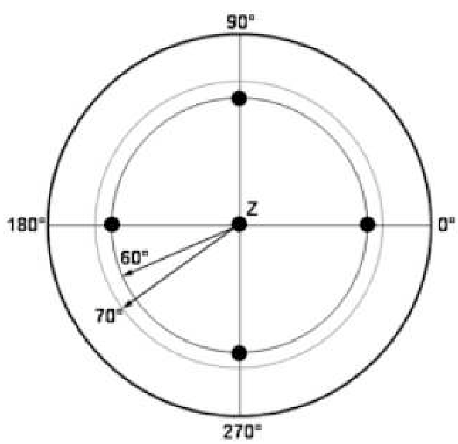

Figure 4. Fisheye view over an observatory. Z marks the zenith. The dots indicate the locations where the skyglow is evaluated in the models. 0° is in the direction of the light source.

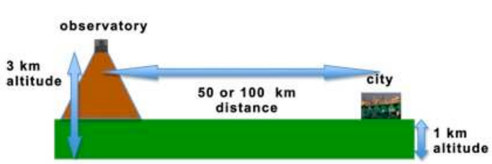

Figure 5. Model parameters

The model parameters (Figure 5) are:

- Altitude of City (source of light): 1 km

- Altitude of Observatory: 3 km

- Aerosol Content of Atmosphere: $K = 0.25$ (Garstang, 1991)

- Ground Reflectivity: 15%

- Distance of Observatory from City: 50km and 100km

Table 1 shows skyglow impact factors *G* for light emitted into the nine zenith angle zones as seen from observatories at 50 and 100 km from the source of light.

Table 1. Skyglow Impact Ratios for Emission from Zenith Angles

Emission Zenith Angle	G_{50km}	G_{100km}
0°-10°	2	0.2
10°- 20°	1	0.2
20°- 30°	0.9	0.3
30°- 40°	1	0.4
40°- 50°	2	1
50°- 60°	4	3
60°- 70°	8	6
70°- 80°	20	30
80°- 90°	40	100

Figure 6 shows sky brightness ratios, relative to the equal downward flux, versus the zenith angle as observed from an observatory. The nine curves are the results for each of the nine emission zones. The zenith angle starts at the horizon away from the city (-90°), goes overhead (0°), and ends at the horizon toward the city (90°). The

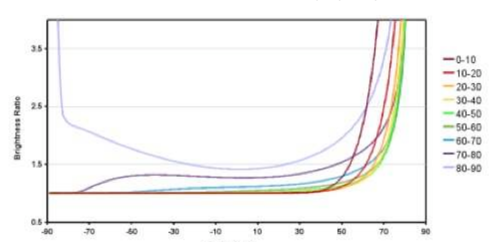

Figure 6. Sky brightness ratios for the nine emission zones vs. zenith angle. The observatory is 50 km away from the light source.

observatory is 50 km away from the city. Figure 7 shows the results for an observatory 100 km away from the city. A *G* ratio of 1.5 indicates that upward emitted light has a 50% greater impact than the same amount of light emitted downward and reflected off the ground.

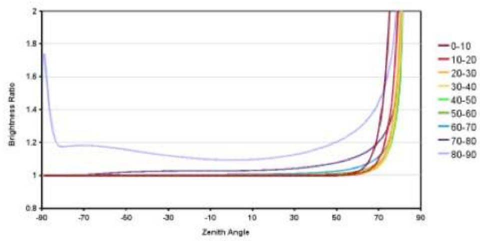

Figure 7. Sky brightness ratios for the nine emission zones vs. zenith angle. The observatory is 100 km away from the light source.

Figure 8 represents an all-sky map showing skyglow looking from the observatory toward the light source. The emission propagates only into zenith angles of 0° to 10°. The blue dot on the top of the diagram is the zenith point above the observatory. The four blue dots from left to right are all at zenith angles of 60° and azimuths of 90°, 0°, 270° and 180°, respectively. The diagram in Figure 9 is the same as in Figure 8, except that the emission propagates only into zenith angles of 80° to 90°. Total flux in lumens is equal to that in Figure 8 (0° to 10°).

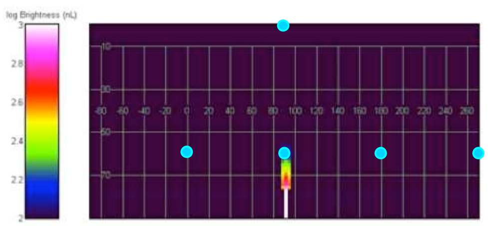

Figure 8. An all-sky map of skyglow looking from the observatory toward the light source where light source emission originates only from emission angles of 0° to 10°.

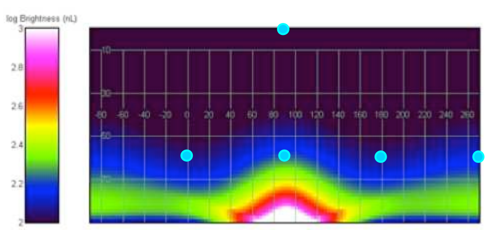

Figure 9. An all-sky map of skyglow looking from the observatory toward the light source where light source emission originates only from emission angles of 80° to 90°.

This analysis and the *G* values of Table 1 show that light emission at 0° to 30° above the horizontal plane is hugely detrimental to dark skies over observatories located 50 to 100 km or more distant from the lights (6x to 100x as bad as equal flux downward).

All observatories, even island observatories, are surrounded by communities (with lights) which produce

Figure 10. The cities of Ovalle and Andacollo seen from Cerro Tololo Inter-American Observatory in Chile are, respectively, about 60 and 30 km away from the observatory. http://www.ctio.noao.edu/

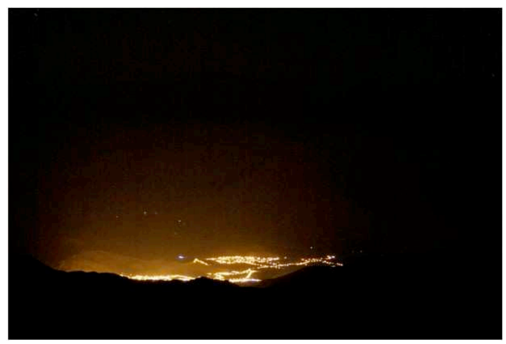

Figure 11. The city of Vicuña seen from Cerro Tololo Inter-American Observatory is about 20 km away from the observatory. http://www.ctio.noao.edu/

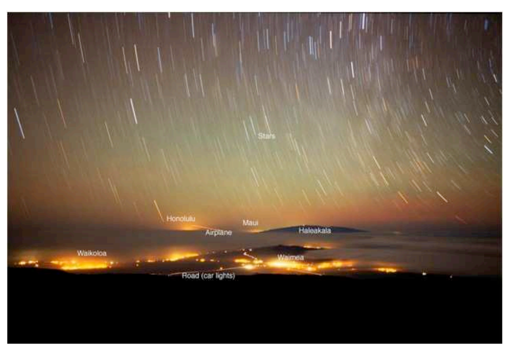

Figure 12. Cities northwest of Mauna Kea Observatory on the island of Hawaii. Honolulu is about 300 km, and Waimea about 30 km, away from the observatory. http://www.ifa.hawaii.edu/mko/

detrimental skyglow, most with potential for continued growth. Figures 10, 11, 12, and 13 show night views from world-class observatories.

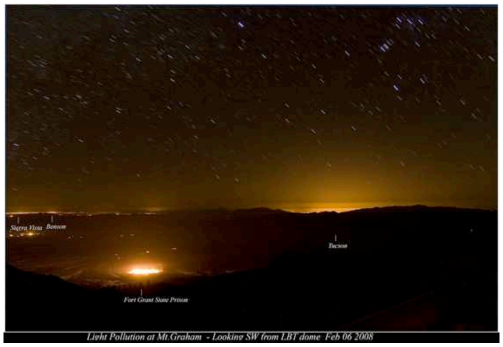

Figure 13. View from Mount Graham, AZ, USA, home of the world's most powerful optical telescope, the Large Binocular Telescope (http://www.lbto.org). The distance from Mount Graham International Observatory to Tucson is about 110 km.

To explore more generally and realistically what happens when light fixtures emit small amounts of direct uplight, a second series of calculations was made using Garstang's models (1986, 1989, 1991) as extended by Luginbuhl et al. (2009a). Here we used Garstang's "standard" uplight intensity distribution (Figure 14; solid line),

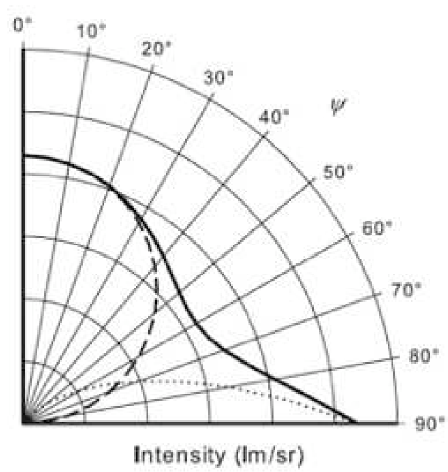

Figure 14. The combined intensity distribution (solid line) from combining light reflected from the ground (dashed line) and light emitted directly upward (dotted line).

consisting of a Lambertian distribution representing light reflected from the ground (dashed line) and a ψ^4 component representing light emitted directly upward (dotted line). The figure shows the combined relation where 10% of the total flux is emitted directly upward and the ground reflects 15% of the remaining 90% directed downward. Direct uplight fractions of 0%, 3% and 10% were evaluated. All other parameters remain as stated before.

As before, $\langle R \rangle$ is the weighted average of the five point ratios. A flux-independent ratio, $\Delta\langle R \rangle$ represents the brightness increase relative to the fully shielded (0%) scenario:

$$\Delta\langle R\rangle = (\langle R_{3\%}\rangle - 1)/(\langle R_{0\%}\rangle - 1)$$

or

$$\Delta\langle R\rangle = (\langle R_{10\%}\rangle - 1)/(\langle R_{0\%}\rangle - 1)$$

Here, $\Delta\langle R\rangle = 1.83$ indicates an 83% increase relative to the increase under fully shielded conditions. Tables 2 and 3 show the fractional sky brightness increase and $\Delta\langle R\rangle$ for observatories at 50 and 100 km from the light source.

Table 2. Fractional sky brightness increases and $\Delta\langle R\rangle$ for observatory at 50 km.

uplight	[Z]	[0]	[90]	[180]	[270]	<R>	Δ<R>
0%	1.84	6.89	1.89	1.72	1.89	2.68	1.00
3%	2.70	9.66	3.04	3.24	3.04	4.06	1.83
10%	4.70	16.13	5.74	6.80	5.74	7.30	***3.76***

Table 3. Fractional sky brightness increases and $\Delta\langle R\rangle$ for observatory at 100 km.

uplight	[Z]	[0]	[90]	[180]	[270]	<R>	Δ<R>
0%	1.08	1.49	1.09	1.08	1.09	1.15	1.00
3%	1.24	2.03	1.31	1.36	1.31	1.42	2.71
10%	1.63	3.29	1.81	2.01	1.81	2.03	6.70

At a distance of 50 km, using fixtures with 3% direct uplight increases the skyglow relative to the fully shielded condition by 83%. Allowing 10% direct uplight increases this figure to 276%. At a distance of 100km, using fixtures with 3% direct uplight increases the skyglow relative to the fully shielded condition by 171%. Allowing 10% direct uplight increases this figure to 570%.

Blocking parameters include E_b as the "blocking" extinction in magnitudes at zenith and β as the "unblocked" fraction that passes between all obstacles (e.g., trees with gaps). With moderate blocking defined by $E_b = 0.3$ and $\beta = 0.1$, values for $\Delta\langle R\rangle$ are reduced by about 2.2x. More model work is needed, because the model did not examine different blocking for direct and reflected light.

Blocking will be greater in towns/cities where structures and/or vegetation are taller. For observatory towns, often in desert locations, vegetation and structures and therefore blocking may be lower. Direct uplight from fixtures will be less blocked than reflected light because most fixtures are mounted above some of the structures and vegetation.

3. CONCLUSIONS

Small percentages of direct uplight emitted into angles just above horizontal have disproportionately large detrimental effects on observatory skies located 50 - 100km or more away. The effect for 3% uplight is much larger than the expected total lighting reductions arising from potentially increased pole spacings.

In the real world, not every lighting installation is professionally designed and most local governments have limited resources for planning and enforcement, making the implementation of photometrically-based uplight regulations problematic. We find the only practical solution is to use fully shielded lighting (zero uplight) within at least 100 to 200 km of observatory sites, as such a regulation can be effectively implemented by a wide range of officials both with and without photometric expertise.

REFERENCES

GARSTANG, R. H. Model for Artificial Night-sky Illumination. *PASP*, **98**, 364-375, 1986.

GARSTANG, R. H. Night-sky Brightness at Observatories and Sites. *PASP*, **101**, 306-329, 1989.

GARSTANG, R. H. Dust and Light Pollution. *PASP*, **103**, 1109-1116, 1991.

LUGINBUHL, C. B. et al. From the Ground Up II: Sky Glow and Near-Ground Artificial Light Propagation in Flagstaff, Arizona. *PASP*, **121**, 204-212, 2009a.

LUGINBUHL, C. B. et al. in preparation, 2009b.

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