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A REDISCUSSION OF THE ATMOSPHERIC EXTINCTION AND THE ABSOLUTE SPECTRAL-ENERGY DISTRIBUTION OF VEGA

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ABSTRACT

For both the Lick and the Palomar calibrations of the spectral-energy distribution of Vega, the atmospheric extinction was treated incorrectly. We present a model for extinction in the Earth's atmosphere and use this model to calculate corrections to the Lick and Palomar calibrations. We also describe a method that can be used to fabricate mean extinction coefficients for any mountain observatory.

We combine selected portions of the corrected Lick and corrected Palomar calibrations with the new Mount Hopkins calibration to generate an absolute spectral-energy distribution of Vega over the wavelength range 3300–10,800 Å. Until better measurements become available, we recommend the use of this calibration for all practical applications.

Subject headings: atmospheres, terrestrial — spectrophotometry — stars, individual

I. INTRODUCTION

Since 1969, we have been working at the Smithsonian Astrophysical Observatory's Mount Hopkins Observatory on a new calibration of the monochromatic fluxes from Vega at several wavelengths in the near-infrared (Hayes, Latham, and Hayes 1975). In the process of preparing these results for publication, we reviewed the spectral-energy distributions of Vega measured at Lick Observatory (Hayes 1967, 1970) and Palomar Mountain (Oke and Schild 1970). Four significant flaws in these previous calibrations became apparent: (1) For the Palomar calibration, the mean vertical extinction coefficients adopted for the data reductions were systematically too large, especially in the ultraviolet. (2) For both the Lick and the Palomar calibrations, the horizontal extinction to the standard source was underestimated at all wavelengths. (3) The platinum blackbody comparison did not contribute to the Palomar calibration in a fundamental way and gave considerably larger errors than the other sources did. (4) For a variety of reasons, the data at three extreme wavelengths in the Lick calibration and at two in the Palomar lamp calibration were judged to be of inferior accuracy.

In this paper we attempt to rectify the above flaws, and we derive corrections to be applied to the Lick and Palomar calibrations. The corrections arising from removal of the platinum blackbody data and the other inferior points are straightforward to calculate, but those for the extinction are quite complicated. As a basis for these calculations, we have adapted a model for extinction in the Earth's atmosphere, a model that is well known to physical meteorologists but appears to be unfamiliar to most astronomers. Using this model, we have derived a procedure for calculating mean extinction coefficients for any mountain observatory. While this procedure is not meant to be a substitute for measuring nightly coefficients, it should be more accurate than the one used by Oke (1965) to calculate the standard extinction coefficients for Palomar Mountain.

In the final sections of this paper, we combine the corrected Lick and Palomar calibrations with the new Mount Hopkins calibration to form an adopted absolute spectral-energy distribution for Vega in the wavelength range 3300–10,800 Å. Until better measurements become available, we recommend the use of this adopted calibration for all practical applications.

II. ATMOSPHERIC EXTINCTION

a) A Model for Atmospheric Extinction

Three sources of extinction in the Earth's atmosphere are important for ground-based stellar photometry: Rayleigh scattering by molecules, aerosol scattering, and molecular absorption. Each of these has its own characteristic wavelength dependence, distribution with height, and variation with time. Throughout the following discussion, we use the general notation $A(\lambda, h)$, or "vertical extinction," for an extinction coefficient (in mag [air mass]$^{-1}$) over an observatory at altitude h (in km) and as a function of wavelength λ (in μ). For the "horizontal extinction" in the line of sight to a standard source located d km from the telescope, we use $A_{\rm hor}(\lambda, d)$, in magnitudes.

i) *Rayleigh Scattering*

Rayleigh scattering by air molecules is well understood both theoretically and experimentally (Penndorf 1957). The Rayleigh vertical extinction is proportional to the local atmospheric pressure, and can be written as

$$A_{\rm Ray}(\lambda, h) = 9.4977 \times 10^{-3}\left(\frac{1}{\lambda}\right)^4\left[\frac{(n-1)_\lambda}{(n-1)_{\lambda=1}}\right]^2 \times \exp\left(\frac{-h}{7.996}\right), \quad (1)$$

where we have assumed an atmospheric pressure of 760 torr at $h = 0$, and the index-of-refraction term is given by

$$\frac{(n-1)_\lambda}{(n-1)_{\lambda=1}} = 0.23465 + \frac{1.076 \times 10^2}{146 - (1/\lambda)^2} + \frac{0.93161}{41 - (1/\lambda)^2}.$$

These formulas were adapted from Penndorf (1957), except that the coefficient 9.4977×10^{-3} was chosen to correspond to Elterman's (1970) optical thickness for $h = 0$, and we have assumed a density scale height of 7.996 km (Penndorf 1957) for the lower troposphere. If these formulae are used to calculate $A_{\rm Ray}$ for a particular night, the largest uncertainty is the deviation of the local atmospheric pressure from standard conditions, which amounts to about 1 percent standard deviation.

ii) *Water and Ozone*

Molecular absorption occurs in lines and bands. Although the passbands used for the Lick, Palomar, and Mount Hopkins calibrations were chosen by Oke (1964, 1965) to avoid telluric lines if possible, water vapor and ozone contribute significant extinction at several of the wavelengths. The ozone is concentrated at altitudes between 10 and 35 km, so its contribution to the vertical extinction does not depend on the altitude of the observatory. To calculate the ozone vertical extinction, we have used

$$A_{\rm oz}(\lambda) = 1.11 T_{\rm oz} k_{\rm oz}(\lambda), \quad (2)$$

where $k_{\rm oz}(\lambda)$ is the absorption coefficient in cm^{-1}, taken from Gast (1960), and $T_{\rm oz}$ is the total ozone above the observatory in atm-cm, taken from Allen's (1963) tabulation as a function of observatory latitude and season. The coefficient 1.11 was chosen to correspond to Elterman's (1970) optical thickness due to ozone at 3200 Å. For Mount Hopkins, this formula gives ozone extinction larger than 0.01 mag (air mass)$^{-1}$ for wavelengths between 5000 and 6790 Å and shortward of 3450 Å. The ozone can vary significantly over time scales as short as a few hours (Mendoza, Moreno, and Stock 1968; Latham and McCargar 1975), so equation (2) is valid only for calculating mean coefficients. The water extinction is nearly impossible to calculate because the amount of water vapor above an observatory is so variable. Extinction measures at Mount Hopkins show that for our wavelengths, water can contribute more than 0.01 mag (air mass)$^{-1}$ at 7100, 8090, 9700, and 10,800 Å (Latham and McCargar 1975).

iii) *Aerosol Scattering*

Aerosol scattering is due to particulates, including mineral dust, salt particles, water droplets, and man-made pollutants (Bullrich 1964; Junge 1963; Gillette and Blifford 1971; Blifford and Gillette 1972; Delaney, Pollock, and Shedlovsky 1973). It is customary to represent the aerosol extinction by an equation of the form (Ångstrom 1964; Penndorf 1954; Junge 1963; Bullrich 1964; Kondrat'yev 1969)

$$A_{\rm aer}(\lambda, h) = A_0 \lambda^{-\alpha} \exp(-h/H). \quad (3)$$

The choice of appropriate values for α, H, and A_0 is not straightforward and is discussed in the following paragraphs.

The distribution of aerosol with altitude has been measured directly with various particle-collection experiments and solar-extinction observations, all from aircraft. In the lower troposphere, the distribution is often approximately exponential but can also be strongly layered, especially near temperature inversions (Rozenberg 1966; Faraponova 1965, 1971; Kondrat'yev *et al.* 1969; Stampfer 1972; Zuyev, Ivlev, and Kondrat'yev 1973). We have adopted a scale height of $H = 1.5$ km as representative of the published data on the distribution of aerosol with altitude (Penndorf 1954; Bullrich 1964; Kondrat'yev 1969; Blifford and Ringer 1969; Blifford 1970; Faraponova 1971). On any given night, however, this scale height may be in error by as much as a factor of 2.

Observed values of aerosol extinction can be deduced from accurate measurements of the total extinction by choosing wavelengths that are free of water-vapor absorption and subtracting the extinction due to Rayleigh scattering and ozone. Both these last two parameters can be calculated with an accuracy of about ± 0.01 mag (air mass)$^{-1}$ for wavelengths between 3300 and 10,800 Å, by using equations (1) and (2). With this procedure, we have analyzed the observed mean extinction coefficients for the Boyden and Le Houga Observatories (Irvine and Peterson 1970), Cerro Tololo Inter-American Observatory (Gutiérrez-Moreno, Moreno, and Stock 1967; Gutiérrez-Moreno and Moreno 1970), Lick Observatory (Hayes 1967, 1970, 1974), Mount Hopkins (Latham and McCargar 1975), and Mount Lemmon (Dunkelman and Scolnik 1959). In each case, α was determined from linear fits on log-log plots of the aerosol extinction versus wavelength. The resulting values for α are given in table 1, along with the observatory, limiting dates, wavelengths covered, and number N of nights reported (except in the case of Cerro Tololo, where N is the number of monthly means). The mean of α for the stellar observations, weighted approximately by the number of nights, is 0.81. We cannot explain why the solar observations at Mount Lemmon and Mount Hopkins give a much larger value of α, and we have arbitrarily adopted $\alpha = 0.8$ as appropriate for nighttime photometric conditions. This value is smaller than those quoted in the literature on atmospheric aerosols, which usually refer to lower altitudes and poorer transparency

TABLE 1

WAVELENGTH DEPENDENCE DERIVED FOR AEROSOL EXTINCTION

Observatory	Dates	Wavelength Range (Å)	α	N	Weight
Le Houga................	1963 May 20–1965 Dec. 14	3590–5012	0.89	82	4
Boyden..................	1964 Jan. 16–1965 Dec. 7	3590–5010	0.78	46	2
Lick.....................	1965 Dec. 17–1966 Oct. 31	3200–6436	0.49	21	1
Cerro Tololo.............	1965 Oct.–1969 Jan. (monthly means)	3200–5800	0.81	24	4
Mount Hopkins (stellar)....	1973 Apr. 19–1973 May 15	6436–10800	0.84	12	0.5
Mount Hopkins (solar).....	1973 Apr. 27–1973 May 21	6436–10800	1.52	20	0
Mount Lemmon (solar)....	1951 Oct. 4	3301–6502	1.0	1	0

conditions, such as are found near urban centers (Ångstrom 1964; Bullrich 1964; Kondrat'yev 1969; Curcio 1961; Dachs, Haug, and Pfleiderer 1966). A few authors have found that the wavelength dependence of the aerosol cannot be fitted by $\lambda^{-\alpha}$, and even report negative α values for some wavelengths (Quenzel 1970; Porch *et al.* 1971; Porch *et al.* 1973; Nikitinskaya, Barteneva, and Veselova 1973).

There is clear evidence for large variations in the amount of aerosol extinction with a time (see, for example, Irvine and Peterson 1970). Diurnal variations as large as a factor of 2 in A_0 have been measured at Mount Hopkins (Latham and McCargar 1975).

b) *Palomar Mountain Mean Extinction*

For the Palomar calibration of Vega, Oke and Schild (1970) used the Palomar standard extinction coefficients. Oke (1965) describes the fabrication of these coefficients for wavelengths between 3200 and 6400 Å as follows: "The values of A_λ used by the author are taken from measurements of the sun made by Dunkelman and Scolnik (1959) at Mount Lemmon, Arizona. Their coefficients (their table III) are converted to magnitudes and multiplied by 1.2. This factor of 1.2 includes an altitude correction of 1.1 and a further factor of 1.1 to make their coefficient agree with that used for the V magnitude in the *UBV* system at Mount Wilson."

Oke's method of normalizing the extinction coefficients taken at Mount Lemmon to the mean V extinction coefficient measured at Mount Wilson does not account properly for the aerosol and ozone. A simple scaling of the Mount Lemmon coefficients by a factor of 1.2 at all wavelengths is incorrect, because both the aerosol scattering and the ozone absorption have different distributions with altitude, and different wavelength dependences, than does Rayleigh scattering.

We now propose an alternate procedure for fabricating mean extinction coefficients for Palomar Mountain (or any other mountain observatory) based on the model for atmospheric extinction presented in the previous section. The main point is that the extinction due to Rayleigh scattering and ozone absorption can be calculated quite accurately for any observatory, by using equations (1) and (2). However, the mean amount of aerosol extinction—that is, the constant A_0 in equation (3)—depends on the observatory location, and can be determined only if observed mean extinction coefficients have been measured at the observatory for one or more wavelengths. In other words, our procedure is to normalize A_0 so that the sum of equations (1), (2), and (3) matches the observed mean extinction at one or more wavelengths.

We have used this procedure to fabricate mean extinction coefficients for Palomar Mountain. In order to be consistent with Oke's normalization to the Mount Wilson V extinction, we have adjusted the amount of aerosol in our coefficients so that they match the Palomar standard extinction interpolated to 5445 Å, the effective wavelength of the V magnitude (see, for example, Young 1974; Ažusienis and Straižys 1966, 1969). The differences between Oke's Palomar standard extinction and our fabricated coefficients for Palomar Mountain are listed in table 2 for nine representative wavelengths. The poorest agreement is in the ultraviolet, where the Oke coefficients are systematically larger by 0.02–0.07 mag (air mass)$^{-1}$. The reason for the large errors in the ultraviolet is that Oke has included too much Rayleigh scattering and ozone absorption, and not enough aerosol scattering. The extinction coefficients measured by Dunkelman and Scolnik (1959) at Mount Lemmon refer to a single day of unusually high transparency (that is, of unusually low aerosol), while the Mount Wilson mean V extinction refers to average conditions of aerosol at that altitude. In effect, Oke's extra scale factor of

TABLE 2

COMPARISON OF FABRICATED EXTINCTION COEFFICIENTS FOR PALOMAR MOUNTAIN

Wavelength (Å)	Extinction: Oke's minus Ours [mag (air mass)$^{-1}$]
3200.............	+0.067
3350.............	+0.035
3704.............	+0.024
4036.............	+0.011
4566.............	−0.007
5556.............	−0.001
6790.............	−0.006
8090.............	+0.007
10400.............	+0.010

TABLE 3

COMPARISON OF FABRICATED AND OBSERVED MEAN EXTINCTION COEFFICIENTS FOR LICK

WAVE-LENGTH (Å)	EXTINCTION COEFFICIENTS [mag (air mass)$^{-1}$]		
	Observed	Observed minus Oke's	Observed minus Ours
3450....	0.708	−0.127	−0.011
3704....	0.538	−0.071	−0.010
4036....	0.399	−0.037	−0.003
4464....	0.282	−0.010	−0.004
4785....	0.234	+0.004	+0.002
5000....	0.207	0.000	0.000

1.1 attributes the higher extinction at Mount Wilson mostly to Rayleigh scattering instead of to aerosol scattering.

In order to demonstrate that our procedure for fabricating mean extinction coefficients works better than Oke's, we have used both methods to calculate mean extinction coefficients for Lick Observatory and Cerro Tololo Inter-American Observatory, where the observed mean extinction has been measured reliably. For Cerro Tololo we averaged the monthly mean extinction reported by Gutiérrez-Moreno *et al.* (1967) and Gutiérrez-Moreno and Moreno (1970), and for Lick we used unpublished measurements by Hayes (1974). For these calculations, we have matched the observed mean extinction at 5000 Å in order to avoid calculating the ozone absorption, which is significant at 5445 Å. The results of these comparisons are given in tables 3 and 4, where we tabulate the mean observed extinction and the observed-minus-calculated differences for the coefficients fabricated according to Oke's and our procedures, respectively.

For both observatories, our method works much better than Oke's, and the errors in our coefficients are never larger than 0.011 mag (air mass)$^{-1}$. The good agreement of our fabricated coefficients with the observed mean extinction at Lick Observatory is especially impressive, because these same data imply a $\lambda^{-0.49}$ wavelength dependence of the aerosol scattering (see table 1), while our procedure assumes a $\lambda^{-0.8}$ dependence.

Although we believe our procedure is a reasonably accurate method for calculating *mean* extinction coefficients for any mountain observatory, we recommend that it not be used as a substitute for measuring nightly extinction coefficients when accurate photometry is the goal. The basic point is that the amount of aerosol can vary from night to night by typically a few hundredths of a mag (air mass)$^{-1}$ (Latham and McCargar 1975). In order to get high accuracy using mean extinction coefficients, one would have to observe the same stars on several nights and hope that this set of nights had the same aerosol on the average as did the set used to determine the mean extinction. *Thus, it is more efficient in the long run to determine nightly extinction coefficients and to observe each program star on only two or three nights, even if it takes half of each night to determine the extinction.* Furthermore, it may turn out that it is sufficient to measure nightly extinction at one or a few wavelengths, then determine the aerosol (and amount of water-vapor absorption, if the work is being done in the near-infrared) from these measures, and then use our procedure to fabricate nightly extinction at the other wavelengths.

When the Palomar standard extinction coefficients (Oke 1965) are used for relative spectrophotometry between stars, the systematic errors introduced by the errors in the standard extinction will usually be less than 0.01 mag. This is because the extinction error gets multiplied by a factor on the order of the difference in mean air mass of observation for the two stars being compared. This difference is usually just a few tenths. However, in absolute-calibration work, the errors are much more serious, because the extinction errors are multiplied by the mean air mass itself, which usually amounts to something like 1.2 or 1.3 air masses.

No attempt was made, either by Oke or by us, to include water-vapor absorption in the extinction coefficients for Palomar Mountain. On humid nights, water vapor can contribute significant absorption at several wavelengths in the near-infrared. In addition, we both assumed that the aerosol is the same over Palomar Mountain as it is over Mount Wilson. This may be a poor assumption, even though the altitudes are nearly the same, because of the proximity of Mount Wilson to the Los Angeles area. With these warnings, we list in table 5 a full set of mean extinction coefficients for Palomar Mountain, fabricated with our procedure.

TABLE 4

COMPARISON OF FABRICATED AND OBSERVED MEAN EXTINCTION COEFFICIENTS FOR CERRO TOLOLO

WAVE-LENGTH (Å)	EXTINCTION COEFFICIENTS [mag (air mass)$^{-1}$]		
	Observed	Observed minus Oke's	Observed minus Ours
3400....	0.680	−0.080	+0.006
3600....	0.541	−0.057	+0.008
4200....	0.308	−0.019	+0.003
4700....	0.215	+0.002	+0.004
5000....	0.179	0.000	0.000

c) *Horizontal Extinction*

For both the Lick and the Palomar calibrations, the horizontal extinction $A_{\rm hor}(\lambda, d)$ was calculated as a fraction of the vertical extinction $A_{\rm ver}(\lambda)$ by using

$$A_{\rm hor}(\lambda, d) = \frac{d}{H} A_{\rm ver}(\lambda) ,$$

where d is the line-of-sight distance from the telescope to the standard source (in km), and H was taken to be the density scale height, 8 km. This relation is incorrect, because it does not take into account the different distributions with altitude and the different wavelength dependences of the various contributors

TABLE 5

MEAN EXTINCTION COEFFICIENTS FOR PALOMAR MOUNTAIN FABRICATED WITH OUR PROCEDURE

Wavelength (Å)	$A(\lambda)$ [mag (air mass)$^{-1}$]	Wavelength (Å)	$A(\lambda)$ [mag (air mass)$^{-1}$]
3200......	1.058	5263......	0.164
3250......	0.911	5556......	0.151
3300......	0.826	5840......	0.140
3350......	0.757	6055......	0.133
3390......	0.719	6435......	0.104
3448......	0.663	6790......	0.084
3509......	0.617	7100......	0.071
3571......	0.575	7550......	0.061
3636......	0.537	7780......	0.055
3704......	0.500	8090......	0.051
3862......	0.428	8370......	0.048
4036......	0.364	8708......	0.044
4167......	0.325	9832......	0.036
4255......	0.302	10255......	0.034
4464......	0.256	10610......	0.032
4566......	0.238	10795......	0.032
4785......	0.206	10870......	0.031
5000......	0.183		

to the extinction. For the Mount Hopkins calibration, we used the more nearly correct formula

$$A_{\rm hor}(\lambda, d) = \frac{d}{8.0} A_{\rm Ray}(\lambda) + \frac{d}{1.5} A_{\rm aer}(\lambda) + \frac{d}{2.2} A_{\rm wat}(\lambda)\,, \tag{4}$$

where we have used 8.0, 1.5, and 2.2 km for the effective scale heights of the Rayleigh scattering, aerosol, and water vapor, respectively. The water-vapor scale height was adopted from data summarized by Plass and Yates (1965). Note that because the ozone is concentrated far above the observatory, it does not contribute to the horizontal extinction.

We have recalculated the horizontal extinction for the Lick and Palomar calibrations using equation (4). The corresponding corrections to the calibration of Vega are given in table 6.

III. ADOPTED CALIBRATION FOR VEGA

a) Data Selection

In this section, we apply corrections to selected portions of the Palomar and Lick calibrations and combine the corrected data with the Mount Hopkins calibration to generate an adopted absolute spectral-energy distribution for Vega over the wavelength range 3300–10,800 Å. We have not included any of the earlier calibrations (e.g., Code 1960; Kharitonov 1963; Bahner 1963; Glushneva 1964; Willstrop 1965; Divan 1966), either because we judged them to have inferior accuracy or because not enough information was available for us to judge their accuracy.

Three types of standard sources were used by Oke and Schild for the Palomar calibration: a tungsten ribbon-filament lamp for 3300–8080 Å, two copper-point blackbodies for 6050–10,800 Å, and a platinum-point blackbody for 3300–10,800 Å. For the platinum blackbody, Oke and Schild adopted a temperature 6 K below the standard freezing point of platinum in order to get agreement with their other sources, thus destroying the value of the platinum blackbody as a fundamental source. Furthermore, they quote an uncertainty of 5 percent, which is two or three times worse than the uncertainties they quote for the lamp and copper blackbody results. Because of these two problems, we have rejected all their platinum blackbody data. Their absolute fluxes for Vega from their lamp and copper blackbodies agree within 0.01 mag at the four shorter overlap wavelengths (6050, 6370, 6800, and 7100 Å), but the lamp data drop off at the two longest wavelengths of the lamp calibration (7550 and 8080 Å) by as much as 0.06 mag. A similar drop-off appears when the Palomar lamp results are compared with the Lick and Mount Hopkins calibrations. Therefore, we have rejected the Palomar lamp data at 7550 and 8080 Å. The Lick calibration was judged to be poorly determined at the extreme wavelengths 3200, 3250, and 10,870 Å, and these points were therefore rejected.

Similar, but not identical, sets of wavelengths were used for the Lick, Palomar, and Mount Hopkins calibrations. We have adopted the Lick wavelengths shortward of 9000 Å and the Mount Hopkins wavelengths longward of 9000 Å. Thus a few of the Lick and Palomar points had to be interpolated to the nearest adopted wavelength. We interpolated linearly and did not attempt to account for line blocking. This may have introduced random errors as large as ± 0.01 mag into the interpolated points. The Lick point at 3704 Å was rejected because of its proximity to the Balmer discontinuity and the resulting difficulty in interpolating it to the nearest adopted wavelength.

b) Corrections to the Lick and Palomar Calibrations

The Lick calibration was corrected from the International Practical Temperature Scale (IPTS) of 1948 to the more recent IPTS of 1968 (Comité International des Poids et Mesures 1969), in order to be consistent with the Palomar and Mount Hopkins calibrations. Then the original adjustments for horizontal extinction, 1/15 of the Lick mean extinction, were replaced with adjustments calculated by using equation (4). This new horizontal extinction and the net changes to the Lick results are given in table 6 for seven wavelengths. Although our revision of the horizontal extinction gives corrections between 0.01 and 0.02 mag for Lick, the net effect on the Lick *color* calibration is less than 0.01 mag.

The Palomar lamp and copper blackbody results from table 1 of Oke and Schild (1970) were averaged at the overlap wavelength and then converted from the original horizontal extinction, 1/20 of the Palomar standard extinction, to a horizontal extinction calculated from equation (4) and our Palomar mean extinction from table 5. To convert the original adjustments for vertical extinction, which were based on the Palomar standard extinction, to our Palomar mean

TABLE 6

SAMPLE EXTINCTION CORRECTIONS TO THE LICK AND PALOMAR CALIBRATIONS

	Lick		Palomar			
Wavelength (Å)	$A_{hor}(\lambda)$ (mag)	A_{hor} Correction (mag)	$A_{hor}(\lambda)$ (mag)	A_{hor} Correction (mag)	A_{ver} Correction (mag)	Total Correction (mag)
3300........	0.071	+0.013	0.051	+0.008	+0.053	+0.061
3636........	0.059	+0.021	0.038	+0.010	+0.035	+0.045
4036........	0.047	+0.020	0.030	+0.011	+0.015	+0.026
5000........	0.030	+0.017	0.018	+0.009	−0.006	+0.003
5556........	0.029	+0.017	0.015	+0.007	+0.000	+0.007
8090........	0.022	+0.016	0.009	+0.006	+0.009	+0.015
10400........	0.016	+0.013	0.007	+0.005	+0.014	+0.019

extinction, we adopted a value of 1.3 for the mean air mass at which Vega was observed (Schild 1974), and used 1.3 times the difference in the two sets of extinction coefficients to correct the Palomar calibration at each wavelength. Our values for the horizontal extinction at Palomar Mountain and the corrections to the Palomar calibration due to horizontal and vertical extinction are given for seven sample wavelengths in table 6. The net effect of these extinction corrections on the Palomar calibration is a large change in the color calibration shortward of 4000 Å. The Palomar flux calibration at 5556 Å is changed by only +0.007 mag.

Previously, there was a discrepancy of about 0.05 mag between the Lick and the Palomar color calibrations in the ultraviolet. Figure 1, which plots the differences between our corrected versions of the Lick and Palomar color calibrations, demonstrates that this discrepancy has been eliminated by our corrections. For wavelengths shortward of 10,000 Å, a very small systematic difference occurs between the two corrected calibrations, amounting to 0.016 mag between 3300 and 10,000 Å. The standard deviation of the individual differences from a linear fit over this wavelength range is 0.011 mag. Using laboratory measurements to compare the Lick and Palomar lamps, Hayes, Oke, and Schild (1970) found a similar scatter and set a limit to systematic differences, which is consistent with figure 1. They concluded that "the differences between [the Lick] and the Palomar calibrations of α Lyr must arise entirely from the star-to-standard-lamp comparisons." We believe the comparison shown in figure 1 confirms this conclusion and demonstrates that the treatment of atmospheric extinction at Palomar Mountain was the primary source of the original disagreement.

At the three wavelengths longward of 10,000 Å, the corrected Lick and corrected Palomar calibrations disagree by about 0.07 mag. We have no explanation for this poor agreement except to note that for both calibrations, these wavelengths could be seriously affected by random errors due to low signal levels and by uncertain amounts of water-vapor extinction. Curiously, if the corrected Lick and corrected Palomar

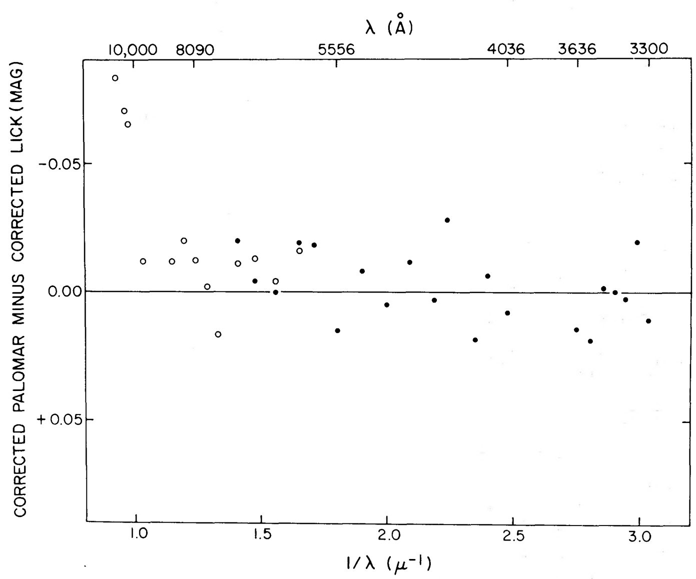

FIG. 1.—Differences between the corrected Palomar and corrected Lick color calibrations of Vega, in magnitudes. The closed circles are the differences for the Palomar lamp data, and the open circles, for the Palomar copper blackbody data.

calibrations are simply averaged between 6800 and 10,800 Å, the resulting average color calibration agrees with that for Mount Hopkins over these wavelengths within an accuracy of about ± 0.01 mag. Because there is no identifiable fault in either of the earlier infrared results, we have decided to retain the Lick and Palomar results longward of 10,000 Å and have given them equal weight when deriving the adopted calibration, as described in the next section.

c) Combining the Data for the Adopted Calibration

To generate an absolute spectral-energy distribution for Vega, we first combine the Mount Hopkins, corrected Lick, and corrected Palomar color calibrations to get an adopted color calibration. Then we use the corrected Palomar and the Mount Hopkins flux calibrations to set the absolute level of the adopted color calibration.

If all the color calibrations were measured at exactly the same set of wavelengths, we could average the magnitudes at each wavelength and then set the zero point (in this case, negligible errors are introduced by averaging magnitude differences instead of intensity ratios because the color calibrations are so similar). However, the Mount Hopkins calibration does not extend shortward of 6800 Å, so we must set the zero points before combining the data in order to avoid an artificial discontinuity in the final adopted color calibration at 6800 Å. Therefore, we first averaged the corrected Lick and corrected Palomar color calibrations with equal weights and normalized the average to 0.00 at 5556 Å. The Mount Hopkins results were treated as two independent color calibrations: one derived directly from the night of scanning, and the other, indirectly from the individual flux calibrations at 6800, 8090, and 10,400 Å on different nights. For both the Mount Hopkins color calibrations, the zero point was set to give the smallest value of the mean deviation from the average of the corrected Lick and corrected Palomar color calibrations. Once these zero points were set, the four color calibrations were averaged with equal weight. The resulting adopted color calibration is given in table 7, in magnitudes $M_{1/\lambda} = -2.5 \log_{10} F_\nu + \text{constant}$. The magnitudes in parentheses are at wavelengths that required interpolation of either the Palomar or the Lick calibrations. In the same table, we list the corrections that must be added to anybody's measured spectral-energy distribution that was previously referred to the Lick calibration (Hayes 1970) or to the Palomar smoothed calibration (Oke and Schild 1970). Where necessary, we have linearly interpolated our adopted calibration in order to derive these corrections at the original published wavelengths. Note that the Palomar corrections also include a renormalization from 5480 to 5556 Å, and thus the entry at 5556 Å is -0.025 instead of 0.000.

At 5556 Å, our extinction corrections make the Palomar calibration 0.007 mag fainter than the published value. We have used our adopted color calibration to transfer the Mount Hopkins flux

TABLE 7

Adopted Color Calibration for Vega $M_{1/\lambda}$ and Corrections to be Added to the Published Lick and Palomar Calibrations

Wavelength (Å)	$1/\lambda$ (μ^{-1})	Adopted	Adopted minus Lick	Adopted minus Palomar
3300...	3.030	+1.137	−0.013	+0.03
3350...	2.985	(+1.145)	−0.025	...
3400...	2.941	+1.129	−0.012	+0.06
3450...	2.899	(+1.115)	−0.012	...
3500...	2.857	+1.097	−0.011	+0.04
3571...	2.800	(+1.077)	−0.001	...
3600...	2.778	...	...	+0.03
3636...	2.750	(+1.059)	−0.003	...
3680...	2.717	...	...	+0.03
4036...	2.478	−0.299	−0.005	−0.016
4167...	2.400	−0.278	−0.012	−0.015
4255...	2.350	−0.263	−0.001	−0.013
4460...	2.242	...	...	−0.032
4464...	2.240	−0.238	−0.023	...
4566...	2.190	−0.199	−0.007	−0.014
4780...	2.092	...	...	−0.012
4785...	2.090	−0.153	−0.012	...
5000...	2.000	−0.103	−0.007	−0.002
5263...	1.900	−0.050	−0.012	−0.011
5556...	1.800	0.000	0.000	−0.025
5840...	1.712	+0.062	−0.018	−0.017
6050...	1.653	...	...	−0.012
6056...	1.651	+0.111	−0.015	...
6370...	1.570	...	...	−0.03
6436...	1.554	(+0.167)	−0.005	...
6790...	1.473	+0.217	−0.006	...
6800...	1.471	+0.219	...	−0.05
7100...	1.408	+0.272	−0.013	−0.04
7550...	1.325	+0.361	−0.011	−0.02
7780...	1.285	(+0.398)	−0.009	...
8080...	1.238	...	...	−0.03
8090...	1.236	+0.429	−0.013	...
8370...	1.195	...	...	...
8400...	1.190	...	...	−0.05
8708...	1.148	(+0.450)	−0.019	...
8804...	1.136	...	...	−0.02
9700...	1.031	(+0.484)	...	−0.03
9832...	1.017	...	−0.020	...
9950...	1.005	...	...	0.00
10250...	0.976	(+0.571)	...	+0.01
10256...	0.975	...	−0.039	...
10400...	0.962	(+0.586)	−0.039	+0 02
10796...	0.926	...	−0.044	...
10800...	0.926	+0.649	...	+0.01

calibrations back to 5556 Å. The flux calibrations from each of the seven nights (one, two, and three nights at 6800, 8090, and 10,400 Å, respectively, and one night of scanning between 7100 and 10,800 Å) were transferred to 5556 Å and then averaged with equal weight, resulting in a flux of $F_\lambda = 3.45 \times 10^{-9}$ ergs cm^{-2} s^{-1} Å^{-1} or $F_\nu = 3.57 \times 10^{-20}$ ergs cm^{-2} s^{-1} Hz^{-1}. This flux calibration was averaged with the corrected Palomar flux calibration to get an adopted monochromatic flux reaching the Earth's atmosphere from Vega at 5556 Å of

$$F_\lambda = 3.39 \times 10^{-9}\ \text{ergs cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}\,,$$

$$F_\nu = 3.50 \times 10^{-20}\ \text{ergs cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}\,,$$

$$N_\lambda = 948\ \text{photons cm}^{-2}\,\text{s}^{-1}\,\text{Å}^{-1}\,.$$

IV. ACCURACY OF THE ADOPTED CALIBRATION

In this section, we estimate the accuracy of our adopted absolute spectral-energy distribution for Vega as a function of wavelength. Our estimates, which are little more than educated guesses, rely heavily on the precisions quoted by the original papers and on our comparisons of the various interpolated calibrations.

We list and discuss the various wavelength regions in order of decreasing accuracy.

1) *Paschen discontinuity*. The color of the adopted calibration between 8090 and 10,400 Å is 0.157 mag. This is very close to the 0.158 mag measured by Hayes *et al.* (1975), who quote an accuracy approaching ± 0.01 mag for their color.

2) *Paschen continuum*. Most of the colors in the wavelength range 4036 to 8090 Å should be more accurate than ± 0.02 mag. For colors covering nearly this full range, the errors may be as large as ± 0.03 mag. This estimate is based primarily on the comparison of the corrected Lick and corrected Palomar calibrations.

3) *Balmer discontinuity*. The color of the adopted calibration between 3636 and 4036 Å is -1.358 mag. From the good agreement between the corrected Lick and the corrected Palomar calibrations across the Balmer discontinuity, we estimate that this color is accurate to ± 0.03 mag.

4) *Balmer and Brackett continua*. The colors in the wavelength regions 3300–3636 Å and 9700–10,800 Å may have errors larger than ± 0.02. In both these regions, atmospheric extinction is a problem: Toward 3300 Å, the ozone becomes a major contributor to the extinction, while water vapor can be an important source of error in the infrared. Therefore, our adopted calibration *cannot* be extrapolated to shorter or longer wavelengths without the risk of large errors.

5) *Flux calibration at 5556* Å. The corrected Palomar and Mount Hopkins flux calibrations disagree by 0.035 mag at 5556 Å. Thus, the ± 0.02-mag accuracy quoted for both seems reasonable to assign to our adopted flux calibration at 5556 Å.

We feel that it will be difficult to improve the calibration of Vega shortward of 10,000 Å using ground-based observations. The basic problem is time variations in the extinction, which limit the accuracy with which nightly extinction coefficients can be determined to something on the order of ± 0.01 mag (air mass)$^{-1}$. The calibration shortward of 4036 Å should be remeasured, but we recommend that this be done from space as part of a program to calibrate the entire Balmer continuum accurately. Longward of 10,000 Å, we expect that the stellar calibration could be improved substantially by ground-based observations, despite the difficulties with water vapor. In the meantime, the accuracy with which spectral-energy distributions can be measured for faint objects is usually limited by the paucity of well-measured secondary standards, and accurate spectrophotometric transfers from Vega to fainter stars are needed.

Dr. A. T. Young called our attention to the fact that the aerosol has a smaller scale height than Rayleigh scattering has, which eventually led to this paper.

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