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MEASUREMENTS OF THE ULTRAVIOLET FLUX OF BETELGEUSE

José H. Peña *

Washburn Observatory
The University of Wisconsin-Madison
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RESUMEN

Se ha llevado a cabo una comparación de modelos atmosféricos para estrellas frías con datos observados con el OAO-2 para Betelgeuse. Los resultados parecen indicar, en concordancia con comparaciones semejantes en las regiones visual e infrarroja, que la abundancia de carbono y oxígeno en esta estrella es menor que la normal.

ABSTRACT

A comparison of model atmospheres for cool stars with observed data from the OAO-2 for Betelgeuse has been carried out. Results indicate that this star must be underabundant in C. and O. This result in the ultraviolet is in agreement with similar comparisons in the visual and infrared parts of the spectrum.

Key words: ATMOSPHERE, STELLAR — LATE-TYPE STARS.

I. INTRODUCTION

The present knowledge of the physical structure of the late-type stars lags behind that for stars of higher temperatures. This is due to difficulties that occur in handling the blanketing effect, and the complication of the equation of state because of the numerous atomic species that contribute electrons when hydrogen ionization is unimportant. Despite these complexities, several attempts have been made in the determination of atmospheric models for cool stars.

Early computations were made by Tsuji (1966), Gingerich, Latham, Linsky, and Kumar (1966), Carbon and Gingerich (1969), and Alexander and Johnson (1972). Several of these works have been compared with observations, mainly in the infrared part of the spectrum with data obtained from the Stratoscope Project (Woolf, Schwarzschild, and Rose 1964). In this paper we consider the heretofore ignored ultraviolet regions.

II. CHARACTERISTICS OF BETELGEUSE

Special attention has been devoted to α Ori because it is the brightest M supergiant star. Its apparent magnitudes for different wavelengths have been given by Code (1960), and are listed in Table 1.

Fäy and Johnson (1973), hereinafter FJ, describe this M2 Iab star as a variable type SRb and report, based on various measurements of the angular diameter, its effective temperature somewhere in the range 3200 to 3790 °K. Johnson (1964) gives a value of 3981 °K.

* Present address: Instituto de Astronomía, Universidad Nacional Autónoma de México.

TABLE 1

MONOCHROMATIC MAGNITUDES OF α ORI

λ	$1/\lambda$	$m(1/\lambda)$	λ	$1/\lambda$	$m(1/\lambda)$
0.340	2.94	+5.20	0.581	1.72	−0.30
0.365	2.74	+4.71	0.605	1.65	−0.44
0.386	2.59	+4.26	0.667	1.50	−0.78
0.404	2.48	+3.29	0.746	1.34	−1.50
0.419	2.39	+2.90	0.800	1.25	−1.62
0.459	2.18	+1.41	0.875	1.14	−1.76
0.506	1.975	+0.58	0.919	1.09	−1.88
0.556	1.80	0.00	1.000	1.00	−2.22

TABLE 2

SCANNED REGIONS OF α ORI

Region	Reference
0.8 — 3.0 μ	Woolf, Schwarzschild, and Rose 1964
2.8 — 14 μ	Gillet, Low and Stein 1968
1 — 4 μ	Johnson and Mendez 1970
0.3 — 11.4 μ	Fäy and Honeycutt 1972
0.8 — 1.1 μ	Wing 1967

III. COMPARISON WITH MODELS

Tsuji was the first to compare model atmospheres for cool stars with observations. He chose α Ori as a sample of the M supergiant star and obtained his observational data from results of the Stratoscope Project. His models for M dwarfs and supergiants include molecular line opacity due to vibration-rotation bands as well as pure rotation bands of H_2O, CO and OH in addition to the sources of continuous opacity such as bound-free and free-free of H^-, free-free H^-_2, and bound-free and free-free of H, Rayleigh scattering of H and H_2 and electron scattering.

The physical characteristics he used for the M supergiant are $T_{eff} = 3000$ °K, log g = 1 and the solar chemical composition. From the comparison of his models with the observations he obtained some discrepancies which he attributed to the difference between the temperature he assumed in his models and that reported by Johnson. The excessive flux obtained from his model as compared to that observed at the violet side of 0.8 μ was interpreted as line blanketing due to atomic lines. TiO and VO bands were not taken into account in the calculation and interpretation of the theoretical flux.

A recent work of the same nature was done by FJ who compared the scans of Betelgeuse given in Table 2, with the more sophisticated models of Alexander and Johnson (1972) and Johnson (1973). The computation of these models were done with ISAC, a modification for cool stars of the LTE code ATLAS, and for temperatures of 3500 and 3800 °K.

ISAC, as ATLAS, takes into consideration the radiation pressure in the HSEQ equation, contribution of convection by the Böhm-Vitense mixing length theory. The calculation of the source function, mean intensities and radiative flux are done with the matrix method and the Krook-Avrett temperature correction scheme. Furthermore, ISAC includes the effect of molecules in the treatment of convection, in the equation of state, and in the calculation of opacity of the stellar material. In addition to the usual sources of opacity, molecular and atomic line blanketing and opacity of H_2O, the infrared CO and the CN red system are considered (A recompilation of the main contributors to the opacity in cool stars is given by Vardya 1966 and Gingerich *et al.* 1967). For atomic line blanketing the method of statistics of Mutschlecner and Keller (1970), hereinafter referred as MK, is used.

Of the several models tried by FJ that gave good agreement in the spectral region from 0.1 to 2.5 μ^{-1}, the best ones have T = 3500 °K. These models are characterized by having C/H and O/H lower than the sun by a factor of 10, and all the other elements were maintained at the same solar abundances. They showed that with solar abundances the infrared CO bands are much stronger than those observed. This could be due either to an overestimate of the CO opacity (too high transition probabilities or too crude mean opacities) or to an underabundance of C and O as has been suggested by Beer *et al.* (1972).

This brief discussion summarizes the results obtained from comparison of models with observations of Betelgeuse in the visual and infrared. In the following pages, we discuss comparisons for the ultraviolet portions of the spectrum.

IV. THE OBSERVED ENERGY DISTRIBUTION

From the OAO scans and the visual observations of Fäy and Honeycutt (1972) a spectral energy distribution of α Ori was obtained in the wavelength range 2450 to 4500 Å.

The OAO spectral distribution for α Ori was available from only one scanner that swept the region between λ2000 and λ4000 with 20 Å resolution but, because of the background, the scans are useful only for $\lambda > 2450$ Å. A detailed description of the OAO-2 Wisconsin instrumentation can be found in a paper by Code *et al.* (1970). The reported ultraviolet distribution of Betelgeuse was done considering an average over 10 scans with an error due to the number of counts compared to the background as indicated in Table 3. (Code, 1975).

TABLE 3

UNCERTAINTIES IN THE OAO FLUXES

Wavelength (Å)	(%) Error
2450	±50
2500	±30
2800	± 5
3000	±10
3250	± 3
> 3250	unimportant

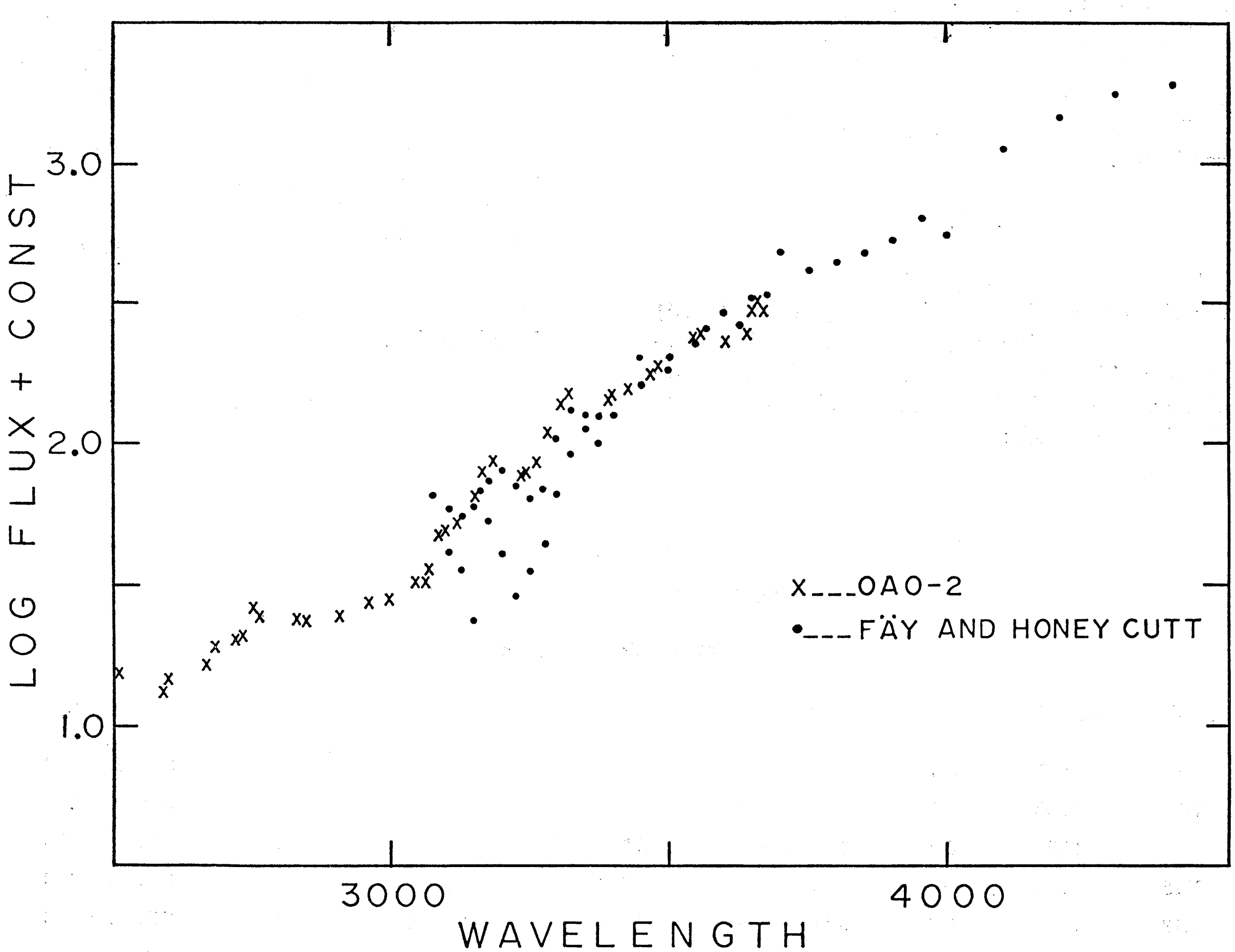

FIG. 1. Extended spectral energy distribution of Betelgeuse.

Fäy and Honeycutt made some ground-based observations specially designed to provide scanner data for comparison with relatively high resolution models of cool stars. These observations are in the range 3400 to 11000 Å and were corrected for terrestrial atmospheric extinction caused by O_2 and H_2O as well as Rayleigh scattering. They report an statistical accuracy of the scan in the region λ3300 – 6000 of 0.012 magnitudes but they claim that a quantitative estimate of the total error is difficult because only one observation was available and because the star is expected to be somewhat variable. Both results after being properly adjusted in relative units of flux per unit wavelength and corrected for interstellar reddening are presented in Figure 1.

Correction for reddening was done considering an E_{B-V} of 0.22, because Doherty (1972) reports (B-V) and $(B\text{-}V)_0$ as 1.86 and 1.64 respectively. The standard extinction curve of Code *et al.* (1974) was employed; this curve agrees with the "average" curve of Bless and Savage (1972) in the region considered.

V. MODELS

The theoretical emergent fluxes were taken from a series of model calculations by Johnson (1973) for cool stars with a wide range in chemical composition. They were computed as discussed previously. The following notation will be used to describe the models:

L refers to the solar composition (Lambert 1968).

SO refers to the standard opacities —the opacity of all forms of hydrogen plus H_2O, CO, and CN.

P refers to the polyatomic free radicals.

MK refers to the Mutschlecner-Keller atomic line blanketing statistics.

Originally, these line blanketing statistics were created to fit the solar atmosphere by making use of a uniformly-smeared-line (single picket) procedure and which assumes LTE. The extrapolation of these statistics to cool stars and to stars that may differ in composition from that of the sun, quoting FJ, represents a significant uncertainty but the absence of better data leaves little alternative.

MKII refers to the MK atomic line blanketing except that at wavelengths larger than 1 μ only 0.1 MK is considered to avoid double counting since the MK plus CN over-blankets the star in the infrared because many of the lines counted by MK were really CN lines and CN opacity is separately included.

MKC has the blanketing reduced by 50% except redward of 1 μ since most of the blanketing in the Sun and elsewhere is probably molecular in this region.

Table 4 lists the characteristics of the models considered.

TABLE 4

CHARACTERISTICS OF THE MODELS

Model	t_{eff} (°K)	log g	Chemical Composition C/H	O/H	N/H	C/O	Opacities
K1	3500	0.0		Lambert			SO, P, MKC
K9	3500	0.0	3.55×10^{-5}	3.55×10^{-5}	9.57×10^{-4}	1.0	SO, P, MKC
K12	3500	0.0	3.55×10^{-5}	1.78×10^{-5}	9.75×10^{-4}	2.0	SO, P, MKC
K15	3500	0.0	3.55×10^{-4}	1.78×10^{-4}	4.96×10^{-4}	2.0	SO, P, MKC
K18	3500	0.0	3.55×10^{-3}	1.78×10^{-3}	4.96×10^{-3}	2.0	SO, P, MKC
J16	3500	0.0	3.55×10^{-5}	3.55×10^{-5}	9.57×10^{-4}	1.0	SO, P, MKII

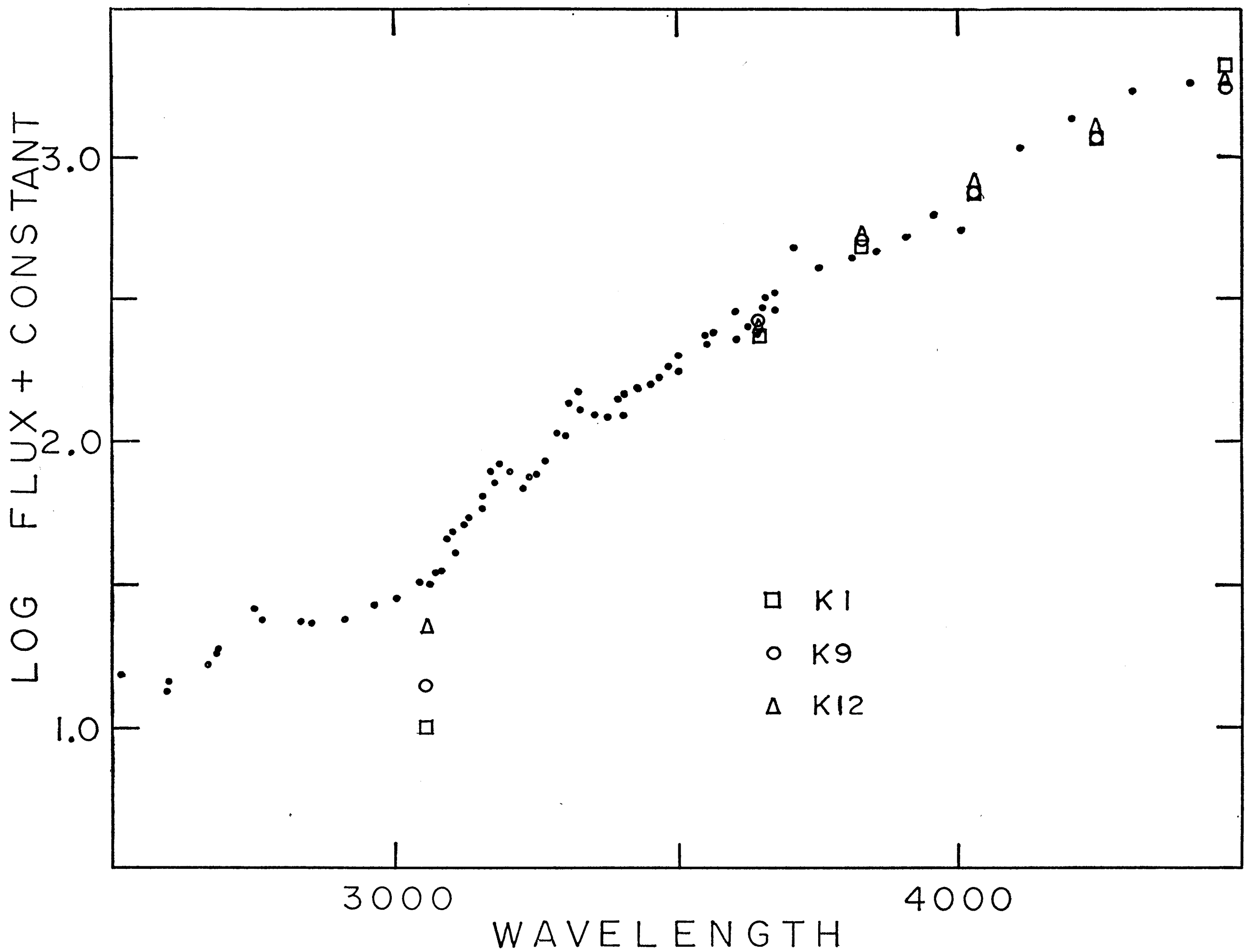

FIG. 2. Effect of decreasing the oxygen abundance. Symbols for each model are indicated on the figure. In going from K1 to K12, the oxygen abundance is systematically decreasing.

Figure 2 shows the effect produced upon decreasing the oxygen abundance. Model K1 has solar abundances and from model K3 through K12 the only parameter varying is the oxygen abundance which is systematically decreasing. FJ report that this reduction in the oxygen allows increasing formation of CN, an important opacity source. Therefore, these models are in order of progressively more CN opacity and hence lower pressure for the same temperature.

In going from K12 to K18, the ratio C/O is constant but C/H is increasing, i.e. the amount of C and O is increasing. Model K12 contains so little C and O that there is almost no cooling due to the molecules CO, but this becomes increasingly important in going to K18. These effects are shown in Figure 3.

Unfortunately, Johnson (1973) does not list all the models that were employed in the FJ work. One closely resembling their best fit is plotted in Figure 4 along with a black body curve for 3500 °K.

VI. DISCUSSION

It is encouraging that the same models that gave a good fit with the observational data in the visual and infrared also fitted in the ultraviolet region.

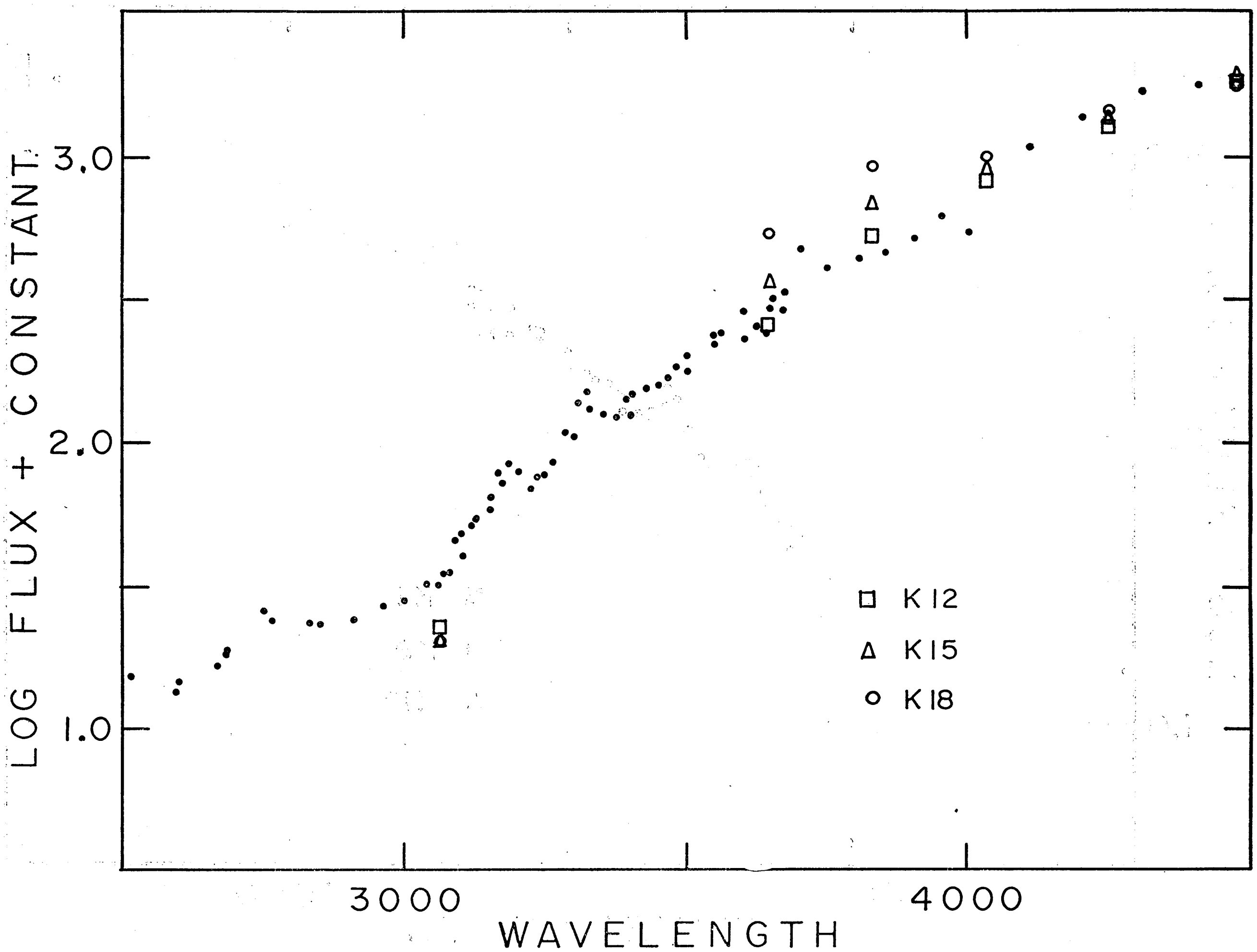

FIG. 3. Effect of decreasing C and O. Symbols for each model are indicated on the figure. C/O is constant but C/H is increased from K12 to K18.

Therefore, the suggestion of the underabundance of C and O in α Ori seems to be strengthened because the models agree in a wider range of the spectrum even when these models use crude approximations to both molecular and atomic opacities.

Although a temperature of 3500 °K was adopted for the atmospheric models, better measurements of the angular diameter would provide more accurate temperatures and thus enable a more realistic comparison. The determination of the temperature is complicated due to the fact that Betelgeuse is a variable star. Several measurements of its angular diameter have been made, but even with the recent interferometric techniques the diameter obtained is still uncertain. As FJ assert, "the changes in the angular diameter are perhaps produced by variations in the light emitted by a circumstellar shell of gas and dust". This shell seems to be coexisting with a chromosphere as suggested by the existence of the helium λ10830 line. Doherty (1972) attributed the emission line Mg II λ2800 and the existence of the bump near 3180 Å (which is due presumably to Fe II) to the chromosphere. Both features can be distinguished in the figures.

To avoid the effects of the variability of α Ori, Johnson (1975) observed this star simultaneously in

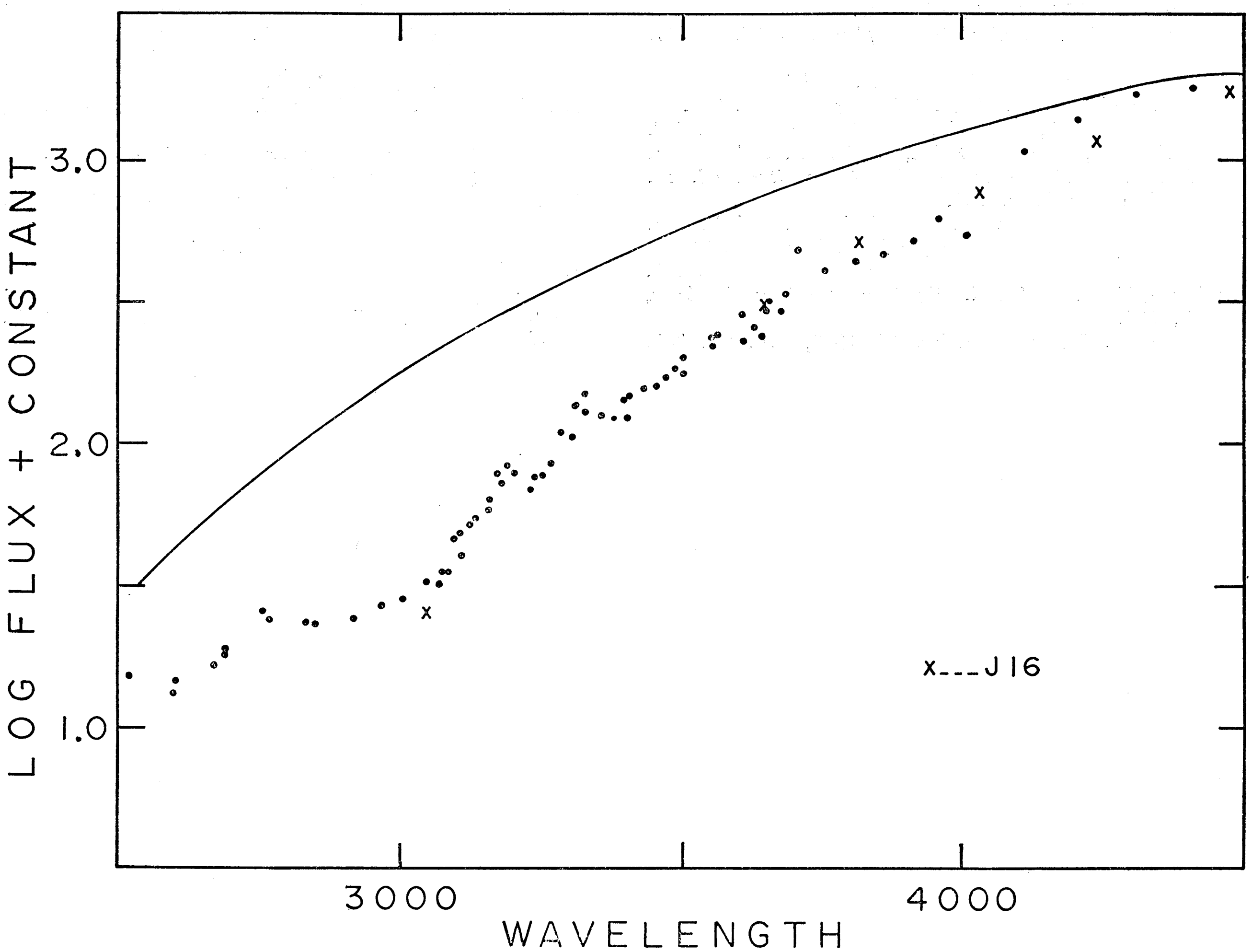

FIG. 4. Model J16 and a "black body" curve for an effective temperature of 3500°K.

the wavelength region from 3500 Å to 3.5 microns from three observing stations. A more extensive data on the energy distribution is expected to be available soon and thus enable a more reliable comparison of observations with models.

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REFERENCES

Alexander, D., and Johnson, H. R. 1972, *Ap. J.*, **176**, 617.

Beer, R., Hutchinson, R., Norton, R., and Lambert, D. 1972, *Ap. J.*, **172**, 89.

Bless, R. C., and Savage, B. D. 1972, *Ap. J.*, **171**, 293.

Carbon, D. F., and Gingerich, O. 1969, *Theory and Observation of Normal Stellar Atmospheres*, "Proceedings of the Third Harvard-Smithsonian Conference on Stellar Atmospheres", ed. O. Gingerich (Cambridge: M.I.T. Press), p. 377.

Code A. D. 1960, *Stellar Atmospheres*, ed. J. L. Greenstein (Chicago: University of Chicago Press), p. 50.

Code, A. D. 1975, private communication.

Code, A. D., Davis, J., Bless, R. C., and Hanbury-Brown, R. 1974, *Wisconsin Astrophysics*, No. **2**.

Code, A. D., Houck, T. E., McNall, J. F., Bless, R. C., and Lillie, C. F. 1970, *Ap. J.*, **161**, 377.

Doherty, L. 1972, *Ap. J.*, **178**, 727.
Doherty, L. 1972, *Stellar Chromospheres*, NASA SP-317, p. 99.
Fäy, T. and Honeycutt, K. 1972, *A. J.* **77**, 29.
Fäy, T., and Johnson, H. R. 1973, *Ap. J.*, **181**, 851.
Gillet, F., Low, F., and Stein, W. 1968, *Ap. J.*, **154**, 677.
Gingerich, O., Latham, D. W., Linsky, J., and Kumar, S.S. 1966, *Colloquium on Late-Type Stars*, ed. M. Hack (Trieste), p. 291.
Gingerich, O., Latham, D. W., Linsky, J., and Kumar, S. S. 1967, *Smithsonian Astrophysical Observatory, Special Report 240*, "Model Atmospheres for Late-Type Stars".
Johnson, H. L. 1964, *Bol. Obs. Tonantzintla y Tacubaya*, **3**, 305.
Johnson, H. L., and Mendez, M. 1970, *A.J.*, **75**, 785.
Johnson, H. R. 1973, *NCAR Technical Note, "Model Atmospheres for Cool Stars"*, NCAR-TN/STR-9S.
Johnson, H. R. 1975, private communication.
Lambert, D. 1968, *M.N.R.A.S.*, **138**, 143.
Mutschlecner, P., and Keller, C. 1970, Solar Physics, **14**, 294.
Tsuji, T. 1966, *Colloquium on Late-Type Stars*, ed. M. Hack, (Trieste), p. 260.
Vardya, M. 1966, *Colloquium on Late-Type Stars*, ed. M. Hack, (Trieste), p. 242.
Weymann, R. 1962, *Ap. J.*, **136**, 844.
Wing, R. 1967, Ph. D. Thesis, University of California-Berkeley.
Woolf, N., Schwarzschild, M., and Rose, W. 1964, *Ap. J.*, **140**, 833.