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NARROW-BAND PHOTOMETRY IN THE 1-4 μm REGION: CALIBRATION AND APPLICATIONS

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RESUMEN

La técnica de fotometría de banda angosta tiene la ventaja importante de que puede proveer información fotométrica y espectroscópica simultáneamente. De 1 μm en adelante la calibración absoluta de la fotometría, que es necesaria para determinar las distribuciones de energía y las temperaturas de color de estrellas frías, ha estado basada generalmente en distribuciones de energía teóricas. Un programa en progreso en el Observatorio Nacional de Kitt Peak está proveyendo mediciones directas de flujos absolutos y monocromáticos en un grupo de estrellas estándar en 13 longitudes de onda. Las temperaturas de color basadas en medidas de banda angosta entre 1.04 y 4.00 μm son especialmente apropiadas para estrellas muy frías y corresponden bien a la nueva escala de temperatura efectiva establecida por medio de observaciones de ocultaciones lunares. Entre las características espectrales que pueden ser medidas con fotometría de banda angosta en la región de 1-4 μm están incluidas las bandas de CO, CN, C_2, OH, H_2O, y SiO. Estas ofrecen la posibilidad de determinar, a partir de datos infrarrojos solamente, clasificaciones espectrales bidimensionales para estrellas de tipos tardíos.

ABSTRACT

The technique of narrow-band photometry has the important advantage that it can provide both photometric and spectroscopic information. Longward of 1 μm, the absolute calibration of the photometry, which is needed for the determination of the energy distributions and color temperatures of cool stars, has generally been based on theoretical energy distributions, but a program now in progress at Kitt Peak National Observatory is providing direct measurements of absolute monochromatic fluxes in a set of standard stars at 13 wavelengths. Color temperatures from narrow band measurements at 1.04 and 4.00 μm are especially well suited for very cool stars and are in good agreement with the new effective temperature scale established from lunar occultation observations. Spectral features that can be measured by narrow-band photometry in the 1-4 μm region include bands of CO, CN, C_2, OH, H_2O, and SiO, and they offer the possibility of determining two-dimensional spectral classfications for late-type stars from infrared data alone.

Key words: STARS-COOL – INFRARED-SPECTRA

I. TECHNIQUES

A wide variety of techniques have been used to study the radiation emitted by stars in the infrared. Those in current use range from wide-band photometry, in which all the radiation within an entire atmospheric window is represented by a single number, to Fourier-transform spectroscopy, which can have resolution great enough to reveal extremely weak atomic and molecular lines. Both techniques have played important roles in the recent development of infrared astrophysics and will continue to do so, but neither is self-sufficient. Wide-band photometry has provided a large part of our current knowledge of the temperatures and bolometric magnitudes of cool stars and the dust shells that often surround them, but its spectroscopic applications are restricted to the crudest classifications: one can, for example, distinguish a carbon star from an M star by *JHK* photometry. High-resolution spectroscopy of molecular features has given us abundance information on the elements C, N, and O and their isotopes in the photospheres of cool stars as well as velocity information in the extended, dynamic atmospheres of late-type variables, but attempts to use such observations to measure colors have usually run into serious calibration problems. In other words, if one tries to use photometry to study stellar spectra or spectroscopy to study magnitudes and colors, the results are usually unsatisfactory.

The technique of narrow-band photometry –by which one makes photometric measurements in carefully-chosen spectral intervals– occupies a middle ground and can provide both photometric and spectroscopic information. With bandpasses of the order of 10-100 A it is possible to measure quantitatively many of the molecular bands that occur in late-type spectra and also to avoid these bands quite effectively for the purpose of measuring the stellar continuum. A cynic might point out that this spectral resolution is too low for spectroscopic analysis, while at the same time the bandpass is too narrow for photometry of faint stars. But we feel that the results that have been obtained by narrow-band photometry speak for themselves. Spectroscopic analysis can be carried out if the photometric indices are interpreted in terms of detailed synthetic spectrum calculations. Photometric applications of narrow-band photometry are indeed limited by photon noise in the case of faint stars, but whenever a sufficient number of photons can be collected, the results are likely to be more accurate than wide-band results because of the ability to avoid telluric absorption bands. Also, narrow-band continuum colors can be interpreted on the basis of synthetic spectra much more easily than wide-band colors which involve radiation from many different atmospheric layers. Although narrow-band photometry is a well-established and frequently-used technique in the visible and near-infrared regions, it has only recently been applied to the infrared. Detectors of sufficient sensitivity in the infrared have been available for some 15 years, but there have been problems in isolating narrow spectral regions for measurement. Interference filters, which can be used to measure indices of molecular band strength and continuum colors, have seldom been employed, mainly because narrow infrared filters that are custom-made to tight specifications are very expensive. Circular variable filters, on the other hand, have been popular, since a single filter can be used to acquire low-resolution spectra. To our knowledge,however, all use of circular variable filters in the infrared has been for scanning continuously over the spectrum rather than integrating at a few selected wavelengths, and therefore their use has been restricted to bright stars.

A scanning spectrometer employing a movable grating and an InSb detector is available for use in the 1-5 μm region at Kitt Peak National Observatory. Such instruments are difficult to build and maintain because, for infrared applications, the grating, as well as the detector must be cooled to reduce the thermal background. The Kitt Peak instrument was originally designed by D. N. B. Hall for eclipse observations in 1973, and it became available for stellar photometry on the 1.3-meter telescope in 1976. Our use of this instrument to study stellar SiO absorption and continuum colors is described later in this paper.

A grating scanner, like a circular-variable-filter photometer, can be used to scan continuously over the spectrum, but this is an inefficient procedure. If one requires complete spectral coverage, better use of the telescope time would be made with a Fourier-transform spectrometer since the same spectrum can be recorded at much higher resolution with this instrument. Often, however, one only needs to know the brightness at a few spectral points. The single-channel grating scanner is a viable research tool if the motion of the grating can be programmed, so that essentially all the time can be spent integrating at the spectral points that are actually needed for analysis. At the present time, a computer-controlled, cooled grating spectrometer appears to be the optimum way to do narrow-band photometry in the infrared, being more flexible than a set of fixed interference filters and easier to calibrate than variable filters or Fourier-transform spectrometers. The situation will change when infrared array detectors come into use, since they will provide an efficient means of recording spectra that can be photometrically calibrated.

The techniques described above have both spectroscopic and photometric applications. We will first briefly consider, in § II, the spectroscopic applications of narrow-band photometry, which include both continuous scans of spectral regions and the measurement of photometric indices of individual spectral features. However, since these spectroscopic applications have recently been reviewed elsewhere (Wing 1979*a*), most of the present review will deal with photometric applications –i.e. the measurement of narrow-band magnitudes and colors. Since the absolute calibration of the photometry plays an important role in the interpretation of the observed colors, we describe in § III a current program of absolute flux measurements in the infrared. In § IV we discuss the colors of late-type giants at narrow-band continuum points in the infrared, interpreted on the basis of synthetic spectra, and in § V we offer some suggestions for further applications of infrared narrow-band photometry.

II. SPECTROSCOPIC APPLICATIONS

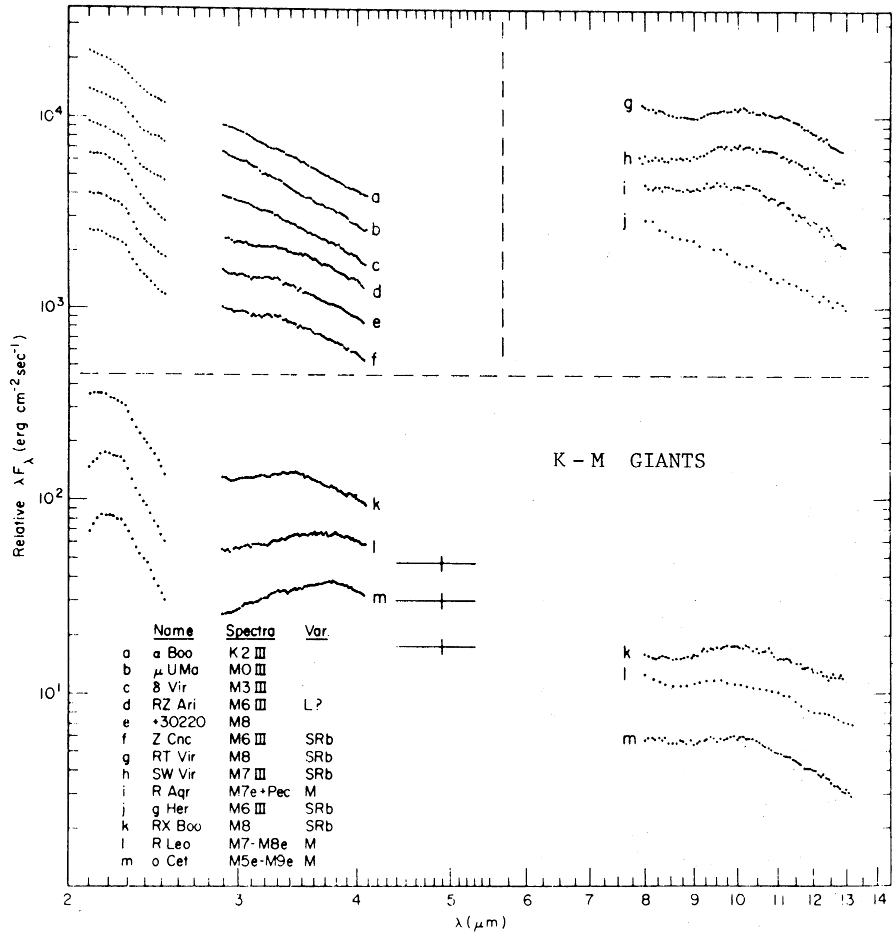
Spectrometers employing circular variable filters with resolutions on the order of $\lambda/\Delta\lambda = 50$ to 100 have been responsible for much of the exploratory work on the infrared spectra of cool stars and infrared sources. This resolution is appropriate for detecting the stronger molecular absorptions that occur in cool stars and studying the shape of the broad emission feature near 10 μm produced by circumstellar grains. Since this work –as well as spectroscopy at higher resolution– has recently been reviewed by Merrill and Ridgway (1979), the present discussion will be limited to a few examples that illustrate the capabilities of the technique.

The cooled-filter-wheel spectrometers described by Gillett and Forrest (1973) have furnished ground-based spectra of numerous objects in the 2-4 μm and 8-13 μm spectral interval (e.g. Forrest, Gillett, and Stein 1975;

Ierrill and Stein 1976*a,b,c*). Examples from the work of Ierrill and Stein (1976*a*), at a resolution of $\lambda/\Delta\lambda = 65$, are hown in Figure 1. In the 2-4 μm region, the only absorption features that can be seen in these normal K and M iants are the (2,0) rotation-vibration band of CO at .3 μm and the broad H_2O depression extending from .3 to 3.7 μm in the cooler stars. Note that there is no vidence, at this resolution, for absorption by the SiO ands near 4 μm.

Similar spectra of cool carbon stars have been ublished by Merrill and Stein (1976*a,b*) and Noguchi *et l.* (1977). Their most noteworthy features are a deep, road absorption band centered at 3.1 μm and, in some ases, a weaker broad feature centered at 3.9 μm. Iigh-resolution observations have shown that the former produced by numerous bands of HCN and C_2H_2 Ridgway, Carbon, and Hall 1978) and the latter at least n part by CS (Ridgway, Hall, and Carbon 1977; Merrill nd Ridgway 1979). With a grating scanner, or with interference filters, it would be feasible to measure the strengths of these interesting features in large numbers of carbon stars by observing them at just a small number of wavelegths. Some such measures of the 3.1 μm band have, in fact, been made by Fäy and Ridgway (1976).

More complete coverage of the infrared spectrum has been obtained by flying similar circular-variable-filter photometers at high altitudes in NASA's Kuiper Airborne Observatory and Lear Jet Observatory. The spectra of Mira variables obtained by Strecker, Erickson, and Witteborn (1978) and shown in Figure 2 are good examples of these results; since these aircraft fly above essentially all the H_2O in the earth's atmosphere (although not completely above some other absorbers), the spectral coverage is nearly complete from 1.2 to 4.2 μm, and the shapes of the stellar H_2O bands are clearly shown. Again, however, the resolution is too low to reveal the 4 μm bands of SiO. Other airborne results include studies of carbon stars (Goebel *et al.* 1980,



ig. 1. Examples of ground-based infrared spectra, obtained with a circular-variable-filter photometer ar resolution $\lambda/\Delta\lambda = 65$. In these ormal K and M giants, the first-overtone CO band at 2.3 μm is most visible in the relatively early types, while the broad wings of the 2.6 m H_2O band are strongest in the latest types. Gaps in the spectra correspond to regions of low atmospheric transparency. From Merrill nd Stein (1976*a*). Courtesy of the *Publications* of the Astronomical Society of the Pacific.

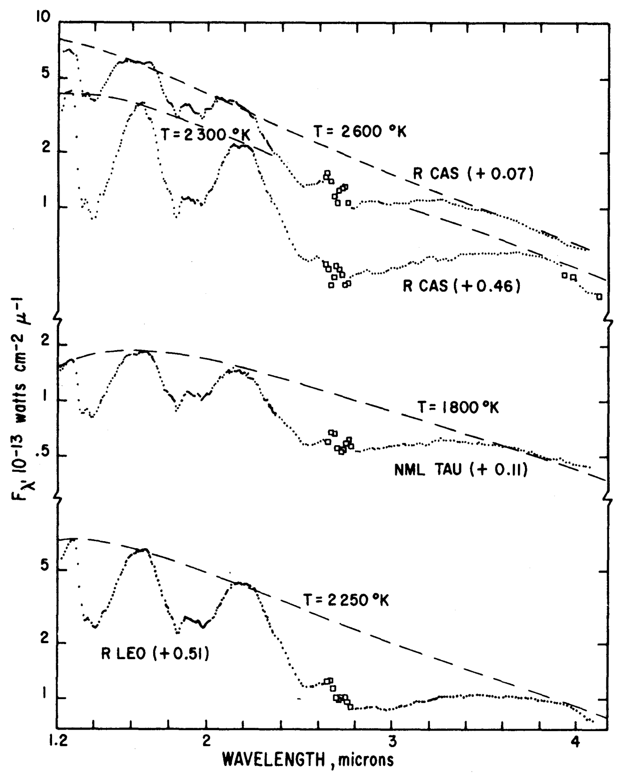


Fig. 2. Airborne spectra of Mira variable from 1.2 to 4.1 μm, showing the shapes of the stellar H_2O bands which account for nearly all the absorption visible at this resolution. A circular variable filter with resolution $\lambda/\Delta\lambda = 70$ was used. From Strecker, Erickson, and Witteborn (1978).Courtesy of the *Astronomical Journal.*

1981), the more recent of which presents evidence for numerous bands of the polyatomic molecules HCN and C_2H_2 in the spectrum of V CrB, a cool carbon Mira variable.

The spectral segment from 3.98 to 4.07 μm, which contains the first-overtone bands of SiO, has been scanned at higher resolution in a sample of 77 late-type stars (Wing, Rinsland, and Joyce 1977; Rinsland 1980). For these observations we used the Kitt Peak grating spectrometer with a bandpass of 5.5 cm^{-1}, corresponding to a resolution $\lambda/\Delta\lambda$ of 450. In the raw data (Figure 3), the SiO bands are clearly seen in late K and M stars, but the shape of the spectrum depends upon the air mass. In Figure 4, the SiO bands are shown in a sequence of giant-star spectra which have been reduced to outside the atmosphere and placed on an absolute flux scale. Here the slopes are independent of the circumstances of the observation and can be compared to blackbody curves. The blackbody continua drawn in Figure 4 are based upon the observed fluxes at 1.04 and 4.00 μm.

Continous scans of stellar spectra are often left on the instrumental system, and in that case one can make use of only the spectroscopic information in the data. To extract the photometric information that is contained in the same data, it is necessary to do additional work and to treat the data as multicolor photometry. If the atmospheric extinction is not a problem, it may be adequate to observe only a single standard star to determine the zero point at each wavelength needed to place the spectra of program stars on an absolute flux scale. This is the procedure generally used, for example in the reduction of airborne spectra (Strecker, Erickson and Witteborn 1979). In the case of ground-based observations, there is a greater need to evaluate the atmospheric extinction and more time to do it; we would then recommend that standard stars be observed throughout the night to provide a direct measurement of extinction and a running check on the stability of the equipment and the transparency of the atmosphere. In the case of our scans of the 4 μm SiO bands, the photometric reduction of the data led to the recognition of strongly wavelength-dependent extinction from pressure-induced transitions of N_2 (Wing and Rinsland 1979). This may well have been the most interesting result from that observing program, and it might have

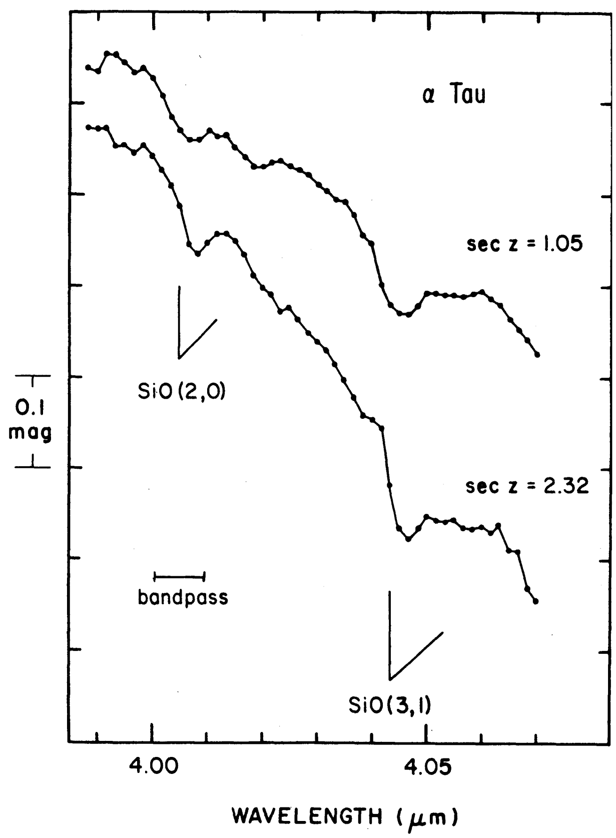


Fig. 3. Unreduced spectral scans of the K giant α Tau at two different air masses, obtained with a grating spectrometer. At this resolution ($\lambda/\Delta\lambda = 450$), the (2,0) and (3,1) bands of SiO are clearly visible. Note that the earth's atmosphere affects the slopes of the spectra. From Wing and Rinsland (1979). Courtesy of the *Astronomical Journal.*

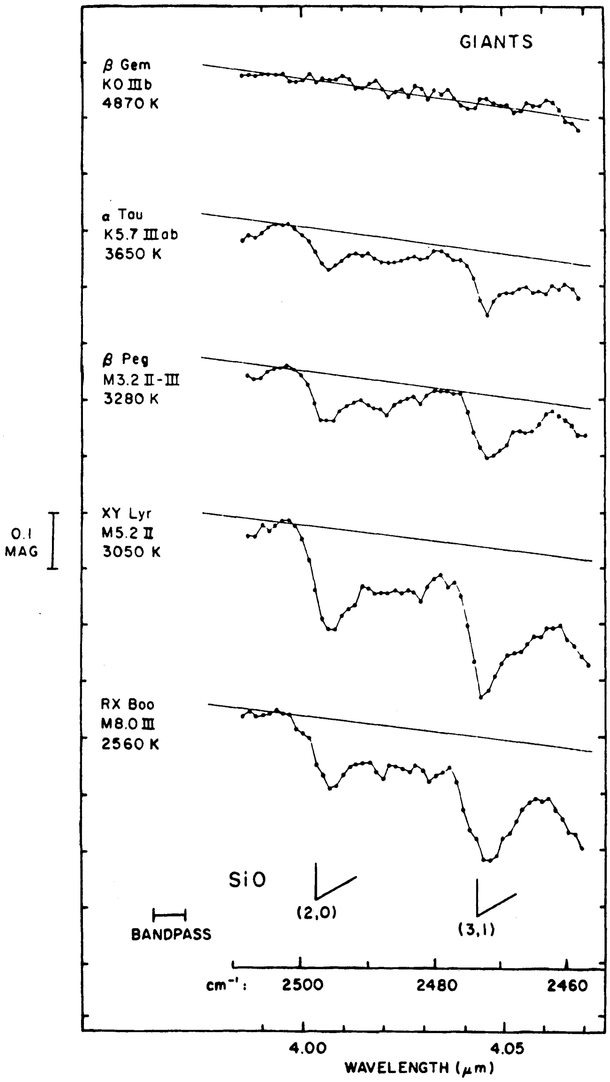


Fig. 4. Spectra of a sequence of K and M giants in the region of the SiO bands. These spectra have been corrected for atmospheric extinction and transformed to an absolute flux scale. The stellar continua are represented by blackbody curves passing through a group of points near 4.00 μm and also through the flux at 1.04 μm. The spectral types based on TiO strength the color temperatures corresponding to the blackbody continua are given below the name of each star.

been overlooked completely if we had only been concerned with measuring SiO equivalent widths.

Narrow-band filters have also been used to measure infrared molecular bands, primarily for classification purposes. Compared to continuous spectral scanning, filter photometry is much more efficient and is likely to lead to more accurate band-strength indices because of the greater ease of observing an adequate number of standards. It is therefore a technique that is well suited to classification programs, once decisions have been made as to the optimum placement of the filters.

In the near infrared, the eight-color system introduced by Wing (1971) provides measurements of TiO, VO, and CN between 0.7 and 1.1 μm. The filters were chosen on the basis of exploratory work with a grating spectrometer (Wing 1967). The molecular band indices derived from this photometry have been calibrated to give two-dimensional spectral classifications that correlate well with the temperature and luminosity classes of the MK system (White and Wing 1978; Wing and White 1978). The magnitudes at the eight filters, when reduced with respect to the standard stars given by Wing (1979*b*), are on an absolute flux scale, and the color temperature T_c (8c) given by the eight-color photometry has been calibrated in terms of effective temperature for K0-M6 giants (Ridgway *et al.* 1980). In stars later than M6 it is not possible to define a very useful color temperature in the near infrared, but the *I(104)* magnitude measured at 1.04 μm remains a good continuum point in even the coolest stars and can usefully be compared to magnitudes measured at longer wavelengths (see §IV). A summary of the classification projects carried out with the eight-color photometry has been given by Wing (1979*a*), together with some suggestions for further applications of the system.

The possibilities for classifying stellar spectra in the 2-4 μm region and the behavior of the various bands that occur there have been reviewed by Wing (1979*a*) and will be mentioned only briefly here. Filter photometry has been used to measures stellar absorption by CO and H_2O in the 2 μm region (Baldwin, Frogel, and Persson 1973; Faÿ and Ridgway 1976; Persson, Aaronson, and Frogel 1977; Cohen, Frogel, and Persson 1978; Pilachowski 1978). Such observations can be used not only for crude classification of individual late-type stars but also to study the stellar component of composite spectra such as globular clusters (Aaronson *et al.* 1978) and galactic nuclei (Frogel *et al.* 1978; Aaronson, Frogel, and Persson 1978).

Other molecular bands in the 2-4 μm region may also be useful for spectral classification but are weaker and must be measured with narrower bands. Two of the molecules being tested by the writers, OH, and SiO, appear to be usable as temperature indicators in M stars (Wing 1979*a*).

III. CALIBRATION OF INFRARED MONOCHROMATIC FLUXES

Measurements of energy distributions of celestial objects are derived from comparisons with standard stars whose energy distributions are known. To be generally useful, the standard stars must be distributed throughout the sky and their flux distributions expressed on a uniform scale of absolute fluxes. In the visible and near-infrared regions, out to the sensitivity limit of photoelectric detectors at 1.1 μm, standard stars such as Vega have been compared directly to calibrated laboratory radiation sources with narrow-band spectrometers (e.g. Hayes 1970; Oke and Schild 1970; Tüg, White, and Lockwood 1977), and other stars distributed about the sky have been compared to the primary standards (e.g. Breger 1976).

No such fundamental measurements of absolute energy distributions have been carried out in the infrared longward of 1.1 μm. The standard wide-band multicolor photometric system has of course been calibrated (Johnson 1966) and has frequently been used to obtain crude absolute energy distributions over a wide wavelength range. This calibration, however, is based upon an assumed energy distribution for Vega rather than actual absolute flux measurements and in any case is not sufficiently detailed for the reduction of spectrophotometric measurements within each atmospheric window. For the latter purpose, it has been common practice to assume blackbody or model-atmosphere energy distributions for particular stars. This procedure –which we have used, for example, for the reduction of our 4 μm SiO scans mentioned in §II, and also to derive the color temperatures discussed in §IV– has been reasonably successful, but it involves two important dangers: (1) if the assumed energy distribution for a standard is incorrect, the entire set of derived energy distributions will contain a systematic error, and (2) the assumptions made by different investigators may not be consistent with each other. In particular there has been some question as to which model atmosphere should be chosen to represent Vega. Lange and Wing (1979) have reviewed the absolute flux measurements of Vega in the visible region and have recommended that the Kurucz (1979) line-blanketed model for $T_{eff} = 9500°$ K, log g = 3.90 be adopted for this star, so that the emitted fluxes calculated from it can be used to place spectrophotometric measurements in various spectral regions (including the infrared) onto a uniform absolute flux scale. Recently, Strecker, Erickson, and Witteborn (1979) have published energy distributions for Vega and 12 other stars from 1.2 to 5.5 μm based on low-resolution scans obtained with airborne circular-variable-filter photometers. This set of fluxes is tied to the model-atmosphere energy distribution for Vega given by Schild, Peterson, and Oke (1971), which in the infrared is consistent with the recommendation of Lange and Wing (1979).

At this time there is a need for both relative and absolute measurements of standard stars in the infrared. With repeated ground-based comparisons of the brightnesses of standard stars in selected narrow infrared bands, it should be possible to improve upon the monochromatic flux differences determined from airborne observations and to enlarge the set of standards. Absolute flux measurements of at least a few standard stars are needed to check the assumptions that have been made about the temperatures and energy distributions of the primary standards. A careful study of the extinction properties of the terrestrial atmosphere is also badly needed; although detailed calculations of atmospheric absorption have been made by Manduca and Bell (1979), actual measurements of extinction with the spectral resolution needed for spectrophotometric reductions are still lacking.

A program is currently in progress at Kitt Peak National Observatory to determine both relative and absolute fluxes in a set of standard stars. In 1979 the writers initiated a program of relative photometry intended to provide accurate monochromatic magnitudes at selected wavelengths in the 1-4 μm range in 47 standard stars uniformly distributed about the sky in an equatorial belt 60° wide. In the same year, Hayes and Ridgway at Kitt Peak acquired a commercial blackbody source with the intention of performing the first direct calibration of infrared photometry. We decided to coordinate the two programs: the absolute measurements are being made with the same instrumentation and in the same 13 wavelength bands that we had chosen for the relative photometry, and the 10 stars being compared directly to the blackbody source are included in our set of 47 standards. The final result of the combined programs will be that the monochromatic fluxes of all 47 stars will be expressed on an absolute scale that is based on direct measurements. Discussions of this project have been presented at IAU Symposium No. 96 in Hawaii (Wing *et al.* 1980) and at the recent meeting of the American Astronomical Society in Albuquerque (Hayes *et al.* 1980).

The measurements for this coordinated program are being made with the Kitt Peak 1.3-meter telescope and a grating spectrometer and InSb detector. The bandpasses are between 30 and 90 A in width and have been selected to avoid hydrogen lines in early-type stars, molecular features in late-type stars, and telluric line absorption. In Figure 5, the spectrum of the G-type giant Hyad ϵ Tau is shown at high resolution in the regions of three of the program bandpasses within the photometric K band. Although a few telluric H_2O lines are included in these bandpasses, their effect is removed satisfactorily by normal photometric reduction procedures; the important point is that these bands are almost entirely free from stellar atomic and molecular absorption lines. It is also important that the regions just outside the bandpasses are also quite clear; because of this, the measured magnitudes are insensitive to the exact bandwidth used and are not subject to errors resulting from small instrumental wavelength shifts. Other program wavelengths range from 1.04 μm to 4.00 μm, a good continuum point just shortward of the SiO (2,0) bandhead, which is particularly useful in the measurement of color temperatures (see §IV). The selection of 1.04 μm as one of our program wavelengths allows direct comparisons of our results with previous measurements (Hayes, Latham, and Hayes 1975).

For the absolute measurements, the blackbody source

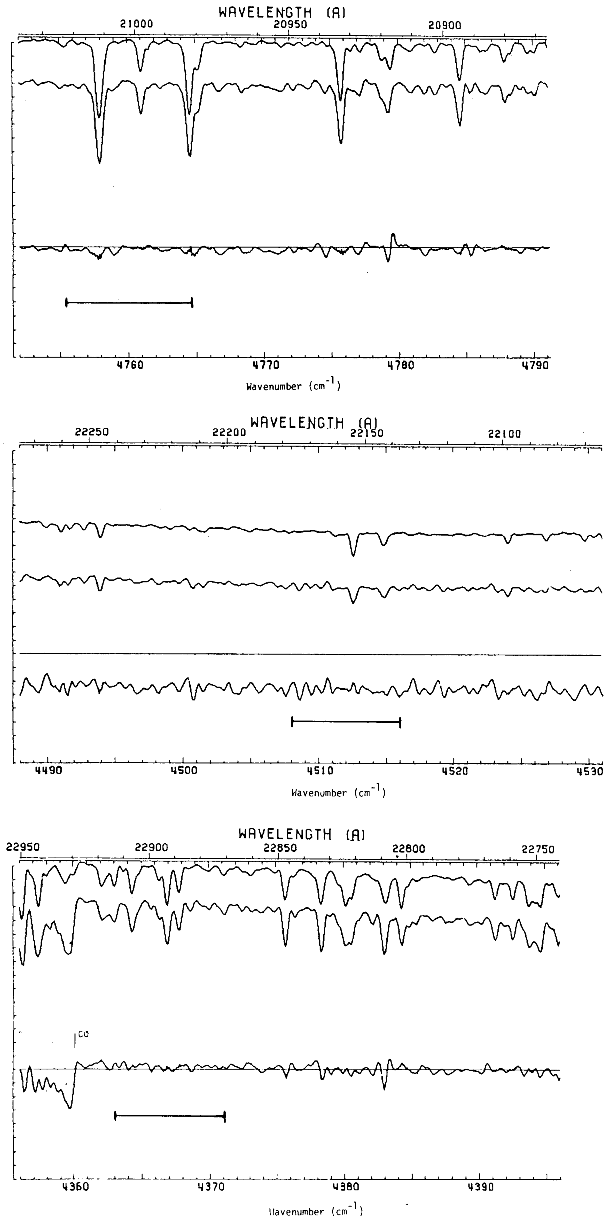


Fig. 5. High-dispersion spectra, obtained with a Fourier-transform spectrometer at Kitt Peak, of the G-Type giant ϵ Tau in the regions of three of the bandpasses on the absolute calibration program: *(a)* the band near 2.10 μm (4760 cm^{-1}), *(b)* the band near 2.21 μm (4512 cm^{-1}), *(c)* the band near 2.28 μm (4367 cm^{-1}). In each case the upper spectrum is of the Sun, the center spectrum is of ϵ Tau as observed, and the lower one is the ratio of the two, in which atmospheric lines have been cancelled out. The positions of the photometric bandpasses are indicated. Note that the band at 2.28 μm is placed just shortward of the (2.0) head of CO.

is mounted on the catwalk of the 4-meter telescope where it can be observed from the 1.3-meter telescope across a distance of 0.5 km. Corrections for the small amount of horizontal extinction at each wavelength will be based on semi-empirical and theoretical relations.

The data obtained to date already show that an acurracy of 1% can be achieved in the relative photometry. There is no reason why infrared magnitudes should not be just as accurate as photoelectric magnitudes at shorter wavelengths, if the same procedures are followed and the main atmospheric absorption bands are avoided. Since we are observing at several different times of year and during the daytime as well as at night, we should be able to eliminate right-ascension effects almost completely. It is more difficult to estimate the errors to be expected in the absolute photometry, but we hope to keep them under 5%. If this accuracy can be achieved, the measurements will be valuable in establishing zero points for comparisons with synthetic colors. The observational data should then provide a meaningful test of the model-atmosphere results; and if the agreement is good, the observed colors can be used in conjuction with model-atmosphere calculations to derive angular diameters and effective temperatures for stars of various types. An important application would be to establish the temperature scale for late-type dwarfs, which is poorly known at present.

IV. COLOR TEMPERATURES OF RED GIANTS

The effective temperature of a star can be determined either from the measurement of its angular diameter and bolometric magnitude or from a comparison of the observed energy distribution with fluxes calculated from model atmospheres. Since these techniques are almost completely independent, an intercomparison of the

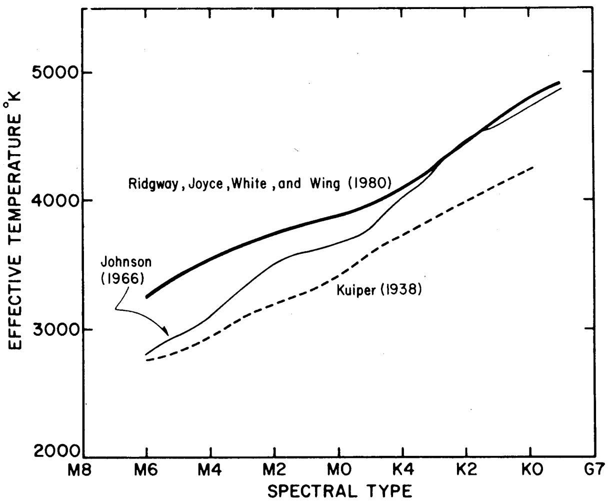


Fig. 6. Comparison of the effective-temperature scale for luminosity class III giants given by Ridgway *et al.* (1980) with older scales by Johnson (1966) and Kuiper (1938). The new scale, which assigns higher effective temperatures to each spectral type, is based entirely upon lunar occultation measurements of angular diameter.

results provides an important consistency check on our knowledge of the stellar temperature scale.

Recently, Ridgway *et al.* (1980) have combined angular diameters from lunar occultations with infrared photometry to derive a revised temperature scale for K0-M6 giants. As we see in Figure 6, this scale assigns systematically higher temperatures to M giant stars than previous calibrations (Kuiper 1938; Johnson 1966; Dyck, Lockwood, and Capps 1974). The new calibration has been given both as a function of spectral type and in terms of the color temperature T_c(8c) measured on the near-infrared eight-color system. Since this scale has been derived with the best empirical data currently available (only determinations of effective temperature with formal errors less than ± 250° K were included), it is important to compare this scale with results based on the model-atmosphere technique.

Several recent studies have compared observations obtained over wide wavelength intervals with model-atmosphere fluxes. Tsuji (1978) derived effective-temperature values for a small sample of M stars by comparing the fluxes computed with his line-blanketed models to spectral scans and wide-band photometry between 0.4 and 5.0 μm. The effective temperatures determined by Tsuji agree very well with values predicted for the same stars by the Ridgway *et al.* (1980) calibration. Continuous scans acquired with the Kuiper Airborne Observatory and NASA Learjet, flying above most of the atmospheric absorption, have also been compared to theoretical spectra. Manduca, Bell, and Gustafsson (1981) have recently compared their model-atmosphere energy distributions to the airborne observations of Strecker, Erickson, and Witteborn (1979), which have resolution $\lambda/\Delta\lambda = 70$ between 1.2 and 5.5 μm. They obtained effective temperatures that agree with the Ridgway *et al.* (1980) scale to within 150°K for the six K and M stars studied. An earlier attempt by Scargle and Strecker (1979), who based their comparisons on the models of Johnson (1974), was less successful, and it is now clear that these early models, which predict very different flux curves than recent models do, should not be used for this purpose.

Although comparisons of model fluxes with observations obtained continuously over a wide range of wavelength provide important information, the great difficulty of acquiring and calibrating the observations has limited detailed comparisons to a few stars. Observations of continuum colors can be used for the same purpose and can be obtained quickly, conveniently, and accurately with a low-resolution scanner or with narrow-bandpass filters. The observed colors can be calibrated in terms of effective temperature with model atmospheres or on the basis of the available direct determinations.

Ideally, any color index used for this purpose should have the following characteristics. The two wavelengths used to form the color index must be widely separated so as to be sensitive to changes in the slope of the energy distribution with respect to temperature. Also, since the spectra of most late-type stars are heavily blanketed in the visible region, the bandpasses should be located in the near-infrared or infrared where continuum regions can be found. Narrow-band measurements are preferable, since even in the infrared, wide-band photometry cannot avoid molecular bands and atomic lines. The difference in the continuous opacities at the two wavelengths should be sufficiently small that the continuous fluxes will both originate in the same range of stellar layers. This will make the color temperatures insensitive to differences in temperature structure caused by composition variations among stars. Color temperatures obtained at wavelengths selected on the basis of these criteria will have values close to the effective temperature, and the remaining differences will be systematic and can be calibrated either with direct measurements (angular diameters and bolometric magnitudes) or with model-atmosphere calculations.

In the 0.7 to 1.1 μm region there are spectral intervals that meet these criteria. Also, this region is accessible to photoelectric detectors and contains the energy maxima of most K and M stars. For stars of spectral types K4 to M6, the eight-color system of Wing (1971) measures continuum points at 0.754 and 1.040 μm with 0.050 μm (50 A)-wide filters. Continuum color temperatures,

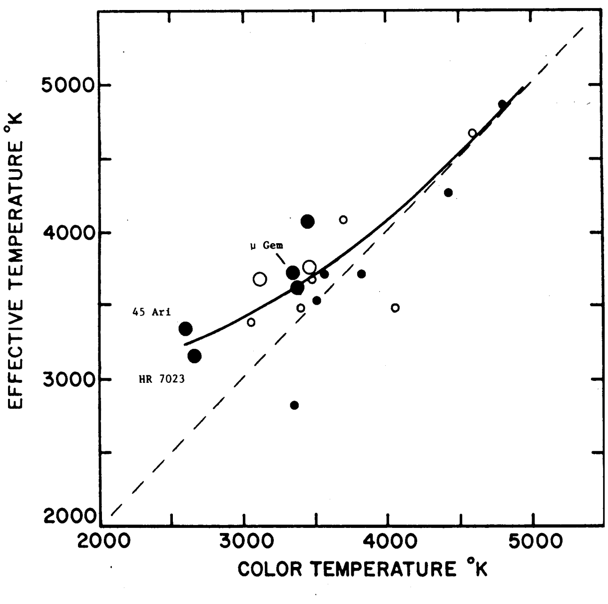


Fig. 7. Effective temperatures based upon lunar occultation measurements (Ridgway *et al.* 1980) plotted against color temperature measured in the near infrared. Large circles represent data with standard errors smaller than 100°K in T_{eff}; filled circles represent stars with two or more independent angular diameter measurements. The solid curve is the adopted calibration. Note that throughout the range of the M stars, the near-infrared color temperatures are lower than the effective temperatures. From Wing and Ridgway (1979). Courtesy of the *Dudley Observatory Reports.*

obtained from blackbody fits to the observed fluxes at these two wavelengths, have been measured for about 2000 stars on this system.

Although the color temperatures from the eight-color photometry agree closely with the new empirical temperature scale for K stars, they are systematically lower than the effective temperatures for M stars (Figure 7). The likely explanation for the discrepancy, which has been discussed by Wing and Ridway (1979), is that there is a source of blanketing in the 0.754 μm bandpass that is present in all M giants and increases moderately in strength from M0 to M6. Recent model-atmosphere calculations indicate that the additional opacity in this region is provided by numerous high-excitation lines of TiO (Piccirillo, Bernat, and Johnson 1981). When the high-J TiO lines are included in synthetic-spectrum calculations, good agreement is obtained for M stars between the model-atmosphere $T_c(8c)$ vs. T_{eff} relation and the empirical calibration of Ridway *et al.* (1980). Although the effective temperatures of normal M stars can thus be estimated quite well from the eight-color photometry by means of this calibration, it is of interest to test color temperatures that use different continuum points to see if any of them are more direct indicators of the effective temperature, especially for the cooler M stars.

Since the *I(104)* magnitude in the 1 μm region is the only good continuum point in late M stars in the near infrared, we are led to consider combining it with measurements at longer wavelengths. Inspection of high-resolution spectra resulted in the selection of four wavelengths for narrow-band photometry with the grating spectrometer at Kitt Peak National Observatory (Rinsland 1980). These continuum points are located within the *J*, *K*, and *L* atmospheric windows at approximately 1.29, 2.10, 2.28, and 4.00 μm. The stellar magnitudes at these wavelengths have been designated *J(129)*, *K(210)*, *K(228)*, and *L(400)*, respectively, and when combined with the *I(104)* magnitude at 1.04 μm they define the color temperatures T_c(*104-129*), T_c(*104-210*), T_c(*104, 228)*, and T_c(*104-400*). The four new bandpasses are also included on the 13-color program of absolute flux measurements described in the preceding section, and as already indicated, they are nearly free of absorption features in stars earlier than about M6 (minor corrections for CN contamination at 2.10 μm were applied). Since the results of the Kitt Peak absolute calibration project are not yet available, we have transformed our photometry to a scale of absolute fluxes on the basis of a model-atmosphere energy distribution for Vega.

For comparison with the observations, emergent fluxes were computed with the line-blanketed, flux-constant model atmospheres of Bell *et al.* (1976*a*) and Johnson, Bernat, and Krupp (1980). The models of Bell *et al.* were calculated with opacity distribution functions for the range 3750°K $\leq T_{eff} \leq$ 5000°K while the Johnson *et al.* grid treated the opacity by the opacity-sampling technique and were computed for 2750°K $\leq T_{eff} \leq$ 4000°K. Since the bandpasses were chosen in regions nearly free of line blanketing, synthetic color temperatures and indices were computed with only continuous opacity sources. The results presented here were obtained with solar-composition models. We did calculate synthetic continuum colors for several metal-poor models from the Bell *et al.* (1976*a*) grid and found that moderate differences in chemical composition will have only a small effect on the continuum color temperatures.

The synthetic color temperatures were found to be strongly wavelength-dependent. The fluxes at 1.29, 2.10, and 2.28 μm, in combination with *I(104)*, give color temperatures that are much lower than the effective temperature, whereas blackbody fits to the continuum fluxes at 1.04 and 4.00 μm yield color temperatures that are much closer to the effective temperature (Rinsland 1980; Wing 1981).

This effect is a consequence of the variation with wavelength of the continuous absorption coefficient in the infrared. In all the models we considered, the dominant continuous opacity source is H^- which has an opacity minimum in the mid-infrared. In Figure 8, the absorption coefficient of H^- is plotted against wavelength for a temperature of 3835°K and an electron pressure of 0.67 dynes cm^{-2}. The bound-free component is largest at 0.85 μm and falls to zero at 1.65 μm.

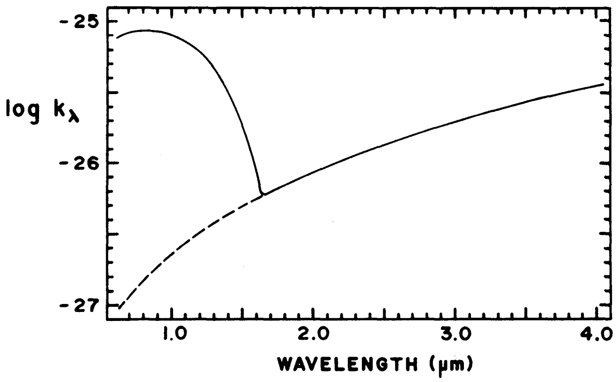


Fig. 8. Absorption coefficient of H^- (in units of cm^{-1} per neutral hydrogen atom) plotted against wavelength for a temperature of 3835°K and an electron pressure of 0.67 dyne cm^{-2}. These conditions correspond approximately to the photosphere in a giant star of effective temperature 3750°K. The solid curve is the total H^- absorption coefficient; shortward of 1.65 μm the free-free component is indicated separately by a dashed line. From Rinsland (1980).

The cross-section for free-free absorption, which increases with wavelength, is less accurately known (John 1979); we have adopted the results of the dipole length calculations of Stilley and Callaway (1970) for this

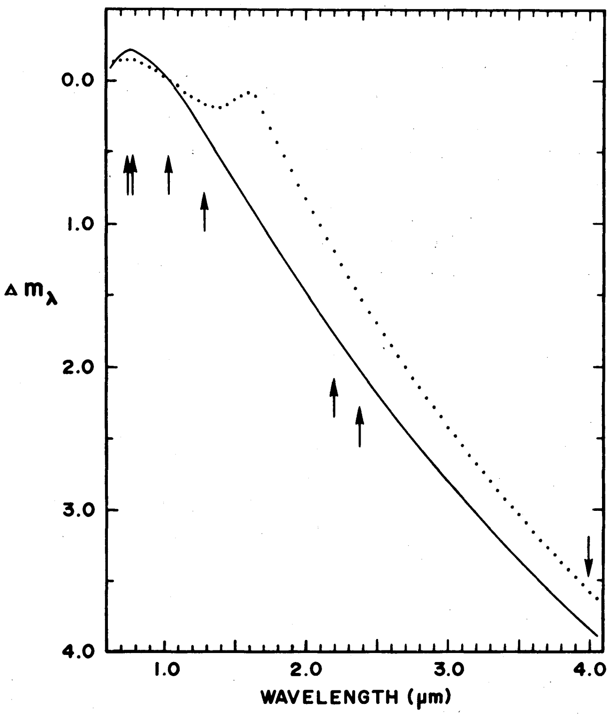


Fig. 9. Comparison of the continuous energy distribution of a Bell *et al.* (1976*a*) solar-composition model atmosphere for $T_{eff} = 3750°K$, log g = 2.25 (*dots*) and a 3750°K blackbody energy distribution (*solid line*). The differences are caused primarily by the wavelength dependence of H^- opacity (see Fig. 8). Arrows indicate the wavelengths of our continuum flux measurements, including three bands of the eight-color system in the near infrared. The curves are normalized to 1.04 μm. From Rinsland (1980).

component. The occurrence of an opacity minimum near 1.65 μm is of course well known, but it may not be sufficiently appreciated that the region of low opacity is very broad. The entire region from about 1.5 to 3.5 μm has significantly lower H^- opacity than does the 1 μm region. The effect of H^- on the shape of the continuous energy distribution is considerable, as can be seen in Figure 9 where the continuum energy distribution from a Bell *et al.* (1976*a*) solar-composition model for $T_{eff} = 3750°K$ and log g = 2.25 is compared to a blackbody curve of the same temperature. Arrows in this figure indicate the wavelengths of our continuum flux measurements.

Color temperatures calculated with the model atmospheres are in good agreement with the observed values for luminosity class II and III stars. The results are illustrated in Figure 10, where color temperatures obtained from the measurements at 2.10 and 4.00 μm, each referred to the flux at 1.04 μm, are plotted against each other. Synthetic values obtained with the grid of Bell *et al.* (1976*a*) are indicated with open symbols while the filled symbols represent color temperatures calculated with the models of Johnson, Bernat, and Krupp (1980). Solid lines connect models with the same valu of log g. The good agreement between the observation (dots and plus signs) and the models verifies that H^- i the dominant infrared continuous opacity source, eve in late M stars. It is also noteworthy that the tw families of models, which used different methods o treating the line opacity, are in excellent agreement wit one another. The large displacement of the observed an calculated colors form the dashed one-to-one line i Figure 10 is entirely the result of lower H^- opacity a 2.10 μm than at either 1.04 or 4.00 μm.

On the other hand, emergent-flux calculation whic include only continuous opacity sources cannot repro duce the rapid decrease in T_c(8c) relative to the othe color temperatures in the coolest stars (Figure 11) Clearly additional opacity must occur within the 0.75 μm bandpass in late M stars, as we noted earlier.

In Figure 12 we have plotted the various colo temperatures –obtained by comparing the flux at 1.0 μm to those at 1.29, 2.10, 2.28, and 4.00 μm– agains the effective temperature. The color temperature computed from models of various effective temperatur show departures from the one-to-one lines caused b opacity differences at the wavelengths involved. It i clear that T_c(*104-400*) is numerically much closer to th

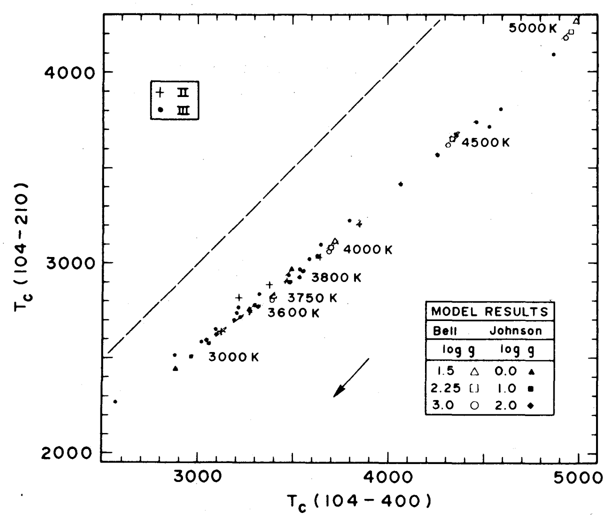


Fig. 10. The relation between two of the color temperature defined by narrow-band continuum points. T_c(*104-210*) is base on measurements at 1.04 and 2.10 μm, while T_c(*104-400*) use the same shortward continuum point but a longward point a 4.00 μm. Observations of normal giant and bright giant stars o types K and M are plotted as *dots* and *plus signs*. Syntheti colors computed from the grid of models by Bell *et al.* (1976*a*) are plotted as open symbols, and those from the grid of Johnso *et al.* (1980) as filled symbols. Lines connect models of the sam surface gravity. Note that the observed and synthetic colors bot define nearly the same relation, and that both are well displace from the dashed one-to-one relation because of the effect of H^- The arrow indicates the approximate slope of the reddening line From Rinsland (1980).

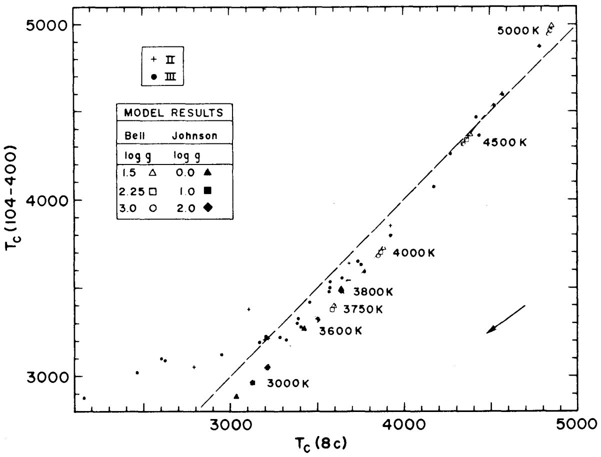


Fig. 11. The color temperature T_c(*104-400*) plotted against the color temperature measured in the near infrared on the eight-color photometric system. Here the observed colors diverge from the synthetic continuum colors, especially at the lower temperatures, because of the effect of TiO on T_c(8c). Lines and symbols have the same meanings as in Fig. 10. From Rinsland (1980).

effective temperature than the other color temperatures are, mainly because the H^- opacity has similar values at 1.04 and 4.00 μm.

Stellar observations are represented in each section of Figure 12 as a solid curve. These were derived by plotting the observed color temperatures against the eight-color color temperatures T_c(8c) for a sequence of giant stars, drawing a mean relation through the observed points, and transforming the relation to a function of effective temperature on the basis of the T_c (8c) – T_{eff} calibration given by Ridgway *et al.* (1980). In each case the curve representing the observations agrees well with the model-atmosphere results. Thus the model-atmosphere calculations confirm the new effective-temperature scale obtained by the occultation technique.

The magnitude at 4.00 μm, which we call *L(400)*, is a particularly useful one to measure in late-type stars. Standard-star magnitudes for this wavelength and a discussion of its applications can be found in Rinsland and Wing (1981). One favorable characteristic of this magnitude, noted above, is the near-equality of the opacity in late-type stars to that in the 1 μm region, so that the color index *I(104)-L(400)* is an excellent indicator of the effective temperature. Another important feature of the magnitude at 4.00 μm, which is well shown in the aircraft spectra of Figure 2, is that it avoids stellar water bands very successfully, so that T_c(*104-400*) remains a useful color temperature in even the coolest M stars. This is important, since these very cool stars are the ones for which the eight-color photometry cannot provide an adequate color index.

Of course, other color temperatures besides T_c(*104-400*) can be calibrated for use as indicators for the effective temperature. However, all other color temperatures that we have tested involve such large opacity differences that they will be sensitive to differences in the atmospheric temperature structure and should therefore be regarded as less desirable temperature indicators. They may, however, be useful for other purposes. As noted by Bell *et al.* (1976*b*), this sensitivity to temperature structure may offer an observational method to study the effect of convective energy transport on the structure of stellar atmospheres.

V. FUTURE APPLICATIONS

The original objective of our observational program with the Kitt Peak infrared grating spectrometer was to study the behavior of the molecular bands of CO, OH, H_2O, SiO, C_2, and CN by making integrations at a relatively small number of wavelengths. A 17-point photometric system (Rinsland, Wing, and Joyce 1977) designed for this purpose was developed for the Kitt Peak scanner. Unfortunately, flexure in the instrument caused wavelength shifts too large to be tolerated, and this program was not carried out.

Recently, several important improvements have been made in the Kitt Peak scanner that make it more stable against wavelength shifts and allow the wavelength scale to be accurately established. The grating is now spring-loaded, and our experience has shown that it can be driven to any wavelength point with satisfactory accuracy. The wavelength scale can be checked while the telescope is pointing to any star by placing a narrow-band filter in the beam and scanning across the bandpass, or by observing sharp features in a polystyrene film, the wavelengths of which have been accurately measured with a Fourier-transform spectrometer. We now feel that the system is stable enough to allow spectral features to be measured by observing at only a small number of wavelength points, rather than scanning continuously. Thus, it should now be possible to carry out our original program in an efficient manner.

Some of the possible spectroscopic applications of narrow-band photometry in the infrared have been discussed by Wing (1979*a*). For classification purposes, it appears that the OH and SiO bands can be used as temperature indicators in M and late K stars, while the CO bands are sensitive to the luminosity. However, the data available to date suggest that these bands are not as sensitive to the physical parameters as are the TiO and CN bands in the near infrared, nor do they separate the effects of temperature and luminosity so cleanly. Thus for many purposes it may be useful to acquire eight-color photometry in the 1 μm region in conjunction with measurements at longer wavelengths.

Probably a more important application of narrow-band photometry of infrared molecular bands will be the determination of the relative abundances of the light

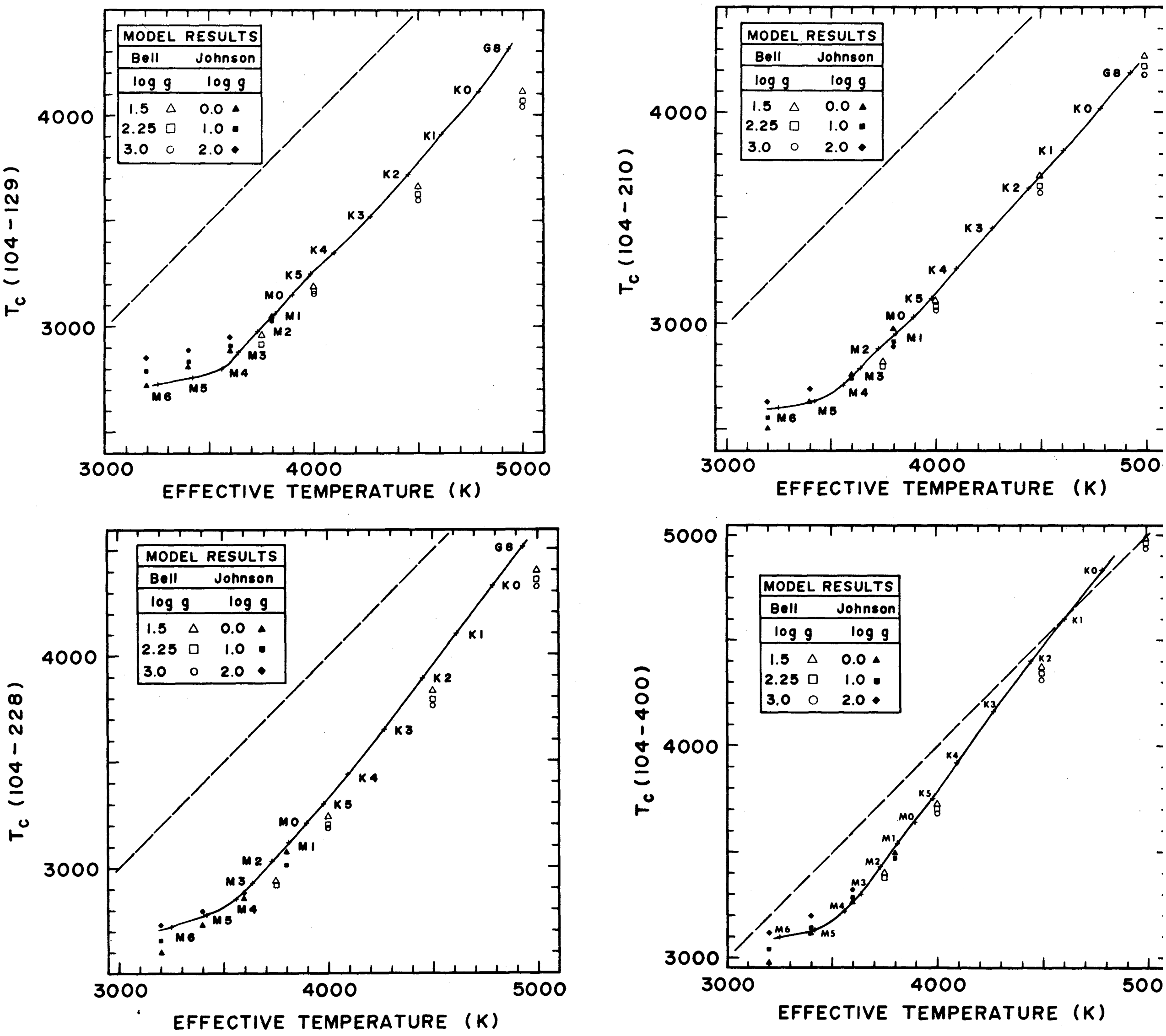


Fig. 12. Comparison of the behavior of four color temperatures, each using a different longward continuum point, as a function of th effective temperature *(a)* T_c*(104-129)*, *(b)* T_c*(104-210)*, *(c)* T_c *(104-228)*, *(d)* T_c*(104-400)*. Symbols represent synthetic colors compute from model atmospheres, as indicated in the legends. The lines labeled with spectral types are the mean observed relations (see text). Th agreement between the observed and synthetic colors is in all cases satisfactory, although small systematic differences are evident. Not that the color temperature T_c*(104-400)* is much closer to the effective temperature than are the other color temperatures. Froı Rinsland (1980).

elements H, C, N, and O. For this purpose it will be necessary to calibrate the narrow-band indices by means of synthetic spectra. It should also be possible to measure carbon isotope ratios in K and M stars from narrow-band measurements of the (2,0) band of $^{13}C^{16}O$ near 2.3 μm (see Figs. 6 and 7 of Wing 1979*a*). To reduce saturation effects, the strength of this isotopic band can be compared to that of the (5,2) band of $^{12}C^{16}O$, which is relatively clean and of similar strength, as suggested by Rinsland, Joyce, and Wing (1977).

Measurements of color temperatures at our infrare continuum points have so far been restricted to norm giants and a handful of other stars. Similar observatioı of M supergiants may be useful in evaluating sphericit effects in their extended atmospheres, while obse vations of late-type dwarfs are needed to test the atmospheric models and to check the completeness (the infrared opacity sources that have been included i computing them. Measurements of continuum colors (carbon stars may solve the long-standing problem (placing the temperatures of carbon and M stars on tl ame scale. Finally, we would like to encourage extenive observations of the *L(400)* magnitude in Mira 'ariables, in conjunction with eight-color photometry.)ne of the chief obstacles to an understanding of the)ulsational properties of Miras has been the difficulty of letermining their effective temperatures (Wing 1980). ;ince the *I(104) – L(400)* color appears to be the most lirect photometric indicator of the effective temperaure that can be obtained for late M stars, a photometric)rogram of this nature might go a long way toward ınraveling the cyclical variations in temperature, lumiıosity, and radius in these stars.

In closing, we would like to acknowledge that our)bservations in the 1-4 μm region have depended ›ntirely upon instrumentation developed at Kitt Peak National Observatory. In particular, Dr. Richard R. Ioyce has been responsible for several important im)rovements to the grating spectrometer used for the)rograms described here.

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DISCUSSION

Mendoza, E.: Do you have any observations on NML Cyg?

Wing: We have a single rather noisy observation of NML Cyg in the region of the SiO bands. Its spectrum rises steeply to longer wavelengths, and there is no evidence of spectral features. Evidently at 4 μm we are observing the thermal continuum from circumstellar grains.

Calvet: Is there any indication of variability in the SiO feature in Mira variables?

Wing: Yes. We have only a few observations of Miras, but they show that the bands are much stronger near minimum in typical Miras. In fact, the bands sometimes disappear completely at maximum. We have also observed problable emission in the SiO bands in the case of some supergiant stars, and it is possible that the same phenomenon may sometimes occur in Miras.

Popper: The absolute temperature calibration for cool stars appears to be approaching a satisfactory situation. There remains a large gap in the F-G-K region, that, in my opinion, is still poorly calibrated.

Wing: It is true that there are very few direct temperature determinations in the middle range. There are 3 or 4 usable determinations for G and K giants from lunar occultations, but their error bars are rather large and many more measurements will be needed to establish the temperature scale definitively in that range. The calibrations that are used in the F-G-K range depend heavily upon the Sun, even for the giant stars,

Campins: Su sistema puede ser provechosamente aplicado a observaciones de asteroides ya que cubren la región espectral en donde se encuentran bandas de olivina y piroxeno.

Wing: Yes, and for that purpose it should be useful that we are obtaining accurate relative photometry for a set of standard stars distributed around the ecliptic.

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