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THE EFFECTIVE TEMPERATURES OF EARLY-TYPE STARS DERIVED FROM TD 1 SATELLITE ULTRAVIOLET PHOTOMETRY

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ABSTRACT

A grid of model atmospheres has been calculated, and the resulting energy distributions have been compared with measured energy distributions of 14 stars of spectral types between B0 and A2. Both supergiants and main-sequence stars are represented on the list. The energy distributions are from a combination of TD 1 satellite data and ground-based photometry, and extend from 1300 Å to 5500 Å. A temperature scale is derived for the main-sequence stars and for the supergiants, and this is compared with values obtained for five of the stars for which angular diameters have been measured. For the star ϵ Ori, we were able to derive the luminosity from our data and the angular diameter, assuming it to be a member of the Orion association. This luminosity implies that the mass of this B0 Ia star is 20–25 $M_\odot$.

Subject headings: atmospheres, stellar — early-type stars — luminous stars

I. INTRODUCTION

In the last two years, ultraviolet fluxes of a variety of bright stars have been measured with the ultraviolet sky survey telescope (S2/68) aboard the TD 1 satellite (described by Boksenberg *et al.* 1973). In previous papers, the data from this satellite have been used to study the behavior of ultraviolet colors for early-type stars and the effect of luminosity on these colors (Humphries, Nandy, and Kontizas 1975; Nandy, Thompson, and Humphries 1974). Because of the scatter in the color-color diagrams using these ultraviolet colors, it is desirable to determine the influence of various parameters on the ultraviolet flux. For this purpose we have constructed a series of model atmospheres to compare with the measurements. The present paper is intended to show that the models are capable of reproducing the observations quite well. The temperature scale of B and early A stars which is implied by the combination of the models and the satellite data is derived.

II. THE MODEL ATMOSPHERES

The calculations were done using the model-atmosphere program ATLAS (Kurucz 1970, 1973*b*). The version used allows the inclusion of line opacity through the use of distribution functions (Kurucz, Peytremann, and Avrett 1972). These distribution functions are based on about 750,000 spectral lines, and it has been shown by Kurucz (1973*a*) that they are capable of reproducing the solar spectrum reasonably well over the range from 1500 Å to 1000 μ. We have calculated a grid of model atmospheres with temperatures ranging from 7500 K to 22,500 K, and with gravities of 10^2 and 10^4 cm s^{-2}. This range of gravity and temperature should be sufficient for the present purpose of comparison with B and early A main-sequence and supergiant stars.

The effects of the line blanketing are illustrated in Figure 1. For the hotter models (20,000 K) it is seen that the chief effect of the line blanketing is in the form of an increase in the continuum flux ranging from about 5 percent at 6000 Å to about 15 percent in the ultraviolet around 1500 Å. At 15,000 K the effects are largely the same, although there is some sign of line absorption in the region from 1400 Å to 2500 Å. At 10,000 K there is still an increase in the visual flux of about 5 percent due to backwarming, but in the ultraviolet the effects of line absorption are much stronger. Also illustrated in Figure 1 are the effects of variations in the gravity. Actually, the effect of gravity on the energy distributions is relatively small compared with the effects of temperature changes. For example, a change in the gravity from $\log g = 4$ to $\log g = 2$ would be equivalent to a change in temperature of less than 500 K at 10,000 K (depending on exactly how the comparison is made). Therefore, in using the fluxes to determine the temperatures of B and A stars, the gravity will not need to be known with great accuracy.

III. THE TEMPERATURES OF EARLY TYPE STARS

Fourteen B and early A stars, listed in Table 1, have been chosen from the TD 1 sample for the present project, since they are little reddened or unreddened. Their absolute ultraviolet data corrected for interstellar extinction have been taken from Humphries *et al.* (1975), in which the error in absolute calibration is estimated as ± 10 percent. The color excesses were determined from the spectral types and the measured $(B-V)$ colors taken from Blanco *et al.* (1968), and the

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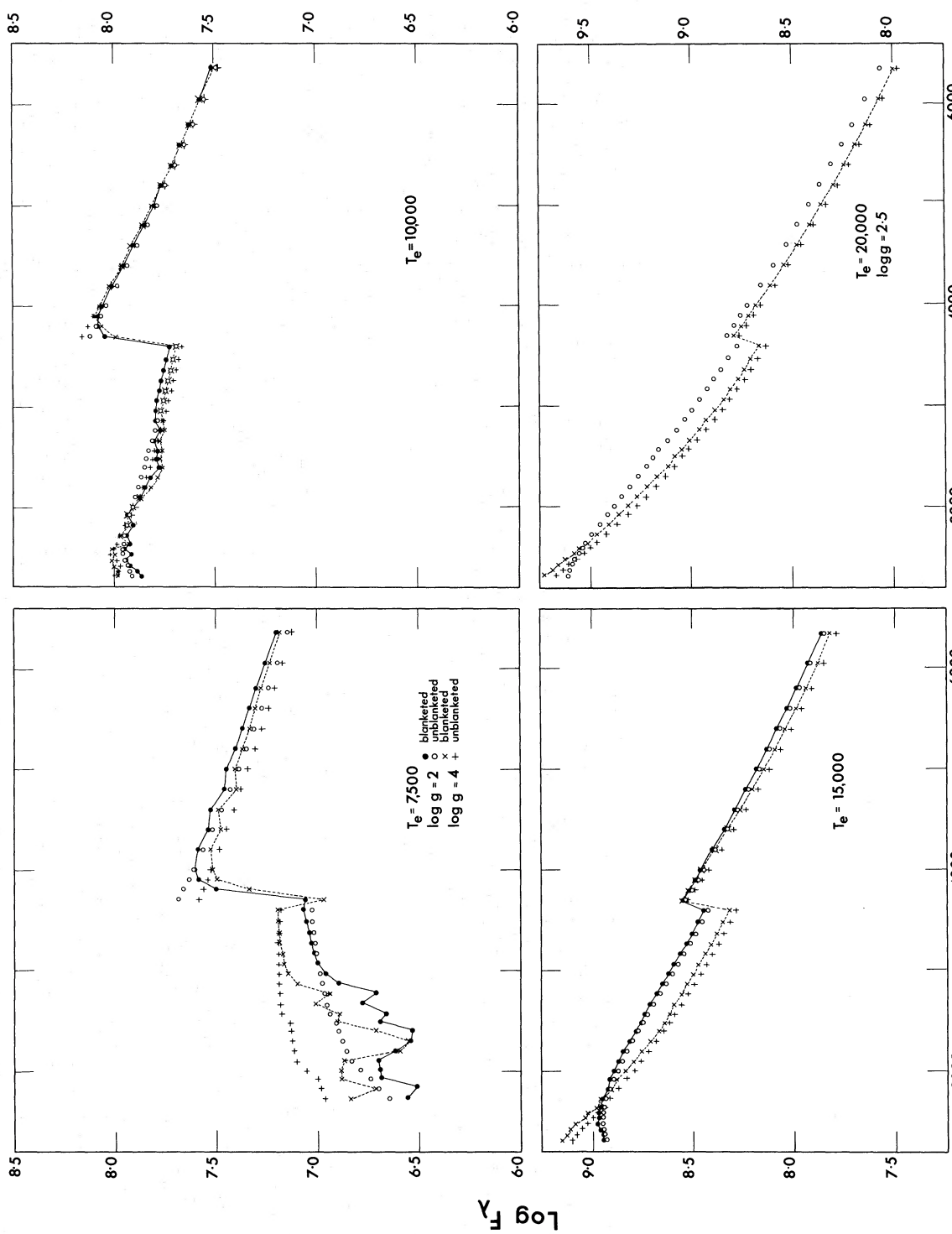

FIG. 1.—The effect of line blanketing and variations in gravity on the model energy distributions for temperature range between 22,000 K and 7500 K. The unit of flux is ergs cm^{-2} s^{-1} sr^{-1} nm^{-1}. In panel T_e = 20,000 K, log g = 2.5 has been used instead of log g = 2.

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TABLE 1

DATA FOR B AND A STARS

Name	HD Number	Spectral Type	E_{B-V}	Q	$T_{\rm eff}$ (K) energy distribution	$T_{\rm eff}$ (K) (angular diameter)
ν Ori	36512	B0 V	0.04	−0.89	24300 ± 1200	...
ϵ Ori	37128	B0 Ia	0.05	−0.90	18000 ± 800	21300 ± 900
	37209	B1 V	0.03	−0.74	19800 ± 900	...
	64760	B1 Ib	0.04	−0.88	18200 ± 800	...
κ Cen.....	132200	B2 V	0.02	−0.61	19000 ± 900	...
ϵ CMa.....	52089	B2 II	0.00	−0.77	19000 ± 900	20100 ± 800
α Gru.....	209952	B5 V	0.03	−0.36	13050 ± 400	13700 ± 400
η CMa.....	58350	B5 Ia	0.02	−0.68	12500 ± 400	13100 ± 300
η Aqr.....	213998	B8 V	0.00	−0.19	11300 ± 300	...
β Ori	34085	B8 Ia	0.00	−0.65	11800 ± 300	11700 ± 200
γ Oph	161868	A0 V	0.04	+0.01	8600 ± 150	...
	94367	A0 Ia	0.13	−0.62	12500 ± 800	...
ϵ Gru.....	215789	A2 V	0.02	+0.02	8000 ± 150	...
α Cyg.....	197345	A2 Ia	0.03	−0.30	9500 ± 200	...

extinction corrections were made using the mean extinction curve of Bless and Savage (1972). Since the reddening of these stars is small, the error arising from uncertainties in the extinction law is negligible. For each of the stars, the visual magnitude was used along with the Oke and Schild (1970) calibration to determine the flux at 5500 Å. For those stars in the list with measured colors on the Strömgren *ubvy* system, the flux at 4665 Å was determined from the $b-y$ color with the calibration derived by Breger (1974). The calibration of Johnson (1966) was used to determine the flux at 4400 Å from $(B-V)$. All of these data are plotted for each star in Figure 2. For the stars HD 132200, HD 161868, and HD 213998, Willstrop (1965) has measured energy distributions throughout the visual range, and his data are also plotted.

The measured energy distributions, extending from 1300 Å, to 5500 Å, were fitted to the model fluxes in order to establish the temperature. For the class V stars the models with $\log g = 4$ were used, while for the supergiants and giants the models with $\log g = 2$ were used. In view of the small effect of gravity on the energy distributions, these gravities are not critical. The temperatures are listed in column (6) of Table 1. The errors given there represent the result of a ±10 percent uncertainty in the ultraviolet fluxes, except for HD 94367, where a ±20 percent uncertainty was estimated. The greater error for that star arises from the relatively large photometric errors, the large color excess, and the consequent uncertainty in the absorption correction in the ultraviolet. In Figure 2, model flux distributions interpolated to the appropriate temperature are shown with each of the observed flux distributions. It can be seen that there is good agreement between the calculations and the observations.

Angular diameters of five of the stars in Table 1 have been measured by Hanbury Brown, Davis, and Allen (1974). With these data and the measured fluxes, we can use the models to give another estimate of the temperature. The flux at several ultraviolet wavelengths was used, and the temperatures in column (7) of Table 1 represent the mean of the values. It can be seen that only in the case of HD 37128 does the value determined in this way differ significantly from that determined by the energy distribution fitting. This discrepancy may be related to non–LTE effects, as this is one of the hottest and most luminous of the stars in our sample. Although the differences for the remainder of the stars are of the order of the errors, there is a definite trend toward better agreement in the cooler stars. If this is a real effect, its cause is not clear. The agreement between the two methods is, however, good enough to allow us to be reasonably confident that the scale derived is correct to within the accuracy implied by the quoted errors.

In Figure 3 we have plotted the effective temperature from Table 1 against the spectral type and against the parameter, $Q = (U-B) - 0.72\,(B-V)$. Also shown in the diagram are the temperature scales derived by Johnson (1966) from multicolor photometry, and by Schild, Peterson, and Oke (1971) (SPO) from spectral scans combined with model atmospheres. It can be seen that our scale is slightly cooler than the SPO scale for the most part, but in fair agreement with that of Johnson. Additionally it can be seen that the supergiants are cooler at the same value of Q than the main-sequence stars, but that in the plot of temperature against spectral type there is a crossover, so that the supergiants are cooler at early spectral type but hotter at later spectral type. Our Q-temperature relation for the dwarfs can be represented by

$$\log T_{\rm eff} = 3.958 - 0.481Q\,. \qquad (1)$$

The A stars were omitted from this least-squares solution because Q is no longer a good temperature indicator at that spectral type. For the supergiants the relation is

$$\log T_{\rm eff} = 4.010 + 0.294Q + 0.642Q^2\,. \qquad (2)$$

In this case, HD 52089 has been omitted because of its lower luminosity. If the color $(B-V)$ is used, we get

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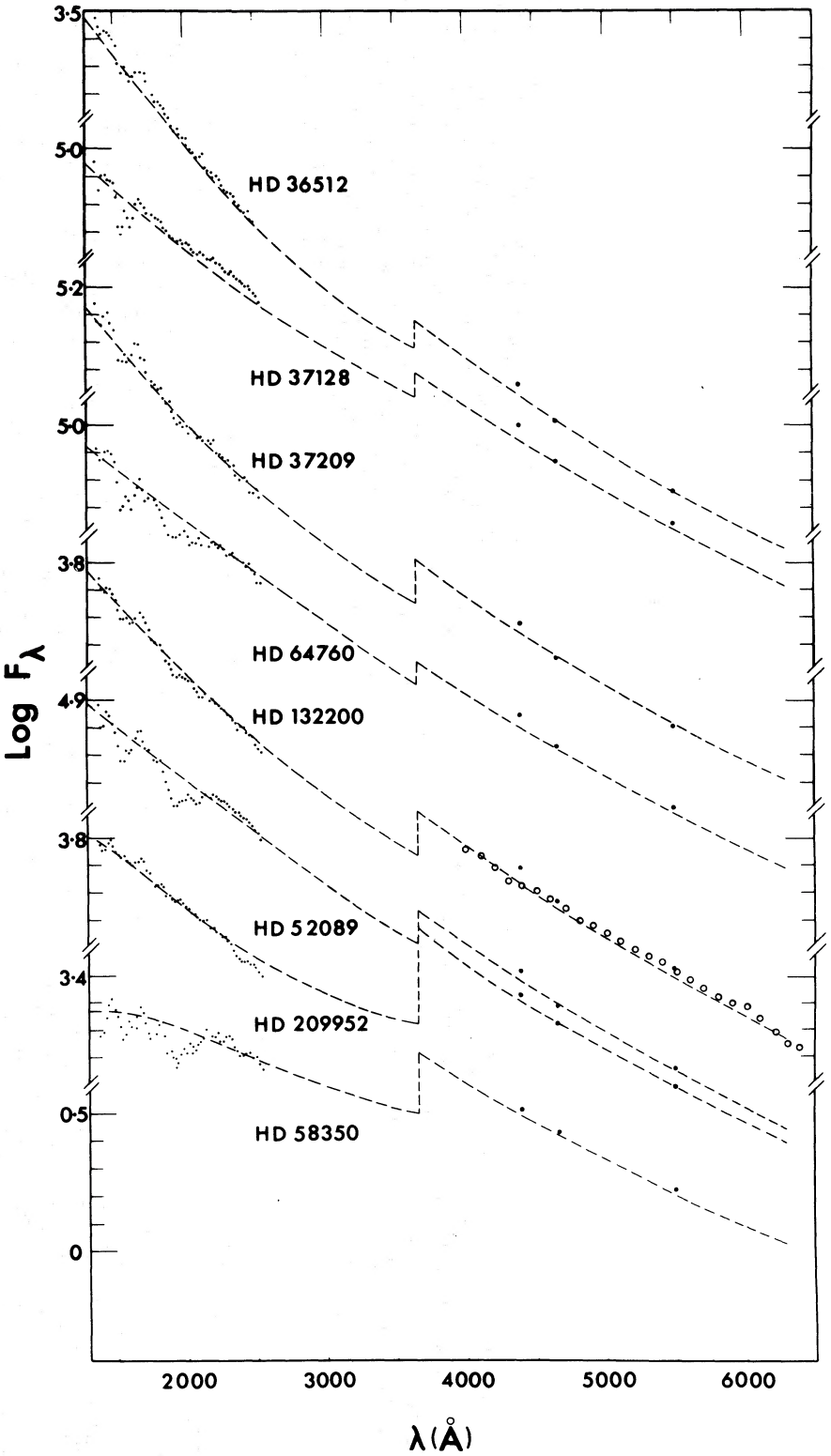

FIG. 2*a*

FIG. 2.—The observed flux distributions of the stars compared with model fluxes

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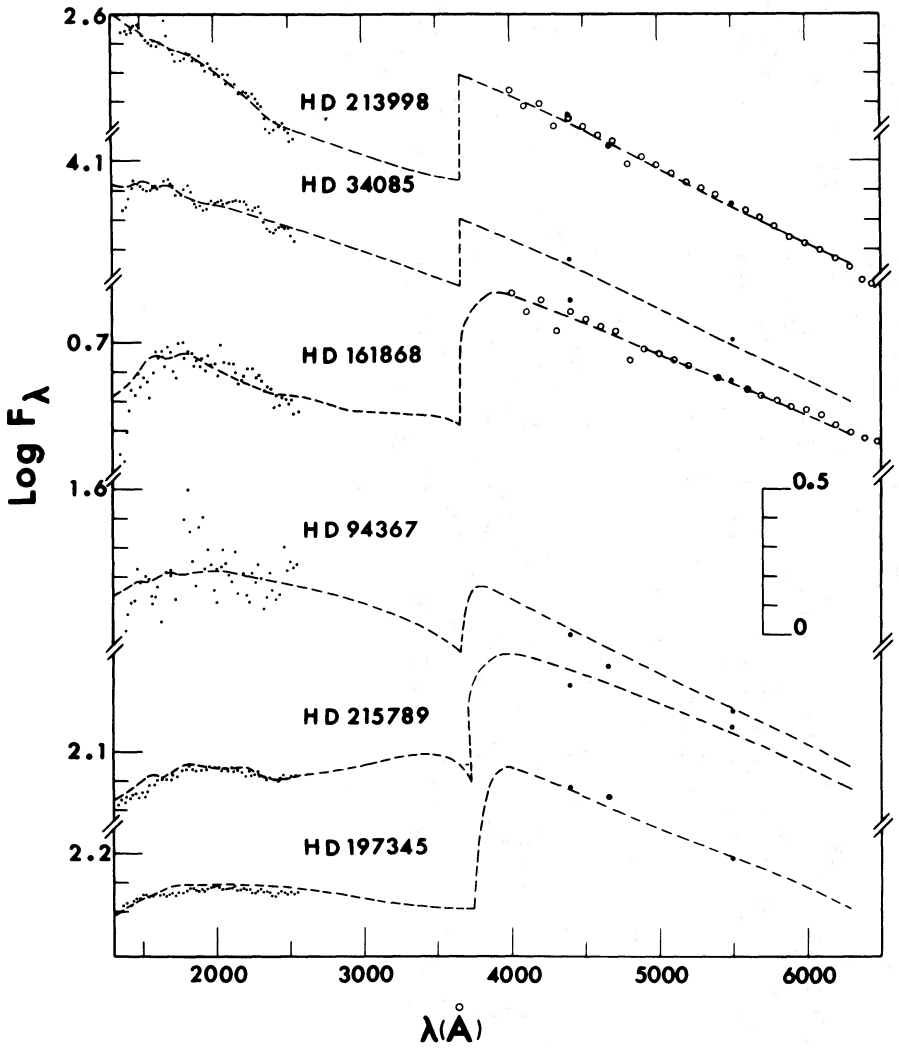

FIG. 2b

FIG. 2.—*Continued*

the following color-temperature relations:

$$\log T_{\rm eff} = 3.940 - 0.773\,(B-V) + 2.300\,(B-V)^2 \text{ (main sequence)}, \quad (3)$$

$$\log T_{\rm eff} = 4.058 - 0.886\,(B-V) \text{ (supergiants)}. \quad (4)$$

In this case the A stars were included, but HD 52089 was still omitted.

IV. THE LUMINOSITY AND MASS OF ϵ ORIONIS

The probable membership of ϵ Ori in the Orion association makes it possible to derive further information about this star. The color excess, $E_{B-V} = 0.05$, is in good agreement with Penston's (1973) estimate of $E_{B-V} = 0.07$ for the foreground reddening in this region. If we then adopt the distance to the cluster derived by Walker (1969) of 470 pc and the angular diameter found by Hanbury Brown *et al.* (1974), we obtain a radius for ϵ Ori of 34.8 $R_\odot$, and with the temperature of 18,000 K the luminosity becomes $1.14 \times 10^5\,L_\odot$. The use of the hotter temperature of 21,300 K from Table 1 raises this to $2.24 \times 10^5\,L_\odot$. A major uncertainty in this determination is the distance of the star. For example, if we adopt a distance of 400 pc as indicated by a recent photometric study by Penston, Hunter, and O'Neill (1974), the luminosity of the star becomes $0.824 \times 10^5\,L_\odot$ (using the temperature of 18,000 K). Regarding these three estimates of the luminosity as extremes, we can then compare the position of this star in the temperature-luminosity diagram with theoretical calculations. This is done in Figure 4, where the three positions are plotted along with the evolutionary tracks computed

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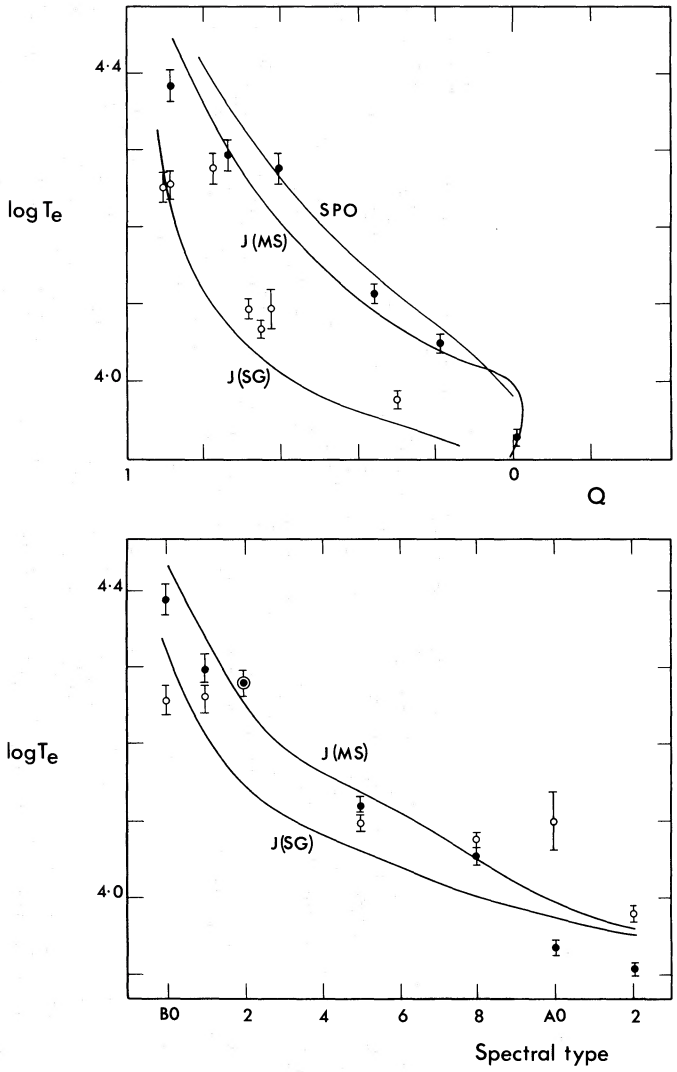

FIG. 3.—*Top*, the effective temperature versus *Q*. *Bottom*, the effective temperature versus MK Spectral type. *Open circles*, supergiants; *filled circles*, main-sequence stars. *Solid lines*, temperatures from Johnson (1966) and from Schild, Peterson, and Oke (1971).

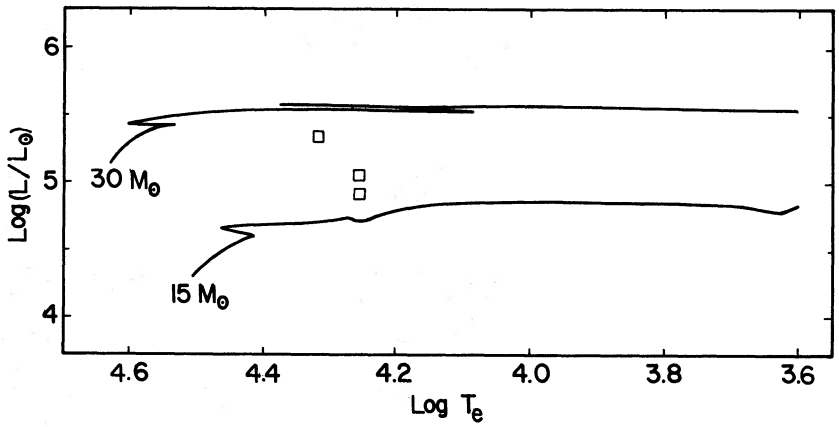

FIG. 4.—The location of ϵ Ori in the temperature-luminosity diagram for various assumptions about its distance and temperature. Also shown are the evolutionary tracks for stars with 15 and 30 $M_{\odot}$.

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by Iben (1967) for a star of 15 $M_\odot$ and by Stothers (1966) for a star of 30 $M_\odot$.

It can be seen that the star ϵ Ori has evolved from the zero-age main sequence; taking a mean value of $1.4 \times 10^5 L_\odot$ for its luminosity, a rough interpolation shows that its mass is 21 $M_\odot$. The mass-luminosity relation for the observed early-type binary stars (Stothers 1972), on the other hand, gives a mass of 25 $M_\odot$ for ϵ Ori. This mass is considerably less, for example, than the value of 50 $M_\odot$ given by Allen (1974) for a BO supergiant. However, although there are some uncertainties in our determination, it does not appear possible to increase the luminosity sufficiently by reasonable adjustments of the observed quantities to result in an appreciably higher mass. For example, to increase the mass to 30 $M_\odot$ would require that the luminosity be increased to about 4×10^5. This in turn would require that the star be nearly 800 pc away. That a star at that distance in the Orion region should have a very small color excess is quite unlikely. Therefore, we conclude that ϵ Ori has a luminosity of $\log L/L_\odot = 5.1 \pm 0.25$, and a mass in the range from 20 to 25 $M_\odot$.

V. CONCLUSIONS

The effective temperatures of early-type main-sequence and supergiant stars obtained by fitting the observed energy distributions with the model calculations using the ATLAS program are in general agreement with the temperature scale derived by Johnson. The supergiants are cooler than the corresponding main-sequence stars at early B types, but hotter at later types, and the crossover occurs near B8.

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