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TEN MICRON PHOTOMETRY OF 25 STARS FROM B8 TO M7*

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ABSTRACT

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A photometer employing a liquid hydrogen-cooled mercury-doped germanium photoconductor whose spectral response is limited to the 8 - 14 μ region by a low pass interference filter and a BaF_2 window coupled with the cell's threshold wavelength has been placed at the east arm Cassegrain focus of the 200 inch Hale telescope.

Twenty-five stars have been measured. The earliest star for which two measurements have been obtained is the B8Ia star β Orionis. The latest star is the M7e star χ Cygni. The brightest star, 1.37×10^{-14} watts/cm^2 , is α Orionis. The carbon star DS Peg was also measured. In a two-color diagram formed with B and V there is an intrinsic increase in dispersion going to later type stars and a systematic trend away from the blackbody relation. The ratios of the stellar fluxes to those expected from blackbodies of the published stellar effective-temperatures and angular diameters are not far from one. A systematic trend exhibited may not be real because of the assumptions involved in interferometric diameter determinations. DS Peg does not appear overly peculiar in the two-color plots, but χ Cygni falls on the opposite side of the blackbody curve ("blue excess") compared with most of the late type stars.

The fluxes presented here have not been corrected for presently - uncertain telescope transmission losses which may be important.

I. INTRODUCTION

In a now classic paper, Coblentz (1914) reported the results of the first attempt to measure stellar radiation at all wavelengths observable from the surface of the earth, using the 36 inch Crosley reflector of the Lick Observatory. He later extended these efforts with the 40 inch reflector of the Lowell Observatory (Coblentz, 1922). He reported the detection of some small amount of radiation which he believed to be of wavelength in excess of 4 μ . Neglecting the doubt that filter transmission was known with sufficient precision to insure against a shorter wavelength leak, the 8 - 14 μ radiation would have been swamped by the atmospheric transmission of radiation between 4 and 5 μ .

The most extensive work in stellar radiometry was done with the 100 inch telescope at the Mount Wilson Observatory by Pettit and Nicholson (1928). It is the basis for what is still the most widely used bolometric-correction and effective-temperature scale (Kuiper, 1938), exclusive of very early stars (Popper, 1959).

All such early observations of infrared radiation were made with thermal detectors operated at ambient temperature. In addition to possessing very low responsivities, these devices are subject to the statistical photon noise of the total radiation emanating from 4π steradians of 300°K radiation, together with the real thermal fluctuations in the conductive as well as radiative energy-exchange coupling to their environment.

In the last 10 to 15 years the long-wavelength threshold in the

response of quantum detectors, in particular photoconductive and photovoltaic devices, has been extended sufficiently to allow stellar photometry considerable beyond 1 μ . Whitford (1948), Felgett (1951), and Hiltner (Stromgren, 1955) have done extensive work with the lead-sulfide cell. Johnson (1962) has established a four band infrared color system with effective-wavelengths at 1.3, 2.2, 3.6, and 5.0 μ , using an indium antimonide cell and bands accurately defined with interference filters.

The present paper reports the measurement of 25 stars from B8 to M7 using a photometer incorporating a liquid-hydrogen-cooled mercury-doped germanium[1] photoconductor sensitive to radiation from 8 - 14 μ . These are the first observations of stars at such a long wavelength. Quantum detectors have not been successfully used for this purpose before and thermal detectors have never possessed sufficient sensitivity, at least in previous modes of operation. [See Westphal, Murray, and Martz (1963) and Murray and Wildey (1963, plus the other paper in this issue hereafter referred to as Paper I.)]

II. THE OBSERVATIONS

The star α Orionis was successfully observed on two nights with the photometer attached to a 19 inch telescope at a 12,800 foot site on the gounds of the University of California's White Mountain Research Station. This observation has already been reported (Murray and Wildey, 1963) and the equipment and observatory described (Murray and Wildey, Paper I; Westphal, Murray, and Martz, 1963).

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[1]Manufactured by Texas Instruments, Inc.

The results presented here were obtained with the same photometer, but attached to the 200 inch telescope of the Palomar Observatory at the east-arm Cassegrain focus. The observations were collected during twilight periods, when the regular night observer was off the telescope, from October 22 to November 5 and December 12-15, 1962. The visual stellar image was focused on a defining aperture of 5.9 seconds-of-arc diameter located in the center of an aluminized diaphragm. Guiding was done through a periscope focused on the aluminized diaphragm. The starlight then entered the photometer through a barium flouride window, whose weak reflection was also of some help in guiding. This diaphragm aperture would be considered too small for ordinary UBV photoelectric photometry except under the best seeing conditions. However, 8 - 14 μ scans across the image of Betelgeuse under conditions of normal seeing were flat-topped and sharp-shouldered, suggesting that seeing may be better in the 8 - 14 μ region than in the visible. The diameter of the diffraction disk was slightly more than 1 sec. of arc.

The responsivity of the cell was calibrated for each run except for two runs where α Orionis, based on its measurement on other nights, was used to establish the absolute power scale. α Orionis was measured every run and its residual was used to obtain a systematic correction for the run. This correction was only applied when it was obvious that all stars measured that night were systematically off, in order not to obtain unwarranted compounding of the primary photometric error.

The formal probable-error of a single observation of α Orionis was computed to be six percent in flux, including, necessarily, random errors arising from not only fundamental sources of noise (Johnson, shot, generation-recombination, photon) but also those arising from non-stationary

fluctuations in sky-and-telescope brightness and from variations in atmospheric extinction, responsivity, and calibration procedure.

Systematic errors which may be present in the power scale presented here are discussed in more detail in Paper I. We estimate that total systematic errors are not in excess of a few tens of percent from the combined effects of systematic errors in the atmospheric extinction model assumed and systematic errors in the calibration procedure arising from non-unity emissivities of the black bodies and from the fact that their radiation is not detected through the telescope so that it may be treated rigorously as equal to that from unknown celestial bodies as far as the effects of parallax, diffraction, and vignetting are concerned. We further recognize the possibility that the present aluminum coatings of the 200 inch telescope mirrors may be too thin to provide the very high reflectivity at 10 μ expected from such surfaces. See the footnote to Table 1 regarding telescope transmission losses.

III. THE REDUCTIONS

The reduction procedure for observations of extended objects is described in detail in Paper I, but it will be given cursory consideration here in order to establish a point of departure for the development of the reduction procedure for point sources.

The signal in microvolts from a celestial blackbody of temperature T which completely fills the focal plane diaphragm aperture, with or with-

out the intervention of the telescope system*, is given by

$$S = R_o \int_{8\mu}^{14\mu} B_\lambda (T)\, S(\lambda)\, e^{-K_\lambda \sec z}\, d\lambda \; ; \qquad (1)$$

where $S(\lambda)$ is a normalized response function which we have measured, $B_\lambda(T)$ is the Planck function at the temperature of the black body, and the exponential term is the atmospheric extinction. The extinction term can be considered to have such a form, where K_λ is the atmospheric absorption-scattering coefficient per unit air mass cm^2 and sec Z is the number of air masses through which the observation is made, providing that it is based on extinction measurements of sufficient wavelength resolution; otherwise it must be considered a general function of λ and sec Z to be determined empirically. In Paper I, an extinction model based on a $(\sec Z)^{\frac{1}{2}}$ law was used. Subsequent measurements at Palomar, however, by Westphal (private communication), though not yet complete, seem to indicate that the wavelength-integrated law for stellar objects obeys, at least on some days:

$$\mathrm{Log}\, \frac{S}{S_o} = -a \sec Z \qquad (2)$$

Where a is very approximately 0.05. This is the law which has been used in the present paper, although we fully recognize that any extinction correction scheme must be considered preliminary at this stage.

Returning to equation 1, the integral has been developed as a one parameter family of curves in the parameter sec Z with T as the independent

*By virtue of the correspondence of the F ratio of the telescope to the F ratio describing the conical field of view of the optically unassisted photometer and ignoring any transmission losses within the telescope.

variable. R_o is determined with the liquid N_2 vs. water-ice calibration by knowing S and entering the curves with $T = 273^o$ and sec Z = 0. The brightness-temperatures of unknown extended sources can thereafter be obtained by entering the curves with $\frac{S}{R_o}$ and sec Z.

With regard to the reduction for stars, development begins by assuming their 8 to 14 μ color-temperature equals their published effective-temperature in order to take best account of the color-dependence of the wavelength-integrated responsivity.

Let S' be the signal a star would yield if it were a uniformly bright disk and greatly overlapped the field of view, and let S^* be the real signal from the star. Then at any sec Z the ratios of these two signals is given by the ratio of the star's real solid angle to the solid angle transformed to object space accepted by the focal plane diaphragm aperture, which we will call Ω^* and Ω_o respectively. Thus

$$\frac{S^*}{S'} = \frac{\Omega^*}{\Omega_o} \tag{3}$$

However S' is given by equation 1. Thus substituting into equation 3 and taking Ω^* under the integral we obtain:

$$S^* = \frac{R_o}{\Omega_o} \int_{8\,\mu}^{14\,\mu} F_\lambda \; S(\lambda) \; e^{-K_\lambda \; \text{Sec } Z} \; d\lambda \tag{4}$$

where F_λ is the monochromatic flux at earth from the star.

Entering our set of curves at Te we multiply S^* by the ratio of the integral for sec Z = 0 to that for sec Z of the observation, which we read from the curves. This number can be put into equation 4 for the case where sec Z = 0 on the right hand side of (4). Thus:

$$S^* \frac{\int_{8\mu}^{14\mu} B_\lambda (Te) \; S(\lambda) \; d\lambda}{\int_{8\mu}^{14\mu} B_\lambda (Te) \; S(\lambda) \; e^{-K_\lambda \sec Z} \; d\lambda} = \frac{R_o}{\Omega_o} \int_{8\mu}^{14\mu} F_\lambda \, S(\lambda) \, d\lambda \quad (5)$$

Without higher wavelength resolution the result cannot be expressed in a form more meaningful than that of a wavelength-averaged monochromatic flux whose effective-wavelength is given by:

$$\lambda e = \frac{\int_{8\mu}^{14\mu} \lambda B_\lambda (T_e) \; S(\lambda) \; d\lambda}{\int_{8\mu}^{14\mu} B_\lambda (T_e) \; S(\lambda) \; d\lambda} \quad (6)$$

which, for a star, has been calculated to be always about 10.2 μ.*
The flux on the right hand side of (5) thus comes out of the integral and the final answer is:

$$\overline{F_\lambda} = \frac{S^* \Omega_o}{R_o} \frac{\int_{8\mu}^{14\mu} B_\lambda (T_e) \; S(\lambda) \; d\lambda}{\int_{8\mu}^{14\mu} \int_{8\mu}^{14\mu} B_\lambda (T_e) \; S(\lambda) \; e^{-K_\lambda \sec Z} \; d\lambda \; S(\varphi) \; d\varphi} \quad (7)$$

We thus see that assumed stellar temperatures serve only in the capacity of determining λ_e and in allowing for the color dependence of the extinction correction. In the present paper an empirical <u>integrated</u> extinction model has been used which is only valid under the assumption that since it was determined using the sun and since all stars have temp-

*In our earlier note (Murray and Wildey, 1963) the number given for λ was 9.7μ . This latter value (9.7) is <u>in</u> fact the <u>median</u> wavelength of $S_\lambda B_\lambda$ (T) and is <u>less</u> identifiable with $\overline{F_\lambda}$ than 10.2 μ . The previous note defines λ_e correctly but the 9.7 μ figure is in error.

eratures so high as to present nearly the same spectrophotometric gradient in the 8 to 14 μ region, they obey the same integrated extinction law. Thus we have used:

$$\overline{F_\lambda} = \frac{S^*_\nu \, d\nu_o \; 10^{a \sec Z}}{R_o \int_{8\,\mu}^{14\,\mu} S(\lambda) \; d\lambda} \tag{8}$$

Equation 7, however, is the general reduction equation with which a unique extinction model will lead to the exact extinction correction for a black body flux emitted at any temperature, and is the one which, hopefully, can be referred to in future work with refined extinction models.

As a matter of interest, the ratio $\overline{F_\lambda} / F_{\lambda_e}$ has been computed for a 3200° blackbody and been found to be 0.96 ± 0.02 m. e.

IV. RESULTS

The most significant value of the data will be realized when photometry and spectrophotometry in other regions of the spectrum have been put on an absolute power scale so that the absolute monochromatic fluxes for stars can be constructed over as wide a range and with as high a resolution as possible. It is now possible to do this in the photomultiplier region using the calibration of Willstrop (1960). Overlap between the wavelength responses of photomultipliers and photoconductors may soon obviate the need for an independent absolute calibration in the near infrared. Much of the rocket ultraviolet stellar photometry

is already on an absolute scale. This kind of approach is also needed to put the bolometric-correction scale on a sound basis, though the present observations are at too long a wavelength to be very important for this part of astronomy. In the meantime the present data can be presented in several ways that are of interest.

Table 1 shows the results for the stars measured in the present study. Column three gives the formal probable error from all the measurements of each star. A blank indicates that the star was measured only once. The spectral types in column four are from Johnson and Morgan (1953) and the tabulation of Johnson (1962).

Figure 1 shows a color-color diagram where B-V is plotted against $V + 2.5 \log \overline{F_\lambda}\, 10^{16}$. V and B-V are from Johnson and Morgan (1953) and from an unpublished side program of bright star UBV photoelectric photometry incorporated in a lunar photometry program (Wildey and Pohn, in preparation). Stars measured only once have not been plotted. Also plotted is a blackbody curve normalized to pass through α Lyr. B-V was taken from Arp (1961). The other color ($V+2.5 \log \overline{F_\lambda}\, 10^{16}$) was the one normalized and was computed assuming monochromatic magnitudes at effective-wavelengths of 5540A and 10.2 μ. The stars appear to fall on the blackbody curves from earliest type through F. Beginning at K the scatter about the blackbody curve increases together with a systematic trend downward. The latest star in the plot, however, falls above the curve. This is the Mira variable χ Cygni. The carbon star DS Peg does not depart noticeably from the general trend of normal late type stars.

In Figure ~~two~~ 2 is displayed the color-color diagram of Johnson's K-L (1962) versus $L + 2.5 \log \overline{F_\lambda}\, 10^{16}$. Again stars measured only once

TABLE 1

STAR	$F_\lambda \times 10^{-16} \frac{watts}{cm^2 \mu}$	P.E.*	Sp
α Ori	137	1.8 %	M2M3Iab
ρ Per	13.1	6.8	
α Tau	27.8	2.8	K5 III
δ Tau	1.44	4.1	KO III
α CMa	6.24	4.1	A1 V
ι Aur	6.60		
α Aur	10.50	0.7	G8 III+F
μ UMa	4.60	6.6	MO III
α UMa	3.49	7.6	KO III
α Cmi	4.03	2.9	F5 IV-V
α Ceti	7.60		M2 III
α Per	1.67	14.9	F5 Ib
β Gem	6.11	1.4	KO III
β Ori	1.76	0.4	B8 Ia
α Lyr	1.88	1.6	AO V
γ Dra	5.54	18.5	K5 III
α Her	37.6		
χ Cyg	45.2	0.2	M7 e
η Ori	3.8		B2 III
ε Aur	7.2		
α Leo	4.1		B7 V
DSPeg	3.20	3.7	C6 3
RLyr	13.8	9.8	
δ Lyr	6.34	5.3	
μ Cep	3.67	13.4	M2 Ia

*These error values are relative only. The above fluxes have not been corrected for the telescope transmission losses inasmuch as the considerations involved in a complete correction factor are not settled at the present time. This correction factor can range from 1.23 for the case of thick fresh aluminum coatings, to more than 2.0 (!) for older aluminizations of low thickness possibly present in the optics of the 200 inch telescope.

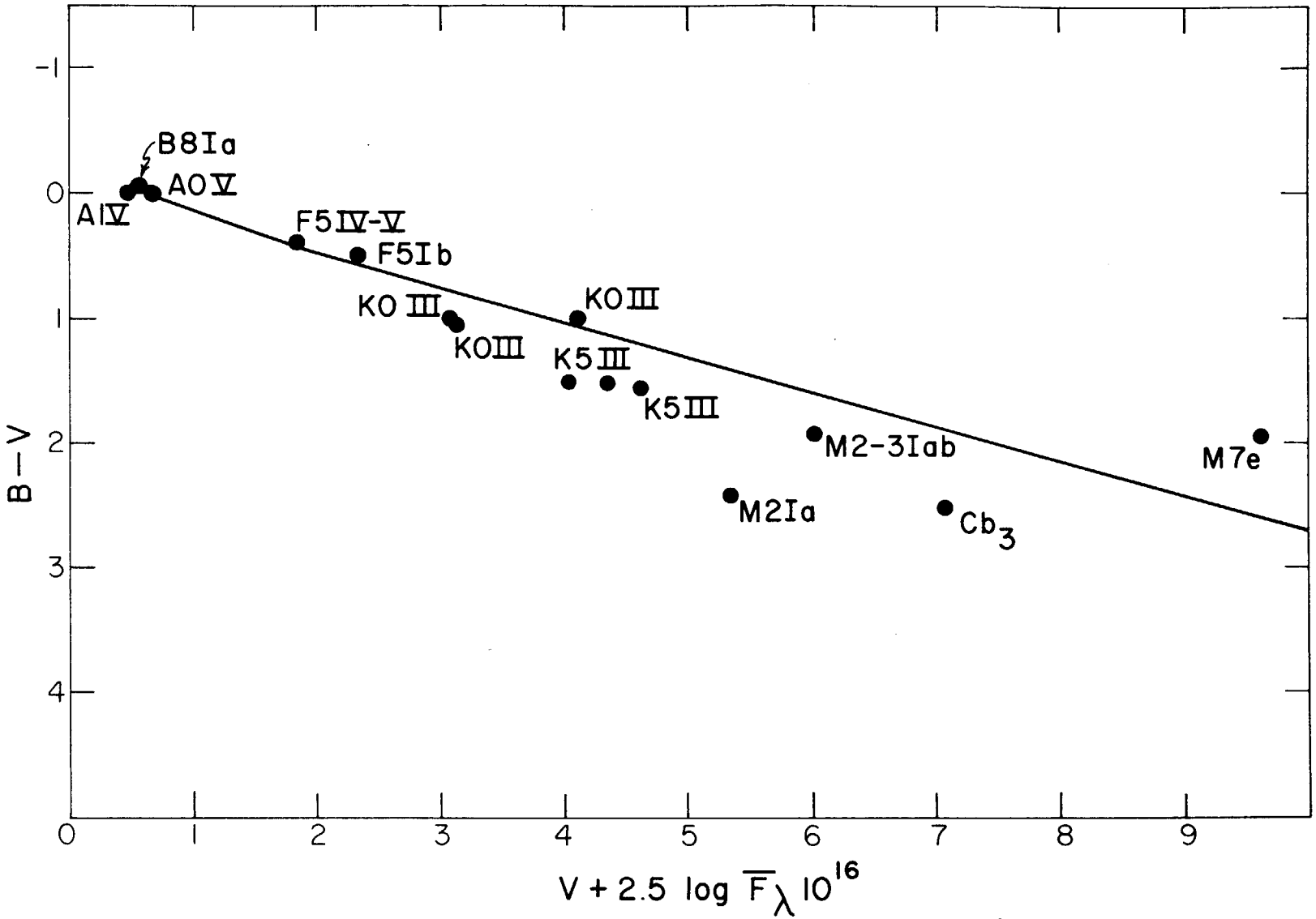

Figure 1. Two color diagram of Johnson B-V vs. $V + 2.5 \log \overline{F}_\lambda 10^{16}$ where $\overline{F}_\lambda$ is the observed average 8 - 14 μ flux in watts/cm^2/μ. A blackbody curve arbitrarily normalized to Lyr is shown for comparison.

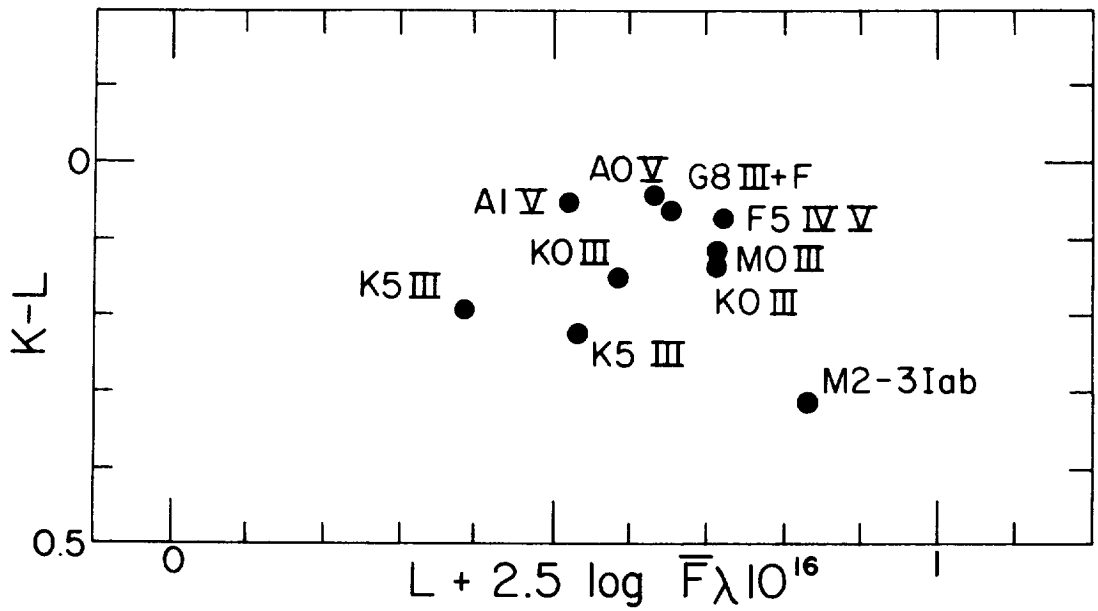

Figure 2. Two color diagram of Johnson's near infrared K - L vs. L + 2.5 log $\overline{F_\lambda}$ 10^{16}.

have not been plotted. A fairly systematic trend is exhibited from earliest type through F, but beyond this there appears what honesty demands be termed a scatter diagram.

In Figure ~~three~~ 3 we have plotted the ratio of the measured flux from each star to the flux expected from a blackbody possessing that stars published diameter and effective-temperature. It should be pointed out that the latter two parameters are not measured independently. The open circle represents α Ceti, which was measured only once and yields a relatively weak infrared signal. The three late type stars have individual effective-temperatures and interferometer diameters (Pease) published by Pettit and Nicholson (1928). The early star is Sirius whose diameter was obtained by quantum interferometry by Hanbury Brown and Twiss (1956) from which the effective-temperature was calculated by Popper (1959). There may be a systematic trend from deficit to excess of flux as one goes to lower temperatures.

V. DISCUSSION

The first thing which is striking is the disagreement between the fluxes for α Orionis as measured at Palomar and at White Mountain which amounts to about a factor of three even if the same extinction models are used. If the star is assumed to behave nearly like a blackbody such a variation in flux so far out on the foot of the Plank function implies a huge temperature variation, approximately from 1600° to about 3500°. Extensive efforts to vitiate this by searching for errors in the reduction and the measurement of parameters related thereto, and also by making

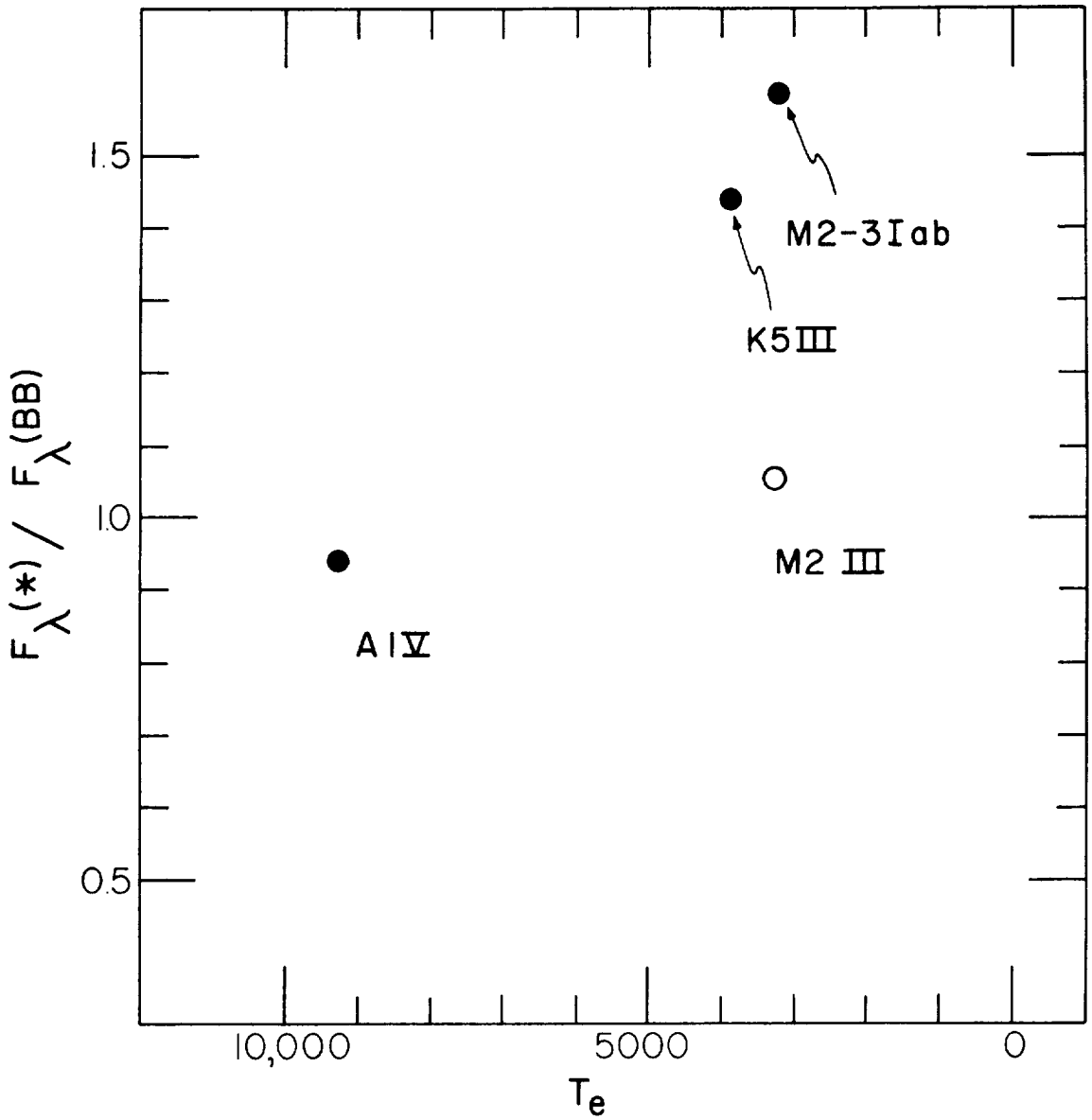

Figure 3. Comparison of measured stellar 8 - 14μ flux to that expected from a blackbody. The diameter and effective temperature of the blackbody is taken in each case to be the published value of the corresponding star.

reasonable adjustments of atmospheric extinction have been fruitless. Neither can the difference be explained by the spilling of light out of the focal plane aperture due to either seeing or diffraction. Preliminary reduction of Jovian brightness-temperature measurements at Palomar yield a result in reasonable agreement with the White Mountain data making it difficult for the α Ori discrepancy to be explained by differences in atmospheric or telescope transmission losses. Betelgeuse was not measured during the December run at Palomar so that any possible variation between November and December has gone unrecorded.

The greater scatter of the late type stars relative to the early types in Figure 1 appears to be real because in general the early types gave the weaker signals. One can think of the scatter as arising from at least two causes: (1) Since these stars are giants they are farther away and are suffering from variable amounts of reddening, or, (2) The later stars actually constitute a more heterogeneous group and exhibit greater dispersion due to the atmospheric effects of differences in age and chemical composition.

The first possibility requires that the interstellar absorption at 10 μ not be negligible relative to that at 5500A because only in this way will the reddening trajectories be significantly non-coincident with the intrinsic unreddened blackbody two-color relation. Such a scattering law is not suggested by current ideas regarding the interstellar medium (Dufey, 1957, page 213).

With regard to the second possibility, in the case of the early stars the tightness of the plot can be made reasonable. It seems likely that we do not look into atmospheric layers where the temperature is low

enough for extreme wavelength - and - temperature sensitive forms of 8 - 14 μ opacity such as those arising from molecular transitions to be significant. It is thus expected that the opacity will be primarily due to free - free transitions of H^- or H II. In the long wavelength limit the stimulated emission term will be nearly as large as the positive absorption term. The overall absorption will go as λ^2. Thus the longer the wavelength the higher the absorption coefficient and the narrower the temperature range of the contributing atmospheric layers. One should thus obtain as good a blackbody as one can have as long as the assumption of local-thermodynamic-equilibrium remains valid for these outermost layers. The departures from LTE for 10 Lacertae, computed by Traving (1957), are sufficiently small at sufficiently shallow mean optical depths, even for bound-free transitions of hydrogen, as to suggest that blackbody surface emission is a reasonable corrollary of high infrared opacity.

The molecular species which may be populating the cool, tenuous, outermost layers of giant late-type stars is, however, not a subject upon which narrow theoretical restrictions can be placed. Considering also the possibility that high altitude stratifaction effects in these atmospheres may be important, an 8 - 14 μ opacity that is strongly sensitive to chemical composition, temperature, and surface gravity (hence initial chemical composition, mass, and age) is not a priori unreasonable. Limber (1958) has suggested that water bands might be present in the infrared spectra of these stars. These considerations suggest a basis for the dispersion of late type stars in Figures 1 and 2, and possibly also the variation of the 10 μ flux of Betelgeuse, but in the case of

Figure 1, B-V can certainly be the source of dispersion for late type stars.

The systematic trend exhibited in Figure 3 may be due to the spectral-type dependence of the systematic error in the assumed limb-darkening coefficient used in the reduction of the interferometry. Agreement would be approached by an increase of the coefficient for late types and a decrease for the early type. In any case, the observations suggest that 8 - 14 μ stellar radiation is only of thermal origin.

The original contribution of Mr. James A. Westphal to the design and development of the specialized instrumentation used in this investigation and his assistance in gathering some of the observations have been of inestimable value. The observing assistance of Messrs Dowell Martz, Ralph Wilson, Howard Pohn, Kenneth Watson, and Dr. Gerry Neugebauer is gratefully acknowledged. We wish to express particular thanks to the Mount Wilson and Palomar Observatories for permission to use the 200 inch telescope, and for continued help and encouragement. It is a pleasure to thank Dr. R. P. Kraft and Dr. J. B. Oke for critical readings of the manuscript. This research has been supported by the National Aeronautics and Space Administration under Grant NsG 56-60 and by the National Science Foundation under Grant G-25210.

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