CLASSIFICATION BY PHOTOELECTRIC MEASUREMENTS OF MOLECULAR BANDS: CURRENT STATUS AND FUTURE PROSPECTS

Robert F. Wing

Ohio State University

ABSTRACT

As a classification technique, photoelectric narrow-band photometry is especially effective in the case of late-type spectra, in which molecular bands furnish the most sensitive criteria. Measurements of molecular bands with bandpasses of about 50 Å can be made very efficiently, and for normal stars they can be calibrated in terms of temperature and luminosity. In the case of normal late-type giants and supergiants, two-dimensional classifications can be obtained from measurements of TiO and CN; for very cool giants and for dwarfs it is useful also to measure VO and CaH, respectively. All these molecules have bands in the red and near-infrared spectral regions, where cool stars are relatively bright and where photometric accuracy is highest.

Several projects which exploit the advantages of narrow-band photometry seem particularly deserving of attention in the near future. The current status of work in each of these areas is reviewed.

1. INTRODUCTION

The term "narrow-band photometry" usually refers to measurements through bandpasses 10 to 100 Å wide. It is a technique which, unlike photometry with wider bands, can provide measurements of individual spectral features and thus can be used to classify spectra. Classifications so obtained are true spectral classifications, in contrast to the so called "photometric classifications" which are based upon measured colors and assumed correlations between colors and spectral characteristics.

Atomic lines can be measured by narrow-band photometry only if they are very strong, and most of the conventional atomic classification criteria cannot be employed for this reason. Molecular bands, on the other hand, are often easier to measure by narrow-band photometry than by techniques using higher spectral resolution. A molecular band consisting of numerous closely spaced lines may produce a measurable effect on a suitably placed filter even when its individual lines are too weak to be visible spectroscopically. Furthermore, the bands of certain molecules are extremely sensitive to temperature or pressure, making them particularly useful for classification. It seems to me, therefore, that narrow-band photometry is most useful as a classification tool in the case of the relatively cool stars of types K and M.

In Table I, the molecules that are most useful for classification purposes in normal K and M stars are grouped according to the spectral regions in which their principal bands fall. I start with the red region, since work in the blue is hindered by low flux levels and atomic-line contamination, while the entire visual (yellow) region is depressed by TiO absorption to such an extent that quantitative work on other spectral features is almost hopeless. This list is restricted to molecules with strong, easily measurable bands and is by no means a complete list of the molecules visible in these regions. Most of the molecules listed have been thoroughly studied, but two of them - OH and SiO - have been measured in relatively few stars and their usefulness as classification criteria is being tested only now. Other bands appear in the spectra of extremely cool stars or stars of peculiar composition, and indeed the main use of the 3-4μ region for classification purposes will probably be to study these less common objects. Still longer wavelengths don't appear very promising for classification: the 5 window, aside from being a rather poor window in the atmospheric absorption, is nearly obliterated by the stellar CO fundamental band, and in the 8-14μ window most stars studied to date show continuous spectra without photospheric features.

2. THE 7000-11000 A REGION: THE EIGHT-COLOR PHOTOMETRY

My own work has concentrated on the 7000-11000 Å region because it provides strong bands of three molecules - TiO, VO, and CN - that are well known to be useful for the classification of K and M stars, in a region near the energy maxima of these same stars. The use of these bands in the two-dimensional classification of

TABLE I

MOLECULES USEFUL FOR CLASSIFICATION

OF NORMAL K AND M STARS

Region	Molecule
0.6-0.8 μ ("red")	TiO, CaH
0.8-1.1 μ ("one-micron")	VO, CN
1.5-2.4 μ ("two-micron")	CO, OH, H_2O
3 - 4 μ	SiO

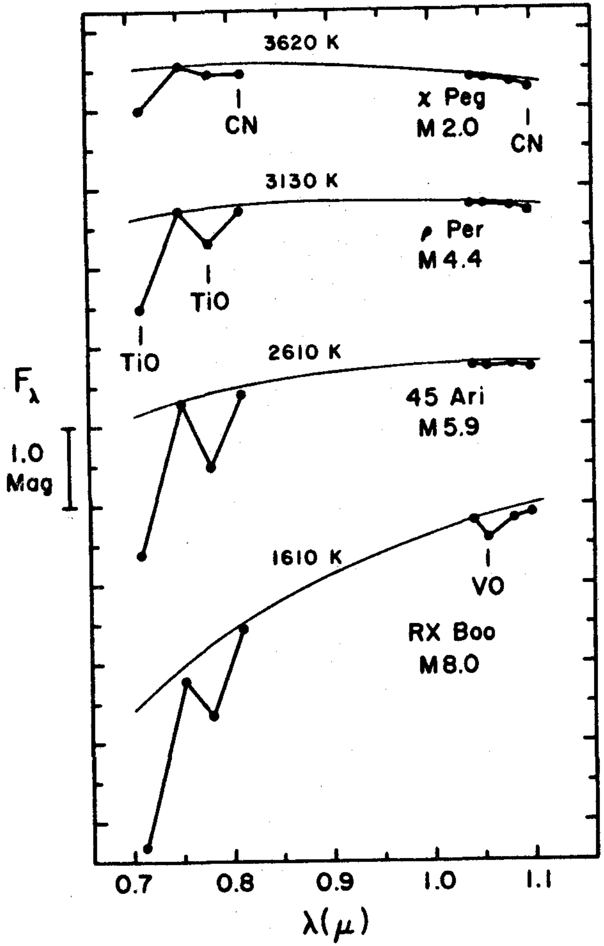

Fig. 1. Eight-color spectra of representative giant stars of types M2-M8, measured with interference filters. The spectral classifications are based on the depressions by TiO at the 1st and 3rd filters; points affected by CN and VO absorption are also labeled. Each spectrum has been fitted with a blackbody curve of the indicated temperature. From Wing and Warner (1979).

normal K and M stars has recently been reviewed (Wing and White 1978). By good fortune, nature has provided two molecules, TiO and CN, which can be measured easily and accurately in this region, and which respond almost orthogonally to temperature and pressure, respectively, throughout the range from K4 to M8. To study the low-luminosity K and M stars, and especially to distinguish subdwarfs from dwarfs, it is advantageous to include a measurement of CaH (Jones 1973; Mould 1976; Mould and McElroy 1978a). In the M8-M10 stars it is harder to make useful measurements of TiO because of blending by other molecules, but the temperature-sensitive VO bands in the relatively clean 1μ region are then available (Wing and Lockwood 1973).

To obtain quantitative measures of TiO, VO, and CN, I have been using a set of eight interference filters (Wing 1971). A few representative eight-color "spectra" are shown in Fig. 1, where the molecules responsible for the principal depressions are identified. The reason for using eight filters to measure only three molecules is that I have attached a great deal of importance to determining the level of the continuum as well as possible in the various kinds of cool stars (including carbon stars), and four of the filters are intended for this purpose. I have also considered that the measurement of CN, which is relatively weak in M stars, is sufficiently important to warrant the inclusion of an additional filter so that two different CN bands can be measured. The emphasis of the eight-color system is thus closely tied to the advantages of this particular spectral region; in the blue, visual, and red regions, by contrast, there is no possibility of measuring either the continuum or the CN strength in M stars. Most systems of narrow-band photometry do not bother with the continuum at all, and the indices that are formed are functions of several variables. In the eight-color photometry, the choice of the filters and the reduction procedure have been dictated by a desire to separate the variables as cleanly as possible - to produce a TiO index that depends only upon the TiO band strength, a CN index that depends only upon the CN band strength, and a color temperature that depends only upon the slope of the continuum and not upon the strengths of spectral features. "Clean" indices such as these can be used directly for spectral classification, and ultimately it should be possible to calibrate the molecular indices in terms of column densities and the color temperatures in terms of effective temperatures.

Before discussing future applications of this technique, I would like to make two points of a general nature about classification by the eight-color photometry. The first is that the spectral type scale used on the eight-color system is the same for all luminosity classes. That is, the same numerical relation between photometric TiO index and spectral type is used for all M stars from subdwarfs to supergiants. Of course, it would have been possible to employ a different relation for each luminosity class in order to achieve the best possible agreement with previously published types, but it seemed to me that the eight-color photometry would be serving us better if we used it to establish a unified scale for the temperature classification of all M stars. This objective was discussed at an earlier meeting of Commission 45 in Cordoba (Wing 1973), and now it is most gratifying to be able to report that the unification of the scale has been achieved, not only in the types assigned photometrically but also in recent spectroscopic classifications. This result is documented elsewhere in this volume (Wing and Yorka 1979), where the types assigned by various authors have been plotted against the eight-color types. For the calibration of the TiO index in terms of spectral type, Keenan's types for class III giants were chosen because of their high internal consistency. These illustrations show that there now exist sets of spectroscopically-determined types for dwarfs, giants and supergiants that all agree with the eight-color types and hence also with each other.

The other point concerns the meaning of the luminosity classes given by the eight-color photometry, which are based on CN. This molecule is very sensitive to luminosity but also to the abundances of C, N and O. Consequently one should only attempt to make relatively crude luminosity distinctions on the basis of CN. The subdivisions that I use with the eight-color photometry are V, III, II, Ib, Iab and Ia. To this extent, the eight-color luminosity classifications almost always agree with those assigned on the MK system from atomic-line ratios, and this agreement shows that the subdivision of the supergiants into classes Ib, Iab and Ia on the basis of CN is meaningful (White and Wing 1978). But if we try to make fine distinctions between stars of lower luminosity, say between IIIa giants and IIIab giants (as we might be tempted to do, to exploit the photometric accuracy of the CN index), the results from CN do not in general agree with those indicated by atomic lines. Rather, this comparison serves to separate the strong-CN giants from the weak-CN giants. Note that both kinds of classification are needed to recognize M giants with strong or weak CN, since spectrograms showing atomic lines are needed to give composition-free luminosity classes, while the CN strengths of M stars can be measured only in the infrared.

Now, what about the future? For the remainder of this section, I would like to discuss five observing programs involving eight-color photometry of normal K and M stars. These are all to some extent under way and substantial progress should be made during the next several years.

The most obvious of these programs is simply the classification of a large number of bright K and M stars. In the Catalogue of Bright Stars there are about 1000 stars (or about 11% of the catalogue) which have types in the range that can be classified by the eight-color photometry, namely K4 and later. In the most recent edition of the BS (Hoffleit 1964), 80% of these stars are listed with classifications that are more than 40 years old, and it seems to me that stars in the BS deserve better than this. It should not be difficult to correct this problem, since the observations can be made with a small telescope, say one of 50 cm aperture. I have made a start by observing about one-quarter of these stars and have prepared a tabulation of the spectral types, infrared magnitudes, and color temperatures for 280 stars in the BS (Wing 1978). The temperature classes, based on the TiO strength near 7100 Å, in most cases represent substantial improvements over the ones previously available, and although the luminosity classes from CN are subject to the difficulty discussed above, I have tried to make them as useful as possible by including spectroscopically-determined luminosity classes in the table also, whenever they are judged to be more accurate than the eight-color luminosity classes.

A second project, which could make use of the same eight-color photometry of bright stars, is the recalibration of the mean relations between color index (on any system) and spectral type. In the tables published by Johnson (1966) for his wideband system, for example, the main source of uncertainty comes from the spectral classifications that he used, which were taken from miscellaneous sources. There are some indications that when the same photometry is sorted according to the improved spectral types from the eight-color photometry, it will be seen that small but systematic changes are needed in the mean relations. In that case a revision would also be required in the often-used mean relation between bolometric correction and spectral type.

A third project, which would require a larger telescope, is the two-dimensional classification of stars suspected of being M supergiants but not yet classified on the MK system. Essentially all the M supergiants that do have MK classifications have already been observed on the eight-color system, and comparisons of both the spectral types and the luminosity classes obtained by the two methods have been published (White and Wing 1978). The next job will be to obtain similar data for fainter, more distant M supergiants - for example, those on the Warner and Swasey Observatory objective-prism survey lists, or M stars with large color excesses in the IRC catalogue (Neugebauer and Leighton 1969). The importance of the faint M supergiants is that they should be useful in defining the spiral arms of the Galaxy at large distances from the Sun, even in directions of heavy obscuration, and the importance of the eight-color photometry in this connection is that it provides, at least in principle, all the information needed to determine the distance of an M supergiant and to place it on a map of galactic structure.

The determination of distances of M supergiants proceeds as follows. The information provided by the eight-color photometry consists of an apparent magnitude $\underline{I}(104)$ measured at 10400 Å, a color temperature measuring the apparent slope of the near-infrared continuum, a spectral type based on TiO, and a luminosity class based on CN. This is essentially the same as the information given by the combination of UBV photometry and two-dimensional MK classifications, and the distance is found in the same manner. Work along these lines is now in progress by N. White (Warner and Swasey stars) and by J. Warner and the writer (IRC stars). There are three important advantages in using the eight-color system in this work: (1) the spectral classification is obtained simultaneously with the photometric magnitude and color; this is important because most M supergiants are variable, but it is a great convenience in any case, since one observer with one instrumental set-up can do the whole job; (2) the spectral type from TiO is measured very accurately, and this should provide an accurate intrinsic color to be compared to the observed color, leading to a good determination of the interstellar reddening; and (3) the interstellar absorption in $\underline{I}(104)$ is only one-third as great as in $\underline{V}$, so that a given error in the measured color excess results in a smaller error in the distance. Of course, in order to obtain distances from photometry and spectral classifications it is necessary to use certain calibrations - specifically, the relation between spectral type and intrinsic color for each luminosity class, and a table giving the absolute magnitude M(104) for each spectral type and luminosity class - and the <u>dis</u>advantage of using eight-color photometry of M supergiants in galactic-structure work at this time is that these calibrations are not known with sufficient precision. This is, however, a disadvantage that can be eliminated by further observational work.

Fourth on my list of tasks for the eight-color photometry, then, is the determination of the calibrations mentioned above. I think the best way to proceed is to observe both early-type and late-type stars belonging to the same clusters and associations, with the same narrow-band filters. This procedure eliminates the problem of the change of effective wavelength with spectral type, and it allows the color excesses found for the early-type stars to be applied directly to the cool stars in their vicinity for the determination of their intrinsic colors. A major observational effort will be required to obtain sufficiently precise photometry of faint blue stars in narrow bands in the infrared, but fortunately the early-type stars will need to be observed in only two of the eight filters to establish their color, and the calibrations need to be worked out only once in order to make it possible to use the M-type supergiants in galactic-structure studies.

The fifth and last of my proposed tasks for the eight-color photometry is to look for evidence of abundance variations between one star cluster and another. In this case the eight-color photometry provides the relation between TiO strength and color temperature for each cluster. Mould and McElroy (1978b) have taken up this work and find that clusters known to be metal-poor show weakened TiO bands for their temperature. It will clearly be of great interest to extend this work to clusters whose metallicities are not well established. Unfortunately, an abnormal relation between TiO strength and temperature can be recognized only if the effects of interstellar reddening on the color temperature can be allowed for, and therefore the method will probably prove most useful for high-latitude, low-reddening globular clusters. Of course, this method also requires that the cluster contain one or more stars of type K4 or later, but the number of clusters, both galactic and globular, which are known to contain late-type members seems to be increasing steadily.

3. THE STARS OT TYPE S

We turn now to a problem that cannot be handled satisfactorily by the eight-color photometry in its original form, but which has been treated by a modification of it - namely the measurement of molecular band strengths in stars of type S. These stars have such complex infrared spectra, with so many different molecules sometimes present (Wing 1972), that I considered it hopeless to study them adequately with a photometric system as simple as the eight-color system. Therefore, although the eight-color system was designed to be useful for both M stars and carbon stars, it was not expected to be useful for the S stars, and in particular it does not measure the molecules ZrO and LaO by which the S stars are recognized.

What then does one do if one is interested in the S stars? This question has been investigated very thoroughly by Piccirillo (1976, 1977a, 1977b), and since his work is not otherwise represented at this Colloquium, I would like to show you some of his results. First, he obtained continuous spectral scans for many S stars (see Piccirillo 1976) in order to select the best positions for interference filters serving to measure band strengths and continuum points. Surprisingly, he found that six of the filters of my eight-color system were optimum choices for S stars, and that he needed only two new filters - one for ZrO, and one for LaO - to arrive at a modified eight-color system measuring TiO, VO, ZrO, LaO, CN, and an unidentified band, as well as the infrared magnitude and color temperature.

Well, that sounds very simple. In practice, the application of narrow-band photometry to the S stars is enormously difficult. Each of these molecules has not just one band but a whole system of bands, and these systems overlap. Even when the filters are placed in their optimum positions, many of them are affected by two or three different molecules, and the problem of untangling the measurements to obtain separate indices of the strength of each molecule is certainly not trivial. This can be done, however, because not all of these molecules are present in the same spectrum.

The spectra of four mild S stars on Piccirillo's modified eight-color system are shown in Fig. 2. On comparison with Fig. 1 we see that Piccirillo has added filters at 6510 Å and 7945 Å (to measure ZrO and LaO, respectively) and has omitted the filters at 8120 Å and 10540 Å. These mild S stars have rather strong TiO absorption which is responsible for the depressions at the second, fourth and fifth filters (there is no LaO in these stars) and which also contributes to the ZrO depression in the first filter. The eighth filter is depressed by CN. A blackbody curve has been fitted to the points of least blanketing in each of the two groups of filters, yielding the color temperature.

The spectra of strong S stars, shown in Fig. 3, have quite a different character since TiO is weak or absent. Now the depressions at the third and fifth filters are due mostly to LaO, and the fourth filter takes over as the best continuum point in the absence of TiO. In these strong S stars, most of the absorption at the second filter is due to an unidentified band, the behavior of which has been documented by Piccirillo (1976).

The process of extracting indices of the strength of each molecule from the measured depressions at each filter is an algebraic manipulation involving the known ratios of the depressions at the various filters by each molecule (determined from observations of stars showing only one or two of the molecules). The next step - that of going from the molecular indices to a spectral classification - is more difficult and highly subjective. It is by no means certain, at this stage, what is the best way to express the classification of an S star in terms of its observable parameters. Piccirillo's efforts did not result in a simple, useful classification scheme for S stars; but I don't think a scheme can ever be found that is both simple and useful for S stars.

Despite this rather unsatisfying result, I consider that

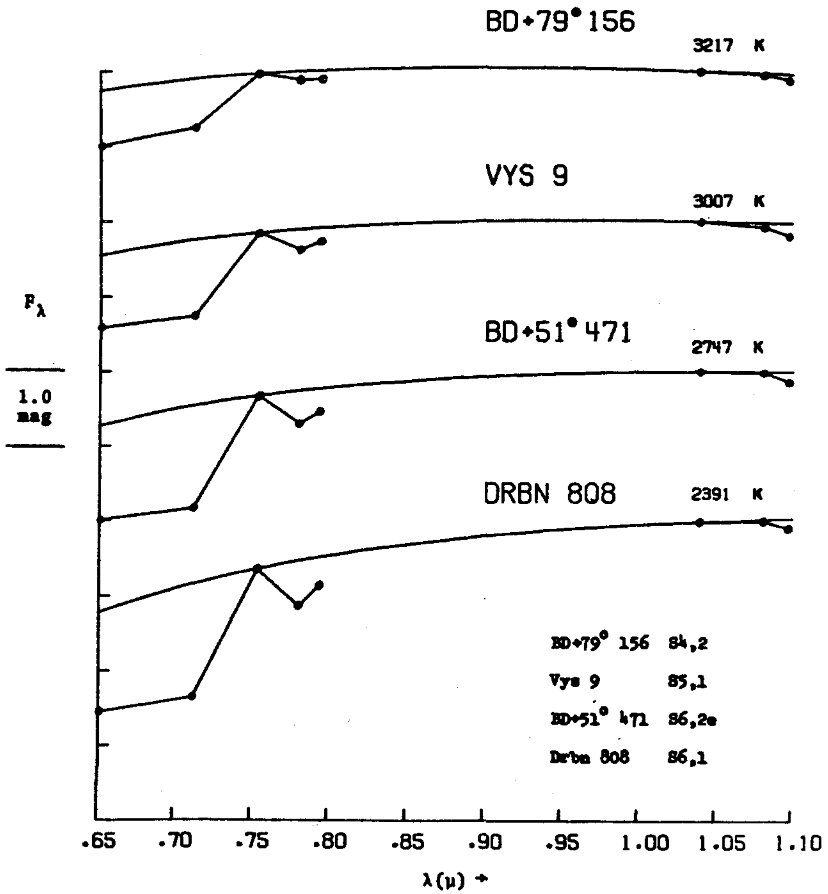

Fig. 2. Spectra of mild S stars on Piccirillo's (1977a) photometric system. The relative flux per unit wavelength interval, in magnitudes, is plotted against wavelength. The 2nd, 4th, and 5th filters are depressed by TiO, the 1st by ZrO and TiO, and the 8th by CN. The high points in each group of filters are joined by a blackbody curve of the indicated temperature. The two-dimensional spectral types are by Keenan (1954).

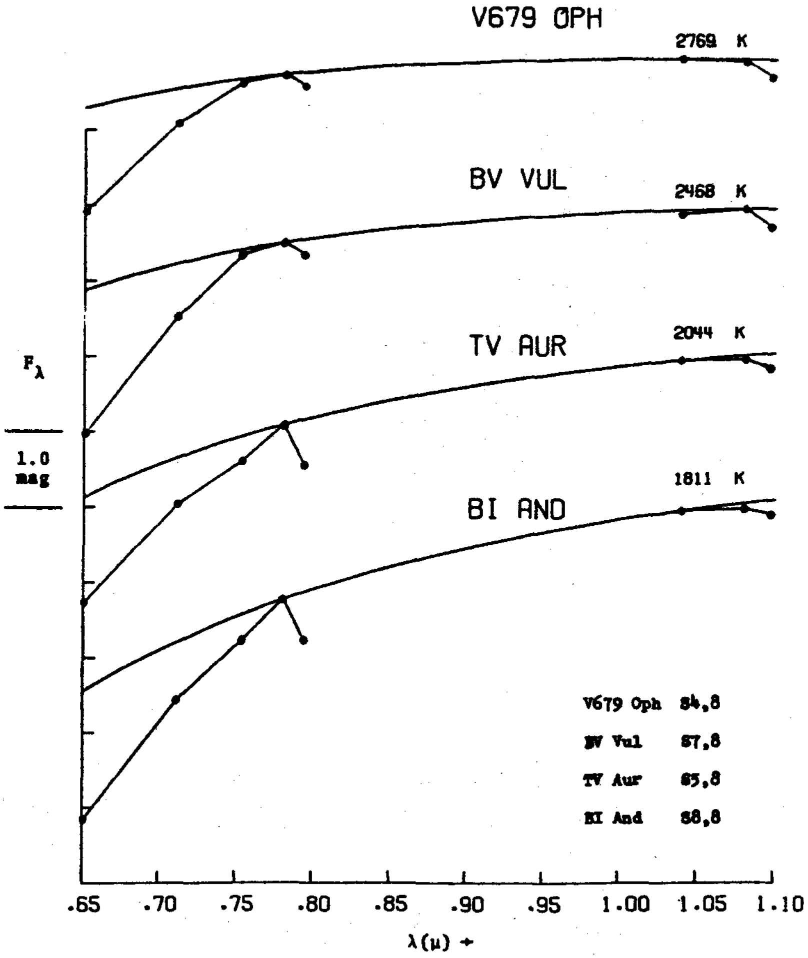

Fig. 3. Spectra of strong S stars (Piccirillo 1977a). Here the 4th filter is the best continuum point in the short-wavelength region. TiO is weak or absent; an unidentified band depresses the 2nd filter, while LaO depresses the 3rd and 5th filters. See caption to Fig. 2.

Piccirillo has made an important advance in the classification of S stars. This advance has come not from the narrow-band photometry itself but from the theoretical work that he also carried out in order to interpret the photometry. To account for the measured band strengths and their differences from star to star, he calculated column densities on the basis of model atmospheres that were computed for opacities appropriate to S stars. Now, I can appreciate the sentiment - already expressed more than once at this Colloquium - that a classification system should be purely empirical and not tied to any set of theoretical calculations. But sometimes in the history of our subject we have found ourselves so much in the dark that we have gladly accepted any guidance that we could get. Now, if we were content to classify S stars simply by stating the strength of this and the strength of that, there would be no need for theoretical guidance - and our classifications would be of very little value to other astronomers. But if we wish to give a temperature index, or perhaps a gas-pressure index, or an O/C ratio index, or an s-process enhancement index, then we must have some way of knowing what spectral features behave in what manner as a function of the physical or composition variables.

I will give just two examples of results from Piccirillo's (1977a) work that help to explain the behavior of spectral features that play a role in the classification of S stars. First, as I mentioned during the discussion of the paper by Boeshaar and Keenan (1979), the atmospheric structure of late-type stars is very sensitive to the O/C ratio (see Scalo 1973). The S and SC stars, in which the O/C ratio is close to unity, have relatively transparent atmospheres because they are unable to produce large quantities of molecules containing either oxygen or carbon (other than CO, which is a relatively ineffective absorber). Consequently the atmospheres of S stars are built differently from those of either the M stars of the carbon stars. The temperature-pressure relations for four atmospheric models calculated by H.R. Johnson by his opacity-sampling technique and discussed by Piccirillo (1977a) are shown in Fig. 4. These models all have the same effective temperature and gravity but differ in O/C. In layers of equal temperature, throughout the line-forming region, there are pressure differences of 1 to 2 orders of magnitude between the various models, in the sense that the highest pressures are found in the most transparent atmospheres. Thus we can begin to understand why the S stars show enhancements (relative to M giants) of the same spectral features as are enhanced in the M dwarfs: the sodium D-lines, 4226 Å of Ca I, and molecules with low dissociation energies such as CaH (Greene and Wing 1975) and FeH (Nordh, Lindgren, and Wing 1977). Among the normal M stars these features are useful as luminosity indicators, but among the S and SC stars they are so sensitive

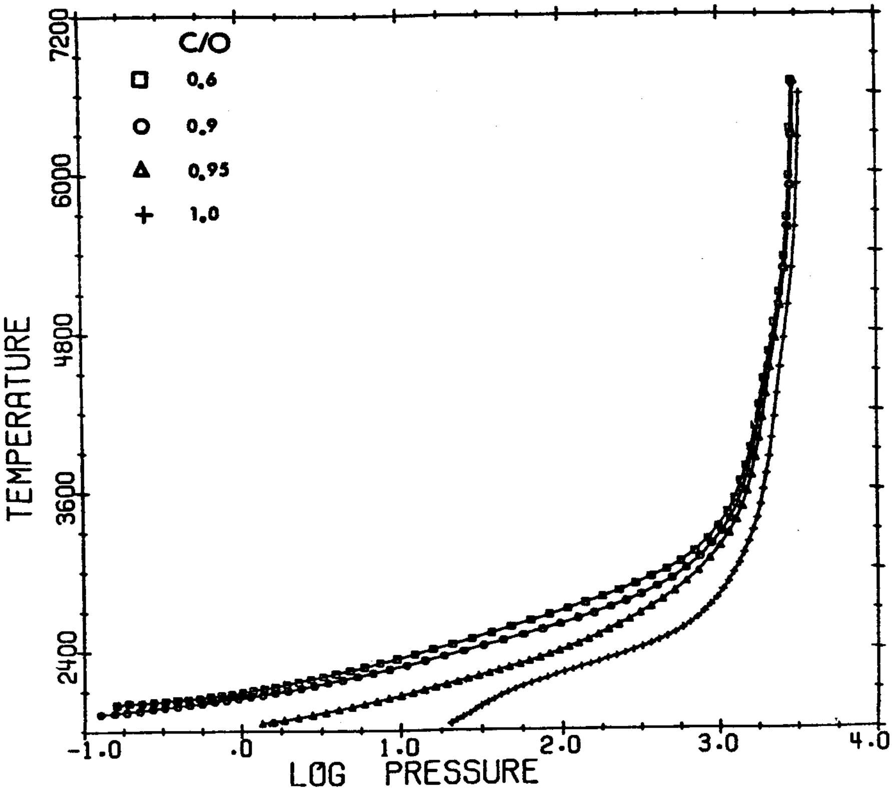

Fig. 4. The relation between temperature and pressure for four atmospheric models, all having the same effective temperature (T_e = 3000° K) and gravity (log g = 0.0) but differing in the atmospheric abundance ratio of carbon to oxygen. The figure is from Piccirillo (1977a) and is based on unpublished models computed at Indiana University by H.R. Johnson.

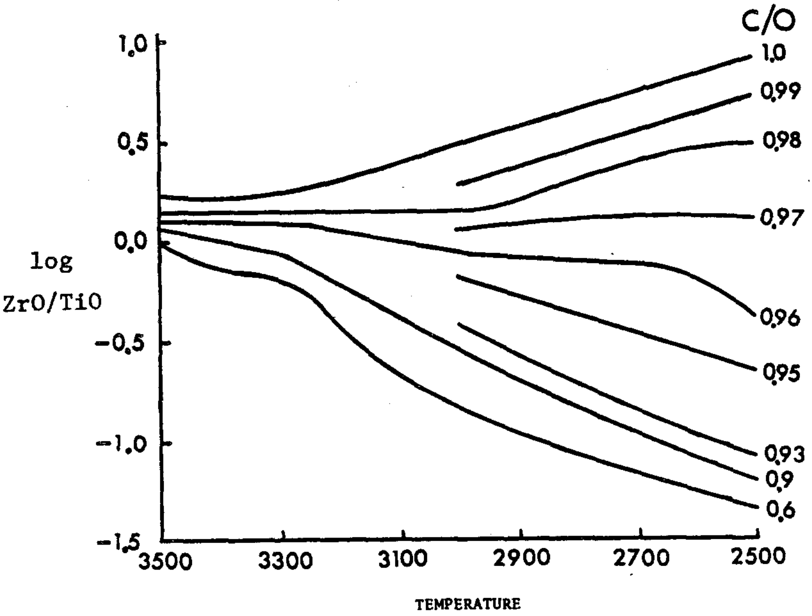

Fig. 5. The logarithm of the ZrO/TiO column-density ratio is plotted against temperature for various values of the ratio of carbon to oxygen. Except for the variable carbon abundance, the abundances used in these calculations are solar. From Piccirillo (1977a).

to O/C that we must avoid using them as indicators of physical parameters.

The second result concerns the ZrO/TiO ratio. We might wish to use this directly-observable quantity as an indicator of the elemental abundance ratio Zr/Ti - i.e. as an indicator of the enhancement of the s-process elements. Or, knowing that ZrO is more stable than TiO and better able to compete for the oxygen in stars with reduced oxygen, we might wish to use it as an O/C indicator (Scalo 1974). Well, which is it? That the answer depends upon the temperature is shown in Fig. 5. At high temperatures, around 3500 K, ZrO/TiO is insensitive to O/C (because CO is not fully formed, and there is plenty of oxygen available) and can therefore be used as an s-process indicator. But at lower temperatures, the ZrO/TiO ratio becomes extremely sensitive to O/C and is then useless as an s-process indicator. Thus the theoretical calculations are indispensible for choosing the best classification criteria for S stars and delineating their limits of applicability.

This is not the place to discuss what Piccirillo learned, or was unable to learn, astrophysically about S stars and their evolution. I mention his work only as a recent advance in the spectral classification of a very difficult kind of star, one that will require further work in the future. I think it illustrates very well how the interplay of theory and observation can sometimes lead to progress in classification.

4. POSSIBILITIES FOR CLASSIFICATION IN THE 2-4μ REGION

The spectral region between 1.5 and 4.2μ - the region of the H, K and L filters of broadband photometry - contains rotation-vibration bands of several of the most abundant molecules in stellar atmospheres, including CO, H_2O, OH and SiO. Measurements of these bands have played an important role in the determination of the elemental abundances of H, C, N and O, and their isotopes, but they have seen relatively little use in spectral classification. These bands are simply not as effective as indicators of temperature and pressure as are the TiO and CN bands in the red and one-micron regions. However, it is important that we should establish classification criteria based on these bands, since extremely cool or heavily reddened stars are actually much easier to observe in this region than at shorter wavelengths.

The behavior of various infrared molecular bands has been summarized by Spinrad and Wing (1969) and Hyland (1974). The extensively-studied CO bands show a positive luminosity effect in oxygen-rich stars similar to that of the CN bands, but the CO bands, unlike the CN bands, are also quite sensitive to temperature. Consequently the CO strength does not indicate either the temperature or the luminosity unless one of these quantities is independently known. The H_2O bands are difficult to use for several reasons: they too are sensitive to both temperature and luminosity, they appear only in very cool stars (rather like the VO bands in the 1μ region), and they coincide roughly in wavelength with bands of CN (Wing and Spinrad 1970). The OH and SiO bands, which are only now beginning to be studied systematically, seem to behave in a manner similar to TiO but are not nearly as strong as the principal TiO bands.

In the 3 - 4 μ region, a large number of stellar spectra have recently been observed at low resolution (Merrill and Stein 1976a, b, c; Merrill 1977; Noguchi et al. 1977) These spectra show very few spectral features - in particular the 4 μ SiO bands are not evident at this resolution - but they do show a very strong band centered at 3.1μ, recently identified with HCN and C_2H_2 (Ridgway, Carbon and Hall 1978), in all cool carbon stars. Consequently, spectroscopy in the 3 - 4 μ region has been useful for distinguishing carbon stars from M stars but not as yet for more refined classification. Narrow-band photometry of the 3.1μ feature in carbon stars has been carried out by Fay and Ridgway (1976).

The remainder of my discussion will be restricted to the normal stars of types G, K and M, and to the molecules that show promise as criteria for the classification of these stars in terms of temperature and luminosity. Emphasis will be given to spectral features that are strong enough to be measurable by narrow-band photometry.

4.1 The CO and H_2O Bands

Medium-resolution spectra in the region of the K filter (2.0-2.4μ) readily show the first-overtone bands of CO in virtually all stars of types G and later, while H_2O distorts the shape of such spectra in the case of very cool, oxygen-rich stars. The spectra of two giant stars illustrating these features are shown in Fig. 6. In giant stars, the absorption by CO increases steadily with decreasing temperature throughout the range G5 to M8, partly as a result of decreasing H^- opacity (Hyland 1974). Absorption by H_2O, on the other hand, appears in giants only at types M6-M10. Hyland (1974) has discussed the use of medium-resolution spectra in classifying IRC sources, at least to the extent of distinguishing M supergiants, late M giants and carbon stars.

It is clear from Fig. 6 that a three-color photometric system

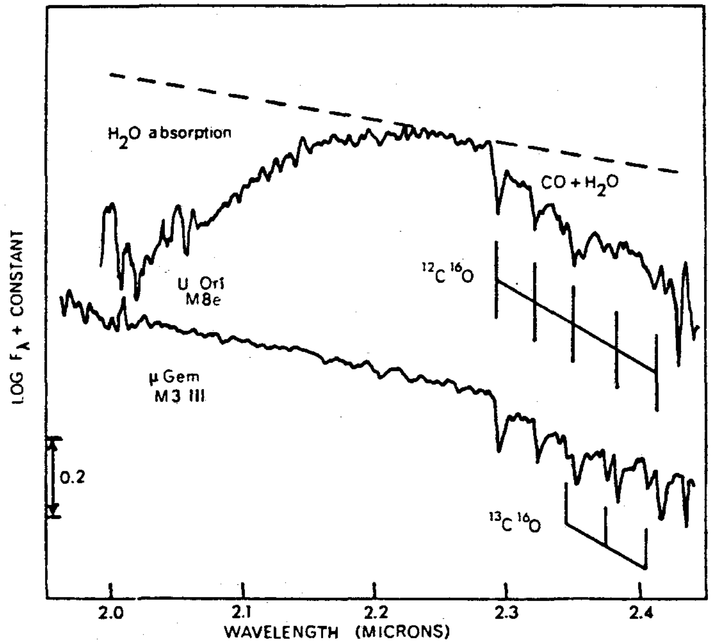

Fig. 6. Spectra of two M giants in the two-micron region (resolution 6 cm^{-1}). The Mira variable U Ori shows strong H_2O absorption, and both stars show prominent bands of $^{12}C^{16}O$. Bands of the isotopic species $^{13}C^{16}O$ are clearly visible in μ Gem but not in the cooler star, in which H_2O absorption interferes with the region of the CO bands. From Hyland (1974).

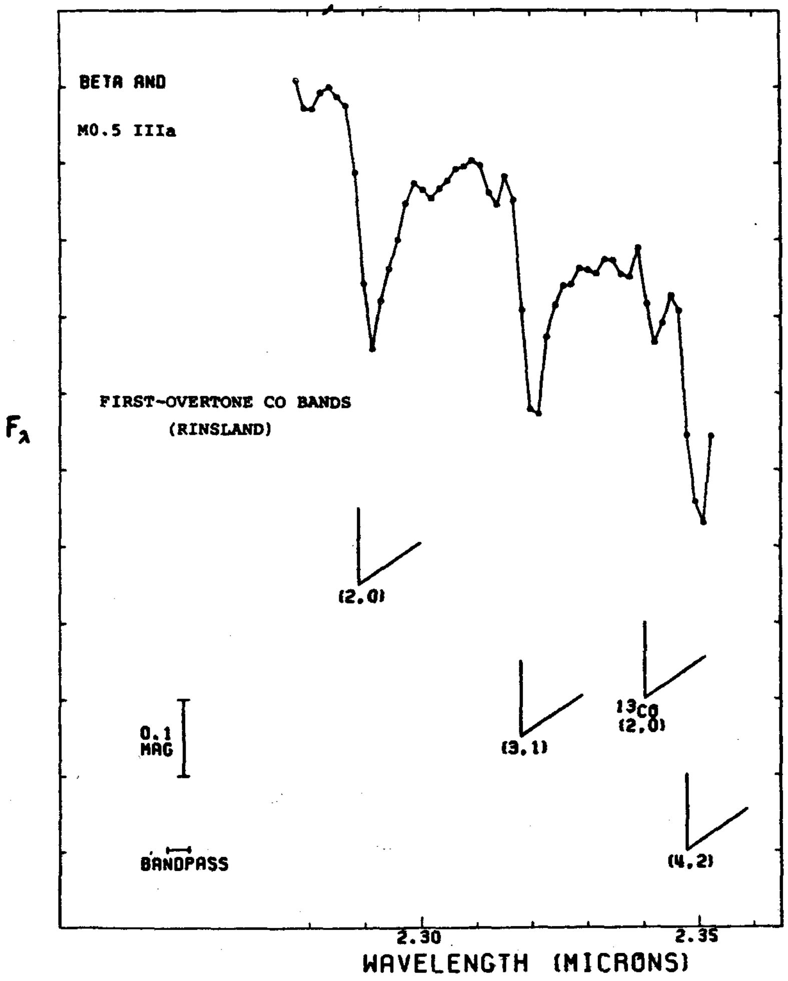

Fig. 7. A scan of the region of the (2,0), (3,1) and (4,2) bands of CO in the early M giant And, obtained with a grating scanner and a 6 cm^{-1} bandpass. The flux per unit wavelength interval is plotted on a magnitude scale. Note that the (2,0) band of the isotopic molecule $^{13}C^{16}O$ is easily measurable. Unpublished data by C.P. Rinsland.

could be set up to provide indices of the strengths of CO and H_2O in much fainter sources. Baldwin et al. (1973b) have used narrow-band filters centered at 2.10, 2.20 and 2.31 to measure CO and H_2O indices in late-type dwarfs as well as giants. Additional measurements of dwarfs, with slightly different filters, have been made by Persson et al. (1977). Dwarfs are clearly separated from giants by these measurements, the dwarfs having weaker CO and stronger H_2O at a given temperature. From similar measurements of the integrated light of galaxies, Baldwin et al. (1973a) were able to conclude that most of the infrared light from the nuclear regions of spiral galaxies is emitted by late-type giants.

Mould (1978) has recently succeeded in securing high-resolution (0.3 cm^{-1}) spectra of several M dwarfs with a Fourier-transform spectrometer. They show that the H_2O absorption is as strong in M1-M2 dwarfs as it is in M6-M7 giants; in Barnard's star, an M3.8 subdwarf, H_2O is nearly as strong as in the spectrum of U Ori shown in Fig. 6. Atomic lines of neutral Na, Ca, Mg, Al and Si are also greatly enhanced in the dwarfs; some of these lines are as strong as the CO bandheads, which are much weaker than in giants. Spectra of such high resolution are not practical to use in general-purpose classification programs, but they are extremely valuable as a guide to interpreting spectra of lower resolution.

One of the most important uses of the infrared CO bands has been in the determination of the isotope ratio $^{12}C/^{13}C$, particularly since the CO bands appear in K and M stars as well as in carbon stars. Ridgway (1974a, b) has shown that the $^{13}C^{16}O$ bandheads are quite prominent in the spectra of K giants at 4 cm^{-1} resolution but are invisible at 16 cm^{-1} resolution. A resolution of 6 cm^{-1} (Fig. 6) is adequate to show these features. Rinsland, as part of his thesis work at the Ohio State University, has obtained scans of the first-overtone CO bands with a 6 cm^{-1} bandpass to explore the possibility of measuring carbon isotope ratios by narrow-band photometry. An example of his CO spectra, which have a photometric accuracy of 1%, is shown in Fig. 7. It is anticipated that, with the help of synthetic spectrum calculations, useful carbon isotope ratios can be derived from photometric measurements at a small number of wavelengths at this resolution.

4.2 The OH and SiO Bands

As noted above, the usefulness of the CO and H_2O bands for spectral classification is limited by the fact that they do not separate the effects of temperature and luminosity clearly. Their usefulness would be greatly increased if some other molecule could be measured to pin down one or the other of these physical variables. One possibility is to measure CN as a luminosity indicator so that CO can serve as a temperature indicator. However, the CN bands in the 2 μ region are much weaker than those near 1 μ, and they are poorly placed with respect to atmospheric H_2O absorption. Another possibility is to measure the bands of OH and/or SiO. There is little information in the literature about their behavior as a function of temperature or luminosity, but the possibility exists that one or both of these molecules may prove useful as a temperature indicator.

Although OH has been studied at high resolution (Beer et al. 1972), its imprint on low-resolution spectra is small because its band structure is quite open. It has not been clear whether any of the OH bands produce enough absorption over an interval of several wavenumbers to be measurable by narrow-band photometry. Rinsland has explored the OH spectrum with the aid of theoretical calculations and high resolution stellar spectra made available by P. Connes; the region of the (4,2) bandhead near 1.5 μ, shown in Fig. 8, seems to be the most promising region observable from the ground. Although the synthetic spectrum shown is preliminary and does not represent an optimum fit to the observed spectrum of α Her, it is clear that nearly all the absorption in this region is due to OH in this M5 star. The CN lines in this region are quite weak, and there is no contamination by CO. Unfortunately, the region of concentrated OH absorption is only about 3 cm^{-1} wide.

The most favorable bands of SiO are the first-overtone bands near 4 μ, first observed in a stellar spectrum by Cudaback, Gaustad and Knacke (1971). As already noted, these features are quite weak. They are, however, distinctly visible in many spectra scanned with a 5.5 cm^{-1} bandpass. In Fig. 9, the (2,0) and (3,1) bands can be seen in the spectra of α Tau (K5 III) and δ Oph (M0.5 III), although they are not evident at the warmer temperature of β Gem (K0 IIIb). Wing, Rinsland, and Joyce (1977) and Rinsland and Wing (1978) have obtained SiO scans of 77 representative late-type stars and find that the band strength in giants increases steadily with decreasing temperature until at least type M5. The luminosity dependence of the bands has not been clearly established, however, since supergiants have been found that have both stronger and weaker SiO bands than giants of the same spectral type.

4.3 Narrow-Band Classification Photometry

As we have seen, simple sets of two or three narrow-band filters have been used to measure several of the stronger molecular

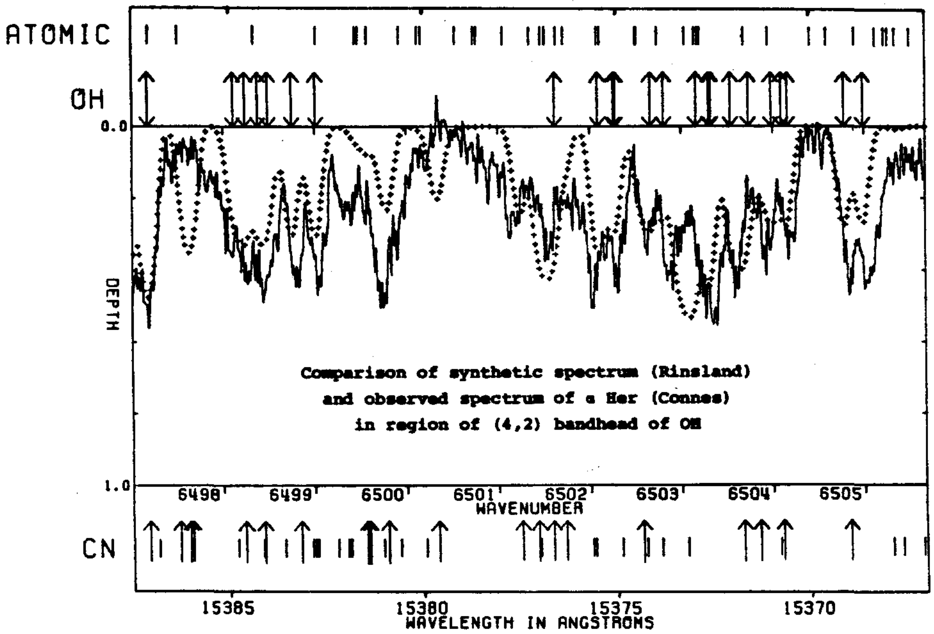

Fig. 8. The region of the (4,2) bandhead of OH, at high resolution. The continuous curve is the spectrum of the M5 star α Her, observed by P. Connes with a Fourier-transform spectrometer; the broken curve is a synthetic spectrum. Most of the observed absorption is due to OH, the lines of which are marked above the spectrum. Also indicated are the positions of atomic lines and CN lines (arrows indicate $^{12}C^{14}N$, short lines $^{13}C^{14}N$), which are minor contributors in this region. Unpublished work of C.P. Rinsland.

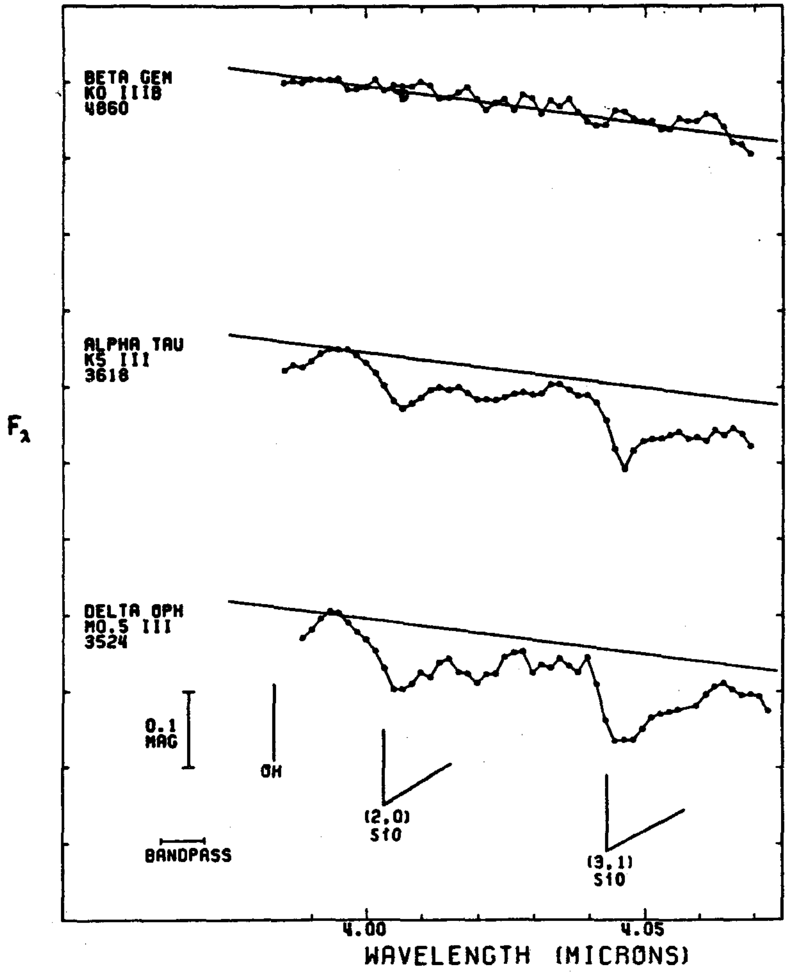

Fig. 9. The region of the first-overtone bands of SiO near 4 μ in three giant stars. The observations were made with a grating scanner (5.5 cm^{-1} bandpass) and are plotted on a magnitude scale. The SiO band strength increases with advancing spectral type. The continua are blackbody curves which pass through the mean of several points shortward of the SiO (2,0) bandhead and through the measured flux at 1.04 μ ; the blackbody temperature from this fit is given beneath the spectral type of each star. From Rinsland and Wing (1978, and in preparation).

bands in the 2 - 4 μ region. These measurements have been useful for crude classification (distinguishing carbon stars from M stars, or dwarfs from giants) but have not produced spectral classes that are as refined as those available from visible spectroscopy or 1 μ classification photometry. The problem is that the strong bands of CO and H_2O, by themselves, are relatively ineffective in providing separate indices of temperature and luminosity, while the bands of other molecules which might yield the necessary additional information are very much weaker.

We have considered using interference filters to establish a system of classification photometry measuring continuum points and bands of several molecules in the 2 - 4 μ region. Such a system would function in the same way as the eight-color system in the 1 μ region but would measure a completely different set of molecules. Suitable filters can be manufactured, but unfortunately the cost of a large set of filters meeting the precise specifications required for work on weak spectral features in the infrared is prohibitive.

The infrared grating scanner of Kitt Peak National Observatory, which is used with an InSb detector at the 1.3-m telescope and can be programmed to perform integrations at a pre-selected set of wavelengths, offers a more economical means of doing multicolor narrow-band photometry in the infrared. Rinsland, Wing and Joyce (1977) have described a 17-color photometric system designed for this instrument. Since it was motivated primarily by an interest in chemical abundances, this system is more complex than an optimum system for spectral classification. However, we feel that any successful general-purpose classification system in the 2 - 4 μ region will have to measure many of the same spectral features and continuum points at comparable resolution. In particular, we recommend including the strong (2,0) band of CO (for use on G and early K stars), the much weaker (5,2) band of CO (for use on cooler stars in which the strong CO bands are too saturated to provide a sensitive criterion), the (2,0) band of $^{13}C^{16}O$, the (4,2) band of OH, the (2,0) band of SiO, and a set of continuum points as specified by Rinsland, Wing, and Joyce. It is not necessary to include an additional point to measure H_2O, because when H_2O is present it affects the entire spectrum in such a way that several indices of its strength are already available.

We have found that the main difficulty in carrying out infrared classification in the manner described by Rinsland, Wing and Joyce (1977) is the flexure of the scanner, which causes uncontrollable wavelength shifts amounting to 10-20 percent of the widths of our narrow bandpasses. Consequently it has proved necessary to scan over each spectral feature with a several-point program, instead of making a single integration. This difficulty obviously reduces the efficiency of the system and hinders its application to faint objects. However, Rinsland is proceeding with the calibration of this system and is applying it to abundance analyses of relatively bright stars. His work will show how each spectral feature behaves as a function of temperature and luminosity and will thus indicate whether accurate spectral classifications can be obtained from measurements of molecular bands in the 2 - 4 μ region. If his results are favorable, the application of this technique to fainter stars, once an instrument of sufficiently precise wavelength-setting accuracy becomes available, will be an important area in the classification of the future.

Observations from high-altitude aircraft and satellites will undoubtedly play a significant role in the future classification of late-type stars. Among the advantages of such observations are the availability of stronger bands of OH and CN than can be measured from the ground in the 2 - 4 μ region and, most important, the possibility of extending measurements of H_2O to warmer stars.

I am greatly indebted to John Piccirillo and Curtis P. Rinsland for allowing me to discuss their unpublished results, and for helpful comments.

REFERENCES

Baldwin, J.R., Danziger, I.J., Frogel, J.A. and Persson, S.E. (1973a). Astrophys. Letters, 14, 1.

Baldwin, J.R., Frogel,J.A. and Persson, S.E. (1973b). Astrophys. J. 184, 427.

Beer, R., Hutchison, R.B., Norton, R.H. and Lambert, D.L. (1972). Astrophys. J. 172, 89.

Boeshaar, P.C. and Keenan, P.C. (1979). In IAU Colloq. No. 47, Spectral Classification of the Future, M.F. McCarthy, A.G.D. Philip and G.V. Coyne, eds., Vatican Obs. p. 39.

Cudaback, D.D., Gaustad, J.E. and Knacke, R.F. (1971). Astrophys. J. (Letters), 166, L49.

Fay, T.D. and Ridgway, S.T. (1976). Astrophys. J. 203, 600.

Greene, A.E. and Wing, R.F. (1975). Astrophys. J. 200, 688.

Hoffleit, D. (1964). In Catalogue of Bright Stars, Yale University Observatory: New Haven.

Hyland, A.R. (1974). Highlights of Astronomy 3, 307.

Johnson, H.L. (1966). Ann. Rev. Astron. Astrophys. 4, 193.

Jones, D.H.P. (1973). Mon. Not. Roy. Astron. Soc. 161, 19P.

Keenan, P.C. (1954). Astrophys. J. 120, 484.

Merrill, K.M. (1977). In IAU Colloq. No. 42, The Interaction of Variable Stars with their Environment, R. Kippenhahn, J. Rahe, and W. Strohmeier, eds., Veroff der Remeis-Sternwarte Bamberg, V. 11, No. 121, p. 446.

Merrill, K.M. and Stein, W.A. (1976a). Publ. Astron. Soc. Pacific 88, 285.

Merrill, K.M. and Stein, W.A. (1976b). Publ. Astron. Soc. Pacific 88, 294.

Merrill, K.M. and Stein, W.A. (1976c). Publ. Astron. Soc. Pacific 88, 874.

Mould, J.R. (1976). Astrophys. J. 207, 535.

Mould, J.R. (1978). Astrophys. J. in press.

Mould, J.R. and McElroy, D.B. (1978a). Astrophys. J. 220, 935.

Mould, J.R. and McElroy, D.B. (1978b). Astrophys. J. 221, 580.

Neugebauer, G. and Leighton, R.B. (1969). Two-Micron Sky Survey - A Preliminary Catalog (NASA SP-3047).

Noguchi, K., Maihara, T., Okuda, H., Sato, S. and Mukai, T. (1977). Publ. Astron. Soc. Japan 29, 511.

Nordh, H.L., Lindgren, B. and Wing, R.F. (1977). Astron. and Astrophys. 56, 1.

Persson, S.E., Aaronson, M. and Frogel, J.A. (1977). Astron. J. 82, 729.

Piccirillo, J. (1976). Publ. Astron. Soc. Pacific 88, 680.

Piccirillo, J. (1977a). unpublished Ph.D. dissertation, Indiana University.

Piccirillo, J. (1977b). Bull. Amer. Astron. Soc. 9, 294.

Ridgway, S.T. (1974a). Highlights of Astronomy 3, 327.

Ridgway, S.T. (1974b). Astrophys. J. 190, 591.

Ridgway, S.T., Carbon, D.F. and Hall, D.N.B. (1978). Astrophys. J. 225, 138.

Rinsland, C.P. and Wing, R.F. (1978). Bull. Amer. Astron. Soc. 10, 408.

Rinsland, C.P., Wing, R.F. and Joyce, R.R. (1977). In Symposium on Recent Results in Infrared Astrophysics, P. Dyal, ed., (NASA TM X-73190), p. 32.

Scalo, J.M. (1973). Astrophys. J. 186, 967.

Scalo, J.M. (1974). Astrophys. J. 194, 361.

Spinrad, H. and Wing, R.F. (1969). Ann. Rev. Astron. Astrophys. 7, 249.

White, N.M. and Wing, R.F. (1978). Astrophys. J. 222, 209.

Wing, R.F. (1971). In Proceedings of the Conference on Late-Type Stars, G.W. Lockwood and H.M. Dyck, eds., (Kitt Peak National Observatory Contr. No. 554), p. 145.

Wing, R.F. (1972). Mem. Soc. Roy. Sci. Liege, 6th Ser. 3, 123.

Wing, R.F. (1973). In IAU Symp. No. 50, Spectral Classification and Multicolour Photometry, Ch. Fehrenbach and B.E. Westerlund, eds., p. 209.

Wing, R.F. (1978). Spectral Classifications and Color Temperatures for 280 Bright Stars in the Range K4-M8 (unpublished report; available on request).

Wing, R.F. and Lockwood, G.W. (1973). Astrophys. J. 184, 873.

Wing, R.F., Rinsland, C.P. and Joyce, R.R. (1977). In Symposium on Recent Results in Infrared Astrophysics, P. Dyal, ed., (NASA TM X-73190), p. 35.

Wing. R.F. and Spinrad, H. (1970). Astrophys. J. 159, 973.

Wing, R.F. and Warner, J.W. (1979). in preparation.

Wing, R.F. and White, N.M. (1978). In IAU Symposium No. 80, The HR Diagram, A.G.D. Philip and D.S. Hayes, eds., p. 451.

Wing, R.F. and Yorka, S.B. (1979). In IAU Colloq. No. 47, Spectral Classification of the Future, M.F. McCarthy, A.G.D. Philip and G.V. Coyne, eds., Vatican Obs., p. 519.

DISCUSSION

Garrison: In the spectra of some M giants, especially Mira variables, there is sometimes a considerable general weakening of the absolute strengths of TiO, so that visual classifiers use band ratios rather than absolute strengths. Can you detect this phenomenon with your filter system and eliminate its effects?

Wing: In the case of non-Miras, in which a general weakening of the bands may occur as a result of metal deficiency, it does not matter which TiO band one uses, or whether one uses absolute or relative strengths. These all give the same spectral type, and the weakening can be detected by comparison with the color of the star. In the case of the Mira variables, there is a serious problem in that different TiO bands often give different spectral types, but this is true of the band ratios as well as the absolute strengths. With the eight-color photometry the phenomenon can be detected because two TiO bands are measured — one from the ground state and one from an excited vibrational level — but there is nothing that can be done about it. The two bands are formed in different parts of the atmosphere, and I do not know how to say what spectral type is the "correct"

Vardya: Can one say anything about the luminosity class of S stars?

Wing: No, not from the spectrum. Most of the information we have about the luminosities of S stars is from statistical studies of their motions. The spectral features that might be expected to be sensitive to luminosity are, unfortunately, also very sensitive to the atmospheric structure and hence to the C/O ratio.

Vardya: What is the minimum information you require before you can say that a star is a Mira variable?

Wing: There are several ways to define a Mira variable, which are not exactly equivalent. Normally the classification of a variable as a Mira is based upon its light amplitude. But often a single spectrogram is sufficient to recognize a Mira unambiguously.

Mould: I would like to add to Wing's reply to Garrison that the veiling of some Mira and M supergiant spectra has the character of high temperature bound-free and free-free emission. The effect seems to be minimal in the bright 1μ region relative to the optical region, where the stellar flux is so very much less.