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From The Ground Up I: Light Pollution Sources in Flagstaff, Arizona

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ABSTRACT. We develop an estimate of the complete outdoor lighting of Flagstaff Arizona, as well as lighting-use densities (lumens per acre) for a number of different land uses. We find a total outdoor light output of 173 million lumens (Mlm) including sports lighting, and 139 Mlm without sports lighting, with an uncertainty of about 7%. The average fraction escaping directly upward from light fixtures is estimated to be 8.3%. After correcting approximately for near-ground blocking described in the accompanying paper by Luginbuhl et al., total uplight is estimated at 17.9 Mlm or 12.2 Mlm with and without sports lighting, respectively. Of these 17.9 Mlm, 33% arise from sports lighting, when it is on; when sports lighting is off, commercial and industrial lighting account for 62% with the remainder dominated by residential (14%) and roadway lighting (12%). We show that the 1989 Flagstaff lighting code that limited total outdoor lighting on new construction has reduced the growth rate of lighting, resulting in a 17% growth in light escaping into the sky from 1989 to 2003, compared to a 43% increase expected if the 1989 code had not been enacted. If all legally nonconforming lighting installed before 1989 were to be brought into compliance with the code, we would expect sky glow in Flagstaff to actually decrease by 36% compared to that in 2003; if all lighting, including residential, could be converted to fully shielded fixtures, sky glow would decrease to about half the current value. The implications for the most effective ways to address sky glow through lighting codes are discussed.

1. INTRODUCTION

Astronomers have long been concerned with increasing sky brightness at observatories due to artificial outdoor lighting (see, for example, Hoag et al., 1973). These concerns have led to involvement of professional astronomy in the development and enactment of civil regulations on the use of outdoor lighting or lighting codes. To inform the development of such codes, we must develop a better understanding of the influence of the technical details of lighting equipment, lighting design practices, and land uses.

This need is underscored by recent events in Coconino and Pima Counties, Arizona. During the recent development of a long-term land-use plan for Flagstaff and the surrounding areas in Coconino County, it has become clear that lighting code standards developed to address sky-glow concerns for the local astronomical observatories become inadequate if land near observatories, originally expected to be developed for low-density residential uses, is instead urbanized. In Pima County, planners and observatories grappled with the consequences of the proposed creation of a new large community (Canoa Ranch) about 20 km from the Fred Lawrence Whipple Observatory on Mount Hopkins. Civil planners, developers, lighting designers, and astronomers alike found themselves in unfamiliar territory as they tried to predict the sky-glow consequences of land-use planning decisions.

Efforts at understanding how night sky brightness is affected by artificial lighting have taken two approaches. The first and simplest "sky-down" approach (Fig. 1) was originally purely observational (e.g., Walker 1973, 1977), based on photometric measures that were used to derive empirical relations between

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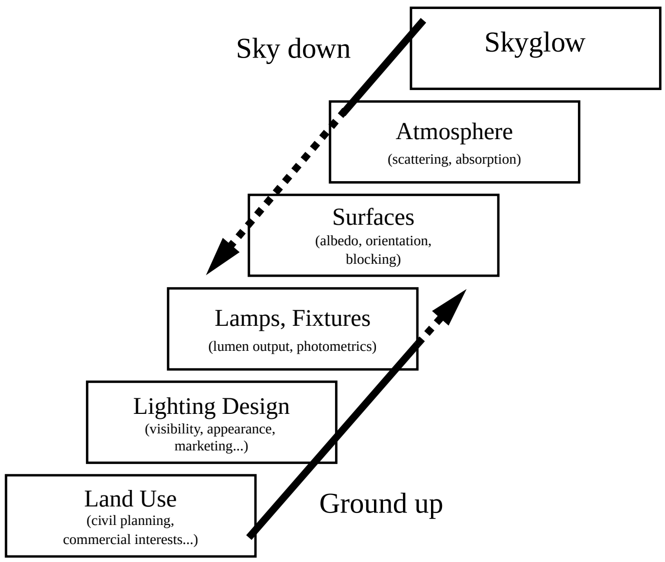

FIG. 1—Flowchart linking sky glow to artificial light use.

those measures and distances and sizes of cities producing artificial sky glow. This work did not produce specific information about how lighting use on the ground related to sky glow, assuming only that the light output of cities would be proportional to the population.

This approach was elaborated by Treanor (1973) and Garstang (1986, 1989b, 1991a) by using a physical understanding of atmospheric content and structure and the interaction of light with its components to construct models that link sky brightness and a very generalized description of artificial lighting.

Garstang, for example, used the sky brightness measurements principally from Walker (1977) taken at various distances from Salinas, California, combined with his models and measures of typical surface reflectance to estimate the total light output of cities and average fixture uplight fraction (10%), which when combined with population figures produces a per capita measure of the luminous output of cities (1000 lumens per capita). These values, combined with a certain function describing the intensity of upward-directed light as a function of angle relative to the zenith, characterizing his "standard model," have been used in subsequent studies to model night sky brightness from many different locales (Garstang 1988, 1989a, 1989b, 1991b, 2000; Cinzano 2000a, 2000b, 2000c; Cinzano & Diaz Castro 2000; Cinzano & Elvidge 2003, 2004; Falchi & Cinzano, 2000; Cinzano et al. 2000a, 2000b, 2001a, 2001b).

These sky-down approaches, taking as fundamental input measures of sky brightness and working downward to deduce characteristics of lighting on the ground, have successfully linked sky glow to physical processes in the atmosphere and, through simplified assumptions about the interaction of light with the ground (surfaces), total light outputs of cities. It has not attempted to go further to establish connections to the complex geometric environment near the ground, the way land is used and lighted, or the optical characteristics of lighting fixtures.

The second, "ground-up," approach traces processes in the reverse direction, beginning with measures of light output on the ground and working upward to deduce the expected sky glow. Of these ground-up studies, few have considered the first two links (Fig. 1) in the chain of land use and lighting design, and the majority have incomplete information concerning lighting on the ground (Walker 1977) or have been concerned principally with electrical power consumption (Broglino et al., 2000; Vandewalle et al. 2001; Pierce, 2002) and therefore lack vital details needed to determine total luminous fluxes. The remainder, though listing information on luminous fluxes and sometimes uplight fractions, often include only partial lighting inventories and/or do not indicate whether initial or mean lamp outputs are listed, or whether luminaire efficiency factors are included (Pedani, 2004; Broglino et al. 2000). The net result is that the luminous fluxes in most previously published studies cannot be related to the total luminous flux emitted into the near-Earth environment or propagated into the atmosphere.

One exception is a study by Lockwood et al. (1990). They combined public information on street lighting with estimates of the amount produced by homes and commercial properties to produce an estimate of the lumen output of the city of Flagstaff, Arizona, of 50 Mlm or 1200 lm per capita.

Another exception is the study by Narisada & Kawakami (1998). Their results for Japanese cities indicate that pedestrian area lighting and signs account for the majority of the upward flux in most areas (20%–87%, median 57%). Unfortunately, total lumen amounts are not reported, so these percentage figures cannot be converted to absolute fluxes.

The goal of our study is to complete the ground-up chain from observable lighting use on the ground to resultant sky glow. To do this we undertook to inventory the entire light output for the City of Flagstaff, Arizona, beginning with on-the-ground lighting surveys, seeking to characterize both the relations between land use and lighting, as well as any measurable effects of Flagstaff's aggressive efforts in outdoor lighting regulation.

1.1. Flagstaff as a Study Site

Flagstaff has a long and unusual history of community efforts to preserve dark skies. In 1958 (Portree 2002), Flagstaff adopted the first known legal regulations pertaining to the use of certain kinds of outdoor lighting (sweeping searchlights). This was followed in 1973 by the adoption of Flagstaff's and Coconino County's first comprehensive outdoor lighting codes. Then in 1989, Coconino County, followed shortly after by Flagstaff, adopted new outdoor lighting codes that established limits on the total amount of light, prohibition on the use of white-background internally illuminated signs, and strict requirements for shielding and the use of low-pressure sodium lighting for certain applications.

Other characteristics of the community may contribute to unusually low light outputs. Due to local laws there are no billboards in the city limits (illuminated or otherwise), and very few illuminated billboards are located in the county within 15 km of Flagstaff. Further, though Flagstaff has 17 auto dealerships, in most communities a source of huge amounts of nighttime lighting, the Flagstaff sales lots are only minimally illuminated. Finally, Flagstaff, like many communities, does not seek in general to provide continuous roadway illumination. In most areas average roadway illumination levels fall considerably below levels commonly seen in larger communities.

1.2. The 1989 Coconino County and Flagstaff Lighting Codes

The 1989 lighting codes for the first time anywhere established overall limits on the amount of outdoor lighting. Originally, four Lighting Zones were created in Coconino County and three in Flagstaff, the boundaries depending on distance from the two dark-sky astronomical sites at the Naval Observatory and Anderson Mesa. In Zones I through III, developments are limited to a total of 25,000, 50,000, and 100,000 initial lamp lumens per acre of the parcel being developed. These limits were designed, in concert with expected land uses near the observatories, to limit brightening of the night sky at the United States Naval Observatory Flagstaff Station and Lowell Observatory's Anderson Mesa site.

The standards of the 1989 lighting code have had a significant effect on the amount of lighting used on nonresidential properties (including most multifamily and apartment uses), but little effect on average shielding for such development and little or no effect on the shielding or amount of light used in single-family residential developments. Further, the preponderance of roadway lighting in Flagstaff had been fully shielded since shortly after the adoption of its previous lighting code in the early 1970s, so the effect of the 1989 code has been principally to produce a shift of municipal roadway lighting to low-pressure sodium.

1.3. The Flagstaff Lighting and Land-Use Study

In 2002 we began an effort to improve understanding of the relationships between the effects of the 1989 lighting code and land use, its associated outdoor lighting, and the resultant impacts on the night sky. We seek to ascertain the amount of light produced in Flagstaff by a variety of different land uses, from commercial and industrial to residential and municipal such as roadway and sports lighting.

The specific objectives for this study are to

1. Determine the total amount of outdoor lighting in Flagstaff and how much of this light is propagated into the night sky;
2. Determine the amounts of outdoor lighting used for different types of land use;
3. Determine the proportions of light used for different purposes;
4. Determine how outdoor lighting practices changed with the adoption of the 1989 outdoor lighting codes in Coconino County and Flagstaff;
5. Provide guidance for astronomers and others seeking to mitigate light pollution.

Section 2 describes how we estimated light outputs. Section 3 gives our analysis and results, compares the light outputs determined in this study both with the limited information available from other workers who have done similar studies and with the light outputs determined by Garstang (1986, 1988, 1989a, 1989b, 1991a, 1991b, 2000) in his models of the effects of city lighting on sky glow, and finally examines the impacts of the 1989 Flagstaff outdoor lighting code. Section 4 presents a summary and conclusions.

2. DATA COLLECTION METHODS AND RESULTS

All fixed lighting was divided into seven categories: public, pre-1989 commercial, pre-1989 industrial, pre-1989 multifamily residential, post-1989 commercial/industrial/multifamily residential, single-family residential, and internally illuminated signs. Data collection methods were devised for each category, with the overall initial goal of producing a specific estimate (per unit, as described in § 2.9) for each category accurate to 25% or better. The methods are described in the following subsections; the data collected in each category are summarized in Table 1.

This study benefited fortuitously from a list including all major development projects built within the city beginning in April 1991 by the Flagstaff Community Development Department. Because this list includes projects beginning only a year and a half after the adoption of the lighting code, it was used to differentiate between projects developed before and after the adoption of the 1989 code. According to US Census Bureau data, Flagstaff's population increased 3.9% during 1990; this growth rate indicates that during the 18-month period between adoption of the current lighting code and beginning of the development project list we would expect Flagstaff to have grown by under 6%. Given the other uncertainties in this study, and that treating the few projects developed in the interim as "pre-1989" projects rather than the "post-1989" projects that they really were produces an error proportional to the *difference* in the amount of light used pre- and post-1989, this project list accounts accurately enough for lighting installed since the adoption of the 1989 lighting code. In what follows we will often refer to "pre-1989" and "post-1989" lighting: in some cases this is based on the April 1991 list. Nonetheless, for consistency we will always refer to 1989 as the fiducial time.

It is important to note at least one category of lighting that we did not include or study, which may be a substantial contributor to the total light output of the city. We have no estimate of the

TABLE 1
LIGHTING SURVEY RESULTS

Category	N	Units surveyed	Unit Type	Mean lm per unit	Fractional error	Mean fraction up[a]	Fractional error
Shopping centers	9	101.56	Acre	85,800	0.21	0.018	0.63
Auto dealers	4	15.83	Acre	37,000	0.37	0.075	0.66
C-stores	3	3	Each	224,000	0.24	0.005	1.01
Hotels	9	16.10	Acre	80,000	0.24	0.053	0.48
Banks	2	2.72	Acre	128,000	0.57	0.011	0.55
Restaurants	5	3.95	Acre	242,000	0.41	0.069	0.67
R&D	3	77.97	Acre	19,700	0.42	0.025	0.44
Industrial	7	13.99	Acre	20,800	0.23	0.128	0.44
Downtown bus. dist.	3	5.86	Acre	27,200	0.45	0.063	0.81
Post-1989 LZ II	7	10.71	Acre	21,700	0.23	0.041	0.52
Post-1989 LZ III	7	21.39	Acre	22,500	0.35	0.045	0.42
Post-1989 apts. LZ II[b]	…	…	Apt	1,410	0.23	0.041	0.52
Post-1989 apts. LZ III[b]	…	…	Apt	1,100	0.35	0.045	0.42
Residential	115	115	Each	604	0.22	0.380	0.40
Apartments (com.)	2	230	Apt	2430	0.45	0.153	0.71
Apartments (res.)	3	74	Apt	833	0.23	0.359	0.59
FUSD	3	18.24	Acre	14,300	0.23	0.037	0.50
NAU	1	210	Acre	6,930	0.20	0.089	0.40
Municipal	34	183.35	Acre	13,600	0.20	0.057	0.40

NOTE.—N denotes the number of sites surveyed.
[a] Includes direct upward component only (not reflected).
[b] Per apartment values deduced using undifferentiated post-1989 figures above combined with total acreages and apartment units developed since 1989.

contribution of light spilling from windows. In some commercial shopping centers large display windows allow considerable amounts of the interior lighting to spill outdoors; in residential areas it is possible the amount of light spilling from windows is similar to that produced by outdoor lighting fixtures. However, as a small city, Flagstaff does not present a nighttime landscape filled with banks of illuminated office windows as might be seen in large urban areas, and we feel the error introduced is small.

2.1. Public

Detailed lighting inventories for roadway and sports lighting were gathered from records of the City of Flagstaff and the Arizona Department of Transportation (ADOT). Essentially 100% of the Flagstaff and ADOT roadway lighting uses fully shielded fixtures, while privately owned lighting for roadways typically uses dusk to dawn fixtures with some of the poorest shielding characteristics.

Mean lumen output for each lamp, as determined from manufacturers' literature, was then entered into a spreadsheet, a procedure followed likewise for all lighting categories described in the following subsections. There was no attempt to identify specific lamp manufacturer or catalog number; for every instance of a particular lamp type and wattage the same mean lumen output was used. Examination of lamp catalogs from several manufacturers shows that mean lamp lumen outputs for lamps of a particular technology (e.g., HPS, LPS, etc.) and wattage do not vary greatly; in most cases the entire range is no greater than about 10% of the mean.

To address schools, lighting inventories were taken at two elementary and one middle school. A lighting inventory was obtained for approximately two-thirds of Northern Arizona University (NAU), which comprises a total of 450 acres situated on the south side of western Flagstaff. The University data included photographs of all fixture types and lamp type and wattage gained with the assistance of the University Capital Assets and Services staff.

Information concerning other Flagstaff municipal lighting was gathered from lighting inventories performed by city staff in 2001 as part of Flagstaff's effort to become the world's first International Dark-Sky City.[3] These inventories contain complete information on lamp type and wattage at all city-owned facilities, though little information was gathered concerning the shielding of the fixtures and no photographs were taken. Since the authors are familiar with much of this lighting, a substantial amount of information concerning fixture type and shielding was added from the authors' recollections.

Data for all public lighting, except schools, was essentially complete and needed no extrapolation. For both public schools and the University, total lighting was estimated by simply extrapolating the per acre values determined from the samples.

[3] See www.darksky.org for more information.

2.2. Pre-1989 Commercial and Industrial

There are approximately 2500 commercially and industrially zoned parcels in the City of Flagstaff, comprising over 2900 acres (though not all are developed). Due to the impracticality of surveying all of this lighting, a sampling strategy was devised. Eight subcategories were identified (shopping centers, auto dealers, convenience stores [c-stores], hotels, banks, restaurants, research and development, and industrial), and a selection of sites within each was surveyed. In an attempt to minimize errors arising from the necessary extrapolations, larger samples were collected from the categories judged to contribute greater proportions to the total lighting budget. More than half of the shopping centers and auto dealerships were surveyed, while only a relatively smaller sampling of hotels, banks, restaurants, and industrial properties were included.

Each site to be surveyed was visited during the daytime. From visual inspection, aided by binoculars, an inventory was composed listing number of fixtures, lamp type, lamp wattage, and location (pole, building side, canopy). The location of each fixture was indicated on a parcel map, and a digital photograph was taken of each fixture type. In many cases, lamp wattage and sometimes lamp type were not discernible, particularly for fixtures with prismatic lenses, and an educated guess was entered at this point into the inventory form.

After the initial survey, three lumen totals were calculated for each site, intended to represent the minimum, nominal, and maximum amount given the uncertainties for any fixtures with missing information. Where lamp type and wattage were certain, the mean lumen output of the lamp was simply included toward all three totals. Where lamp type and/or wattage was uncertain, lumen output corresponding to the guessed lamp type and wattage was included toward the nominal total, while one half and twice this figure were included toward the minimum and maximum estimates. This approach is thought to allow generously for uncertainties.

If the minimum total for the site was within 10% of the nominal estimate (and therefore the maximum within 20%), data for the site were considered adequate and no further information was sought to resolve any missing information. If the minimum estimate was more than 10% less than the nominal, additional information was sought, with the goal of reducing the uncertainty until the 10% criterion was met or exceeded. This additional information was often obtained by revisiting the site with higher magnification optics (an 800 mm focal length spotting scope), by contacting the owner of the site, or by contacting the firm contracted to maintain the lighting.

Guessing wattages for unknown lamps introduced uncertainty into the process. However, when wattages were ascertained as described above for fixtures initially entered as guesses, they were in the majority of cases determined to in fact be within a factor of 2 of the estimated output, increasing our confidence in this technique for estimating the uncertainty in the light output for each site.

For the eight use-specific commercial and industrial categories listed in Table 1, the local phone book along with the Flagstaff geographic information system (GIS) database were used to produce total parcel and acreage inventories. The post-1991 development list provided by the City differentiated parcels developed after adoption of the 1989 code. The mean lumens per unit values of Table 1 were then applied to these acreages to produce estimated total light outputs for each category. We judged the data gathered for the bank subcategory to be insufficient for a reliable extrapolation; though the results for the sample of two sites are included in Tables 1, 2, and 3 for completeness, no attempt was made to extrapolate this category and all remaining bank sites were included in the miscellaneous post-1989 and existing commercial categories.

Industrially zoned property was found to often utilize only a portion of its parcel; therefore each industrial parcel was examined on aerial images and where appropriate the extrapolation was reduced by the fraction judged to be undeveloped.

There is a large number of nonresidential parcels that do not fit into any of the commercial/industrial categories initially chosen for the study, developed both before and after the 1989 lighting code. These properties were split into four categories based on their zoning.

About 117 acres are included in the "near-downtown" areas (zoning "C2E"). These properties include ordinary single-family residences and residential-style apartments, as well as uses such as banks, offices, and a variety of small-scale retail commercial. Using the GIS database, residences and apartments were removed; the remaining properties will have some lighting for uses such as small parking lots and security lighting. For these a lumen per acre value approximately half that of typical highway commercial (see next paragraph) was used, or 40,000 effective lumens per acre with 10% direct uplight. An uncertainty of 50% in the per acre output and 40% in the uplight fraction were assumed for this and other "guesstimated" values.

Most of the remainder of these properties, including 125 acres and classified "C3E," are typical highway commercial developments located along the principal arterial roads of the city. Most of the hotels extracted into their own subcategory are located in this area, as well as several of the shopping centers and dozens of the restaurants. For this category a lumen per acre value representative of hotels and shopping centers was used, 80,000 effective lumens per acre.

The C1E and C4E zones are included for completeness, though they include a total of only 37 acres. Values of 20,000 and 40,000 lm per acre were used, respectively.

2.3. Downtown Urban District

Three blocks totaling nearly 6 acres in the downtown urban district (zoned "C5E") were surveyed. The area devoted to roadways was excluded, as was all lighting associated with roadways and sidewalks because this lighting is included in the roadway lighting category (§ 2.1). The total light output was

TABLE 2

Total Effective Outdoor Light Outputs and Associated Values by Category

Category	Unit	Total units						
	Type	Pre-1989	Post-1989 LZ2	Post-1989 LZ3	Total lm surveyed	Total/surveyed	Total lm category	Fraction Flagstaff
Shopping centers	Acre	183.98	22.86	5.07	8,720,000	1.88	16,400,000	0.095
Auto dealers	Acre	33.46	0	2.69	585,000	2.22	1,300,000	0.007
C-stores	Each	37	0	4	672,000	12.47	8,380,000	0.048
Hotels	Acre	105.83	12.62	0	1,290,000	6.79	8,740,000	0.050
Banks	Acre	2.72	…	…	348,000	1.00	348,000	0.002
Restaurants	Acre	36.42	20.47	2.01	954,000	9.73	9,290,000	0.054
R&D	Acre	97.59	0	0	1,540,000	1.25	1,930,000	0.011
Industrial	Acre	305.64	62.17	73.04	291,000	32.14	9,350,000	0.054
Signs	Each	718	…	…	…	—	600,000	0.003
C1E	Acre	2.32	0	0	0	—	46,300	0.000
C2E	Acre	116.95	0	0	0	—	4,680,000	0.027
C3E	Acre	125.16	0	0	0	—	10,000,000	0.058
C4E	Acre	35.21	0	0	0	—	1,410,000	0.008
C5E	Acre	27.41	0	0	159,000	4.68	746,000	0.004
Post-1989 misc. com.	Acre	0	158.03	48.28	406,000	12.12	4,520,000	0.026
Residential	Each	16,000	…	…	69,500	139.13	9,670,000	0.056
Apartments (com.)	Each	1,770	1694	508	559,000	12.97	7,250,000	0.042
Apartments (res.)	Each	3,830	192	0	61,600	54.31	3,350,000	0.019
FUSD	Acre	211.06	0	0	261,000	11.57	3,020,000	0.017
NAU	Acre	315.00	0	0	1,450,000	1.50	2,180,000	0.013
Flagstaff muni.	Acre	183.35	67.16	3.55	2,490,000	1.62	4,030,000	0.023
Roadway Flagstaff	Total	1	…	…	20,000,000	1.00	20,000,000	0.116
Roadway private	Total	1	…	…	55,200	1.00	55,200	0.000
Roadway ADOT	Total	1	…	…	7,480,000	1.00	7,480,000	0.043
Automobiles (11pm)	Total	1	…	…	4,000,000	1.00	4,000,000	0.023
Flagstaff sports	Total	1	…	…	25,800,000	1.00	25,800,000	0.149
FUSD sports	Total	1	0	0	8,480,000	1.00	8,480,000	0.049
Total					86,400,000	2.02	173,000,000	1.000
S.E./Total							0.069	
Total w/o sports							139,000,000	

TABLE 3

Direct and Total Uplight and Associated Values by Category

Category	Fraction direct up (pre-1989)	Fractional error	Total lm direct up	Total lm up (unadj.) [a]	Blocking factors	Total lm up (adj.) [a]	Fraction category (adj.) [a]	Fraction Flagstaff (adj.) [a]
Shopping centers	0.018	0.63	306,000	2,720,000	0.65	1,770,000	0.108	0.099
Auto dealers	0.075	0.66	95,600	276,000	0.65	179,000	0.138	0.010
C-stores	0.005	1.01	43,400	1,290,000	0.25	323,000	0.039	0.018
Hotels	0.053	0.48	462,000	1,700,000	0.50	852,000	0.097	0.047
Banks	0.011	0.55	3,990	55,500	0.50	27,800	0.080	0.002
Restaurants	0.069	0.67	624,000	1,920,000	0.50	962,000	0.104	0.054
R&DE	0.025	0.44	48,300	330,000	0.25	82,500	0.043	0.005
Industrial	0.128	0.44	941,000	2,200,000	0.50	1,100,000	0.118	0.061
Signs	0.500	0.00	300,000	345,000	0.65	224,000	0.374	0.013
C1E	0.100	0.40	4,630	10,900	0.25	2,720	0.059	0.000
C2E	0.100	0.40	468,000	1,100,000	0.25	275,000	0.059	0.015
C3E	0.100	0.40	1,000,000	2,350,000	0.50	1,180,000	0.118	0.066
C4E	0.100	0.40	141,000	331,000	0.25	82,700	0.059	0.005
C5E	0.063	0.81	47,300	152,000	0.25	38,000	0.051	0.002
Post-1989 misc com.	[b]	0.40	188,000	837,000	0.50	419,000	0.093	0.023
Residential	0.380	0.40	3,670,000	4,570,000	0.20	915,000	0.095	0.051
Apartments (com.)	0.153	0.71	782,000	1,750,000	0.25	438,000	0.060	0.024
Apartments (res.)	0.359	0.59	1,200,000	1,510,000	0.20	305,000	0.091	0.017
FUSD	0.037	0.50	112,000	548,000	0.50	274,000	0.091	0.015
NAU	0.089	0.40	194,000	492,000	0.50	246,000	0.113	0.014
Flagstaff muni.	0.057	0.40	205,000	778,000	0.50	389,000	0.097	0.022
Roadway Flagstaff	0.001	0.00	24,700	3,020,000	0.25	755,000	0.038	0.042
Roadway private	0.150	0.40	8,290	15,300	0.65	9,960	0.180	0.001
Roadway ADOT	0.000	0.00	0	1,120,000	0.65	729,000	0.098	0.041
Automobiles(11 P.M.)	0.112	0.05	448,000	981,000	0.65	638,000	0.159	0.036
Flagstaff sports	0.071	0.40	1,820,000	5,410,000	0.75	4,060,000	0.157	0.226
FUSD sports	0.133	0.40	1,130,000	2,230,000	0.75	1,670,000	0.198	0.093
Total	0.083		14,300,000	38,100,000		17,900,000	0.104	1.000
S.E./Total				0.090				
Total w/o sports	0.082		11,300,000	30,400,000		12,200,000		

[a] Unadjusted and adjusted for near-ground blocking.

[b] This value is 0.041 in LZ 2 and 0.045 in LZ 3 (see Table 1).

estimated by simply extrapolating this value to the total acreage in the zoning category.

2.4. Post-1989 Commercial/Industrial/Multifamily Residential

Outdoor lighting used on post-1989 projects was evaluated by surveying 14 sites, seven each in Lighting Zones II and III. The results for these sites were quite precise because specific information concerning the fixtures was available from city records and because the sites and fixtures were relatively new, so that the lighting installations had not suffered replacements or additions and the lamp wattages were usually easy to verify on site. The sample included a variety of commercial, industrial, and commercial-style apartments (see § 2.5), and it appears there is little difference in the amount of light used for these different purposes under the lumens per acre standards of the code.

The results of the surveys of post-1989 sites (see Table 1) show that projects in Lighting Zone II use on average very close to the maximum amount allowed (assuming an average fixture efficiency of 0.65, ratio of mean to initial lamp output of 0.80, and dirt depreciation of 0.85, 50,000 initial lamp lumens per acre yields 22,100 mean "effective" lumens per acre); sites developed in Lighting Zone III used nearly the same amount though twice this is permitted. This is an unexpected result, as a general impression of planners and the authors is that most sites use the maximum amount of light allowed, or very nearly so. The variance for the Lighting Zone III sites was larger (Table 1); the sample included three sites with 20,000 effective lm per acre or less, and four with values between 40,000 and 50,000. It seems likely that the value listed for this zone is an underestimate. We note, however, that increasing this value to twice that of the Lighting Zone II value would increase the total lumen output for Flagstaff by just 3.6 Mlm or 2%.

2.5. Residential

Multifamily residential uses (apartments) were divided into two subcategories, "commercial" and "residential," identified using information from the Flagstaff GIS database as well as site visits. The commercial apartment subcategory applies to large apartment complexes (often up to several hundred units), which include illuminated parking areas in addition to typical entry lighting for each of the units. The residential apartment subcategory consists of smaller complexes (usually less than 25 apartment units) and former single-family residences converted to rentals. This subcategory used lighting in a fashion typical of single-family residences, with no general illumination for parking or walkway areas, and only one or a few low wattage typically incandescent lights by entryways. For both subcategories, a survey strategy essentially the same as that described for the commercial and industrial property was used.

As for the commercial subcategories described in §§ 2.1–2.4, a complete list of multifamily residential complexes was then assembled using the local phone book, apartment management services, and the city GIS database. The mean effective lumens per apartment from the sampled apartment complexes was applied for the extrapolation of the pre-1989 units, and the values indicated in Table 1 were applied to the post-1989 units.

All housing types not included in the multifamily residential category were lumped together into the "single-family" residential category. For example, duplexes and triplexes, condominiums and other similar conjoined residential units, manufactured housing, and mobile homes are included in this category. The standards of the 1989 lighting codes have essentially no impact on single-family residential lighting practices, so there was no attempt to distinguish post- and pre-1989 construction in this category.

A lighting survey form was developed and distributed to 500 residences in five separate neighborhoods. The five neighborhoods included traditional single-family developments and a manufactured home development. The residential survey asked the homeowner to list the fixtures installed on their property, indicating the fixture type, lamp type, and wattage. Finally, they were asked to indicate by check mark whether the fixture was used "all night," "evenings only," "seldom or never," or on "motion detector."

Of the approximately 520 forms distributed, 115 (23%) were returned. Lumen outputs were developed on a per home basis, and included only lights indicated as used "all night" or "evenings only."

Using data voluntarily provided in this fashion may introduce biases into the sample, since it is unknown whether the sample returned is representative of all single-family residences in the city or even of the 520 homes given flyers. It is plausible that some of the users of larger amounts of light may either be owners of second homes and therefore not present to respond to the survey, or those with some hostility to lighting regulation and therefore also less likely to respond. In addition, errors are expected due to the unfamiliarity of most residential homeowners with even the simple outdoor lighting specifications (lamp type, wattage) requested.

The total light output for this category was extrapolated, on a per-house basis, by using the total number of single-family residences listed in the Flagstaff GIS database. No figure was added to account for the several rural residential areas located in Coconino County adjacent to or near the city, where approximately 8000 residents live.

2.6. Internally Illuminated Signs

The total light output from internally illuminated signage was crudely estimated. First, an estimate of the light output per sign was determined as follows. Luminance measurements (in candela per square meter) were made of 154 sign surfaces using a Minolta LS-100 luminance meter. The measurements were divided into six colors (white, yellow, orange, red, green, and blue), and average values were determined for each (see Table 4). Next, photographs of 14 signs were measured to determine the proportion of sign surface devoted to "copy" (text, symbols, and logos) and "background." Using the average luminances and the copy/background area ratios, the average light output per square meter for a variety of typical signs was modeled. The models included typical "light-background" signs, signs with strongly colored backgrounds and either white or colored copy, and opaque-background signs where the only illuminated portion was the copy. The average light output determined from the models varied from 900 $\mathrm{lm\,m^{-2}}$ for typical white-background signs (all models similar), to 130 $\mathrm{lm\,m^{-2}}$ for typical colored-background signs (ranging from 45 to 450 $\mathrm{lm\,m^{-2}}$ depending on colors chosen for copy and background), to 30 $\mathrm{lm\,m^{-2}}$ for typical opaque background signs (ranging from 7 to 400 $\mathrm{lm\,m^{-2}}$). Since 1989 the Flagstaff lighting code has prohibited the installation of new signs with white or light-colored backgrounds, and required the use of signs with either strongly colored or opaque backgrounds. Though a number of older signs still exhibit white backgrounds, the preponderance of signs are now of the latter two categories. For purposes of the study we adopted 300 $\mathrm{lm\,m^{-2}}$, a value corresponding to the lower range of the colored-background outputs and the upper range of the opaque backgrounds.

Next, we estimated the number of internally illuminated sign faces, generally including one sign for each commercial property fronting the principal commercial arterials, supplemented by our familiarity with unusual sites such as shopping centers or sites with unusually large signs.

Finally, the total light output from signs was computed by assuming an average area for sign faces of 2.8 $\mathrm{m^2}$ (30 $\mathrm{ft^2}$). The chosen size is representative and corresponds fairly closely to that allowed for freestanding signs under the current regulations. The process described above results in a total estimated output of 600,000 lm. We assigned a large uncertainty of 50% to this value.

Light fixtures used for the external illumination of signs were treated as ordinary outdoor lighting, and their contribution included in the site inventories.

TABLE 4

SIGN LUMINANCE MEASURES

Color	Average luminance ($\mathrm{cd\,m^{-2}}$)	N[a]
White	412	61/36
Yellow	201	12/7
Orange	109	4/2
Red	30	42/24
Green	17	9/5
Blue	7.0	26/16

[a] Number of measures/Number of different signs.

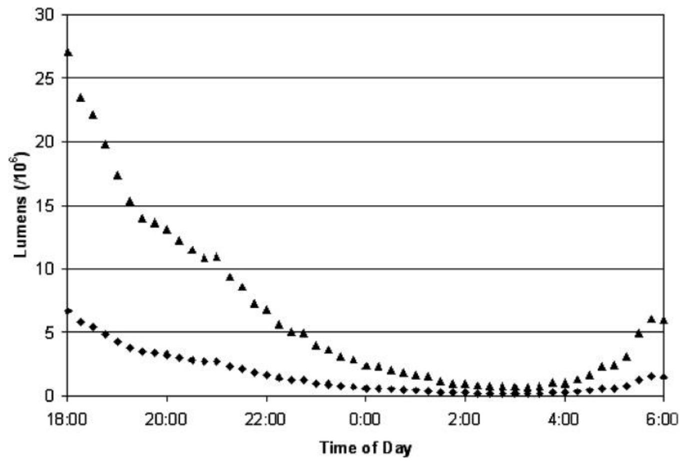

FIG. 2—Estimated total lumen output (*triangles*) and total upward component (*diamonds*) generated by traffic on Flagstaff roadways as a function of time.

2.7. Automobile Headlights

From the Flagstaff Metropolitan Planning Organization (FMPO), counts of vehicles per 15-minute interval passing sampling points located along principal arterials and collector roads are gathered on a regular basis. A subsample of 14 of these data sets obtained during weekdays in 2002 October and November was averaged and then normalized such that the sum of all average 15 minute measures was 1.0. These normalized values represent a figure proportional to the number of vehicles on Flagstaff streets throughout the day. Another datum modeled by the FMPO is the total daily number of trips, defined as the movement of one vehicle from one location to another within a period of 15 minutes or less. Due to Flagstaff's size (typical dimensions of 4 to 5 miles), combined with average traffic speeds (about 20 mph according to Flagstaff's Traffic Engineer), it will be uncommon that any trip would require more than 15 minutes, so we guess that the modeled number of trips should be quite similar to the total number of counted vehicles using Flagstaff roads in a 24-hr period. The normalized average count data were then converted to number of vehicles as a function of time by renormalizing the 15-minute vehicle count data such that the sum of all counts equaled the number of trips per day (420,000). For the evening hours, the number of cars on the road varied from over 7100 at 6:00 P.M. to 170 at 3:15 A.M. Finally, using a market-weighted analysis of headlight low-beam photometric characteristics (Schoettle et al., 2004) showing 3786 effective lumens per auto, 11.2% directed upward, the number of lumens produced by Flagstaff's traffic as a function of time of night was produced. These figures are shown in Figure 2.

2.8. Converting Lamp Lumens to Effective Lumens

The data gathered as described in §§ 2.1–2.5 are estimates of the mean lamp lumen outputs produced in the various categories. To continue to move this light conceptually upward through the flowchart shown in Figure 1, we must next convert these outputs to figures representing light escaping the fixtures in both an upward and downward direction.

Using photometric information available from lighting fixture manufacturers, a database was assembled listing the fraction of lamp output that escapes the fixture (referred to in the lighting industry as the total fixture coefficient of utilization [CU]) as well as fraction directed upward for a total of 21 fixture categories plus two miscellaneous categories serving as catch-alls for fixtures not fitting into the 21 categories. The categories used are illustrated with examples in Figure 3 and listed in Table 5 along with the relevant mean photometric values and the number of fixtures included in the average. Entries indicating $N = 0$ are simply educated guesses. Either photometric information was unavailable for these categories or aiming and therefore relevant photometric values are highly variable for fixtures included in these categories.

Each fixture was classified according to the fixture categories shown in Table 5 and Figure 3. Using the adopted photometric values, as well as a final factor (0.85) intended to compensate for dirt accumulation and other types of deterioration in the light fixtures (referred to in the lighting industry as the luminaire dirt depreciation factor [LDD]), the mean lamp lumens were then converted to total effective lumens as well as effective lumens directed upward.

Because internally illuminated signs are oriented such that the emitting surfaces are vertical, and since we assume the sign faces emit light isotropically, 50% of the flux is directed above the horizontal.

2.9. Computation of Mean Values and Errors

Finally, within each category, mean total effective and total effective upward lumens per unit (typically per acre) were computed from all inventoried sites. In some subcategories several units were explored to serve as the basis for subsequent extrapolation, from simply using a "per acre" lumen output to a "per unit" value (e.g., per apartment, or per service station). The final unit type chosen was that which gave the smallest fractional error E, defined as

$$E^2 = \frac{\text{var}}{\text{mean}^2(N-1)} + (E_{\text{min}})^2,$$

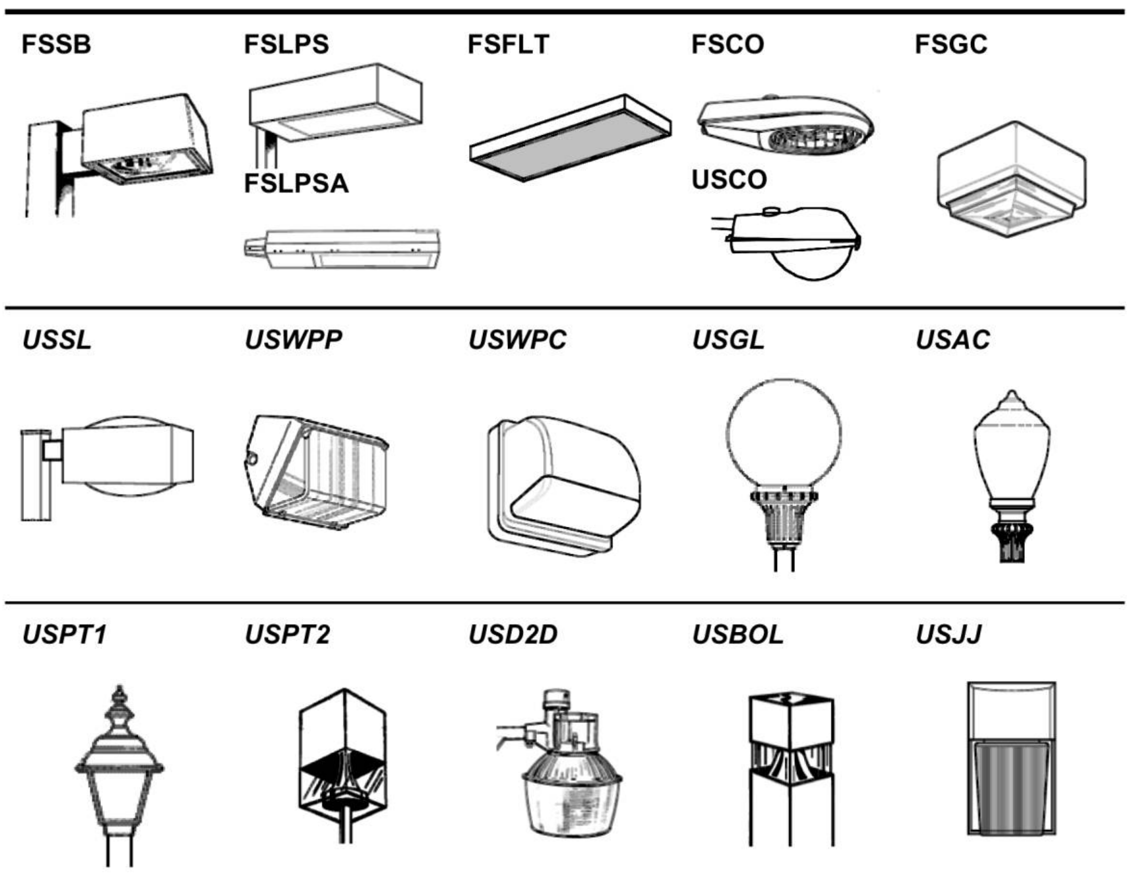

FIG. 3—Illustrations of representative fixtures for the fixture categories of Table 5.

TABLE 5
FIXTURE CATEGORIES AND PHOTOMETRIC VALUES

Code	Description	Down	Up	Total	N
FSSB	fully shielded shoebox	0.71	0.00	0.71	30
FSLPS	fully shielded LPS shoebox	0.59	0.00	0.59	6
FSLPSA	fully shielded LPS Spaulding Palomar	0.55	0.00	0.55	1
FSFLT	fully shielded fluorescent troffer	0.55	0.00	0.55	12
FSCO	fully shielded cobra head	0.72	0.00	0.72	7
FSGC	fully shielded gas station canopy	0.58	0.00	0.58	6
FSCAN	Cans and recessed soffit fixtures	0.70	0.00	0.70	0
FSMISC	fully shielded miscellaneous	0.60	0.00	0.60	0
USSL	unshielded sag lens	0.57	0.01	0.58	2
USWPP	unshielded wallpack prismatic lens	0.46	0.11	0.57	12
USWPC	unshielded wallpack clear lens	0.55	0.02	0.57	5
USGL	unshielded globe	0.35	0.41	0.76	3
USPT1	unshielded posttop carriage-like	0.35	0.10	0.45	2
USPT2	unshielded posttop cone reflector	0.47	0.02	0.49	2
USD2D	unshielded NEMA	0.73	0.13	0.86	2
USBOL	unshielded bollard	0.22	0.08	0.30	7
USCO	unshielded cobra head	0.73	0.03	0.76	4
USJJ	unshielded prismatic “jellyjar”	0.60	0.14	0.74	1
USSP	unshielded sports	0.65	0.10	0.75	0
USRES	unshielded residential mixed	0.40	0.25	0.65	0
USFLD	unshielded upward flood	0.00	0.60	0.60	0
PAR	PAR lamps	0.75	0.25	1.00	0
USMISC	unshielded miscellaneous	0.50	0.06	0.56	0

where the variance (var) was computed from the mean lumens per unit values computed for each of the N sites individually, and $E_{\min}$ is a constant “minimum error” intended to account for unevaluated error sources such as burned-out lamps, unusually poorly (or well) maintained fixtures, and uncertainties associated with fixture photometry. For most categories $E_{\min}$ was set to 0.20 when evaluating the fractional error of the total mean lumens per unit, and 0.40 when evaluating the error of the mean fraction lumens per unit directed upward; for some categories with more certain information (such as the city streetlight inventory) smaller values were chosen for $E_{\min}$. The mean values for all sampled categories as well as the chosen unit are indicated in Table 1. These mean values and fractional errors were used in the extrapolations.

2.10. Total Light Output of Flagstaff

Table 2 shows the total units (citywide), surveyed lumens, extrapolation factors, and total fixture light output for all categories, as well as the fraction each category contributes to the total fixture output for Flagstaff.

Table 3 lists the fractional direct uplight and the total amount of light directed upward (including the portions both emitted directly from fixtures and reflected from the ground). However, using these values as inputs to a model based on Garstang’s approach yields a calculated sky brightness considerably greater than that found by measurements (companion paper Luginbuhl et al. 2009, hereafter GU2). They conclude that blocking by objects near the ground leads to a significant reduction in the upward flux, particularly at angles near the horizontal.

Because a principal goal of this study is to evaluate the relative impact on sky glow of the various lighting and land uses, we adjust the total uplight figures shown in Table 3 by approximate “blocking factors” based on the following consideration (see GU2 for a more detailed discussion of blocking factors). All categories have an initial 0.65 factor applied to account for general blocking by objects located at some distance from the lights (except for a value of 0.75 applied to sports lighting, due to the open nature of the physical environment on and surrounding sports fields). Local conditions such as large amounts of vegetation (typical of residential areas, for example), heavily built environments (typical of heavily urbanized areas) led to further reduction factors of 0.50, 0.25 and finally 0.20, depending on the number and degree of such conditions judged typical for the lighting category (see Table 6). These figures are fairly arbitrary, other than that, in ensemble, they reduce the total upward light outputs to values consistent with the sky glow as described in GU2. The adjusted uplight figures, as well as the effective fraction for each category and the fraction each contributes to the total upward light output for Flagstaff, are also indicated in Table 3.

Table 6 details the conditions used to determine the blocking factors listed in Table 3, including the fraction of lighting in each category mounted on poles, to building sides, or under overhangs (each of these three mounting geometries, respectively, leads to the tendency for greater blocking according to

TABLE 6
LIGHT FIXTURE MOUNTING GEOMETRY AND ESTIMATED BLOCKING FACTORS BY USE CATEGORY

Category	Fixture position[a] Pole	Wall	Overhang	Vegetation/Structural blocking[b]	Overall blocking factor
Shopping centers	0.71	0.12	0.18		0.65
Auto dealers	0.67	0.13	0.21		0.65
C-stores	0.01	0.03	0.95	s	0.50
Hotels	0.50	0.24	0.26	s	0.50
Banks	0.32	0.33	0.35	s	0.50
Restaurants	0.86	0.08	0.06	s	0.50
R&DE	0.69	0.30	0.01	vv	0.25
Industrial	0.02	0.79	0.19	s	0.50
Signs	…	…	…		0.65
C1E	0.6	0.2	0.2	ss	0.25
C2E	0.0	0.5	0.5	ss	0.25
C3E	0.6	0.2	0.2	s	0.50
C4E	0.0	0.5	0.5	ss	0.25
C5E	0.0	0.5	0.5	ss	0.25
Post-code LZ II	0.6	0.2	0.2		0.65
Post-code LZ III	0.6	0.2	0.2		0.65
Residential	0	0	1	svv	0.20
Apartments (com.)	0.15	0.71	0.14	ss	0.25
Apartments (res.)	0	0	1	svv	0.20
FUSD	0.6	0.2	0.2	s	0.50
NAU	0.6	0.2	0.2	s	0.50
Flagstaff muni.	0.6	0.2	0.2	s	0.50
Roadway Flagstaff	1	0	0	vv	0.25
Roadway private	1	0	0		0.65
Roadway ADOT	1	0	0		0.65
Automobiles	…	…	…		0.65
Flagstaff sports	1	0	0		0.75
FUSD sports	1	0	0		0.75

[a] Values listed are lumen fractions. Those listed to 0.01 are as measured in this study; others are assumed.
[b] The additional factors considered to apply to each category: "s" indicates structural blocking; "v" indicates blocking by vegetation. Repetition of a character indicates a factor is considered to be especially strong.

GU2), and other near-ground conditions considered to apply to each lighting-use category.

Though we believe these adjusted figures are accurate enough to allow rough comparison of the contributions of various lighting-use categories to the total uplight generated by Flagstaff, this approach has considerable uncertainty. The blocking factors, as described in the previous paragraphs, are only generally guided by the considerations of GU2. We apply these factors to entire categories of lighting, recognizing that in some instances the real factors may be much larger or much smaller for particular sites within these categories. These real-life variations may lead to small angular scale structure in the sky glow observed over Flagstaff, particularly at large zenith angles, that will be missed by our generalized approach. The factors applied here could be considerably different in other cities, such as desert cities where the amount of vegetation is much lower, small spread-out towns where there is very little multistory construction, or very large cities or central downtown districts where tall buildings dominate.

Figure 4 shows total light outputs broken down by lighting class, as defined by the Flagstaff lighting code. Class 1 is defined as lighting where color rendition is important, such as sports lighting and outdoor sales areas (in application principally service station canopies); Class 2 is general lighting, where simple illumination for visibility or security is needed and color rendition is relatively unimportant (principally roadways, parking lots, and building-mounted area or security lighting); Class 3 is lighting used for decorative purposes.

3. DISCUSSION

3.1. Total Light Output of Flagstaff

The total amount of outdoor lighting in Flagstaff, including sports lighting, automobiles (11 P.M.), and internally illuminated

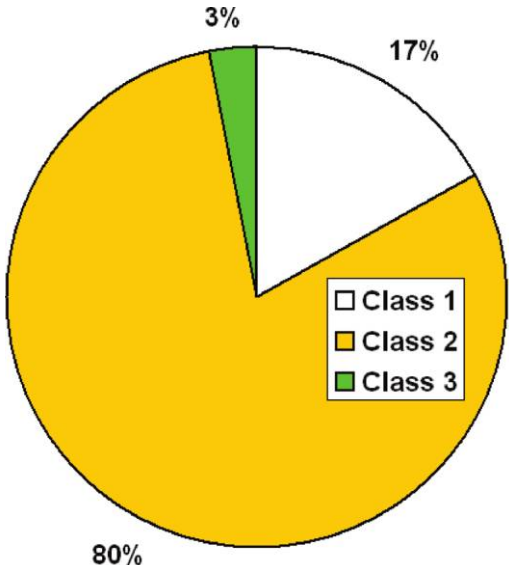

FIG. 4—Total light proportion for commercial and industrial properties by lighting class as described in the text.

signage, is estimated to be 173 million mean effective lm (173 Mlm). This value represents the amount of light escaping light fixtures, accounting for the mean output of lamps whose output varies with time, and the cleanliness and efficiency of lighting fixtures in directing light produced by lamps into the exterior environment. Just over 86 Mlm (50%) of the effective lumen output of Flagstaff was directly surveyed or provided to the authors by other parties. Though fractional uncertainties in many categories were quite large, the estimated error of the total is about 7%.

Of the amount escaping fixtures, 14 Mlm, or 8.3%, is directly emitted above the horizontal. As discussed in GU2, the amount of light ultimately escaping into the atmosphere to cause sky glow is diminished, after exiting fixtures or reflecting from the ground, by interaction with buildings, vegetation, and other objects in the near-ground environment; this process appears to reduce the total amount of light escaping into the sky to less than half that expected neglecting this effect, and affects some lighting categories much more strongly than others. In Table 3 we indicate both the unadjusted uplight (i.e., direct plus reflected components), and the amount of light escaping into the sky after adopting the blocking factors in Table 6.

3.2. Lighting Versus Land Use: Total Lighting and Uplight Amounts

Looking at both the specific (per acre or per unit) and total amounts of light used for the variety of land uses distinguished in this study, sports lighting is the largest user of lighting, utilizing 0.7–1.9 Mlm per acre (unadjusted for blocking) for a typical softball field. With this per acre intensity, lighting for sports facilities (including fields and associated parking lots, walkways, etc.), if all on, can produce a total of 5.7 Mlm (adjusted for blocking) into the night sky (32% of Flagstaff total). This large value is a result of the large amounts of light used, poor shielding, and the generally open nature of the terrain in and around sports fields, leading to low blocking. If blocking is not considered, one category, residential (including apartments) appears to emit a greater amount of light upward (7.8 Mlm), but since residential lighting in Flagstaff's generally forested environment is subject to much greater near-ground blocking than sports lighting, the contribution of residential lighting to sky glow is reduced to about 1.7 Mlm (9.2% of Flagstaff total) and sports lighting (when on) directs by far the largest amount of light into Flagstaff skies of any single category.

We note here that sports lighting is used during the warm season (in Flagstaff from late April to mid-October) and typically in the evening hours between sunset and approximately 11 p.m. While this may appear to be a relatively small fraction of the total "astronomical" nighttime hours (about 10%), it is essentially 100% of the warm season evening hours used by the casual night sky observer.

Apart from sports lighting, the most intense light users on a per unit basis are c-stores and restaurants, at 457,000 and 242,000 mean effective lumens per acre, respectively (the average size of the surveyed c-store sites was 0.49 acres, producing the indicated per acre value from the per unit value in Table 1). These two subcategories account each for a similar amount of total light output, combined producing approximately 10%. But since the majority of lighting on c-store sites is located under canopies resulting in greater blocking, restaurants produce much more light into the night sky at 5.4% of the Flagstaff total versus 1.8% for the c-stores. Coming in at a close third on a lumens per acre basis were the two sampled banks, at 128,000 lumens per acre, but since this category was not further investigated we cannot draw conclusions about the total output from banks.

Next, shopping centers and hotels exhibited similar values of about 80,000 effective lumens per acre. Due to the large area devoted particularly to shopping centers, these categories combined accounted for 15% of the of both the total output and adjusted uplight.

The lowest values considered on a per acre basis were found for schools (both public and university), research and development, and industrial zonings, falling between 7000 and 21,000 lumens per acre. The industrial category also accounts for a large area (about 441 acres) and is relatively poorly shielded (13% emitted directly upward before adoption of the 1989 code), producing 5.4% of the total output and 6.1% of the adjusted uplight.

The moderate value measured for the auto dealerships, 37,000 mean effective lumens per acre, merits comment. As a comparison, approximate lighting inventories for two auto dealerships located in Tucson, Arizona, shows 550,000 and 800,000 mean effective lumens per acre, 15 and 22 times the mean for Flagstaff (D. R. Davis et al. 2007, personal communication). In Flagstaff, auto dealerships account for just 0.7% of the total lumen output and 1.0% of the adjusted uplight. We expect in many communities these figures would be much higher.

Figure 5 shows the adjusted uplight fluxes grouped into seven larger categories as indicated in the key: commercial includes shopping centers, auto dealers, c-stores, hotels, banks, restaurants, C1-5E commercial, and signs; industrial is as before; residential includes single-family homes as well as apartments; roadway includes Flagstaff, private, and ADOT roads; institutional and government includes Flagstaff public schools, Northern Arizona University, and Flagstaff municipal lighting; sports includes both municipal and school district facilities. Here it is clear that commercial lighting accounts for the largest proportion, comprising 36% of the total output when sports lighting is all turned on. When sports lighting is not on, the commercial fraction rises to 53%.

Of the remaining categories, when sports lighting is off, roadway and residential lighting account for 12% and 14%, with the remaining 21% arising from industrial, institutional (including schools), and automobiles. We note here that we are using figures for automobiles based on the 11 P.M. output (4 Mlm; see Fig. 2); adopting the highest outputs based on early evening (6 p.m.) estimates would put the uplight contribution from automobiles at 20%–27% of the total (with and without sports lighting, respectively). That this figure decreases to essentially zero in the early morning may explain at least part of the fading at the Mars Hill site of Lowell Observatory reported by Hoag (see note 32 to Table 7 in Garstang 1989) and Lockwood et al. (1990). The larger effect they observe (30% and 70%, respectively) may reflect that, beginning about a mile from their observing site to the East and again to the South, two one-mile sections of Flagstaff's major arterial roadway are aligned almost directly toward the observatory.

3.3. Lumens per Capita

The population for Flagstaff listed by the US Census Bureau for 2000 was approximately 53,000 residents, which we estimate as 55,000 for the epoch of the study (2003). This corresponds to 3150 effective lm per capita emitted from outdoor lighting fixtures. Without sports lighting, the figure drops to 2520 lm per capita.

3.4. Comparison with Other Work

Turning first to values for total light flux per capita, Garstang finds that 986 lumens per capita produces the best results when compared with the sky brightness measurements of Walker (1977) for Salinas, California, with population 68,600, while measurements from Berry (1976) for 12 cities with population from 2,000–2.5 million are fit best with a figure of 1380 lumens per capita. A much lower value of 277 lm per capita was determined by Cinzano (2000b) in a study in Italy. Finally, based on a lighting inventory rather than sky brightness measures, Pedani (2004) finds 1850 lm per capita before midnight in the Canary Islands. Though we question whether his lighting inventories are complete (they appear to include only public lighting), that this figure is higher than most of those based on sky brightness measures is consistent with the results of this study. These figures are summarized in Table 7.

Turning next to the uplight fraction, the only figure available is that from Garstang (1986), where he finds that 11% direct uplight best fits the data from Walker (1977), though this figure is highly dependent on Garstang's assumed uplight angular distribution. We find in this study 8.3% when including sports lighting and 8.2% with no sports lighting, without considering

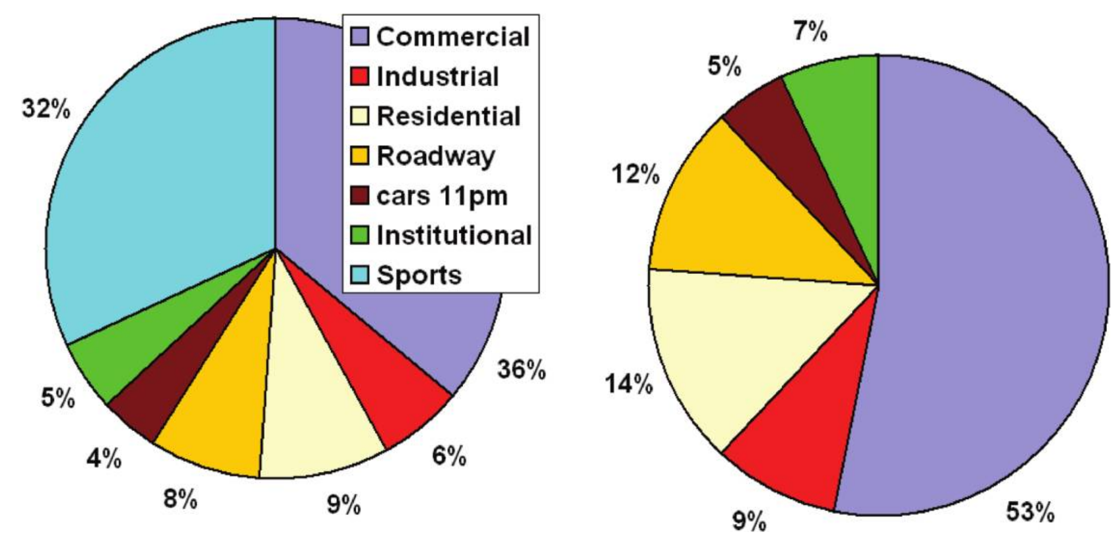

FIG. 5—Adjusted Total Uplight by Category (excluding post-1989 lighting). (*a*) Sports on; (*b*) Sports off.

TABLE 7

LUMENS PER CAPITA VALUES FROM THE LITERATURE

lm per capita	Population	Location	Type	Source
1304/2608[a]	2,500,000	Toronto, Ontario	Model	Garstang (1986)
1380	2000–2,500,000	12 Ontario cities	Model	Garstang (1986)
986	68,600	Salinas, California	Model	Garstang (1986)
277	$<1000 - 1,300,000$	Italy	Model	Cinzano (2000b)
1200[b]	44,000	Flagstaff, Arizona	Inventory	Lockwood et al. (1990)
2610[b]	44,000	Flagstaff, Arizona	Inventory	this study
1850/1000[c]	85,000	La Palma, Canary Islands	Inventory	Pedani (2004)
3150/2520[d]	55,000	Flagstaff, Arizona	Inventory	this study

[a] Values for outer and inner city in two-zoned model.

[b] Without sportslighting.

[c] Values before and after midnight; unknown if lamp output or luminaire output.

[d] Values with and without sportslighting; 11 P.M. local time.

the effects of blocking. Considering, however, the results of GU2, because our figures are based on direct estimates of fixture outputs while the Garstang results are based on best fits to models based on sky brightness measurements combined with his model, comparison of these two figures is not likely appropriate.

3.5. Effects of the 1989 Lighting Code on Flagstaff Lighting

The data obtained in this study on lighting installed before and after the adoption of the current Flagstaff outdoor lighting code allows a prediction of how Flagstaff might have looked today if the 1989 code had not been adopted. Further, it allows us to answer the question of what Flagstaff lighting would look like if it were possible to bring all lighting into conformance with the standards of this code or to achieve perfect shielding of all lighting. These figures define both what has been achieved as well as the outer boundaries of what might be achieved with lighting standards like those of the Flagstaff code.

Table 8 shows the predicted light outputs if the lighting practices measured for the pre-1989 developments had continued to 2003. The categories showing the greatest increase in uplight (indicating conversely the greatest *decrease* attributable to the 1989 lighting code) are miscellaneous commercial, restaurants, and commercial-style apartments. Referring to the amount of light per unit for these categories listed in Table 1, we see that the per acre output of restaurants has been dramatically decreased from 242,000 to about 22,000 lm per acre (a 91% reduction) and commercial-style apartments have gone from 2430 to approximately 1410 lm per unit (a 42% reduction). The largest lighting increases would have been seen in the miscellaneous commercial developments (including developments not falling into the categories distinguished in this study) which we estimate would have developed at an average of 102,000 lm per acre instead of the 22,000 lm per acre under the code. The 1989 lighting code has resulted in a decrease in the *growth* of Flagstaff's uplight output by 13% $(1 - 1/1.15)$. If sports lighting is off, the decrease in the *growth* is 18% $(1 - 1/1.22)$.

Luginbuhl (2001), comparing the brightness of Flagstaff to other cities in the American Southwest on Defense Meteorological Satellite Program (DMSP) cloud-free mosaic images, found Flagstaff to appear 23% fainter than the mean relation for 23 cities of population between about 2000 and 75,000, though severe limitations in using these data for photometric purposes led to large uncertainty. This figure would be compared with the 18% reduction predicted here without sports lighting because the DMSP images were taken at approximately 11 P.M. local time during the winter months. Nonetheless, a figure greater than 18% could be expected due to Flagstaff's history of outdoor lighting control beginning considerably before the adoption of the 1989 lighting code, as noted by Luginbuhl (2001) and confirmed here.

One significant difference between Flagstaff lighting and that of many other cities, and attributable to light pollution control efforts predating the 1989 code, is the near universal full shielding of roadway lighting in the city. As an exercise, we consider the amount of uplight that would have been produced if Flagstaff had utilized the common drop-lens cobra-head luminaires for its roadway lighting. Referring to the total lumen output of the city and ADOT street lighting categories in Table 2 (20 and 7.48 Mlm, respectively), then referring to a typical uplight fraction (3%) and total luminaire efficiency (73%) for drop-lens cobra-head luminaires listed in Table 5 (fixture type USCO), typical total luminaire efficiency for fully shielded cobra-heads and typical low-pressure sodium luminaires used in the city (72% and 55%, respectively), and the appropriate blocking factors from Table 6 (0.25 and 0.65 for city and ADOT streetlighting, respectively), we calculate that the adjusted uplight from streetlighting using drop-lens cobra-head luminaires would have been

$$[(0.73/0.55 \times 20 \text{ Mlm}) \times 0.25 + (0.73/0.72 \times 7.48 \text{ Mlm}) \times 0.65] \times [0.03 + (1 - 0.03) \times 0.15] = 2.0 \text{ Mlm}.$$

TABLE 8
PREDICTED 2003 FLAGSTAFF LIGHTING WITHOUT THE 1989 LIGHTING CODE

Category[a]	Total lumens category	Fraction increase category	Total lm up category (adjusted)	Fraction increase category	Fraction increase Flagstaff
Shopping centers	18,200,000	0.10	1,950,000	0.10	0.01
Auto dealers	1,340,000	0.03	186,000	0.04	0.00
C-stores	9,180,000	0.09	354,000	0.09	0.00
Hotels	9,470,000	0.08	925,000	0.09	0.00
Banks	348,000	0.00	27,800	0.00	0.00
Restaurants	14,200,000	0.35	1,480,000	0.54	0.03
R&DE	1,930,000	0.00	82,500	0.00	0.00
Industrial[b]	9,350,000	0.00	1,210,000	0.10	0.01
signs[c]	600,000	0.00	224,000	0.00	0.00
C1-5E	16,900,000	0.00	1,570,000	0.00	0.00
Post-1989 misc. com.[d]	21,100,000	0.79	1,970,000	3.70	0.09
Residential	9,670,000	0.00	915,000	0.00	0.00
Apartments (com.)	9,660,000	0.25	677,000	0.54	0.01
Apartments (res.)	3,350,000	0.00	305,000	0.00	0.00
FUSD	3,020,000	0.00	274,000	0.00	0.00
NAU	2,180,000	0.00	246,000	0.00	0.00
Flagstaff muni.	4,030,000	0.00	400,000	0.03	0.00
Roadways	27,500,000	0.00	1,490,000	0.00	0.00
Automobiles(11 P.M.)	4,000,000	0.00	638,000	0.00	0.00
Sports[e]	34,300,000	0.00	5,730,000	0.00	0.00
Total	200,000,000	0.13	20,600,000		0.15
Total w/o sports	165,000,000	0.16	14,900,000		0.22

[a] Roadways, existing commercial districts, and sports have been combined into single categories. The columns indicating fraction increase indicate the fractional increase that would have occurred in the indicated category without adoption of the 1989 lighting code.

[b] Pre-1989, this category used fewer lumens per acre than observed on sites after adoption of the code; we therefore assumed no change (increase) would occur if the code was not adopted.

[c] Though the 1989 code prohibited the use of internally illuminated signs with light-colored backgrounds, no attempt was made at estimating the change that might have occurred without this rule.

[d] The post-1989 miscellaneous commercial category uses the average lumens per acre value for all sampled pre-1989 commercial categories (weighted by the total areas devoted to each) or 102,000 lm per acre.

[e] Though four softball/baseball fields were illuminated in the 1989–2003 period, we expect that the higher-quality shielding used for these fields would have been applied whether or not the 1989 code were in place, so no changes are indicated here.

Compared to the adjusted uplight figures of Table 3 for this lighting (1.5 Mlm) and the adjusted total uplight (12.2 Mlm), avoiding these typical unshielded streetlights produces an additional fractional decrease of $(2.0\ \mathrm{Mlm} - 1.5\ \mathrm{Mlm})/12.3\ \mathrm{Mlm}$ or 4%. (This calculation assumes no change in the total lamp lumen outputs used.) This exercise shows that due only to its fully shielded streetlighting and the effects of the 1989 lighting code Flagstaff has accumulated an "uplight deficit" compared to typical cities of approximately 22% $(18\% + 4\%)$, a value remarkably close to the 23% measured by Luginbuhl (2001).

Though Flagstaff has had some form of lighting code in place since 1958 and a comprehensive outdoor lighting code since 1973, widespread rigorous application of the standards to the majority of non-roadway outdoor lighting did not occur until after the adoption of the 1989 code. As a consequence, the majority of the outdoor lighting in Flagstaff was installed with minimal application of shielding standards and no limits on lighting amounts. In Arizona, due to legal issues, this nonconforming "grandfathered" lighting is permitted to remain in use in perpetuity as long as it is not replaced. But the question may be asked, how much would sky glow be reduced if this lighting could be converted to the standards of the new code? In some locales this scenario is legally possible, and even in Arizona the question is not entirely hypothetical: eventually light fixtures will wear out, and replacement parts will no longer be available, though the time frame may be many decades and practically assuring that such worn-out lighting is replaced with conforming lighting is a difficult enforcement issue. Further, using the data gathered in this study, we may estimate the light output of Flagstaff in 1989, as well as the 2003 output under the hypothetical scenario where all outdoor lighting is fully shielded. Though this final condition may be unlikely to achieve in reality, it is useful as a limiting case to help define the minimum impact outdoor lighting might have on sky conditions under the standards of the Flagstaff lighting code. In Table 9 we show total and uplight amounts under these conditions.

Table 9 shows that Flagstaff uplight has increased 17% since 1989, whereas an increase of 43% would have been expected

TABLE 9

Total and Total Adjusted Uplight Output for Five Conditions

Condition[a]	Total lm output	Total lm up (adjusted)	Fractional uplight increase compared to year	
			1989	2003
1989	117,000,000	10,400,000	1.00	0.85
2003	136,000,000	12,200,000	1.17	1.00
2003 A	165,000,000	14,900,000	1.43	1.22
2003 B	94,300,000	7,790,000	0.75	0.64
2003 C	94,300,000	5,770,000	0.55	0.47

[a] Estimated 1989 lighting, 2003 lighting, and three hypothetical scenarios (all excluding sports lighting). Condition 2003 A shows the outputs expected if the 1989 code had not been adopted; condition 2003 B shows those predicted if all outdoor lighting in Flagstaff conformed with the 1989 code (100% compliance/no grandfathering); condition 2003 C shows those predicted if in addition there were no direct uplight from any fixtures (100% full shielding).

based on the lighting practices before the 1989 code was adopted (condition 2003 A). We note that this 43% figure is deduced based on lighting practices and land-use changes only, without direct reference to population growth. US Census Bureau figures indicate that Flagstaff's population during this period has grown by only 25%. That lighting (without the changes caused by the 1989 lighting code) would have grown by almost double this amount indicates that the lumens per capita for Flagstaff would have increased. This increase in lumens per capita is due to the disproportionate increase in high lighting intensity commercial developments. Why there should be such a relatively large increase in such development compared to population growth is unknown to the authors.

Table 9 also indicates that there is considerable room for further improvement in sky conditions if legally noncompliant lighting installed before the code were replaced with code-compliant lighting (condition 2003 B), a condition that would bring the total adjusted uplight to just 64% of the 2003 amount. Even further substantial improvement could be achieved if 100% fully shielded lighting were used in all applications except signs (condition 2003 C). This final condition could bring light escaping into the night sky to less than half that under the 2003 condition.

3.6. Implications for Lighting Codes

There are three principal characteristics of the Flagstaff lighting code affecting sky-glow light pollution: limits on the total amount of light used (lumens per acre caps), shielding standards, and lamp type standards.

To evaluate the benefit in decreased uplight resulting separately for lumens per acre caps and shielding, we compare the light output for only the new commercial, industrial, and apartment developments assuming (1) the total lighting amounts are reduced as measured on the post-code sites while shielding remains as for these categories before the code was adopted, and (2) the total lighting amounts continue as measured on the pre-code sites while shielding is changed to that measured on the post-code sites. We compare these adjusted uplight outputs to those expected if lighting on these parcels had instead followed the trends indicated in the pre-1989 data. Results are presented in Table 10.

From Table 10 it is clear that the lumens per acre caps have resulted in by far the greatest reduction in uplight, producing over a 65% reduction in uplight output for new developments as compared to that expected if the lumen caps had not been adopted and lighting amounts had continued as characterized by our measures of pre-1989 sites.

The net effect of the shielding standards appears to have been almost negligible, resulting in only a 7% decrease. Though the post-1989 direct uplight fraction measured in this study of about 0.043 is lower than the overall average for Flagstaff (0.083), it is nonetheless quite similar to or slightly greater than the weighted average uplight fraction for commercial sites pre-1989 (0.037). Due to this unexpected result, some categories show a net decrease while others a net increase when the pre-1989 value is applied. The higher overall uplight fraction of 0.083 is driven by a few categories with large fractional uplight components, including sports lighting, industrial, and residential lighting (see Tables 1 and 3). Even so, due to the large integrated output of the variety of commercial categories, even fairly good shielding is insufficient to reduce uplight unless yet stricter shielding standards are devised and effectively applied. We note that the relatively minor light pollution reduction attributable to improved shielding in Flagstaff may not be typical, due to unusually well-shielded roadway lighting and the forested environment. Further, we caution against deprecating the value of aggressive shielding standards due to the other (non-sky-glow) benefits fully shielded lighting brings (e.g., decreased glare, light trespass, and concomitant improved visibility).

Finally, for greatest effect, lighting codes should give special attention to roadway and parking lot lighting (so-called "class 2" or "general" lighting), because the preponderance of lighting is used in these applications (see Fig. 4). Large benefits in decreased sky glow (particularly at some distance from the lighting sources) and energy use can be realized here by limiting total amounts of light used (particularly for parking lots), applying strict shielding standards, and taking maximum

TABLE 10

Adjusted Uplight Changes Due to Shielding and Lumens per Acre Caps

	Total adjusted uplight (lumens)				
Category[a]	No code changes[b]	Post-1989 uplight fraction[c]	Fractional change	Post-1989 lumens cap[d]	Fractional change
Shopping centers	257,000	290,000	1.13	65,900	0.26
Auto dealers	13,800	12,100	0.87	8220	0.60
C-stores	34,500	41,800	1.21	3390	0.10
Hotels	98,600	94,100	0.95	27,100	0.28
Restaurants	566,000	506,000	0.90	51,500	0.09
Industrial	364,000	262,000	0.72	364,000	1.00
Post-1989 misc com	1,920,000	1,970,000	1.03	412,000	0.22
Apartments (com.)	375,000	249,000	0.67	201,000	0.53
Apartments (res.)	14,600	14,600	1.00	14,600	1.00
Flagstaff muni	155,000	89,500	0.58	155,000	1.00
Total	3,790,000	3,530,000	0.93	1,300,000	0.34

[a] Includes only categories with development and lighting changes since 1989.

[b] Uses lumens per acre values for each category as listed in Table 1 and uplight fraction of 0.037 (the pre-code commercial weighted average uplight fraction).

[c] Uses 0.043, the average value of the two figures listed in note [b] Table 3.

[d] Uses 102,000 lm per acre as in Table 8.

advantage of the highly efficient and relatively low–sky glow–producing yellow light sources, high- and low-pressure sodium (cf. Duriscoe et al., 2007).

4. SUMMARY AND CONCLUSIONS

We determine that the total outdoor lighting output of Flagstaff (i.e., light exiting fixtures, signs, and automobile headlights) totals 173 Mlm including sports lighting, and 139 Mlm without, with an uncertainty of about 7%. About 8.2% is directly emitted above the horizontal from partially shielded fixtures.

After considering blocking in the near-ground environment (caused by objects such as buildings and vegetation), discussed at length in Luginbuhl et al. (2009), the greatest single-use contributor to sky glow is sports lighting, when it is on accounting for fully one-third of the sky glow of the city. When sports lighting is off, the greatest contributors to sky glow are commercial lighting (53%), residential (14%, including apartments), roadways (12%), and industrial lighting (9%).

By far the majority of lighting (80%) is for so-called Class 2 uses (i.e., general lighting including primarily roadways and parking lots), uses for which the value of color rendition provided by broad-spectrum sources such as metal halide or high-pressure sodium is arguable. In Flagstaff, since the adoption of the 1989 code, these applications require the use of low-pressure sodium, a lighting type which has energy, astronomical, and visual sky-glow advantages. We find that 27% of the total light output of Flagstaff (sports off) arises from low-pressure sodium, 31% from high-pressure sodium, 22% from incandescent, and just 11% from metal halide.

We show that the adoption of the 1989 lighting code has reduced the growth of Flagstaff's sky glow from an expected 43% without the code to just 17%, while the population has increased by about 25%. If all lighting in Flagstaff could be brought within the standards of the 1989 code, Flagstaff sky glow could be reduced to 64% of the 2003 value; if all lighting were fully shielded total output would be reduced to 47%. By far the majority of the improvement in reducing sky glow has resulted from the lumens per acre caps of the 1989 code; the shielding standards appear to have had very little effect because average direct uplight fractions for commercial development have remained at about 4%. This should not be interpreted to say that strict shielding standards are not important for sky-glow reduction but rather that, in Flagstaff at least, the shielding standards of the previous lighting code, combined with municipal policies producing almost exclusively shielded roadway lighting, had been effective in reducing direct uplight emission before adoption of the 1989 code.

The good news is that the *growth* of sky glow in Flagstaff has been reduced from 43% to 17%; the bad news is that Flagstaff's sky glow continues to increase, despite exceptional efforts. It is the prospect of eventually improving even old "grandfathered" lighting that provides the only thin optimism for improved, or at least not continuously degraded, sky conditions at astronomical sites worldwide, to counter the overall apparently inevitable increase in lighting use and resulting light pollution as populations increase and as lighting use per capita appears to increase. If other communities use lighting of amounts and shielding similar to that determined for Flagstaff in this study, replacing all such lighting with adequate amounts of fully shielded lighting can reduce sky glow impacts to one-half or less compared to current values, thus in effect allowing for a doubling of the population with no further sky degradation. Achieving this scenario, however, will require extraordinary efforts in the civil and political arenas.

This study shows that efforts to reduce sky glow will be most effective if focused on reducing the amount of light produced by sports lighting and commercial applications; in the majority of communities with obsolete and poorly shielded sports lighting and without fully shielded roadway lighting, efforts should be focused on improving the shielding in these applications as well. In sports lighting, the latest technologies providing fully shielded or nearly fully shielded fixtures should be demanded, and, further, communities should press for the use of so-called Class IV lighting levels for municipal sports fields rather than the Class III levels (IESNA, 2001) commonly recommended (but not required) by lighting manufacturers and some sports leagues.

In commercial lighting, beyond strict limits on the amount of unshielded light, codes should find ways to limit the total amount of light used to reasonable amounts to prevent the commonly seen escalation of lighting levels resulting from intense commercial pressures. Limits on lighting amounts that are tight enough to effectively limit the use of nonessential lighting (e.g., building façade floodlighting, landscape lighting, other decorative lighting) should be considered by communities for which dark skies are a priority. Flagstaff and Coconino County have found the simple "lumens per acre" approach of their 1989 codes to be highly effective, due principally to its simplicity, which has been shown to allow both technically trained lighting professionals and community planners untrained in the technical details of lighting practice to understand and implement them.

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