LIGHT POLLUTION AT MOUNT WILSON: THE EFFECTS OF POPULATION GROWTH AND AIR POLLUTION

ROY H. GARSTANG
JILA, University of Colorado and National Institute of Standards and Technology, Boulder, Colorado 80309-0440, U.S.A.

ABSTRACT. This is the first part of a study of the historical growth of light pollution at Mount Wilson Observatory. The night sky brightness at Mount Wilson due to light pollution from the Los Angeles basin was calculated for the years from 1910 to 1990, neglecting changes in lighting technology, and without any air pollution ('smog'). The very large effect of population growth is shown. We made a simple extension of our night sky brightness program to include a layer of smog. Two possibilities are discussed, a layer with density decreasing exponentially with height above the ground, and a layer of constant density and finite thickness. The ground level density is determined by the visibility. We assume a smog layer whose density increases from zero in 1920 to appropriate values for the years from 1950. We added this layer to our model and repeated the Mount Wilson calculations. An average smog layer reduces the visual brightness at the present time by about 6 percent.

1. Introduction

One of the sad happenings in astronomy was the deterioration of the Mount Wilson Observatory as a prime observing site, caused by the growing brightness of the night sky. The latter was caused primarily by the growth of the population in the Los Angeles basin. We are investigating some of the details of this deterioration. We are interested in the sky brightness at Mount Wilson on clear, moonless nights, when there is no fog in the Los Angeles basin but when air pollution (referred to below as 'smog') may be present. We think that the problem may be divided into three parts: (1) The growth of the population, which brought with it increased artificial lighting, (2) the growth of smog in the region and (3) changes in lighting technology, leading from incandescent to mercury to sodium lamps. In this paper we investigate the first and second of these factors.

2. The effect of population growth

We began by calculating the brightness of the sky at Mount Wilson caused by light pollution from cities in the Los Angeles basin. We essentially used our standard model (Garstang 1986, 1989a, 1991), not taking into account any changes in lighting technology, and using the photon emission per person given in Garstang (1989a). We included a total of 124 cities in the Los Angeles basin: these included the City of Los Angeles itself, cities in Los Angeles county outside the City of Los Angeles, and many cities in those parts of Orange, Riverside, San Bernardino and Ventura counties nearest to Mount Wilson. For years from 1940 onwards, for which we had detailed census data, the City of Los Angeles was divided into six and treated as six separate cities. The population of each city (or portion of Los Angeles) was obtained from U.S. Census Bureau publications. Some distant cities were grouped by adding the populations of the separate cities. Only incorporated cities were included in our calculations. Distances from Mount Wilson to each city (or group) were measured on the H. M. Gousha road map of California, estimating the position of the city (or group) center as best we could. We decided not to use a different height above sea level for each city. Taking into consideration the cities that contribute the most to the light pollution at Mount Wilson, we estimated a rough average height above sea level $H = 125$ m: the value is not critical. For the Mount Wilson Observatory, the height above sea level is 1740 m.

We write the law of extinction of light as it passes a distance x through the atmosphere as $I = I_0 \exp(-b_{scatt}x)$, where b_{scatt} is measured per unit distance, and includes contributions for scattering and absorption by molecules (including ozone when necessary) and background aerosols (which are always present even in clear air). If b_{scatt} is function of position, $b_{scatt}x$ must be replaced by the integral of b_{scatt} over x. We formulate b_{scatt} by adding the contributions of the air molecules and aerosols. If $N_m = 2.68 \times 10^{19}$ cm^{-3} is the sea level molecular air density and H is the height of the ground above sea level then the density of the air $N(h)$ at a height h above the ground is

$$N(h) = N_m \exp\,(-cH) \exp\,(-ch) f \tag{1}$$

where $f = 1$ for $h + H < 10$ km and $f = 1.568 \exp(-dh - dH)$ for $h + H \geq 10$ km. The parameters c and d describe the assumed atmospheric density–height model (Garstang, 1991). We adopted $c = 0.113$ km^{-1} and $d = 0.045$ km^{-1}. Then the contribution to the scattering is

$$b_{scatt} = N_m \sigma_R \exp\,(-cH) \exp\,(-ch) f. \tag{2}$$

Here σ_R is the Rayleigh scattering cross section for air molecules at the wavelength being considered. We adopted $N_m \sigma_R = 0.0123$ km^{-1} for the V photometric band and 0.0305 km^{-1} for the B photometric band. The background aerosols are treated as having an exponential distribution decreasing with height h above the ground with reciprocal scale height a, so that the contribution to b_{scatt} is taken as $N_a \sigma_a \exp(-ah)$. The number density of aerosol particles at ground level is N_a and σ_a is the cross section for extinction by a particle. Of course we are actually using the value of $N_a \sigma_a$ averaged over particles of many different kinds and a range of sizes, but the kinds and sizes do not need to be specified in our model. It is convenient to introduce a parameter K as a measure of the scattering by background aerosols. It is defined by the equation [Garstang 1986, equation (4)]

$$b_{scatt} = N_a \sigma_a \exp(-ah) = 11.778 K N_m \sigma_R \exp(-cH) \exp(-ah) \tag{3}$$

The coefficient has been increased by 6% to allow for pure absorption by the aerosol particles. The numerical coefficient was originally chosen so that $K = 1$ represented the background aerosols in clear (actually slightly hazy) air on the U.S. east coast. $K = 0.5$

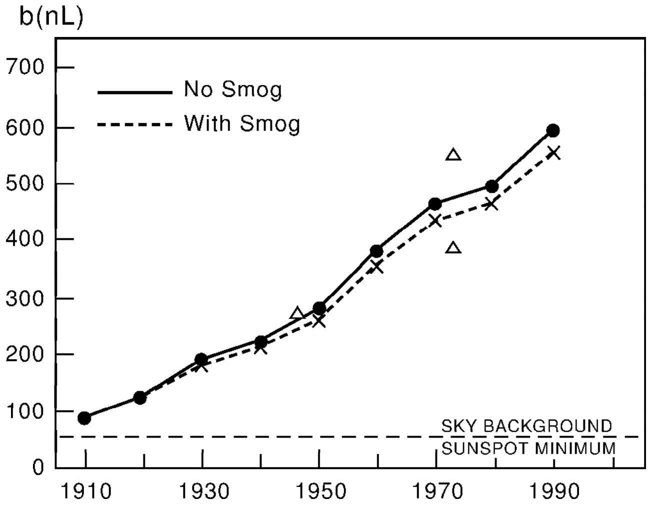

Fig. 1. The brightness b (in nanolamberts) of the zenith sky at Mount Wilson calculated without and with an average smog layer. The results of our reductions of the observations of Bowen in 1947 and of Turnrose in 1973 are shown. All calculations and observations assume a sunspot minimum sky brightness of 55 nL.

is a better approximation for clear air in the western half of the U.S. Using the curved Earth model (Garstang 1989a) it can be shown that for pristine air from the Pacific ocean a value $K = 0.2$ must be assumed to account for visibilities exceeding 110 km that are encountered (Trijonis 1982) in eastern California, Nevada and elsewhere. We used $K = 0.2$ (instead of $K = 0.5$) in all our calculations in this paper. We adopted $a = 0.687$ km^{-1} for the aerosol reciprocal scale height. Other parameters that occur in our model, such as the ground reflectivity and the fraction of light radiated directly upwards, had the usual values we use in our models.

3. Results on population growth effects

Our results are listed in Table I, which gives the B and V brightnesses expressed in magnitudes per square arc second, the photon brightnesses b_B and b_V in photons per square centimeter per second per steradian, the eye brightnesses b in nanolamberts (nL), and the limiting magnitude for a naked eye observer calculated using the program described by Schaefer (1990) with modifications by Garstang (1999). All our results refer to observations at the zenith, and all include night sky background brightnesses corresponding to sunspot minimum, our assumed values for which are listed in the third column of Table I. Our results for the eye brightness are also shown in Fig. 1. The great increase in night sky brightness due to the growth of population is evident.

Our results are subject to some uncertainties. In addition to approximations in the model itself, the population data are subject to uncertainties caused by the large number of incorporations and annexations over the years. We think it not worth the effort it would take to follow all these changes in detail. In addition, we used only incorporated cities: this has proved a satisfactory approximation in our earlier work. The rapid growth after World War I is evident, as is rapid growth after World War II. The reduced growth rate during the depression of the 1930s is also evident.

The rapid growth in the 1980s is due to steady population increases in many cities, especially in the San Fernando Valley and in Orange County. The rate of increase of the Mount Wilson brightness has slowed down somewhat as more of the population increase occurs in cities at larger distances from Mount Wilson. Unfortunately the rate of increase of sky brightness between 1980 and 1990 is about 4% larger than our earlier prediction (Garstang 1989b).

4. Checks on our calculations

There are few observations of the brightness of the night sky at Mount Wilson. However, Turnrose (1974) published two night sky spectra obtained on January 5, 1973. We have integrated the two spectra to find the total sky brightness. His spectra are seriously deficient in one major respect: the bandpasses he used did not include the very strong mercury lines at 5461, 5770 and 5791 Å, although he did give intensities for 4358 Å. We used the strengths of these four lines in the Lick Observatory spectra obtained by Osterbrock, Walker and Koski (1976: we used their Figs. 1 and 2; as they explain, their Fig. 3 is not suitable for this purpose) to make an estimate of the energy missing from Turnrose's results and added our estimates to our calculated sky brightnesses. Turnrose's spectra also omitted the [O I] lines, but in view of the very intense light pollution due to the Los Angeles basin we think that the natural [O I] contribution to the total sky brightness would have been relatively much less important than it was in the Lick spectra, and we did not attempt to estimate it. We obtained for Turnrose's spectrum A (taken at an average zenith distance of 43^o and azimuth 193^o) a sky brightness of 1020 nL, and for spectrum B (average zenith distance 36^o and azimuth 254^o) a brightness of 550 nL. To compare these values with our calculations we must make approximate reductions to the zenith. For this purpose we ran our light pollution program for 1970 and 1980 for the zenith distances and azimuths of Turnrose's spectra and interpolated the results to 1973. We calculated the ratios of the brightnesses from these calculations to the brightnesses interpolated for 1973 from our zenith calculations, and then applied these ratios to Turnrose's observations. We included in our reductions an estimate of the natural sky background brightness in 1973 obtained by using the Ottawa 10.7 cm. flux and the calibration of Walker (1988). The final results we obtained were 550 nL and 380 nL for the two spectra, reduced to the zenith and to sunspot minimum sky background. We show both points in Fig. 1. Both points differ significantly from our calculations, and it is perhaps not valid to average them. However the average does agree very well with our calculations.

Observations of the limiting magnitude of stars viewed with three telescopes at Mount Wilson in 1947 were made by Bowen (1947). A detailed analysis of his observations has been made (Garstang 1999). The best value of the night sky brightness was 330 nL, and the best estimate of the night sky background was 75 nL. In order to reduce this observation to the zenith we ran our program for 1940 and 1950 using zenith distance 30^o and azimuth 90^o, which avoids the worst of the city lights (Bowen said he avoided city lights as much as possible and also avoided the Milky Way). From our calculations we estimated that the pollution part of Bowen's intensity should be reduced by 0.85 to get a zenith estimate. The background estimate of 75 nL refers to the zenith and this should be increased to 79 nL for subtraction from Bowen's total brightness. Thus we estimate the pollution portion of his brightness to be $330 - 79 = 251$ nL, and when reduced to the zenith $0.85 \times 251 = 213$ nL. Adding the sunspot minimum background brightness 55 nL gives a total brightness approximately 270 nL. This value is shown in Fig. 1. The agreement with our calculations is surprisingly good.

5. The smog model

We now turn to the study of the second aspect of night sky brightness at Mount Wilson, the effect of smog. To represent smog we add additional scattering and absorption to that already present in our model. There are two options that are attractive because of their simplicity. In both options the smog is treated as being uniform over the whole city area. One option treats the smog density as decreasing from the ground level upwards according to an exponential law $\exp(-a'h)$, so that we write

$$b_{scatt} = 11.778 K' N_m \sigma_R \exp(-cH) \exp(-a'h). \tag{4}$$

The second option treats the smog as a constant density layer up to a finite height (t) above ground level, and zero density above t, so that

$$b_{scatt} = \begin{bmatrix} 1.778\ K'' N_m \sigma_R \exp(-cH) & 0 \le h \le t \\ 0 & h > t\ \ . \end{bmatrix} \tag{5}$$

We are mainly interested in the extinction along the light paths taken by city light being scattered in the high atmosphere above the observatory leading to brightening of the sky. We are also interested in light reaching the observatory on a direct line of sight from the city. It is easy to show that the total extinction along a light path is the same in the two models if we take $K' = K''$ and $a' = 1/t$, provided that the observatory is well above the smog layer so that at the height of the observatory the tail of the smog exponential is negligible. (At altitudes within the smog layer the two models will give different results.) This applies for rays travelling at any given angle z to the zenith, when the extinction in passing through the layer is the extinction for a vertically travelling ray multiplied by sec z. It is slightly easier to add a second exponential to our model.

We must also consider the intensity of the smog. If we have certain kinds of observations at various altitudes within the smog we may try to fit our models to the observations. If we do we get values of K' and a' for one model and K'' and t for the second model. We generally find that K' and K'' are unequal. To get a better determination of K' and impose $K'' = K'$ we consider the visibility observed by ground based observers. It is conventional in meteorology (see e.g., Middleton 1952, pp. 4, 63, 94) to adopt as the visibility in daylight (also called the visual range) the distance Δx at which a black object would show a brightness (due to scattered light between the observer and the object) of 0.98 of the brightness of the background horizon beyond the object, this being referred to as a contrast of 0.02. This assumes that the atmosphere is uniform along the line of sight. Using the extinction law for light it can be shown that $\Delta x = 3.91/\ b_{scatt}$. This is known as Koschmieder's formula. (We use this definition, but it is a rather extreme definition, and if a contrast 0.05 were adopted instead the constant 3.91 would be replaced by 3.00.) If distances are measured in kilometers then b_{scatt} must be measured in km^{-1}. In the air pollution literature b_{scatt} is often measured in $(10\ \mathrm{km})^{-1}$, and in these units, with Δx in km, the constant becomes 39.1.

We add to the extinction a term of one of the above forms to represent the smog. We determine K' $(= K'')$ by considering the ground level visibility. In our model [Garstang, 1991, equation (7)] with the additional smog term we have

$$b_{scatt} = N_m \sigma_R[\exp(-ch) + 11.778\ K\exp(-ah) + 11.778\ K'\exp(-a'h)]\exp(-cH) \quad (6)$$

for the exponential model, and the same for the uniform layer model except that K' $\exp(-a'h)$ is replaced by K' for $h \leq t$ and by zero for $h > t$. The horizontal visibility is $3.91/\ b_{scatt}$ where for the ground level with $h = 0$ we have

$$b_{scatt} = N_m \sigma_R[1 + 11.778\ K + 11.778\ K']\exp(-cH). \quad (7)$$

For the B band we take the value of K to be 0.492 times K for the V band (Garstang 1989a, p. 323). Extinction by smog aerosols has a wavelength dependence of about $\lambda^{-1.8}$ (Ahlquist and Charlson 1969). Combining this with the λ^{-4} dependence for Rayleigh scattering we see from equation (4) above that K' for the B band must be taken as $(4400/5500)^{2.2} = 0.612$ times the K' for the V band.

Before proceeding to study Los Angeles we tried to check the validity of our smog model. McCormick and Baulch (1962) were the first to study atmospheric smog near the ground by measuring the attenuation of solar radiation as a function of altitude. They used a helicopter to carry a Sun photometer and measured the transmissivity of the atmosphere as a function of the height above the ground in Cincinnati. They worked at heights from the ground up to about 180 m. They made measurements on a number of days both of polluted air near the city center and of 'clean' air outside and upwind from the city. The clean air was not really clean, just significantly less polluted than the city center air. We selected the results for one day, December 6, 1961, for which the transmissivity-height curves had a simple form, suggesting that a single smog layer was present. We integrated b_{scatt} from height h to infinite h, and fitted the result to the observations. For the 'clean' air we got a reasonable fit with our model with $K = 3.5$ and $a = 0.9\ \mathrm{km}^{-1}$. This means an aerosol content at ground level of 17 times that of pristine U.S. western air, in a layer which, if it were of uniform density, would have a vertical thickness of 1.1 km. We then fitted our model to the city center observations, and using the same K and a values for the background aerosols, we got an acceptable fit with $K' = 50$, $a' = 10\ \mathrm{km}^{-1}$. This indicates a very dense smog layer with an equivalent uniform thickness of only 100 m.

Improved measurements in Cincinnati were made by Bach (1971). An extensive series of helicopter observations were made on October 4, 1969, an exceptionally smoggy day when it was almost impossible to see the tops of tall buildings from the street. We selected the 8 a.m. data, the earliest in the day, because we thought it would be closest to representing the pollution during the previous night. We made appropriate corrections to our program because the wavelength used was 5000 Å. No clean air data was available for this particular day; after some trials we got a reasonable fit with $K = 1.8$, $a = 1$ km^{-1}. The observations gave the percentage of the solar attenuation in the atmosphere below a stated height. We calculated this from our exponential model, and determined the best fit. We obtained $K' = 120$, $a' = 14$ km^{-1} (mathematically equivalent to a uniform layer of thickness $t = 70$ m). We also modified our program to calculate the vertical extinction through a uniform layer, and our best fit was $K' = 39$, $t = 110$ m. We judged that both models gave acceptable fits with the observations. However, the total absorption from the ground up to the outside of the smog is twice as much in the exponential model as in the uniform layer model. We should make an independent estimate of K', which might come from visibility observations, but no visibility data at Cincinnati were available to me for this date.

These calculations showed that our models could be used to represent smog layers even under rather extreme conditions. Many additional observations were made by McCormick and Baulch and by Bach in Cincinnati, and by various authors in other cities, including Seattle, San Jose, Oakland, Fort Worth, and Phoenix. Our models could be used to analyze much of this data, but we do not think it profitable to continue such studies here.

6. Application to the Los Angeles basin

Los Angeles smog is very variable, both during a single day and from day to day. It tends to be greatest in the middle of the day, and to lessen in the evenings. In consequence the visibility at any site (in the absence of fog) is usually a minimum in the middle of the day, and is much better in the early morning and in the late afternoon. A Stanford Research Institute (1954) study of visibility at Pasadena showed one day when the early morning visibility fluctuated between 20 and 50 km, and it was reduced to 5 km by mid-day. On another day the visibility was 5 km at 1 p.m. and had improved to 16 km by 3 p.m. Variations of a factor of 2 can occur in a period of an hour.

It is clear that there is no need to investigate any individual day in detail. We must adopt representative values of the parameters. A general study of visibility in the Los Angeles basin (and California in general) by Trijonis (1982) gave 1 p.m. data averaged for the years 1974-1976 at 67 locations in California. Along the California-Nevada border the visibility exceeded 110 km, and this requires a value of $K = 0.2$ for pristine Pacific air, as we mentioned earlier. We adopted this for our calculations on the Los Angeles basin. In the center of the Los Angeles basin the median visibility was 13 km. This leads to $K' = 1.83$ for the average mid-day smog. No data were given on night-time visibility. We have made an estimate by assuming that the night-time visibility is twice that of the day-time, and this leads to $K' = 0.77$.

Cass (1979) analyzed some extensive routine measurements of visibility made at ground level in Los Angeles city. These were made from a rooftop at a height of 25 m in downtown Los Angeles over the period 1965–1974. Omitting a few days when the smog was exceptionally bad and a few days when the relative humidity was unusually high, 390 observations gave an average $b_{scatt} = 0.556\ \mathrm{km}^{-1}$ corresponding to a visibility of about 7 km. On individual days the visibility varied from less than 2 km to more than 30 km; the median visibility, exceeded on half the days, was about 8 km. If we double the latter figure for night-time visibility and follow Cass's suggestion of using the Koschmieder formula as $\Delta x = 3.0/\ b_{scatt}$ we get $K' = 1.03$.

The above work on visibility contains no information about the vertical distribution of the aerosols. For the background aerosols we adopted $a = 0.687\ \mathrm{km}^{-1}$, the value we used above. A good example of the vertical distribution of scattering particles was given by Gloria et al. (1974), who show results quoted from an unpublished study by staff of Meteorologic, Inc. The latter workers used a well-equipped aircraft over Hawthorne Airport in the western Los Angeles basin. They gave the total scattering cross section for light as a function of altitude from the ground up to about 975 m. We analyzed their data assuming $K = 0.2$ and $a = 0.687\ \mathrm{km}^{-1}$ for clear Pacific air. We forced a fit at the ground, which is equivalent to assuming correct ground visibility. For the smog this gave $K' = 3.72$. We then imposed the condition that the total extinction up to height 0.975 km agreed with that calculated from the observations. This gave $a' = 2.55\ \mathrm{km}^{-1}$, equivalent to a uniform layer of thickness 390 m. We fitted a uniform layer model by the same method, and this gave $K' = 3.72$ and $h_{smog} = 360$ m. The two models are quite different at intermediate altitudes, but this need not concern us as far as our planned application is concerned. The difference between $1/a'$ and h_{smog} is due to the neglect of the tail of the smog exponential above 975 m. If we assume a night time visibility of double that in the day time we get $K' = 1.69$, a rather high value, possibly due to slight fog because the relative humidity at the ground was 75%.

We are also interested in the trends of visibility. Holzworth and Maga (1960) summarized earlier unpublished work by M. Neiberger, who studied visibility in downtown Los Angeles for the period 1932 to 1954, and extended it to 1959. The primary conclusion was that visibility got worse from 1932 to 1947, and stayed about the same from 1948 to 1959. The results clearly showed that visibility improved from noon to 5 p.m. From data in their Table VI we estimate a factor of 1.6 improvement. The improvement probably continued to a somewhat later time, and we think that this is some confirmation of our decision to take the night time visibility as twice that at noon. We took the noon data, estimated the weighted average visibility for 1932, 1947, 1948, and 1959, doubled it, and then calculated the values of K' that resulted. We obtained $K' = 0.27$ (1932), 0.73 (1947), 0.55 (1948 and 1959). The reduction after 1947 is thought to be due to the introduction of the first pollution control regulations.

Trijonis (1982) stated that between 1949 and 1966 nearly all locations showed declining visibility, and between 1966 and 1976 nearly all locations showed improving visibility. For coastal and central Los Angeles visibility improved between 1949 and 1976, while in the inland of the Los Angeles basin the visibility decreased.

Particulates are the principal source of poor visibility. An Environmental Protection Agency Report (1994, Figs. 3-5) summarized particulate matter emissions in the whole of the U.S. for the period from 1940 to 1993. The maximum particulate emission appears to have occurred about 1950, slowly declined until 1970, and declined more rapidly after 1970. Ozone contributes to air pollution through photochemical reactions, which produce other particles (especially sulphates). Turco (1997) gives a summary of ozone concentration in the Los Angeles basin from 1970 to 1988, showing a declining trend of about 1% per annum.

Carlin and Kocher (1971) gave an interesting summary of the sources of pollution in the Los Angeles basin from 1900 to 1980. It is clear that pollution was relatively small in 1920 but increased significantly after that. We assume that it was zero in 1920.

The top of the main smog layer is usually at an altitude of about 300 m. Friends tell me that if you have a house on a hill about 1100 ft, say 330 m, above the general ground level you are above most of the smog on most days. The smog does sometimes extend higher, for example in the work by Gloria et al. (1974) there was a second smog layer at a height of about 500 m. There was a report of fluorocarbons in the Los Angeles basin when the top of the smog was at about 1000 meters altitude (Hester et al. 1974), and the smog sometimes goes over the top of Mount Wilson at 1740 m altitude, but these are worst case scenarios.

Taking all the above into consideration we adopted a value $a' = 3.0$ for our assumed exponential distribution, which corresponds to $t = 330$ meters for the height of a uniform layer. We use the exponential distribution in our calculations on Mount Wilson. We are not particularly interested in intermediate altitudes, but it is our guess that the exponential model distribution would be closer to reality that the uniform layer model.

Looking at the values of K' and ignoring the high value of Gloria et al. (1974), we adopt for night time calculations with smog the values of K' listed in the first row of Table I. Although uncertain, we think that these give fair representative values. Using the calibration of Cass (1979) we find that $K' = 0.75$ corresponds to a particulate loading of about 40 μg/m^3 at night, and in the daytime with half the visibility the particulate loading would be about 90 μg/m^3. These values may be compared with the Federal air pollution standard, which is 50 μg/m^3, with the first level alert at 100 μg/m^3.

We now apply our assumptions to the calculation of the effect of smog on night sky brightness at Mount Wilson. For the aerosols we used $K = 0.2$, $a = 0.687$ km^{-1}, $a' = 3.0$ km^{-1}and the values of K' listed in Table I. We added an approximate correction to our model to allow for the slope of the ground from the sea coast to the foothills, keeping the smog thickness the same everywhere. We added a calculation of the extinction along the direct line of sight from each city to the Mount Wilson Observatory. We calculated the limiting visual magnitude seen by an average naked-eye observer, using the procedure of Schaefer (1990) with minor modifications described in Garstang (1999).

Our results are given in Table I. The night sky brightness at the zenith in 1990 was reduced by about 0.11 mag/sec^2 in B and 0.08 mag/sec^2 in V. In photon units the reductions were about 9% in B and 6% in V. These figures relate to our assumed average smog layer. Smog is very variable, and the brightness reduction on any night may be between zero and at least double our calculated amounts. The effect of the smog on the limiting visual magnitude was negligible. One factor which is of significance is that much of the light from the cities which gets scattered in the atmosphere above Mount Wilson passes through the smog layer at only moderate zenith distances. It suffers much less extinction than one might guess from the visibility at the ground. We also calculated the extinction seen by an observer standing on Mount Wilson looking at the cities of the Los Angeles basin at night. Our results are given in Table II. For a nearby city such as Pasadena the transmission along the line of sight in the V band is 0.73 when there is no smog, and 0.59 when there is an average smog layer. For a distant city, such as the Los Angeles port, the transmission is 0.22 without smog and 0.069 with smog. Thus, for this distant city the brightness observed would be reduced by a factor of about 3 by an average smog layer. We see that the apparent brightness of distant cities may be significantly reduced by smog, even if the reduction in sky brightness at the Mount Wilson zenith is relatively small.

We have also given in Table I a few results for the contributions to b_V of Pasadena, Los Angeles, and the nearer part of Orange County. These results illustrate the increasing contributions from distant cities.

The conclusion is clear. The presence or absence of smog in the Los Angeles basin has made very little difference to the sky brightness at Mount Wilson. The huge brightness increase is largely due to the large growth of population in the Los Angeles basin. We hope to deal with the effects of changing lighting technology in a future paper.

Acknowledgements

I am indebted to Dr. Gibson Reaves for several discussions and helpful suggestions, and for kindly sending me a number of publications on Los Angeles smog that were not otherwise available to me.

TABLE I

Night sky brightness at Mount Wilson*

	Smog	Sky	1910	1920	1930	1940	1950	1960	1970	1980	1990
K'	Yes		0	0	0.25	0.50	0.75	0.75	0.75	0.70	0.65
B	No	22.99	22.37	22.00	21.54	21.34	21.10	20.76	20.55	20.49	20.30
	Yes				21.57	21.41	21.20	20.87	20.66	20.60	20.41
b_B	No	0.39	0.69	0.97	1.49	1.77	2.22	3.03	3.69	3.90	4.65
	Yes				1.45	1.68	2.03	2.74	3.32	3.52	4.21
V	No	21.99	21.44	21.10	20.64	20.46	20.22	19.88	19.66	19.60	19.40
	Yes				20.66	20.50	20.28	19.95	19.74	19.67	19.48
b_V	No	0.60	1.00	1.37	2.08	2.46	3.07	4.20	5.13	5.46	6.51
	Yes				2.05	2.38	2.90	3.93	4.78	5.10	6.10
Eye	No	55	91	124	188	223	278	380	465	494	590
	Yes				185	215	262	356	433	462	552
Mag	No	6.19	5.95	5.79	5.57	5.49	5.37	5.21	5.11	5.08	5.00
	Yes				5.58	5.50	5.40	5.25	5.15	5.12	5.03
LA$_V$	Yes		0.23	0.43	0.64	0.80	0.89	1.06	1.17	1.27	1.49
P$_V$	Yes		0.11	0.16	0.29	0.31	0.39	0.43	0.42	0.44	0.49
O$_V$	Yes		—	—	0.01	0.01	0.01	0.06	0.11	0.14	0.17

*K' is the parameter measuring the intensity of the smog. B and V are in magnitudes per square arc second. b_B and b_V are in units of 10^8 photons/cm^2/sec/steradian. 'Eye' is in nanolamberts. 'Mag' is an estimate of the limiting visual magnitude. 'Smog' - no indicates no smog in calculations, yes indicates the values of K' used were those given in the Table. LA$_V$, P$_V$ and O$_V$ denote the contributions to b_V from Los Angeles city, Pasadena and the nearer part of Orange County, all in units of 10^8 photons/cm^2/sec/steradian.

TABLE II

Extinction of light from a city that reaches an observer directly

Date	City	Smog		No Smog	
		B	V	B	V
1990	Pasadena	0.42	0.59	0.58	0.73
	Central Los Angeles city	0.082	0.22	0.22	0.42
	Los Angeles port area	0.013	0.069	0.075	0.22

References

Ahlquist, N. C. and Charlson, R. J. 1969, Atmos. Environ. **3**, 551.

Bach, W. 1971, J. Air Pollution Control Assoc. **21**, 621.

Bowen, I. S. 1947, Publ. Astron. Soc. Pac. **59**, 253.

Carlin, A. P. and Kocher, G. E. 1971, *Environmental Problems: Their Causes, Cures and Evolution, using Southern California Smog as an Example*, Rand Corporation - Carnegie Corporation Report R-640-CC/RC.

Cass, G. R. 1979, Atmos. Environ. **13**, 1069.

Environmental Protection Agency, 1994, National Air Pollutant Emission Trends, 1900—1993, Report EPA-450/R-94-027.

Garstang, R. H. 1986, Publ. Astron. Soc. Pac. **98**, 364.

–, 1989a, Publ. Astron. Soc. Pac. **101**, 306.

–, 1989b, Ann. Rev. Astron. Astrophys. **27**, 19.

–, 1991, Publ. Astron. Soc. Pac. **103**, 1109.

–, 1999, in this volume.

Gloria, H. R., Bradburn, G., Reinisch, R. F., Pitts, J. N., Behar, J. V. and Zafonte, L. 1974, J. Air Pollution Control Assoc. **24**, 645.

Hester, N. E., Stephens, E. R. and Taylor, O. C. 1974, J. Air Pollution Control Association **24**, 591.

Holzworth, G. C. and Maga, J. A. 1960, J. Air Pollution Control Assoc. **10**, 430.

McCormick, R. A. and Baulch, D. M. 1962, J. Air Pollution Control Assoc. **12**, 492.

Middleton, W. E. K. 1952, *Vision Through the Atmosphere*, Toronto University Press.

Osterbrock, D. E., Walker, M. F. and Koski, A. T. 1976, Publ. Astron. Soc. Pac. **88**, 349.

Schaefer, B. J. 1990, Publ. Astron. Soc. Pac. **102**, 212.

Stanford Research Institute 1954, *The Smog Problem in Los Angeles County*, Western Oil and Gas Assoc., pp. 107-108.

Trijonis, John 1982, J. Air Pollution Control Assoc. **32**, 165.

Turco, R. P. 1997, *Earth under Siege, From Air Pollution to Global Change*, Oxford University Press, New York, p. 162.

Turnrose, B. E. 1974, Publ. Astron. Soc. Pac. **86**, 545.

Walker, M. F. 1988, Publ. Astron. Soc. Pac., **100**, 496.