THE ASTROPHYSICAL JOURNAL, 200: 113–121, 1975 August 15

PHOTOMETRY OF O-TYPE STARS, INTERPRETED WITH REFERENCE TO MODEL ATMOSPHERES*

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Received 1975 January 7

ABSTRACT

Strömgren-system colors for O-type stars have been compared with colors calculated by Mihalas from non–LTE model atmospheres and by Mihalas and Hummer from models with extended geometry. Within the accuracy of the observations, effective temperatures derived from the photometry for main-sequence stars agree with those derived by Conti from a ratio of intensities of spectral lines; consistency of the calculated colors with the calculated strengths of the lines is demonstrated for the non–LTE plane-parallel models. For Of stars of luminosity classes III and I, and O stars of luminosity class I, c_1 is consistently more negative than it is for main-sequence stars by an amount that is consistent with the predictions of the models with extended geometry. For stars earlier than type O6, c_1 is consistently more positive than the plane-parallel models predict, and possible reasons for this effect are discussed.
Subject headings: atmospheres, stellar — early-type stars — photometry

I. INTRODUCTION

When LTE model atmospheres for early-type stars were superseded by the non–LTE model atmospheres of Auer and Mihalas (1972), an understanding of O-type spectra became possible. Great progress has also been made on the observational side, in that Walborn (1971) and Conti and Alschuler (1971) have systematically classified the spectra of many stars, and Conti (1973*a*) has used the non–LTE models to derive a relation between his spectral classes and effective temperature and gravity.

In addition, Mihalas (1972) has used the emergent continuous fluxes predicted by non–LTE plane-parallel models of O stars to calculate the Strömgren indices $b - y$, m_1, and c_1. These calculations show that the non–LTE models differ from the LTE models by 0.05 mag in c_1 for $T_{\text{eff}} > 35{,}000$ K, and by a smaller amount at lower temperatures. This difference reflects the fact that, while in LTE the Balmer jump nearly vanishes at an effective temperature of 40,000 K, in non–LTE models it persists and remains sensitive to effective temperature. Therefore, c_1 is a useful indicator of effective temperature even for the hottest O stars. I have obtained *uvby* and Hβ photometry of 101 stars with the aim of comparing effective temperatures derived from this photometry with the temperatures based on the spectral lines. This comparison is an important check on the self-consistency of the non–LTE models.

II. OBSERVATIONS

The observations were made on 17 nights in 1973 January, June, and July with one of the 61-cm telescopes at Mauna Kea Observatory. The observatory's Tinsley photometer is equipped with u, v, b, y, and Hβ filters that were bought to Kitt Peak specifications, and with an EMI 9558QA photomultiplier cooled thermoelectrically to $-20°$ C. Data acquisition is by photon counting, and the paired-pulse correction, assumed to be of the standard form (e.g., Sturch 1972), was determined from the requirement that the transformation of the instrumental β index to the standard system (Crawford and Mander 1966) be linear. Table 1 lists the means and standard deviations of the extinction coefficients from 12 nights; these means were used to reduce all the data.

Transformation to the standard *uvby* system requires a correction for the fact that the effect of Hδ on the v filter of the filter set that defines the *uvby* system is slightly different from its effect on our v filter, or on any other v filter. For unreddened stars, the Balmer-line strengths are correlated with $b - y$, and the standard transformation equations for m_1 and c_1 (Crawford and Barnes 1970) include a term in $b - y$. Since many of the stars in the present program are highly reddened, however, it is more appropriate to use a term in β, so that the transformation equations become

$$m_1 = E + Fm_1\,(\text{obs}) + K\beta\,,$$
$$c_1 = G + Hc_1\,(\text{obs}) + L\beta\,. \qquad (1)$$

TABLE 1

EXTINCTION COEFFICIENTS FOR MAUNA KEA, 1973

	y	$b - y$	m_1	c_1
Mean	0.095	0.040	0.047	0.141
Standard deviation	0.005	0.008	0.015	0.015

* This paper is part of a dissertation submitted to the Graduate Division of the University of Hawaii in partial fulfillment of the requirements for the Ph.D. degree in Astronomy.

Transformation coefficients were determined and applied separately for each night. The values of the coefficients K range between -0.030 and $+0.044$, L ranges between -0.138 and $+0.364$, and the range of β spanned by the standard stars is roughly 0.25 mag.

The stars observed are all in the catalog of Conti and Alschuler (1971). Double-lined spectroscopic binaries and stars with companions that were visible in the aperture of the photometer were not observed or, if observed, were not used in the analysis.

The results for a few stars may be compared with the results of other observers. Five slightly reddened stars are in common with the lists of Crawford and Barnes (1970) and Crawford *et al.* (1971). The mean difference in c_1 between the two sets of observations is -0.003 ± 0.008 (standard deviation). In addition, Crawford has kindly communicated his observations of four highly reddened stars that are in common with this program. The mean differences are: in $b - y$, $+0.008 \pm 0.014$; in m_1, $+0.009 \pm 0.021$; and in c_1, $+0.008 \pm 0.014$ (standard deviations). Both these comparisons show that the present observations are successfully transformed to the standard system.

Photometry of O stars suffers from the problem that both m_1 and c_1 are often more negative than they are for the standard stars, and it is necessary to extrapolate the least-squares straight line that represents the transformation. For c_1 in general, and for m_1 if the reddening is small, the amount of extrapolation required is much smaller than the range of c_1 among the standard stars, and the problem is not serious. Since m_1 becomes even more negative as the reddening increases, the amount of extrapolation for heavily reddened stars may be as large as the range in m_1 among the standard stars, and the accuracy of the transformation is reduced. This tendency is apparent in the night-to-night scatter of the present observations. The rms difference from the mean for a given star is typically ± 0.010 mag for both m_1 and c_1, except that when $b - y$ is greater than about 0.20, the scatter in m_1 is about ± 0.015.

Stars with rms deviations much larger than these values for m_1 and c_1, or larger than ± 0.010, 0.020, and 0.010 for β, V, and $b - y$, respectively, are listed as possible variables in Table 2. Most are supergiants or Of stars, but a few are main-sequence stars. Data from individual nights will be made available on request.

To correct the transformed colors for reddening, I adopted as intrinsic colors values of $b - y$ typical of those computed by Mihalas (1972), which are insensitive to effective temperature and vary only slightly with gravity. The adopted values are $(b - y)_0 = -0.145$ for $\beta > 2.570$ (main-sequence stars and giants) and $(b - y)_0 = -0.120$ for $\beta < 2.570$ (supergiants). According to Crawford and Barnes (1970) and Crawford (1975), the standard law for interstellar reddening is

$$E(c_1) = 0.2E(b - y)\,,$$
$$E(m_1) = -0.3E(b - y)\,. \qquad (2)$$

Because of the small size of the coefficients, the correction for reddening is insensitive to the intrinsic value of $b - y$ that is assumed, and to variations in the reddening law.

Since the colors calculated by Mihalas (1972) ignore the effects of spectral lines, the observed colors need to be corrected for the flux removed from

TABLE 2

STARS THAT MAY VARY

Star	Variable Quantity	Night-to-Night rms Difference: β	V	$b - y$	m_1	c_1
HD 12323......	β, $b - y$	0.049	0.014	0.011	0.014	0.004
HD 12993......	β	0.013	0.017	0.007	0.006	0.012
HD 14442......	$b - y$	0.009	0.017	0.017	0.015	0.010
HD 15570......	$b - y$	0.004	0.016	0.016	0.010	0.009
HD 16691......	β	0.024	0.003	0.007	0.007	0.009
HD 17520......	$b - y$	0.003	0.010	0.014	0.014	0.012
HD 35921......	V	0.005	0.085	0.003	0.003	0.006
HD 45314......	V	0.008	0.026	0.001	0.003	0.009
HR 2781.......	V	0.007	0.072	0.001	0.003	0.005
HR 6245.......	V	0.007	0.026	0.007	0.002	0.011
HR 6263.......	β	0.011	0.008	0.006	0.004	0.009
HR 6272.......	m_1, c_1	0.004	0.016	0.003	0.021	0.015
HR 6716.......	β, c_1	0.014	0.005	0.001	0.002	0.015
HD 166546.....	V, β	0.009	0.030	0.003	0.002	0.003
HD 168112.....	β	0.020	0.019	0.007	0.000	0.012
HD 192281.....	β	0.011	0.009	0.003	0.007	0.005
HD 202124.....	β	0.012	0.011	0.003	0.010	0.007
HD 216532.....	$b - y$	0.003	0.013	0.010	0.020	0.003
Minimum rms for variability....	$b - y < 0.25$	0.010	0.020	0.010	0.010	0.015
	$b - y > 0.25$	0.010	0.020	0.010	0.015	0.015

the bandpass of the v filter by Hδ. I have measured the equivalent width of this line and lines blended with it for 16 O-type stars on coudé spectrograms of dispersion 6.7 Å mm^{-1} obtained at Mauna Kea Observatory. Although Hδ itself weakens by about a factor of 2 from the highest gravities to the lowest ones, the strength of the blended lines increases correspondingly, and all but one of the measured equivalent widths lie between 1.9 and 2.8 Å. To make the correction, I assumed an equivalent width of 3.0 Å if $\beta > 2.600$, which applies to the coolest main-sequence stars only, and 2.20 Å if $\beta < 2.600$. Since the correction to c_1 is only about 0.010 mag per angstrom of equivalent width, errors in this correction are not a major source of uncertainty.

According to the calculations by Mihalas (1972), m_1 has the value +0.060 for all models of O stars. Without requiring any investigation into the properties of individual stars, therefore, this fact makes possible a check on the precision of the observations. Figure 1 shows the observed value of m_1, corrected for reddening and for Hδ as described above, as a function of $b - y$. Of stars are plotted as crosses, and the figure shows that these stars tend to more positive values of m_1, a tendency that has been noted by Osmer (1973) and that is understandable in terms of the effect of the emission lines near 4700 Å on the b filter. Aside from the Of stars, the figure divides itself into two parts. For $b - y$ greater than about 0.25, the scatter is large, probably due to the fact that an increasing amount of extrapolation is required in the transformation as the reddening increases. For values of $b - y$ smaller than about 0.25, however, the values of m_1 for non–Of stars are all near 0.060; more precisely, their mean is 0.059 ± 0.011 (standard deviation).

Figure 1 shows that m_1 is very much larger than 0.060, not only for Of stars but also for some supergiants. If this behavior is really due to the presence of emission lines in the region between 4630 and 4700 Å, near the center of the b filter, the lines will affect c_1 and hence the derived effective temperatures. Therefore, it is important to check whether the emission lines can account for the observed effect and, if so, to correct for them. For each angstrom of equivalent width, they should produce a change in m_1 of +0.010 mag and a change in c_1 of −0.005 mag. The emission lines N III λλ4634–4640 and He II λ4686 will not explain the effect, however, since they do not appear in non–Of supergiants and have insufficient strength (Conti and Alschuler 1971; Conti 1973*b*), even in Of stars. In addition, however, a very faint, broad emission band sometimes appears in this region, even in non–Of stars (see, e.g., Wilson 1958; Mihalas 1971). I have used intensity tracings of coudé plates of 11 stars to estimate the total equivalent width in this band and in the emission lines, drawing the continuum in such a way as to yield the largest possible estimate of the band strength. These rough estimates are listed in Table 3, together with Δm_1, which equals

TABLE 3

TOTAL EQUIVALENT WIDTH OF LINE AND BAND EMISSION NEAR 4700 Å

Star	Date (UT)	W_λ (Å)	Δm_1
HD 34656.....	1972 Oct. 15	2	+0.016
	1973 Jan. 17	0	...
HD 46150.....	1972 Oct. 16	0	+0.003
	1973 Jan. 17	3	...
	1973 Jan. 26	0	...
HD 46966.....	1973 Jan. 16	1	−0.006
	1973 Jan. 22	3	...
HR 2467......	1973 Jan. 16	3	+0.004
HR 2679......	1972 Oct. 14	0	−0.003
	1973 Jan. 27	0	...
HR 2806......	1973 Jan. 22	0	−0.010
	1972 Oct. 16	1	...
HR 6245......	1972 Aug. 6	10	+0.054
9 Sgr.........	1972 Sep. 28	3	+0.005
9 Sge.........	1972 Sep. 28	3	+0.026
HR 7589......	1972 Oct. 4	0	+0.006
	1972 Oct. 15	0.5	...
λ Cep.........	1972 Oct. 2	6	+0.023
	1972 Oct. 3	8	...

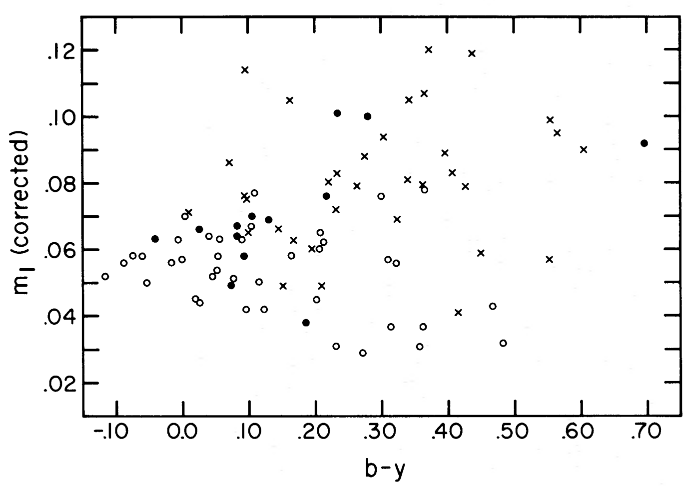

FIG. 1.—The observed m_1 index, corrected for interstellar reddening and for the effect of Hδ on the v filter, plotted against the observed $b - y$ index. *Crosses*, Of stars; *filled circles*, non–Of supergiants; *open circles*, all other stars.

the corrected value of m_1 minus the canonical value 0.060. Since Of stars are known to have variable emission spectra (e.g., Brucato 1971), comparison of the equivalent widths with photometry obtained at a different time may not be valid. Nevertheless, in roughly half the stars listed, the expected relation $\Delta m_1 \cong 0.01\ W$ holds, and in the remaining cases the sense of the disagreement is consistent with the expectation that the equivalent width is overestimated. Therefore, these data suggest that the strength of the emission is sufficient to account for the observed values of Δm_1. By the definitions of the *uvby* color indices, the effect of emission lines on the *b* filter will change the color indices in such a way that $\delta m_1 = -2\delta c_1$. Therefore, adding $\frac{1}{2}\Delta m_1$ to c_1 should compensate for the presence of the emission lines.

Table 4 lists the observations, except for the *V* magnitudes, which agree with those published by Hiltner and Johnson (1956). From left to right, the columns give: star name(s), β, $b - y$, observed m_1, m_1 corrected for reddening and Hδ, observed c_1, c_1 corrected for reddening and Hδ, corrected $c_1 + \frac{1}{2}\Delta m_1$, the number of observations of each star, and spectral types as given by Conti and Leep (1974). The remaining columns will be explained in § III. In addition, I have used the colors given for ζ Pup by Lindemann and Hauck (1973), applying the correction for emission lines, but not those for Hδ and reddening. Since this star is nearly unreddened, the latter two small corrections should cancel.

III. COMPARISON WITH THEORY

a) The Index c_1 and the Effective Temperatures

Mihalas's (1972) calculations show that c_1 is sensitive to effective temperature for all O-type stars, and also to gravity for the cooler ones, while hydrogen-line equivalent widths are sensitive to both temperature and gravity. These relationships are shown in Figure 2, from which effective temperatures and gravities can be read off if c_1 and an equivalent width of Hγ are known. A similar diagram can be made with β index as ordinate; in practice, however, uncertainties in the calibration of this index in terms of equivalent width make this procedure a possible source of systematic errors. (Equivalent widths based on the calibration of Zinn [1970] appear to be systematically too large, and my own calibration errs to a smaller extent in the opposite sense.) Therefore, I have used the equivalent widths of Hγ published by Conti (1973*b*) for all of the stars; he has shown that, except for stars with extended atmospheres, Hγ behaves as the non–LTE models predict. The photometry does show that Hβ behaves similarly to Hγ, as far as differential effects are concerned. Values of effective temperature and of the logarithm of the surface gravity derived from Figure 2 are listed in Table 4 under the headings T PH and G PH. Temperatures and gravities based on the temperature scale of Conti (1973*a*) are listed in Table 4 under the headings T SP and G SP.

A preliminary comparison of the two sets of temperatures showed a small systematic difference, which turned out to be due to the fact that the observed values of c_1 were systematically 0.01 mag more positive than the theoretical ones. This small offset is well within the uncertainties in the zero-point corrections that Mihalas (1972) applied to his calculated colors to put them on the *uvby* system. While the sources of uncertainty are many, the largest is the fundamental calibration of the Balmer jump of Vega, which Hayes and Latham (1975) claim to be uncertain by ±0.03 mag. Clearly, an adjustment of 0.01 mag in the zero point does not violate any observational constraint, and I have (somewhat arbitrarily) added 0.008 to the theoretical colors to obtain the horizontal scale in Figure 2. This adjustment must not be con-

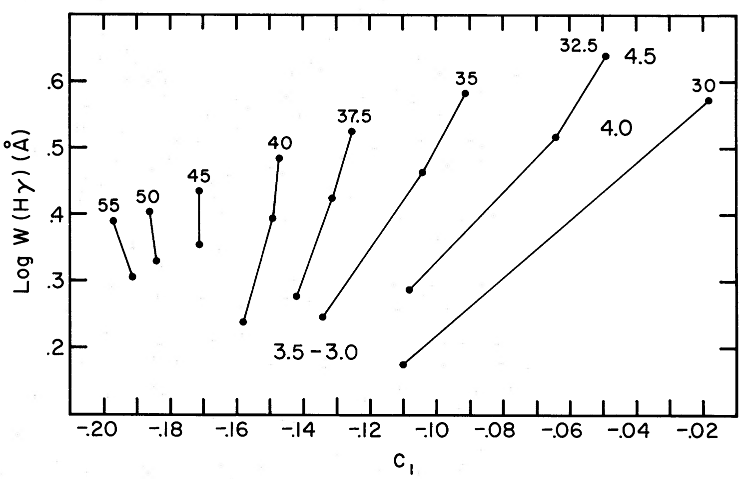

FIG. 2.—The equivalent width of Hγ and the c_1 index calculated by Mihalas (1972) for each of his non–LTE, plane-parallel model atmospheres for O stars. Straight lines connect the points representing models with the same effective temperature; each sequence is labeled with the effective temperature in units of 10^3 K. Points lying in nearly horizontal rows have a common surface gravity, and each row is labeled in large numerals with log *g*.

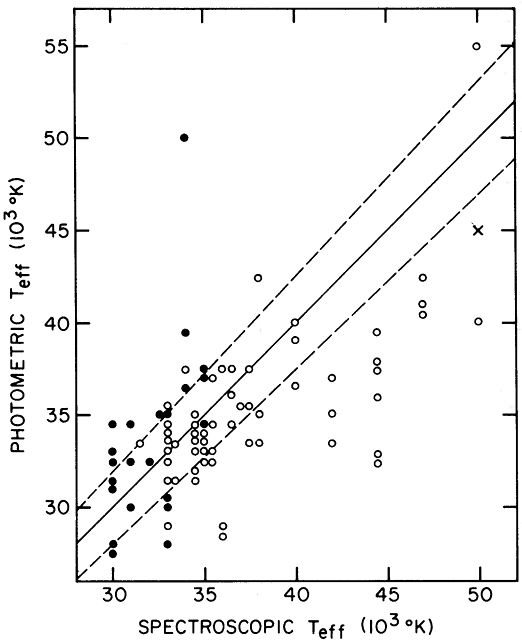

FIG. 3.—Effective temperatures for O stars from this paper compared with those of Conti (1973*a*). The straight line has slope unity and passes through the origin, and the dashed lines show the limits of the observational uncertainties (see text). *Filled circles*, supergiants later than type O6.5; *cross*, ζ Pup (see text).

strued as a new normalization of c_1; that problem must still be attacked observationally.

The temperatures in Table 4 are based on this revision, and the photometric and spectroscopic temperature scales are compared in Figure 3. The solid line in the figure represents perfect agreement between the two scales, and the dashed lines are error limits corresponding to an observational uncertainty of ± 2000 K in the photometric temperature scale near 30,000 K, and ± 3000 K near 50,000 K. The contributions of the individual sources of error to this uncertainty can be estimated from Figure 2 as the result of an uncertainty in c_1 of ± 0.01 mag and a standard error of ± 0.07 in log $W(H\gamma)$ (Conti and Alschuler 1971; Morrison 1975). If a well-calibrated β index were used as a gravity indicator, the observational uncertainty near 30,000 K would be much smaller. For Conti's (1973*a*) temperature scale, the observational standard error, ± 0.10 dex, in the line ratio corresponds to an uncertainty of ± 1000 K in T_{eff}.

Figure 3 shows that, for effective temperatures less than 40,000 K, effective temperatures derived from the photometry of the continuum agree with those derived from the spectral lines to within the accidental observational uncertainties. This agreement means that, to the accuracy with which the zero point for c_1 is determined, Mihalas's (1972) non-LTE models are self-consistent in their treatment of the lines and the continuum.

For two groups of stars in Figure 3, however, the agreement is only approximate. Many of the supergiants with $T_{eff} < 35{,}000$ K, shown in the figure as filled circles, have c_1 indices such that the photometric temperature is several thousand degrees higher than the spectroscopic one. The stars in the right-hand half of the figure (type O6 and earlier) all have photometric effective temperatures that are much lower than the spectroscopic temperatures. It has been suggested (e.g., Conti and Leep 1974; Mihalas and Hummer 1974) that both of these types of star have extended atmospheres. It may, then, be possible to attribute the small systematic effects in Figure 3 to failure of the assumption of plane-parallel geometry in the model atmospheres.

b) *Extended Atmospheres*

In order to examine the results shown in Figure 3 in terms of c_1, I shall define Δc_1 to be the observed c_1 index (including all the corrections described in § II) minus the c_1 index for a model atmosphere with the effective temperature and gravity that Conti (1973*a*) has assigned to the spectral type of the star. Thus, Δc_1 compares the observed color with the predicted one by way of the spectroscopic temperature scale as an intermediate step. It is listed in the last column of Table 4.

Figure 4 shows how the values of Δc_1 are distributed if the stars are grouped according to luminosity class and if Of stars are distinguished from the others. Because Δm_1 is less certain for stars with $b - y > 0.25$ than for less reddened stars, the more reddened stars

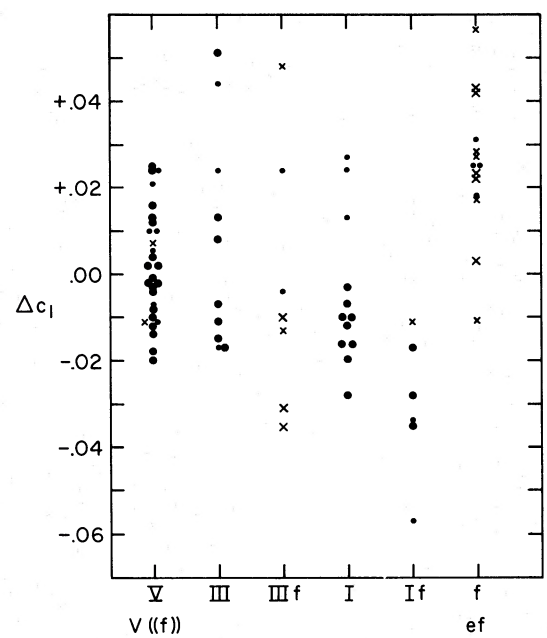

FIG. 4.—The distribution of Δc_1 (defined in the text as a measure of the departure of a star from the prediction of a plane-parallel model) for each luminosity class and for Of stars earlier than type O6.5. *Crosses*, stars classified as O(f) and O((f)) by Conti and Leep (1974); *small symbols*, stars with $b - y > 0.25$.

TABLE 4

PHOTOMETRY OF O-TYPE STARS AND DERIVED ATMOSPHERIC PARAMETERS

STAR	BETA	B-Y	M1	M1 COR	C1	C1 COR	C1-EM	N	SP TYPE	T SP	G SP	T PH	G PH	DEL C1
HR 65 AO CAS	2.555	-0.017	0.038	0.057	-0.105	-0.100	-0.101	4	O9.5III	BINARY		NOT USED		
HD 12323	2.593	0.048	0.011	0.052	-0.086	-0.094	-0.098	4	ON9V	34500	4.0	35000	4.2	-.002
HD 12993	2.596	0.232	-0.065	0.031	-0.082	-0.130	-0.145	4	ON6.5V	40000	4.0	39000	3.9	+.002
HD 13268	2.585	0.165	-0.020	0.058	-0.063	-0.099	-0.100	4	O7...	NOT RELIABLE		NOT USED		
HD 14434	2.564	0.198	-0.021	0.060	-0.088	-0.126	-0.126	4	O6.5(EF)	36-40000		34000	3.3	---
HD 14442	2.595	0.367	-0.058	0.079	-0.077	-0.150	-0.140	4	O6EF	42000	---	37000	3.5	+.018
HD 14633	2.577	-0.077	0.051	0.058	-0.129	-0.116	-0.117	4	ON8.5V	35500	4.0	34500	3.5	-.008
HD 14947	2.553	0.365	-0.023	0.107	-0.091	-0.162	-0.138	4	O5.5F	44500	---	32500	LT3	+.031
HD 15137	2.569	0.118	-0.010	0.050	-0.076	-0.100	-0.104	4	O9.5III	31500	3.7	33500	3.5	-.015
BD60 498	2.654	0.502	-0.203	-0.027	0.073	-0.018	-0.062	3	O9.5V	33000	4.0	32500	4.0	+.010
HD 15570	2.549	0.564	-0.095	0.095	-0.067	-0.178	-0.160	3	O4F	50000	---	40000	LT4	+.025
HD 15629	2.601	0.417	-0.110	0.041	-0.069	-0.150	-0.159	3	O5(F)	47000	---	42500	LT4	+.017
HD 16691	2.552	0.426	-0.070	0.079	-0.087	-0.170	-0.160	4	O5F	47000	---	40500	3.5	+.017
HD 17505	2.603	0.366	-0.088	0.047	-0.043	-0.112	-0.119	3	O6(F)	BINARY		NOT USED		
HD 17520	2.608	0.315	-0.100	0.018	-0.015	-0.071	-0.092	3	O9V	BINARY		NOT USED		
HD 17603	2.591	0.554	-0.136	0.057	-0.007	-0.117	-0.119	4	O8.5I(F)	32000	3.3	32500	LT3	-.011
BD60 586	2.620	0.314	-0.081	0.037	-0.028	-0.084	-0.095	4	O8III	35000	3.7	35000	4.3	+.024
BD60 594	2.589	0.358	-0.103	0.031	-0.024	-0.095	-0.109	3	O9V	34500	4.0	35000	3.9	-.011
HD 19820	2.603	0.467	-0.129	0.037	0.019	-0.070	-0.081	4	O9III	BINARY		NOT USED		
HR 1123 40 PER	2.613	0.058	0.019	0.063	0.024	0.019	0.020	4	B0.5V			NOT USED		
HD 24431	2.603	0.362	-0.097	0.037	-0.004	-0.072	-0.083	4	O9V	34500	4.0	31500	3.5	+.021
HR 1228 XI PER	2.574	0.083	0.010	0.067	-0.118	-0.138	-0.134	4	O7.5I	34000	3.3	36500	3.7	-.007
HR 1542 ALPHA CAM	2.541	0.093	0.007	0.058	-0.104	-0.121	-0.122	4	O9.5I	30000	3.0	31000	LT3	-.012
HR 1712 AE AUR	2.609	0.274	-0.077	0.029	-0.021	-0.069	-0.084	5	O9.5V	33000	4.0	33000	3.9	-.007
HD 34656	2.574	0.094	0.017	0.076	-0.123	-0.145	-0.136	3	O7I((F))	35000	3.3	37000	3.6	-.002
HD 35921	2.579	0.225	-0.034	0.062	-0.082	-0.129	-0.128	4	O9.5...	BINARY		NOT USED		
HD 36879	2.582	0.212	-0.030	0.062	-0.093	-0.139	-0.137	4	O7.5III	36000	3.7	37500	3.7	-.011
HR 1897 THETA2 ORI A	2.586	0.021	0.013	0.045	-0.089	-0.091	-0.099	4	O9V	34500	4.0	-----	---	-.003
HR 1931 SIGMA ORI	2.598	-0.088	0.054	0.056	-0.086	-0.068	-0.070	4	O9.5V	33000	4.0	33000	4.1	+.002
HR 1996 MU COL	2.589	-0.115	0.057	0.052	-0.109	-0.089	-0.092	4	O9V	34500	4.0	34000	3.9	+.004
HD 41161	2.576	0.028	0.008	0.044	-0.110	-0.117	-0.125	4	O8V	36500	4.0	36000	3.7	-.010
HD 42088	2.595	0.124	-0.023	0.043	-0.113	-0.141	-0.149	4	O6.5V	40000	4.0	40000	4.1	-.001
HD 45314	2.504	0.195	-0.056	0.023	-0.211	-0.248	-0.266	3	OBE			NOT USED		
HD 46056	2.590	0.209	-0.030	0.060	-0.088	-0.131	-0.131	5	O8V(E)	36500	4.0	37500	4.0	-.012
HD 46149	2.597	0.202	-0.042	0.045	-0.077	-0.115	-0.123	4	O8.5V	35500	4.0	37000	4.2	-.014
HD 46150	2.594	0.168	-0.014	0.063	-0.116	-0.148	-0.146	5	O5.5((F))	44500	---	39500	3.9	+.023
HD 46202	2.617	0.209	-0.022	0.065	-0.042	-0.077	-0.074	4	O9V	34500	4.0	32000	3.8	+.024
HD 46223	2.591	0.232	-0.026	0.072	-0.112	-0.161	-0.155	3	O5((F))	47000	---	40500	3.8	+.022
HD 46485	2.596	0.311	-0.062	0.057	-0.076	-0.136	-0.137	4	O7.5...	34-37500		38000	3.8	-.009
HD 46573	2.579	0.324	-0.056	0.069	-0.078	-0.143	-0.139	4	O7.5V((F))	37500	4.0	37500	3.7	-.011
HD 46966	2.593	0.051	0.010	0.054	-0.084	-0.094	-0.097	4	O8.5V	35500	4.0	32500	3.6	+.012
HR 2422 HD 47129	2.531	0.102	0.024	0.077	-0.123	-0.141	-0.132	4	O7.5IIIF	BINARY		NOT USED		
HR 2442 HD 47432	2.555	0.188	-0.039	0.038	-0.082	-0.117	-0.128	4	O9.5I	30000	3.0	32500	LT3	-.020
HR 2456 S MON	2.582	-0.101	0.063	0.063	-0.117	-0.099	-0.098	5	O8III((F))	COMPANION		NOT USED		
HR 2467 HD 48099	2.585	0.041	0.022	0.064	-0.121	-0.131	-0.129	3	O6.5V	40000	4.0	36500	3.8	+.016
HD 52266	2.577	0.078	0.000	0.051	-0.093	-0.110	-0.114	4	O9.5V	33000	4.0	33500	3.3	-.018
HD 52533	2.594	0.006	0.037	0.070	-0.084	-0.089	-0.083	3	O8.5V	35500	4.0	33000	3.9	+.025
HD 53667	2.541	0.253	-0.055	0.042	-0.050	-0.098	-0.107	4	B0.5III			NOT USED		
HR 2679 HD 53975	2.586	-0.000	0.027	0.057	-0.112	-0.115	-0.116	4	O7.5V	37500	4.0	35500	3.8	+.013
HR 2694 HD 54662	2.584	0.099	-0.015	0.042	-0.098	-0.119	-0.128	4	O7III	37000	3.7	35500	3.6	+.007
HR 2781 29 C MA	2.528	-0.057	0.098	0.104	-0.174	-0.160	-0.138	4	O8.5IF	BINARY		NOT USED		

TABLE 4—*Continued*

STAR	BETA	B-Y	M1	M1 COR	C1	C1 COR	C1-EM	N	SP TYPE	T SP	G SP	T PH	G PH	DEL C1
HR 2782 TAU C MA	2.560	-0.042	0.053	0.063	-0.126	-0.114	-0.113	4	O9I	31000	3.3	32500	LT3	-.003
HR 2806 HD 57682	2.572	-0.052	0.039	0.050	-0.112	-0.102	-0.107	4	O9V	34500	4.0	34000	3.7	-.004
HR 6245 HD151804	2.488	0.097	0.062	0.114	-0.159	-0.176	-0.149	4	O8IF	33000	3.3	30000	LT3	-.035
HD152233	2.564	0.165	0.032	0.105	-0.107	-0.138	-0.115	3	O6(F)	42000	---	34000	3.5	+.043
HR 6263 HD152249	2.553	0.219	-0.011	0.076	-0.092	-0.134	-0.125	3	O9.5I	30000	3.0	34500	3.4	-.028
HR 6272 HD152408	2.427	0.136	0.101	0.165	-0.159	-0.184	-0.132	3	O8IF	33000	3.3	28000	LT3	-.027
HD157857	2.565	0.209	-0.037	0.049	-0.089	-0.129	-0.135	5	O7...(F)	35-38000		37500	3.8	+.003
HR 6672 HD162978	2.557	0.099	0.022	0.075	-0.130	-0.148	-0.140	4	O8.5III((F))	34000	3.7	-----	---	-.031
HD163800	2.571	0.264	-0.023	0.079	-0.089	-0.142	-0.133	5	O7I((F))	35000	3.3	37500	4.0	+.006
HR 6716 HD164402	2.555	0.072	0.003	0.049	-0.074	-0.086	-0.092	4	B0IB	29000	3.0	NOT USED		
HD164438	2.587	0.321	-0.069	0.056	-0.051	-0.118	-0.120	5	O9III	33000	3.7	35500	3.8	-.017
HR 6736 9 SGR	2.573	0.100	0.005	0.065	-0.123	-0.146	-0.143	5	O4((F))	50000	---	34500	LT3	+.042
HD165052	2.582	0.150	-0.009	0.065	-0.103	-0.136	-0.133	5	O7...	BINARY		NOT USED		
HD166546	2.564	0.103	0.010	0.067	-0.092	-0.112	-0.109	4	O9III	33000	3.7	-----	---	-.007
HD166734	2.566	0.822	-0.164	0.104	-0.038	-0.203	-0.180	5	O7.5IF	BINARY		NOT USED		
HR 6823 16 SGR	2.569	0.091	0.007	0.063	-0.107	-0.126	-0.124	3	O9III	33000	3.7	35000	3.4	-.017
HD167659	2.578	0.220	-0.014	0.080	-0.079	-0.126	-0.116	4	O7I((F))	35000	3.3	34500	3.5	+.020
HR 6841 HD167771	2.566	0.151	-0.020	0.049	-0.091	-0.121	-0.126	4	O8I(F)	33000	3.3	35000	3.4	-.013
HD167971	2.556	0.606	-0.112	0.090	-0.054	-0.173	-0.158	4	O7.5IF	34000	3.3	39500	LT3	-.034
HD168075	2.598	0.398	-0.055	0.089	-0.101	-0.176	-0.161	4	O6.5III((F))	38000	3.7	42500	4.0	-.013
HD168076	2.564	0.406	-0.061	0.083	-0.128	-0.208	-0.196	4	O4(F)	50000	---	55000	4.3	-.011
HD168112	2.606	0.553	-0.094	0.099	-0.050	-0.161	-0.141	4	O5.5((F))	44500	---	37500	3.6	+.028
HD169582	2.569	0.438	-0.037	0.119	-0.085	-0.172	-0.143	4	O5.5(F)	44500	---	37500	3.5	+.027
HD171589	2.579	0.274	-0.020	0.088	-0.076	-0.132	-0.118	4	O7.5V((F))	37500	4.0	33500	3.3	+.007
HD175754	2.545	0.010	0.045	0.071	-0.156	-0.155	-0.149	4	O8III((F))	34000	3.7	37500	3.4	-.035
HD175876	2.562	-0.007	0.040	0.063	-0.152	-0.149	-0.148	4	O7...	35-38000		37000	3.4	-.013
HD186980	2.557	0.145	0.000	0.066	-0.100	-0.127	-0.123	3	O8III((F))	35000	3.7	33500	3.3	-.010
HR 7574 9 SGE	2.530	0.070	0.042	0.086	-0.143	-0.155	-0.142	3	O8IF	33000	3.3	35000	LT3	-.038
HR 7589 HD188209	2.534	0.023	0.035	0.066	-0.109	-0.112	-0.108	2	O9.5I	30000	3.3	31500	3.3	-.010
HD192281	2.581	0.339	-0.048	0.081	-0.052	-0.122	-0.111	5	O5.5(EF)	44500	---	32500	3.3	+.058
HD192639	2.547	0.305	-0.019	0.094	-0.058	-0.117	-0.100	5	O7.5IIIF	36000	3.7	28500	LT3	+.024
HD193443	2.590	0.368	-0.061	0.078	0.006	-0.069	-0.060	5	O9III	33000	3.7	29000	3.4	+.044
HD193514	2.574	0.373	-0.017	0.120	-0.032	-0.107	-0.077	5	O7.5III(F)	36000	3.7	29000	3.4	+.048
HD195592	2.539	0.698	-0.138	0.092	0.014	-0.121	-0.105	5	O9.5I	30000	3.3	28000	LT3	+.013
HR 8023 HD199579	2.579	0.109	0.014	0.077	-0.082	-0.107	-0.098	5	O6.5III	38000	3.7	33500	3.8	+.051
HD201345	2.572	-0.013	0.034	0.056	-0.106	-0.103	-0.105	5	ON9.5V	33000	4.0	34000	3.8	-.020
HD202124	2.543	0.237	0.007	0.101	-0.058	-0.104	-0.083	5	O9.5I	30000	3.0	27500	LT3	+.027
HR 8154 68 CYG	2.559	0.053	0.019	0.058	-0.109	-0.117	-0.118	5	O8V	36500	4.0	34500	3.5	-.002
HR 8327 HD207198	2.571	0.280	-0.011	0.100	-0.047	-0.105	-0.085	5	O9I	31000	3.3	-----	---	+.024
HD207538	2.594	0.301	-0.042	0.076	-0.024	-0.082	-0.074	5	O9.5V	33000	4.0	31500	3.8	+.005
HR 8428 19 CEP	2.555	0.132	0.006	0.069	-0.099	-0.124	-0.119	5	O9I	31000	3.3	34500	3.4	-.010
HD210809	2.538	0.106	0.014	0.070	-0.111	-0.130	-0.125	4	O9I	31000	3.3	30000	LT3	-.016
HR 8469 LAMBDA CEP	2.549	0.235	-0.009	0.083	-0.100	-0.145	-0.134	5	O6EF	42000	---	35000	LT3	+.025
HR 8622 10 LAC	2.585	-0.060	0.046	0.058	-0.113	-0.103	-0.104	6	O8III	35000	3.7	32500	3.5	+.013
HD216532	2.606	0.483	-0.136	0.032	0.032	-0.056	-0.069	3	O9.5V	33000	4.0	31500	3.8	+.010
HD216898	2.613	0.469	-0.121	0.043	0.021	-0.063	-0.071	3	O9V	34500	4.0	33000	4.0	+.023
HD217086	2.606	0.539	-0.145	0.040	0.017	-0.083	-0.092	2	O6.5...	COMPANION		NOT USED		
HD218915	2.547	0.083	0.016	0.064	-0.104	-0.118	-0.116	3	O9.5I	30000	3.3	32500	3.3	-.016
BD602522	2.623	0.342	-0.020	0.105	-0.103	-0.165	-0.142	3	O6.5IIIEF	38000	3.7	35000	LT3	-.004

NOTES.—Spectral types: A row of three dots is equivalent to a colon in Conti and Alschuler's (1971) notation, which means that they could not assign a luminosity class.

Spectroscopic log g: Dashes mean that Conti and Alschuler (1971) did not assign a luminosity class because the spectral type of the star is too early.

Photometric T_{eff}: When the photometric gravity is given as LT3, Hγ is weaker than predicted by the lowest-gravity model, and the temperature is determined by a rough extrapolation of the predicted colors to lower gravity.

TABLE 5

MEAN VALUES OF Δc_1 BY STELLAR LUMINOSITY CLASS

Class	$\langle\Delta c_1\rangle$	Class	$\langle\Delta c_1\rangle$
V........	+0.000	I........	−0.014
III.......	+0.007	If........	−0.031
IIIf......	−0.018	I........	+0.024

are plotted with small symbols. The mean value for each grouping is given in Table 5.

Four O7 If stars have been excluded from Figure 4 and Table 5. For such stars, the data presented by Conti (1973*b*) show that lines of H, He I, and He II all indicate $\log g \simeq 4.0$, and the lines of Si IV are the only ones that indicate a low gravity. Since the lines of Si IV weaken at high effective temperatures, Si IV may not be a reliable indicator of gravity at such an early spectral type. Therefore, these stars are probably physically different from the other stars of luminosity class I, in which Hγ is weak.

Consistent with the behavior shown in Figure 3, Δc_1 tends to be negative for stars of classes IIIf, If, and I, and positive for the Of stars without luminosity classifications, which are all earlier than spectral type O6. For the main-sequence stars, the standard deviation of Δc_1 about the mean is 0.016, which is no larger than expected from observational uncertainty if the uncertainty in the spectroscopically determined effective temperature is taken into account. Thus the observed differences—particularly the difference between class V and class If—amount to 3 or more standard deviations and are probably not due to observational error.

It is interesting to attempt to interpret these admittedly small differences in terms of the calculations by Mihalas and Hummer (1974). For an effective temperature of about 39,500 K, for non–LTE, and for several extended geometries, they have calculated $u - b$ and $b - y$. Since the giants and supergiants of Figure 4 all have lower effective temperatures than does the extended model atmosphere, a comparison between the observed and calculated colors can be only approximate and is best done differentially. By the definitions of the *uvby* colors, changes in the colors are related as follows:

$$\delta c_1 = \delta(u - b) - 2\delta(b - y) - 2\delta m_1 . \quad (3)$$

For the differences between a plane-parallel model and a typical extended model, Mihalas and Hummer (1974) give $\delta(u - b) = +0.023$ and $\delta(b - y) = +0.018$. Then, $\delta c_1 = -0.013$ if $\delta m_1 = 0$. For their most extended model, $\delta c_1 = -0.038$. The expected weakening of Hδ as the atmosphere becomes more extended has a negligible effect on c_1. The mean Δc_1 indices shown in Table 5 for classes IIIf and I agree closely with the typical calculated value, −0.013, but the mean for class If approaches the value for the most extended model. Therefore, the data suggest that the extended model-atmosphere calculations are applicable to these stars. The equivalent widths of He II λ4542 and He I λ4471 will presumably also be affected by extended geometry. Therefore, the effective temperatures derived from these lines by means of the plane-parallel model atmospheres must be regarded with caution, and so must the above argument, since it depends on these effective temperatures.

One may also ask whether it is possible to interpret the behavior of the hotter Of stars in terms of extended atmospheres. For this purpose, I refer to the very recent calculations by Kunasz *et al.* (1975), which include two extended models (serial numbers 15 and 16) with $T_{\rm eff} \simeq 50{,}000$ K and $\log g \simeq 4.1$. As did Mihalas and Hummer (1974), these authors give $u - b$ and $b - y$ only, and it is necessary to apply equation (3) and to assume $\delta m_1 = 0$ as before. The result is $\delta c_1 = -0.018$ for model 15 and $\delta c_1 = +0.005$ for model 16. Clearly, these values do not approach the observational value, +0.024, of Δc_1 given for class f in Table 5. The value calculated for model 16 is, at least, positive, and constitutes a modest step in the right direction. It must be concluded that these particular models do not reproduce the observed values of Δc_1. Perhaps other models based on the same physics but with different values of the input parameters would do so. Two other possible interpretations of the discrepancy are: (1) the physical basis of the extended model atmospheres may be inadequate at this high temperature, or (2) there may be a systematic error in the spectroscopic temperature scale for the early Of stars.

IV. CONCLUSIONS

A comment on the utility of *uvbyβ* photometry as a method of determining effective temperatures and gravities of O-type stars is in order. In principle, its accuracy is comparable to that of the spectroscopic method. As Figure 3 shows, the precision actually attained for stars without extended atmospheres is as high as can be expected if photographic rather than photoelectric Balmer-line equivalent widths are used.

A fundamental difficulty arises, however, for the later-type giants with emission lines, later-type supergiants, and nearly all stars of type O6 and earlier. The fact that the hydrogen lines are weaker in such stars than predicted by the plane-parallel models would not by itself be an insurmountable problem. Rather, Figure 2 shows the basic difficulty, which is that the lines of constant effective temperature, if extended to lower gravities, nearly converge; on this basis, it might have been expected *a priori* that the effective temperature would become indeterminate. The observations bear out this expectation, in that, as Figure 3 shows, nearly the same effective temperatures are derived for the stars with spectroscopic $T_{\rm eff} \geq 42{,}000$ K (O6 and earlier) as for supergiants with spectroscopic $T_{\rm eff} \sim 33{,}000$ K (O7 to O8). These stars all have corrected c_1 indices in the range −0.17 to −0.13, and log W(Hγ) in the range 0.10 to 0.25. For a star with these characteristics, the photometric method should not be applied. If the equivalent width of Hγ is 2 Å or greater, as in ζ Pup and HD 168076, the photometric temperature agrees reasonably well with the spectroscopic one, and the photometric method is usable.

The previous discussion does not mar the fact that, for stars to which plane-parallel geometry applies, the photometric and spectroscopic temperature scales agree. The definiteness with which this statement can be made is, of course, limited by the accuracy of the transformation of the theoretical colors to the standard *uvby* system. To this level of accuracy, self-consistency of the non–LTE plane-parallel models is demonstrated. For stars of type O6.5 and later and classes IIIf, If, and I, the observed values of c_1 are systematically more negative than the predicted values, by an amount that agrees with the predictions of the extended model atmospheres of Mihalas and Hummer (1974). For stars earlier than type O6.5, c_1 is systematically more positive than predicted by plane-parallel models. This effect, though unexplained, may be due to the presence of extended atmospheres in these stars.

It is a pleasure to thank S. C. Wolff for helpful discussions and advice and, in particular, for suggesting this problem. This research was partially supported by NSF grant GP-29741.

REFERENCES

Auer, L. H., and Mihalas, D. 1972, *Ap. J. Suppl.*, **24**, 193.
Brucato, R. J. 1971, *M.N.R.A.S.*, **153**, 435.
Conti, P. S. 1973*a*, *Ap. J.*, **179**, 181.
———. 1973*b*, *ibid.*, p. 161.
Conti, P. S., and Alschuler, W. R. 1971, *Ap. J.*, **170**, 325.
Conti, P. S., and Leep, E. M. 1974, *Ap. J.*, **193**, 113.
Crawford, D. L. 1975, *Pub. A.S.P.*, in Press.
Crawford, D. L., and Barnes, J. V. 1970, *A.J.*, **75**, 978.
Crawford, D. L., Barnes, J. V., Hill, G., and Perry, C. L. 1971, *A.J.*, **76**, 1048.
Crawford, D. L., and Mander, J. 1966, *A.J.*, **71**, 114.
Hayes, D. S., and Latham, D. W. 1975, *Ap. J.*, **197**, 593.
Hiltner, W. A., and Johnson, H. L. 1956, *Ap. J.*, **124**, 367.
Kunasz, P. B., Hummer, D. G., and Mihalas, D. 1975, preprint.
Lindemann, E., and Hauck, B. 1973, *Astr. and Ap. Suppl.*, **11**, 119.
Mihalas, D. 1971, *Ap. J.*, **170**, 541.
———. 1972, *ibid.*, **176**, 139.
Mihalas, D., and Hummer, D. G. 1974, *Ap. J.* (*Letters*), **189**, L39.
Morrison, N. D. 1975, *Ap. J.*, in press.
Osmer, P. S. 1973, *Ap. J.*, **181**, 327.
Sturch, C. 1972, *Pub. A.S.P.*, **84**, 666.
Walborn, N. R. 1971, *Ap. J. Suppl.*, **23**, 257.
Wilson, R. 1958, *Mém. Roy. Soc. Liège*, 4th Ser., **20**, 85.
Zinn, R. J. 1970, *Ap. J.*, **162**, 909.

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