THE MEASURE OF LIGHT POLLUTION AND THE POPULATIONS OF CITIES

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ABSTRACT A program to measure the night sky brightness has been in progress for some years in order to calibrate the extent of the night sky brightness surrounding the Van Vleck Observatory. Both the central intensity and the areal extent of the brightest sky caused by campus and city were repeatedly measured in order to gauge the extent of the problem. For this purpose, portable visual photometers were designed which have remained stable and usable for nearly a decade. They are now useful for the measurement of the effects of increases in urban growth and of the more flexible attitude of the campus administration toward excess campus lighting. The inability to define city populations which realistically model and predict the measured sky brightness is the largest source of uncertainty. The observatory is in the Northeastern Corridor where the observed brightness is the sum of the illumination from a number of overlapping city sources. Present light pollution studies have not correctly defined the model for the population of an urban area. The two paradigmatic definitions now available for use are shown to be flawed for light pollution comparisons. An algorithm, unlike any in present use, must be sought which distinguishes between individual core cities within metropolitan areas.

INTRODUCTION

The Van Vleck Observatory on the Wesleyan University campus has been active in instruction and observational research for more than half a century. Until the mid 1970's, its skies were sufficiently dark for its objectives to be attained. But at that time a wave of feminism brought about an unprecedented series of new campus lighting installations which threatened to terminate every aspect of the astronomical enterprise at Wesleyan. At that time, efforts of the observatory faculty, staff and students to negotiate a reduction of the night sky brightness through shielding and choice and location of fixtures, proved fruitless. Only after the inauguration of a study of the brightness of the night sky at the observatory, and some time to pass to allow reason to replace passion, did our efforts begin to bear results.

Two subsequent stages can be identified in the attitude of the Wesleyan University community since the rapid growth of lighting of the 1970's. The first occurred about 1980, and was marked by a change in the attitude of the administration from neglect (of the astronomy department and its needs) to accommodation and compromise. This shift was not shared by the consensus attitude of the student body until about five years later, the shift marking the transition to the third and present stage in the perception of outdoor lighting on the campus.

A recapitulation of the negotiations, the changing student attitudes and other social factors which resulted in a partial success in reducing the light pollution near the observatory lies outside the scope of this paper. But one of the significant ingredients bringing about the improvement in the nighttime environment, was the study of light pollution in its various contexts and the careful measurement of the night sky brightness and its variation with location, seasons and other potential causes of variation.

The program, involving a number of students at all levels, included the development of portable visual photometers which could be calibrated against the photoelectric photometers of the observatory. The visual photometers were designed and built along the lines described by Pike and Berry (1978). The frames are constructed from aluminum tubing, and teflon slides were required in order that the photographic wedges could be moved smoothly with no jerking motion, and yet remain fixed in position even with the unit held in a vertical position, aimed at the zenith. Batteries, bulb and milliammeter complete the design. The weight of each unit is three and one half pounds and the unit cost was held to about $80. A brief description of the program shortly after its inception has been given elsewhere (Upgren et al. 1981). A review of the measurement of light pollution including the use of portable photometers is based in part on early results of this study (Dawson 1984). The observations and reductions closely follow the procedures outlined in these references.

The visual photometers show no drift with time and a mean of three visual readings made by an experienced observer has an internal error of about ± 0.15 mag. in sky brightness per unit area when compared to simultaneous photoelectric measures. Although a number of units were made, only the author made a sufficiently large number of observations for analysis. These were centered at the Van Vleck Observatory (VVO) and at the author's residence at a suburban site three kilometers to the Southwest known as Laurel Hill (LH). Observations with the portable photometers were made at other locations but at only these two were they numerous for a reliable sky brightness to be measured. The recent results of these observations and of the photoelectric observations made at the observatory are close to those reported in the earlier paper and indicate that the brightness of the night sky has not greatly changed from the time of the preliminary report (Upgren et al. 1981). The zenith brightness at the LH site is about three times natural illumination, or about visual magnitude 20.5 per square arcsecond and at VVO, the sky brightness continues to average about 20 times the level of natural illumination, or about 18.5 magnitude per square arcsecond. With the installation of a gallium arsenide photocell for the 0.6-meter Perkin reflecting telescope at the observatory site, many more observations of high precision have been made. They show some variation from one night to another, but little or no seasonal variation can be detected. The chief obstacle towards interpreting the measured light intensity levels has been the failure to obtain realistic figures for populations of the nearby communities in order to achieve a credible model for the area. At VVO this is not too important because the sky brightness levels are very high and are dominated by the lights of the surrounding Wesleyan campus and by downtown Middletown less than one kilometer away. But at LH, where contributions made by other urban areas compete with Middletown, their population is a very significant factor in the interpretation. The remainder of this paper examines the prevailing definitions of city sizes used heretofore in studies of the brightness of the night sky and shows that they are unsuitable for astronomical considerations.

THE ESTIMATION OF URBAN POPULATIONS

The estimation of the populations of cities which are useful for the models for sky brightness from manmade illumination (e.g. Walker 1973) is not an easy or straightforward procedure. The model of Walker and the recent models of Garstang (1986) are satisfactory for small communities. Garstang estimates the population, P, of an urban area from the World Almanac but this practice can lead to a large and avoidable error. Communities of about 5,000 to 10,000 can probably be safely assumed to be adequately represented by the population residing within the corporate limits, since their suburban population is generally small to nonexistent. For larger communities, especially those in excess of 25,000 to 50,000, the metropolitan population should be estimated and used.

For American cities, the World Almanac and most atlases rely upon the metropolitan population estimates which are now made by the Office of Management and Budget (OMB) of the U.S. Government, and formerly were the responsibility of the U.S. Census Bureau. These are called Metropolitan Statistical Areas (MSA's, formerly Standard Metropolitan Statistical Areas) and are given for each urban area with a core city of at least 50,000 population. The most severe problem in the use of MSA's lies in the strictures governing their definition. For sociopolitical reasons, an MSA must be defined along county lines, except in New England where township boundaries suffice. These arbitrary boundaries frequently lead to large inequalities. An example illustrates their shortcomings; Duluth lies at the Southern end of a county which is larger in land area than Connecticut and Rhode Island combined and includes all of the communities lying along the Mesabi Range some 60 miles to the North, containing the rich iron ore deposits of Northern Minnesota. Their combined population equals or exceeds that of Duluth. Consequently, the MSA of the Duluth-Superior urban region is spuriously very large and of no use for sky brightness estimates. Most MSA's are not so grossly ill-defined, but anomalies of this kind and magnitude are commonplace.

The Rand McNally atlases provide the only other readily available estimates of metropolitan populations. These estimates do not share the worst inequities of the MSA's. The Rand McNally delineation of the areal extent of an urban region is defined as a contiguous area surrounding one or more core cities, which has a population density exceeding a critical value indicative of urban and suburban conditions. For ease of comparison, each metropolitan area has been defined by Rand McNally and Company according to this and other consistent rules (Forstall 1970). Specifically, "a metropolitan area includes a central city, neighboring communities linked to it by continuous built-up areas, and more distant communities if the bulk of their population is supported by commuters to the central city" (Rand McNally World Atlas, 1975 Edition). Precise definitions of both the MSA and the Rand-McNally model, called Ranally Metro Area or RMA, are given in the Rand McNally Commercial Atlas and Marketing Guide, 118th Edition, 1987, along with latest census data and estimates for all American and Canadian MSA's and RMA's.

Urban areas are much more realistically defined under the Rand McNally scheme than they are by the OMB, but those with more than one core city raise additional problems. In the Western United States, where much of the concern with sky brightness levels and their correlation with city populations has originated, population densities are low and relatively small single-core cities are the norm. But as amateur astronomers and smaller astronomical centers become more involved with the lighting problem and its study, the special cases of multicentered urban areas becomes of pressing interest.

The two largest urban areas in Florida illustrate one of the most vexing problems of overlapping adjacent communities. The Miami-Fort Lauderdale area is considered as one region by both Rand McNally and the OMB, whereas the Tampa Bay area is separated into two. Although the centers of the two core cities in the former area are separated by 26 miles, the land area in between them never falls below the minimum urban density, currently set at 70 people per square mile. The city centers of Tampa and Saint Petersburg are less than half as far apart but the intervening space is mostly taken up by the waters of Tampa Bay, and consequently the region is separated into two distinct urban centers. The San Francisco Bay area further illustrates the frailty of this approach. Until recently, Rand-McNally listed three separate urban regions there with San Francisco, Oakland and San Jose as the core cities. When regional population growth raised the entire perimeter of the bay above the critical population-density value, the three were redefined as one. Urban areas in other countries, especially those in underdeveloped areas, are more difficult to estimate and intercomparison between them and American or European cities requires a number of other parameters. Chandler and Fox (1974) have given a full description of the methods of estimation of city populations of the past and present. Some, such as the size of the standing militia and the number of hectares within the walled area of a city are no longer very appropriate for the latter twentieth century. But others including some that may not now be recognized may turn out to be closely matched to the city sizes best handled by sky brightness models such as those of Garstang.

Attempts to model the sky brightness of the area surrounding the Van Vleck Observatory face difficulties of these kinds. Central Connecticut is typical of the Northeastern Corridor with a number of core cities within each of its many subregions, however they may be defined. The problem of their separation and identification is not easily solved but may not be insurmountable. One method useful for gauging the separation, extent and influence of core cities lies in the angular estimates of skyglows from the brightest portions of urban areas upon the ceilings (or undersides) of uniform layers of clouds. This nocturnal effect is known to most astronomers but it is rarely described. It is briefly treated in the delightful little book entitled "Light and Colour in the Open Air" by M. Minnaert (1954). From the altitudes of the glows above cities, the linear height of the ceiling of the cloud layer can be derived if the distances to the cities are known and vice versa. Even the most casual inspection of these skyglows shows that core cities and concentrations of population, even if within a single MSA or RMA must be treated individually.

As mentioned above, from the VVO site, the glow due to the campus and nearby city lights precludes the recognition of glows above other cities but from the suburban LH site, those of eight separate and distinct city centers are readily identified. The eight recognizable core cities are listed in Table I along with their distances and azimuths as seen from LH, and the angular and linear sizes of the brightest area of each skyglow. The last three columns list the names of the MSA and RMA in which each city is included (identical in all cases except that Waterbury is included with the New Haven MSA but not the RMA) and the 1985 estimates of the MSA and RMA population in thousands.

TABLE I CITY CENTERS IDENTIFIED FROM NOCTURNAL GLOWS

City	Dist.	Az.	Extent		RMA	Pop. (1000's)	
	(km)		Ang	Lin		MSA	RMA
Hartford	27	0	30	14	Hartford	1075	1035
New Britain	18	332	15	5	"	"	"
Middletown	5	33	40	4	"	"	"
New Haven	32	220	15	8	New Haven	774	509
Meriden	10	277	20	4	"	"	"
Bridgeport	58	230	8	8	Bridgeport	820	446
Waterbury	31	276	10	5	Waterbury	774*	209
New London	53	110	5	5	New London	246	261

*Included in the MSA of New Haven

Several points are worth noting in the table. Two pairs of cities lie nearly in the same directions as seen from LH, New Haven and Bridgeport, and also Meriden and Waterbury. In each case, the glow produced by the more distant city can be seen lying below that of the closer city but separate and distinct.

The estimation of populations for these areas might be better done by summing the communities immediately surrounding each with the population density held to a higher value than the critical value of the RMA definition. Several indices appear to correlate more closely with the observed brightness distribution than do the MSA and RMA totals. Among those worthy of further investigation are the summation of very local population counts and the circulation of local newspapers.

Three ways of determining urban area populations appear to be the most suitable from among many determined and displayed by Smith (1974) for the state of Connecticut. New England has not experienced rapid growth in the last 20 years, and the use of 1974 population data introduces only a small error. The populations for each region and core city are given in Table II for each of the three. In the table, the figures listed under Model 1 refer to the populations of the SMSA's. Unlike the modern MSA's, these did not as frequently combine core cities into large urban agglomerates. Model 2 refers to the population of each city within a limit set by the location of the population density minimum line between it and its neighbors, regardless of the density itself. The final column shows the populations determined for each city from the circulation of the most widely circulated daily newspaper of that city. The total circulation for all of the cities is a factor of 4.5 smaller on average than the figures of the other two methods, thus each circulation figure was scaled upwards by 4.5.

TABLE II RESULTS FOR THREE POPULATION MODELS

City	Population in Thousands Model 1	Model 2	Model 3
Hartford	700	578	765
New Britain	150	136	112
Middletown	not defined	56	40
New Haven	450	418	450
Meriden	50	72	40
Bridgeport	500	344	360
Waterbury	200	180	292
New London	200	164	135

The reasonable agreement between the three models is not surprising in part because they are not fully independent of each other. Collectively, they merely represent a first attempt to define indices that are at least somewhat correlated with the skyglow pattern which the cities produce. They do avoid the worst excesses present in the MSA and RMA data currently available and when sky brightnesses from more locations become accessible, they should form a starting point for modeling the data.

In conclusion, it is hoped that this brief study of city populations alerts those working in the measure of sky brightness and the extent of light pollution to the dangers of using the most available population figures at hand, especially in regions of high overall population density.

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