SCANS AND NARROW-BAND PHOTOMETRY OF LATE-TYPE STARS IN THE ONE-MICRON REGION

R. F. WING

Perkins Observatory, The Ohio State
and
Ohio Wesleyan Universities, Delaware, Ohio, U.S.A.

Abstract. A summary is given of the molecular bands occurring in the near-infrared spectra of cool stars, especially those having sufficient strength and freedom from contamination to be measurable by narrow-band photometry. In some cases useful indices of both temperature and luminosity can be obtained from such measurements. Several bands remain unidentified, including the 9910 Å band in late M dwarfs and at least nine bands in cool S stars.

Three topics of a spectroscopic nature are discussed. (1) In Mira variables, grossly different spectral types are sometimes obtained from zero-volt and excited TiO bands of the same band system. (2) A few M stars have been found to show bands of both VO and CN at the same time. They may be the coolest known supergiants, although there remains some doubt as to their luminosities. (3) The first results are given from a program of measuring crude C^{12}/C^{13} ratios from narrow-band photometry of sensitive points on the profile of the $\Delta v = +2$ band sequence of CN. The observations require only a few minutes per star, and the method can be applied to G and K giants and supergiants as well as to carbon stars.

1. Introduction

Narrow-band photometry obtained with scanners or interference filters is well suited to the measurement of molecular bands in the spectra of late-type stars. The method has great speed and accuracy, and the low spectral resolution is not a disadvantage in studies which only require indices of the integrated band strength. In the $1-\mu$ region, where the continuum is usually better defined than in other photoelectrically-accessible regions, the method has been applied to a variety of spectroscopic problems as well as to the determination of color temperatures and spectral types.

The present discussion will be limited to molecular bands, since the $1-\mu$ region contains only a few atomic lines strong enough for measurement by narrow-band photometry, and these have been avoided on most of the photometric systems used in this region. An important exception is the scanner system of Spinrad and Taylor (1969), which includes the temperature-sensitive Ca II line at 8662 Å and the luminosity-sensitive Na I doublet near 8190 Å. Consideration will be given to bands occurring throughout the near infrared from roughly 7000 Å to 11000 Å, since most of the observing programs involving the $1-\mu$ region span this entire interval.

1.1. TEMPERATURE CLASSIFICATION

Among the ordinary oxygen-rich stars of types G, K, and M, molecular bands sensitive primarily to temperature appear in the $1-\mu$ region only in types K4 and later: the strongest TiO bands are first measurable at K4 and the VO bands appear at about M5. CN bands can be measured in the G and early K stars but they convey little information about the temperature, being more useful as indicators of the luminosity

Contopoulos (ed.), Highlights of Astronomy, 285–306. *All Rights Reserved*

and/or composition. The TiO band strengths, on the other hand, are particularly good temperature indicators since they show relatively little dependence on the luminosity and – rather surprisingly – are also nearly independent of the metal abundance (Wing, 1973b; Glass and Feast, 1973). There are numerous TiO bands in the near infrared, as shown in Figure 1 (below). Any of them can be used equivalently to classify the nonvariable or small-range semi-regular or irregular variable stars; however, this is not the case for Mira variables, for which different bands often indicate different spectral types (see Section 4 below). Maximum sensitivity to spectral type is obtained by using the strongest band, the three-headed (0, 0) band of the γ system near 7100 Å, which is also the only TiO band to appear in K4 stars. The growth of this band with decreasing temperature is so rapid that all decimal subdivisions of the spectral subclasses (e.g. M2.1, M2.2, etc.) can meaningfully be used for observations having the normal photometric accuracy of 1 or 2%.

In the late M stars the TiO bands are very strong and are accompanied by bands of VO and H_2O. The H_2O bands have not been used for classification purposes, since their measurement is affected by the same bands in the Earth's atmosphere, but their behavior seems to be parallel to that of the VO bands near 1.05 μ, which serve as a very sensitive temperature criterion for classes M8–M10. There is evidence from the weak TiO bands near 1 μ (Lockwood, 1973) that the TiO abundance continues to increase beyond M8, although the photometric indices measuring stronger TiO bands at shorter wavelengths become saturated as a result of deterioration of the continuum. For this reason, we recommend using VO alone for photometric classification in the range M8–M10 (Wing and Lockwood, 1973). The VO strength is certainly very sensitive to temperature in this range, as is shown by its behavior in Mira variables, but its dependence upon the luminosity has not been established observationally. Fortunately (for classification purposes), stars with abnormal VO/TiO ratios such as those discussed in Section 5 appear to be relatively rare.

1.2. LUMINOSITY CLASSIFICATION

Of the various molecules with bands in the near infrared, only CN is of much use as a luminosity indicator; the others either show little dependence upon luminosity or appear in only certain types of stars. The positive correlation between CN strength and luminosity has long been known from observations of bands in the violet system. Griffin and Redman (1960), who made photoelectric measurements of the 4215 Å band, confirmed that the main luminosity classes of G and K stars are well separated by their CN strengths, but they cautioned against using CN as a luminosity criterion because many stars were found to have abnormally strong or weak CN strengths for their temperatures and luminosities.

The infrared CN bands show the same behavior as the violet bands, but whereas the violet bands cannot be measured in stars later than about M0 (because they are then much weaker than the strong atomic lines in their vicinity), the infrared bands can be observed to type M4 or even M5. Wing (1967c), using infrared scanner observations, found that the M giants, like the G and K giants, often have anomalous CN strengths, so that the CN bands cannot be trusted to give more than a coarse indication of the luminosity.

A more encouraging result was obtained in the case of M supergiants by White (1971, 1972). He measured the infrared CN bands in all M supergiants that had been classified on the MK system and found that the MK luminosity classes Ia, Iab, and Ib could be distinguished with a high degree of confidence on the basis of CN strength. We really don't understand why the CN bands 'behave themselves' better in supergiants than in giants, but it may reflect the fact that all the supergiants are young Population I stars, while the giants are from a mixture of populations with a wide range in age and mass.

Late-type dwarfs can be recognized in the infrared by the absence or near-absence of CN absorption. Significant CN strengths are sometimes seen in K dwarfs but never, to my knowledge, in M dwarfs. Dwarfs later than about M3 do show a single luminosity-sensitive band at 9910 Å (Wing and Ford, 1969), but it is still unidentified (see Section 2.1 below) and has not been included on the narrow-band photometric systems used to date for general classification purposes. Apart from the 9910 Å band, the M dwarfs show only the TiO bands, since even Wolf 359, which has the strongest TiO bands ever measured in a dwarf (Joy, 1947; Wing, 1973a), is not cool enough to show VO bands or the $1-\mu$ bands of water.

1.3. CARBON AND S-TYPE STARS

The $1-\mu$ spectra of carbon stars are dominated by the red system of CN to such an extent that it is difficult even to establish the presence of anything else. Relatively weak bands of the C_2 Phillips system have, however, been identified in a few stars of high carbon abundance class (McKellar, 1960a). A few additional absorptions have been noticed occasionally on scanner records (Wing, 1967c) and on image-tube spectrograms (Wing, 1972), but they have not been studied systematically. Several attempts have been made to indentify HCN and C_2H_2, both of which have favorable bands from the ground state near 1.03 μ. The earlier results were inconclusive, but according to Fujita (1973), M. Hirai recently has found strong evidence for C_2H_2 (and weaker evidence for HCN) on high-dispersion spectrograms. Once the identifications of these features are firmly established, narrow-band photometry could be used effectively for a survey of the occurrence and behavior of these interesting molecules.

The S stars are difficult to study by narrow-band photometry because of the great variety in their molecular spectra (Wing, 1972). Every molecule found in the infrared spectra of M stars can also be found in S-star spectra, which in addition show bands of ZrO near 9300 Å (always) and of LaO near 7400 Å and 7900 Å (if sufficiently cool). Those showing the LaO bands are further complicated by several unidentified bands which are discussed in the next section.

2. Unidentified Molecular Bands

Among the giants and supergiants of types G, K, and M, I am not aware of any unidentified spectral features that can be seen at low resolution in the 7000–11000 Å range. This is not to say that all the little wiggles in the spectra have been accounted for, since such detailed studies have only been carried out for a few stars. It would not be surprising if the very late M stars have detectable absorptions which cannot be attributed to TiO, VO, or H_2O; but if such features exist, they have not been noticed to date, and indeed they would be very hard to find owing to the great strength and spectral coverage of the known bands.

In the near-infrared spectra of other types of cool stars, there are ten molecular bands which remain unidentified – one in M dwarfs and nine in S stars – and which are definite enough to have been specifically discussed in the literature. This I think is a good number of unidentified features: not depressingly large, yet large enough to prevent us from becoming bored, overconfident, or unemployed.

2.1. The 9910 Å band in M dwarfs

M dwarfs differ from M giants in the $1-\mu$ region in having greatly enhanced features due to atomic sodium and potassium and an unidentified molecular band centered at 9910 Å (Wing and Ford, 1969). These features are illustrated in Figure 1, where

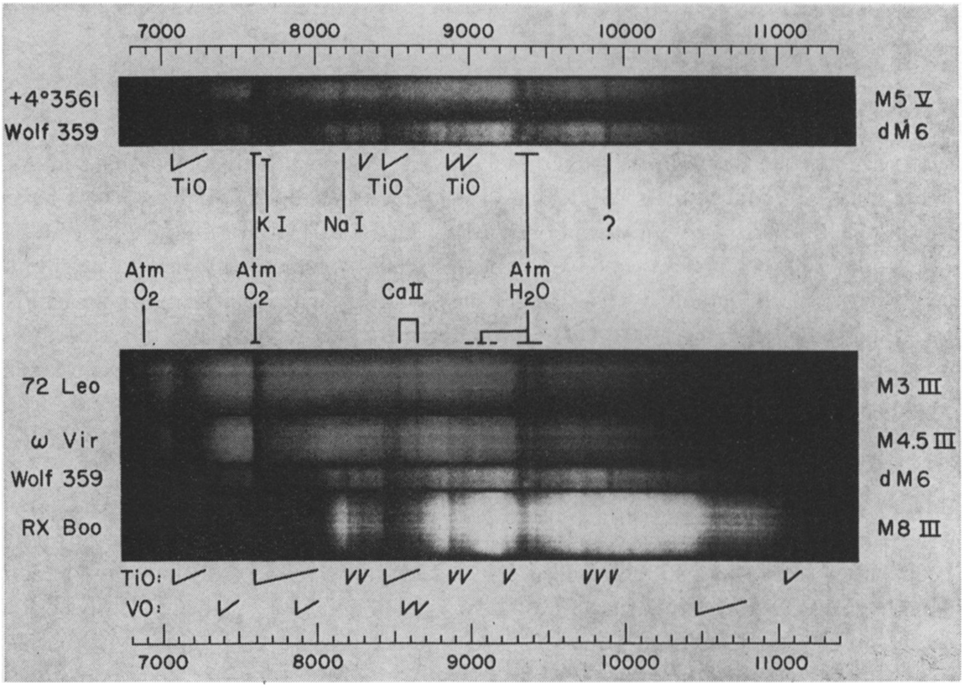

Fig. 1. Spectrograms of M dwarfs and giants in the 7000–11000 Å region taken with a Carnegie S-1 image tube at the 72-in. Perkins telescope in collaboration with W. K. Ford, Jr. Wolf 359, which shows great enhancements of lines of neutral potassium and sodium and an unidentified band at 9910 Å, is compared to Barnard's star = BD + 4°3561a (*above*) and to a set of giant stars (*below*). Bands of TiO and VO are marked beneath the spectra.

the spectrogram of Wolf 359 on which the 9910 Å band was discovered is compared to a sequence of M giants (*below*) and to the somewhat warmer dwarf, Barnard's star (*above*). These plates were taken with the Perkins 72-in. telescope of the Ohio State and Ohio Wesleyan Universities and an S-1 Carnegie image tube; the original dispersion was 250 Å mm^{-1}. Note that the 9910 Å band does not appear in giants of any spectral type and is considerably stronger in Wolf 359 ($M_V = 16.7$) than in Barnard's star ($M_V = 13.3$).

Whitford (1972, 1974) has used scanner observations of this band to evaluate the contribution of late M dwarfs to the integrated spectra of external galaxies. It is a very useful band for that particular problem because it is exclusively an M dwarf feature, and it occurs in the spectral region where M dwarfs might be expected to make their greatest contribution to a composite spectrum.

In stars the 9910 Å band shows the same behavior as one in the visible region which Pesch (1972) has identified with CaOH. It seemed natural to suppose that the 9910 Å. band might be produced by the same molecule, and Dr Paul Byard and I checked this possibility with a laboratory experiment. By holding a piece of calcium carbide in an oxygen-enriched bunsen flame, we obtained a bright yellow flame, a spectrogram of which showed that most of the visible light was radiated in the Pesch band. An infrared spectrogram of the same flame showed some bands of calcium monoxide but, unfortunately, showed nothing attributable to the hydroxide and nothing at 9910 Å. The band thus remains unidentified. We are planning to study other metallic hydroxides in a similar manner, and we certainly would also encourage any other attempts to identify this important feature.

2.2. Unidentified bands in s stars

The S-type stars – particularly the S-type Mira variables at minimum light – are the richest source of unidentified molecular bands in the $1-\mu$ region. The four Keenan bands near 8500 Å (Keenan, 1950) have defied all attempts at identification for more than two decades, despite their sharp, easily-measurable bandheads and the considerable strength that they occasionally attain. It has, however, been established that they are not all produced by the same molecule (Wyckoff, 1970; Wing ,1972). Five additional bands – not as strong or sharp, but occurring in the same stars – have been found by the writer at longer wavelengths. They, too, are unidentified. Their wavelengths, appearance, and behavior are reported in Wing (1972). One of them is centered at about 9900 Å; it seems unlikely that it is the same as the band appearing in M dwarfs, but the available observations do not rule out this possibility. Between the unidentified bands in cool S stars evidence is sometimes seen of additional structure which should be examined at higher spectral resolution than has been employed to date.

2.3. The importance of the unidentified bands

The reasons for being interested in the bands shown by cool S stars and in the 9910 Å band in M dwarfs are quite different. The 9910 Å band, as far as we know, occurs in *all* stars of sufficiently low temperature and high gas pressure; identifying this band is therefore not likely to teach us anything about chemical abundances or nucleosynthesis. The usefulness of the band lies in the fact that it uniquely identifies cool dwarfs and the contribution they make to integrated spectra. For this purpose we can go ahead and use the band without waiting to learn its identification, which is not even relevant.

In contrast, the bands in S stars are of little practical use as long as they remain unidentified, but their identifications may prove to be extremely interesting. The S stars show great enhancements of features due to the heavy *s*-process metals and rare earths, abnormal abundance ratios among the light elements C, N, and O, and the presence of the unstable element technetium and possibly even the still more unstable promethium. We need all the observational clues we can get to help us understand the nuclear processes which have occurred in S stars. Since the unidentified bands found in these stars do not appear in normal M stars of any temperature, they probably involve elements that are greatly overabundant in S stars. Thus their eventual identification may well have significance reaching far outside the relatively narrow field of infrared spectroscopy.

3. The Eight-Color Photometry

A large part of the currently-available data on molecular band strengths in the near infrared has been obtained on an eight-color system employing interference filters of approximately 50 Å width (Wing, 1971a). The system measures five quantities: the $I(104)$ magnitude (Wing, 1967a), the continuum color, and the strengths of TiO, VO, and CN. The filters are centred at 7117, 7544, 7809, 8122, 10395, 10544, 10804, and 10975 Å; they measure the strongest bands of all three molecules as well as the best available continuum points in most kinds of cool stars. Since 1969, the writer and several collaborators at the Ohio State University have made more than 4000 observations on this system using various telescopes at the Kitt Peak, Cerro Tololo, and Lowell Observatories.

In a related development, a five-color system measuring $I(104)$ magnitude, color, TiO, and VO has been set up by Lockwood at Kitt Peak. It too has been used extensively, primarily for studies of Mira variables (Lockwood, 1972) and infrared stars.

Here I would like to present a brief summary of the projects involving narrow-band photometry of molecular bands in the near infrared that have been carried out or are now in progress. The observations discussed here have been made on the Ohio State eight-color system unless otherwise stated.

3.1. BRIGHT STARS

In order to provide a large body of homogeneous data on the colors, spectral types, and CN strengths of bright stars, I am observing all stars expected to be brighter than $I(104) = +2.5$ at 1.04 μ. There are approximately 1000 such stars, mostly late-type giants, and the observations are 70% complete. Stars showing TiO absorption are being classified according to an index of the strength of the (0, 0) band near 7100 Å, calibrated with giant stars classified on the MK system by Keenan. The same calibration is also being used for stars of other luminosity classes.

3.2. M SUPERGIANTS

Colors and spectral classifications for 135 M supergiants are being prepared for publication by White and the writer. The strong correlation between CN strength and MK luminosity subclass found by White (1971, 1972) greatly enhances the value of these stars for galactic structure studies, particularly in the case of obscured regions which are best observed in the infrared. White is now studying the variability and intrinsic colors of these stars.

3.3. M DWARFS

Since a new list of standards for the spectral classification of M dwarfs was presented at Córdoba in 1971 (Wing, 1973a), the project has been enlarged, with the collaboration of C. A. Dean, to include essentially all stars within 10 pc of the Sun. The observations are more than 50% complete and will be used to study the shape and intrinsic width of the lower main sequence.

3.4. CARBON STARS

Approximately 350 of the brighter carbon stars have been observed by Baumert (1972) and the writer on the eight-color system, some of them repeatedly. Baumert has shown that carbon stars of the various variability classes tend to lie in different regions of a diagram of CN strength vs color temperature; in particular the Mira variables have substantially weaker CN than the semi-regular or irregular variables of the same temperature. Baumert (1974) has also derived mean absolute infrared magnitudes for carbon stars grouped in various ways, using the $I(104)$ magnitudes and a statistical analysis of their proper motions.

3.5. R CORONAE BOREALIS STARS

Eight-color photometry of R CrB and RY Sgr has been obtained at both maximum and minimum light. At faint phases both stars show an excess flux in the seventh filter attributed to emission in the He I line at 10830 Å; it will, of course, be important to secure a spectrogram or continuous scan to confirm this identification. On one occasion emission by the CN molecule was observed in R CrB (Wing *et al.*, 1972).

3.6. RED GIANTS IN GLOBULAR CLUSTERS

Fourteen red variable stars belonging to the southern globular clusters 47 Tuc, ω Cen, and NGC 362 have been classified by narrow-band photometry (Wing, 1973b, c). The types observed in 47 Tuc are in the range M3.1 to M7.5; stars as late as M5 also occur in ω Cen although several of its variables are of type K. Despite the great difference in the metallicities of these clusters, there is no clear systematic difference in the TiO strengths at a given temperature. Three carbon stars in the field of

ω Cen have been studied by Wing and Stock (1973), although one of them has been found not to belong to the cluster (Smith and Wing, 1973).

3.7. INFRARED STARS

Objects which are bright enough at 2 μ to be included in the IRC catalogue (Neugebauer and Leighton, 1969) and yet faint enough visually to have been excluded from older catalogues nearly always turn out to be late M stars or (much less frequently) carbon stars. Narrow-band photometry is an efficient means of identifying and classifying such stars. Lockwood has used his five-color system extensively for this purpose (Lockwood and McMillan, 1971) and will soon publish additional finding charts and spectral classifications.

The general area of the sky in the direction of the galactic center contains a concentration of IRC objects and the largest proportion of unidentified sources. Some 50 of these have been observed on the eight-color system by Warner and the writer. Only one carbon star has been found, and one object proved to be the combined signal from an M8 star and the heavily-reddened globular cluster Terzan 5 (Wing *et al.*, 1973). All the others observed to date are M giants and supergiants, having types in the range M3–M9 and varying degrees of interstellar reddening. Attention has already been called to the three objects which appear to have the highest luminosities, greatest distances, and closest proximities to the galactic center of the stars in this sample (Wing and Warner, 1972).

3.8. MIRA VARIABLES

Lockwood's (1972) large body of five-color photometry has been combined with observations on the Lick 27-color scanner system (Wing, 1967b, c) and the Ohio State eight-color system (Baumert and Wing, 1974) to produce a catalogue of the ranges in spectral type and $I(104)$ magnitude of approximately 300 Mira variables. This is now being prepared for the printer by Lockwood and the writer. Light curves in $I(104)$ and concurrent spectral types have been published for 25 variables (Lockwood and Wing, 1971).

Of all the Miras studied, the infrared star IK Tau (NML Tau) is the only one which consistently reaches spectral type M10 at minimum light, if our rather stringent criterion for this type is employed (Wing and Lockwood, 1973). In fact we have considered it necessary to introduce types later than M10.0 to accomodate the extraordinary spectrum of this star.

4. Anomalous TiO Band Strengths in Miras

Classification by narrow-band photometry is generally based upon the strengths of a relatively small number of spectral features, and often only one. For example, the types published to date for K4–M6 stars observed on the eight-color system depend solely upon the strength of the (0, 0) band of TiO near 7100 Å. In such a case the type can be assigned to the same accuracy as the photometric measurement, since there is no conflicting evidence. The question arises, however, whether the same precise type would have been assigned if some other spectral feature had been used as the criterion. The spectroscopic classifier, after all, normally inspects many features before deciding on the type and is frequently aware that the types indicated by the various criteria are not identical.

Lockwood and I have looked into this question by comparing the types assigned to M stars on our respective photometric systems, which use different bands (and different reduction procedures) to determine the TiO strength. Lockwood's (1972) five-color system measures the (2, 3) band of the γ (triplet) system near 7800 Å and the (0, 0) band of an infrared singlet system near 8900 Å. These are also the features that I used on the Lick scanner system (Wing, 1967b; Wing and Spinrad, 1970); neither arises from the ground state of the molecule, since the former band is excited vibrationally and the latter electronically. The eight-color system, on the other hand, uses the (0, 0) band of the γ system, which does arise from the ground state. A program of simultaneous observations on all three systems was carried out, so that the types assigned could be compared for variable stars as well as non-variables. Systematic differences should be negligible since the same stars have been used to calibrate the spectral-type indices on all three systems, the primary standards being those of Keenan (1963).

For the non-variable and small-range variable M stars earlier than M8, the agreement in the types was excellent, the differences being no larger than expected from the uncertainties quoted on the respective systems. For stars later than M8 the agreement was again excellent if the types were based on VO alone; however, as mentioned earlier, we found that our systems do not give a reliable TiO index in the very late types because of absorption in the filters used as continuum points.

The surprise came when comparing results for Mira variables in the range M4–M7, for which the types depend on the TiO strength. The agreement, frankly, was terrible, with discordances up to two subclasses, usually in the sense that Lockwood's types were earlier than mine. Typical differences for Miras were five to ten times as large as those for non-Miras in the same range of spectral type. It is to be noted that the problem is present even at relatively early spectral types, for which the level of the continuum is well established on all three photometric systems. It is necessary to conclude that the different bands of TiO are simply telling different stories about the TiO abundance, and hence the temperature, of the star.

As it happens, the (2, 3) band used on Lockwood's system is also measured on the eight-color system, by the third filter whose primary function is as a continuum point in carbon stars. It has therefore been possible to confirm that the measurements of this band on the different systems are self-consistent, and it is consequently possible to assign types for Miras from the eight-color photometry that are the same as would be given on Lockwood's system. Further, although the discrepancies were first noted by comparing results from two different systems, the effect can be studied by means of the eight-color photometry alone.

The phenomenon is illustrated in Figure 2, where the Mira variable U Cet, observed one month past maximum on 5 November 1969, is compared to 56 Leo, a small-range irregular variable also known as VY Leo. Although the two stars have similar TiO (0, 0) band strengths at filter 1, U Cet has a much weaker (2, 3) band than 56 Leo and a much bluer energy distribution. From comparisons with many other stars we can state that 56 Leo is a normal, unreddened giant, in that its color and both of its TiO bands all indicate the same spectral type, M5.8 III. For U Cet, on the other hand, we obtain M6.0 from the (0, 0) band but M4.5 from the (2, 3) band, while the energy distribution is that of a normal giant of type M3! What, then, should we say was the spectral type of U Cet on 5 November 1969?

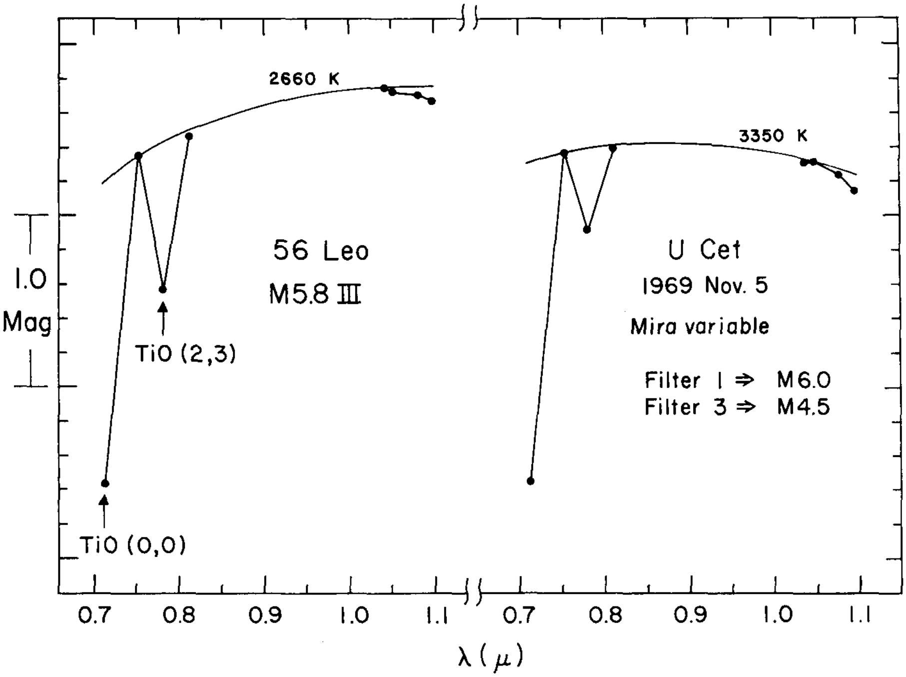

Fig. 2. Eight-color spectra of the normal giant 56 Leo (*left*) and the Mira variable U Cet (*right*). F_λ is plotted on a magnitude scale against the wavelength in microns. Blackbody curves of the indicated temperatures have been fitted to the spectra. Filters 1 and 3 are depressed by TiO; note that the relative strengths of these bands are very different in the two stars.

While it is clear that the absolute strength of at least one of the TiO bands observed in U Cet is affected by some process which renders it unreliable as a spectral-type indicator, it should be equally clear that one would do no better to use their relative strengths, as is done in the spectroscopic classification of Miras (Merrill *et al.*, 1962; Keenan, 1966). In the example shown in Figure 2, the excited band is so much weaker than the zero-volt band that one would have to assign a type later than M8 to U Cet on the basis of the relative band strengths. This is another way of saying that the two bands imply an implausibly low vibrational temperature.

Although the discrepancies shown in Figure 2 are fairly typical, it would be wrong to imply that the (0, 0) band always indicates a later type than the excited band in Miras, or that the bands are always too strong for the color. This is *usually* the sense of the discrepancy, but as we have shown in previous work (Wing, 1967c; Spinrad and Wing, 1969; Lockwood, 1972), each Mira executes large loops in diagrams of band strengths vs color, so that occasionally the bands appear of normal strength or even weak for the color.

In discussing the loop phenomenon, we were led to conclude that the measurements of band strength and of continuum color refer to two different layers of the atmosphere having appreciably different temperatures. Now it seems that we must go a step farther and conclude that contributions to the zero-volt and excited TiO bands are likewise coming from different layers, the cooler one of which is considerably cooler than the photosphere. It does not seem unreasonable to suppose that a cloud of TiO molecules formed at minimum light (the phase of lowest temperature, greatest band strength, and greatest physical extent) is left behind as the star contracts, becoming brighter and warmer in the photosphere. Such a cloud would quickly cool, so that it would absorb mostly from the ground state and very little from excited states, thus altering the relative and absolute band strengths of the underlying photospheric spectrum. It is not clear, however, how long this cloud should be expected to survive as a significant contributor to the (0, 0) band. By following several Miras with eight-color photometry throughout their cycles, it may be possible to determine whether this picture is basically correct.

Another factor which may come into play is a differential radial velocity between two layers contributing to the absorption. Since the lines of the (0, 0) band are no doubt often saturated while those of a weaker excited band may not be, the effect of a velocity difference would be to increase the strength of the (0, 0) band without affecting the excited band. Observations of line doubling in Mira variables (Merrill and Greenstein, 1958; Maehara, 1968; Spinrad and Wing, 1969) show that such effects do occur, and instances of line broadening are presumably much more common than clear cases of line doubling.

An interesting example of discrepant types from different TiO bands in a Mira variable has been noted in the spectroscopic literature by Wyckoff (1970), who observed the 1966 minimum of Z Oph in the near infrared. It is not clear to me, however, whether this is an example of the same effect that we have been discussing here, since she did not observe the bands from the ground state. Since the classification of M stars by photographic spectroscopy can have an accuracy of one-quarter of a subclass (Keenan, 1963), while the discrepancies in the types of Miras indicated by different bands commonly amount to one or two full subclasses, one might wonder why this effect was not already well known. The answer probably lies in the fact that the TiO (0, 0) bands are in general too strong to measure on photographic plates whenever the excited bands are strong enough to use for classification. It might nevertheless be worthwhile to re-examine plate collections of early-type Miras to try to find further examples of this phenomenon.

5. Stars Showing Both VO and CN Bands

In normal giant stars the CN bands are fairly strong throughout the interval G5–M3, passing through an intensity maximum in the middle K types and fading to invisibility after about M5. The VO bands show completely different behavior, appearing only in the late M stars and becoming strongest in the latest types. It is sometimes possible to detect both molecules in stars of types M5.5 or M6.0, but the region of overlap is very small and both molecules are then very weak.

Supergiants of types G, K, and M show stronger CN bands than giants of the same spectral types. The enhancement is most pronounced in the M stars since the bands do not fade with decreasing temperature as fast in the supergiants as in the giants. The coolest supergiants known – and which are certain from cluster or association membership to be post-main-sequence supergiants – have types around M4.5 or M5.0 and quite substantial CN strengths. These stars are not cool enough to show appreciable VO absorption, but their CN strength leads one to suspect that if sufficiently cool supergiants exist, they might show both VO and CN bands strongly. When the type is later than M4, the presence of CN can really only be tested at the (0, 0) band near 11000 Å, since the bands at shorter wavelengths become swamped by the strong TiO absorption.

5.1. VX SAGITTARII

This unusual star seems to combine some of the properties of supergiants and Mira variables without being a certain member of either category. Its long mean cycle length (732 days) and the semi-regular nature of its variations are characteristic of late-type supergiants, as are some of the spectral details which show that the atmosphere is greatly extended; however, its large amplitude, its late spectral type at minimum, and the irregular decrement of its Balmer emission lines are properties generally associated with Mira variables. Recent discussions of its spectrum have been given by Wallerstein (1971) and by Humphreys and Lockwood (1972). Most of the attention recently given this star was stimulated by the discovery of its very strong radio OH emission lines (Caswell and Robinson, 1970) and far-infrared excess (Humphreys *et al.*, 1972). In these respects VX Sgr resembles two other very remarkable objects, VY CMa and NML Cyg.

When VX Sgr was first observed on the eight-color system on 15 June 1971, I was so struck by the unusual shape of its spectrum in the last four filters that I was afraid something had gone wrong with the equipment. This observation is shown in Figure 3, where the depressions attributed to VO and CN are labeled and are seen to be quite strong. Although I have given reasons above for thinking that these molecules could conceivably both be strong in the same spectrum, no spectrum like this had ever been observed before.

It should be stated clearly that the observation of CN absorption does not necessarily prove that VX Sgr is a supergiant. It is hard to prove anything about an object that is unique. All I can say is that this is how I think the spectrum of an extremely cool supergiant should look, if such stars exist.

The spectrum of VX Sgr can be classified if the VO strength is used for the temperature class (Wing and Lockwood, 1973) and the CN strength for the luminosity class (White, 1971). The result for 15 June 1971 is M8.4 Ia. I prefer to give this type as M8.4 Iap, where the 'p' is a reminder of the peculiar nature of this object and a warning that the usual calibrations in terms of temperature and absolute magnitude may not apply to it.

An interesting series of observations of VX Sgr, also made in 1971, has been reported by Humphreys and Lockwood (1972), who observed the spectral type to progress from M4 in February to M9.5 in October, the latter type being entirely unprecedented for supergiants and very unusual even for Mira variables. One of their spectrograms was taken on the same night as the eight-color observation shown here, and they classified it as M5e I, much earlier than my classification. It appears that this discrepancy is the result of yet another spectral peculiarity of this star that has not previously been pointed out: the VO bands are abnormally strong relative to the TiO bands. All the types earlier than M8 given by Humphreys and Lockwood are based on TiO absorption seen on spectrograms in the blue, while their latest types are from photometry on the five-color system and thus depend primarily on the VO strength. Both molecules were individually observed to strengthen as the star became fainter, but there was probably a discontinuity in the classifications when the criterion changed.

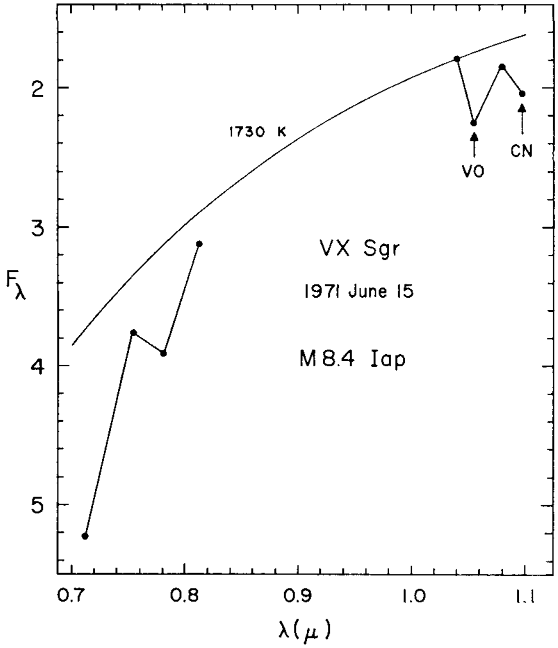

Fig. 3. The eight-color spectrum of VX Sgr on 1971 June 15, showing the simultaneous presence of bands of VO and CN. On this date the TiO type was M5 and the VO type M8.4. The position of the blackbody continuum was estimated in the manner discussed in the text. No corrections for interstellar reddening have been applied to these data.

Although it is the fortunate circumstance of simultaneous observations on 15 June 1971 that gives the best evidence for a systematic difference between the TiO types and VO types of VX Sgr, some supporting evidence can be found in the eight-color observation of Figure 3 alone. It is difficult to measure the TiO strength in the infrared when VO is also present because none of the first four filters is then a good continuum point; the additional presence of CN in this case makes the situation still worse. Nevertheless, we have estimated the position of the continuum (represented in the figure by a blackbody curve) in this region by requiring the depressions of filters 2 and 4 due to VO and CN, respectively, to be of normal strength relative to the depressions at filters 6 and 8 by the same molecules. Then the absorption by TiO at filters 1 and 3, measured relative to this continuum, indicates a spectral type of M5, in agreement with the result of Humphreys and Lockwood (1972) for the same date and confirming that a discrepancy exists between the TiO types and VO types.

5.2. RELATED OBJECTS

We now ask whether any other stars show signs of the two spectral peculiarities – the simultaneous presence of VO and CN, and the abnormally great strength of VO relative to TiO – which can be detected by the eight-color photometry and which set VX Sgr apart from the vast majority of late M stars. It is natural to look first at VY CMa in view of its many similarities to VX Sgr (Wallerstein, 1971), but I have never observed VY CMa when it was cool enough to show the VO bands, and I don't know if it ever is.

W Hya, one of the brightest stars in the infrared (Wing, 1971b), has long been known to have abnormally strong VO bands for its TiO strength (Cameron and Nassau, 1955). Furthermore its variability type, like that of VX Sgr, is difficult to assign: Keenan (1966) considers it a Mira variable for spectroscopic reasons, but it has the small amplitude of a semi-regular variable. It seems to me possible that it is a very cool supergiant, although I have not been able to detect CN in its spectrum. This possibility can be checked directly by a trigonometric parallax measurement; if it is only a giant, it should be one of the nearest M giants to the Sun with an easily measurable parallax.

The star whose infrared molecular spectrum seems most similar to that of VX Sgr is none other than the famous infrared star and intense OH emitter, NML Cyg. Its classification as an M6 star by Wing *et al.* (1967) was based upon the sum of the TiO and VO indices, but as we pointed out, the VO bands are slightly stronger and the TiO bands slightly weaker than in a normal M6 giant. The discrepancy is not as large as shown by VX Sgr, but it is another reason for considering these stars to be closely related. Furthermore, although this was not clear from the raw data used by Wing *et al.* (1967), the (0, 0) band of CN is fairly strong in NML Cyg, and its identification has been confirmed by continuous scans obtained by Spinrad and the writer. Neither VO nor CN is as strong in NML Cyg as in VX Sgr, however. Herbig and Zappala (1970) have classified this star as M6 III since no indicators of high luminosity were seen in the 7000–9000 Å region, but I believe that this simply shows once again the importance of observing the uncontaminated CN (0, 0) band near 11 000 Å whenever the oxide bands are strong. Most authors (e.g. Johnson, 1967), on the basis of its very red color, have considered NML Cyg to be a distant and heavily-reddened supergiant, and this interpretation would seem to be supported both by the presence of CN and by the abnormal relative strengths of VO and TiO. At least we can say that NML Cyg resembles VX Sgr more closely than an ordinary giant.

Figure 4 shows the eight-color spectrum of V1804 Sgr = IRC −30350, which we suggest may be a cooler version of VX Sgr (Wing and Warner, 1972). The CN strength indicated by the last filter is less than in VX Sgr but still enough for a Ia luminosity classification; the VO bands indicate type M9.1. The position of the 'continuum' has been estimated in the same manner as described above for VX Sgr. This star is extremely red, and at the time of this observation its visual magnitude was estimated to be $V \approx 17.5$.

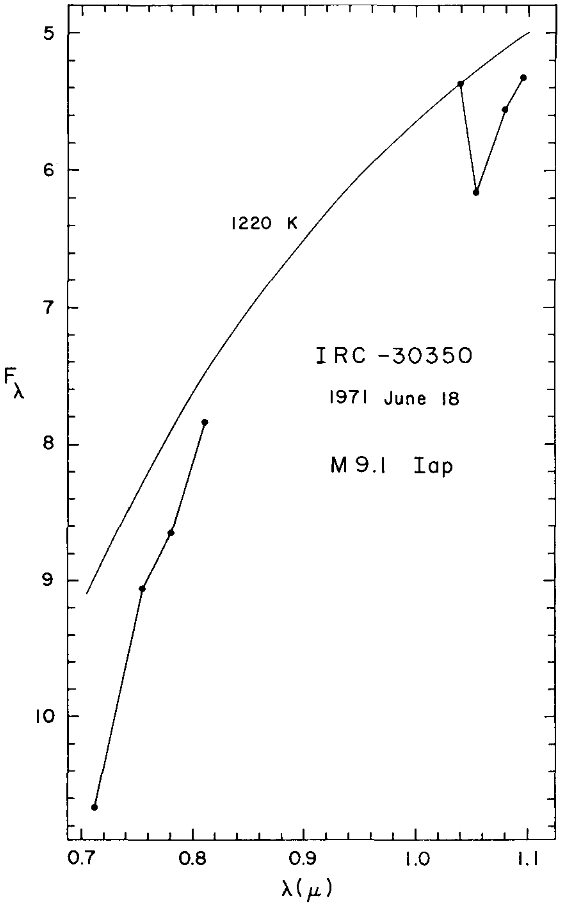

Fig. 4. The eight-color spectrum of the infrared star IRC −30350, which has been identified with the little-studied variable V1804 Sgr. It has stronger VO bands and a redder color than the observation of VX Sgr shown in Figure 3, but it also seems to have substantial absorption by the (0, 0) band of CN in the last filter. The star was barely visible at $V \approx 17.5$ when observed on 1971 June 18 with the 150-cm telescope at Cerro Tololo Inter-American Observatory.

We have seen that measurements of the near-infrared bands of TiO, VO, and CN provide a means of singling out stars that have spectacular characteristics in the far-infrared and radio regions. They also give us a way of knowing that stars like NML Cyg and V1804 Sgr, which are so faint at short wavelengths that their spectras are largely unknown, are related to better-known objects like VX Sgr and VY CMa. At the present time we don't even know if these stars are pre- or post-main-sequence objects. However, the recognition of similarities and differences in their molecular spectra, by indicating their relationship to each other and to other stars, may prove to be an important step towards understanding their evolutionary state.

6. The Measurement of C^{12}/C^{13} Ratios by Narrow-Band Photometry

Until quite recently, the only observational data on carbon isotope ratios outside the solar system had come from carbon stars, whose C_2 bands in the visible region made the detection of C^{13} very easy. Most carbon stars were found to have substantial amounts of C^{13}, with C^{12}/C^{13} ratios in the range 4 to 20 or so, while a few did not show detectable C^{13} features. Since carbon stars have obviously abnormal compositions, it was perhaps natural to regard their low C^{12}/C^{13} ratios as abnormal, and it was generally assumed (for lack of evidence to the contrary) that normal giant stars have C^{12}/C^{13} ratios near the solar/terrestrial value of 90.

The first identifications of features involving C^{13} in non-carbon stars, except for the Sun, were made in 1968 by Connes *et al.* (1968) and by Spinrad (Spinrad and Wing, 1969), both independently analyzing the same high-resolution infrared spectra of α Ori obtained by Connes. They identified numerous lines of $C^{13}O^{16}$ near 2.3 μ and found that the bandheads were strong enough to be visible at much lower resolution. Shortly thereafter, the paper by Johnson *et al.* (1968) showing medium-resolution infrared spectra of various late-type giants and supergiants appeared just as Spinrad and I were completing a review of infrared spectra (Spinrad and Wing, 1969), and we saw that star after star showed the same little dips that had been identified with $C^{13}O^{16}$ in α Ori. The implication that normal evolved giants and supergiants have mixed processed material to their surfaces was not hard for me to accept since I had already drawn this conclusion from the weakness of CN in T Tau stars.

During the past few years, C^{12}/C^{13} ratios have been derived for a few K giants from high-resolution material (Lambert and Dearborn, 1972; Krupp, 1973; Upson, 1973) using bands of CH and CN as well as CO. While detailed studies such as these no doubt provide the most reliable results, they are feasible for only the brightest stars. A somewhat larger number of stars can be reached by means of medium-resolution spectroscopy of the infrared CO bands (Ridgway, 1974). However, to investigate the incidence of various isotope ratios among stars of all luminosities, metallicities, and populations, including peculiar stars and members of clusters, it is necessary to develop a method for obtaining crude isotope ratios for much fainter stars. Dr Irene Marenin-Little and I have found that narrow-band photometry can provide this information in an efficient manner.

6.1. THE PHOTOMETRIC SYSTEM

There are problems associated with using any of the various molecular bands containing carbon for photometric measurements of the isotope ratio. The C_2 bands are not strong enough for this purpose except in the carbon stars, and thus would provide no new information. The violet CN bands and the G band of CH are badly contaminated by atomic lines, while the CO bands lie beyond the range of photoelectric detectors. Of the various bands of the CN red system, those lying longward of the (0, 0) band at 11000 Å are favorable from the standpoint of the direction of the isotope shift, but unfortunately the strongest $C^{13}N^{14}$ bandheads lie in regions of strong atmospheric water absorption and have been detected only in scans made from the Stratoscope balloon (Wing and Spinrad, 1970).

We are left with the red CN bands lying shortward of the (0, 0) band. Their $C^{13}N^{14}$ components are hard to identify on spectrograms because their shifts are in the wrong direction (i.e. the $C^{13}N^{14}$ bands lie within the $C^{12}N^{14}$ bands), but they must nonetheless affect the absorption profile of the band. The idea is to measure photoelectrically a small number of points on the band profile that are sensitive to the contribution by $C^{13}N^{14}$. We have chosen the (2, 0) band near 7900 Å as being the best combination of band strength and freedom from contamination by stellar atomic lines and atmospheric water lines, while also having an adequately large isotope shift.

In order to choose the optimum bandwidths and central wavelengths for these measurements, Dr Marenin-Little computed synthetic spectra for the $\Delta v = +2$ sequence of CN for various temperatures, CN abundances, and C^{12}/C^{13} ratios. Two of these spectra are illustrated in Figure 5; both were computed for a temperature of 3000 K and for the same amount of $C^{12}N^{14}$ (more than in a K giant, but less than in a typical carbon star), but they differ in the amount of $C^{13}N^{14}$, corresponding to $C^{12}/$

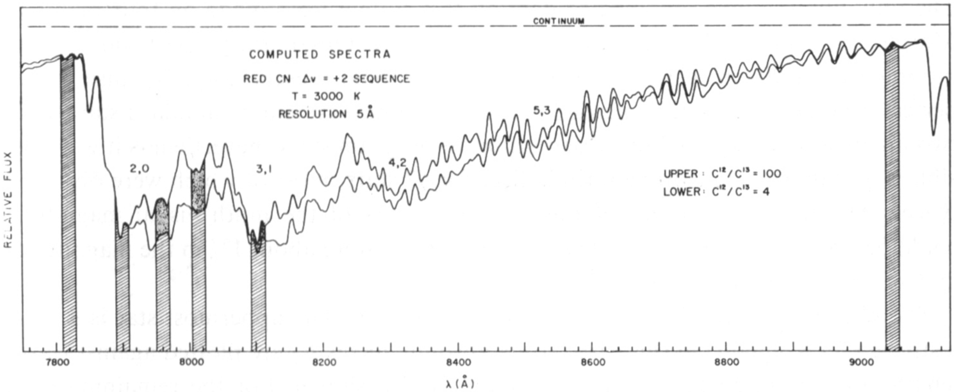

Fig. 5. Synthetic spectra of the CN molecule in the region 7800–9100 Å, calculated by I. R. Marenin-Little and plotted on a linear scale. They show the effect of varying the amount of $C^{13}N^{14}$ while holding $C^{12}N^{14}$ constant. The upper curve has $C^{12}/C^{13} = 100$ (close to the solar value) and the effect of $C^{13}N^{14}$ is negligible; the lower curve has $C^{12}/C^{13} = 4$. The vertical columns represent 20 Å bandpasses selected for scanner measurements of the isotope ratio.

C^{13} ratios of 100 and 4. Details of the calculations will be given elsewhere; suffice it to say here that the positions, strengths and profiles of approximately 5000 lines were computed for each spectrum before a smearing function was applied to degrade the resolution to 5 Å.

Our choices of the regions to be measured are indicated by the six vertical columns in Figure 5, which represent 20 Å bandpasses centred at 7820, 7900, 7960, 8014, 8104, and 9048 Å. The first and sixth points have been placed just shortward of the first heads of the (2, 0) and (1, 0) bands, and they serve to establish the level of the best available approximation to the continuum. The second point measures $C^{12}N^{14}$ and is almost completely independent of the isotope ratio, while the third point is very sensitive to the presence of $C^{13}N^{14}$. Thus the relative depressions at points 2 and 3, taken with respect to a continuum fitted to points 1 and 6, yield an index of the isotope ratio. Points 4 and 5 are intended to provide redundant information, and to serve as a check that the isotope ratios obtained are not a function of the band strength.

Observations on this system can most conveniently be made with a photoelectric scanner having an instrumental resolution of 1 or 2 Å. Because of the importance of the continuum point at 9048 Å, it is necessary to use an S-1 cell, although the other points could be measured with much more sensitive detectors. Reductions follow the procedures used for the eight-color photometry: the data are reduced to an absolute flux system by means of observations of standard stars which have been tied to α Lyr, which in turn is assumed to follow the energy distribution of the model adopted for it by Schild *et al.* (1971). A blackbody curve is passed through the continuum points, and the depressions at the other points measured from this continuum become the raw data from which CN abundances and carbon isotope ratios can be derived.

6.2. OBSERVATIONS AND RESULTS

The only observations obtained to date on this system were made on four nights in March and April 1972, with the Harvard College Observatory spectrum scanner mounted on a 90-cm telescope at Kitt Peak National Observatory. Because of imperfect weather and the time needed to establish a new system of standard stars, only two nights were really used for observations of program stars; nevertheless it was possible to obtain carbon isotope ratio indices for 47 stars, most of which were observed twice. Despite the small size of the telescope, stars of the ninth visual magnitude could be observed in about 1 h. The probable errors were about 1% in the magnitudes and somewhat less in the indices.

The observations of 17 stars are plotted in Figure 6. The uppermost star is ϕ Aur, a strong-CN K3 giant; in this case the six absolute fluxes F_λ are plotted against wavelength, and the fitted blackbody continuum is also shown. For the remaining stars – for greater convenience in interpreting the spectral shapes, and to save paper – we have plotted only the depressions at the first five points, i.e. the magnitude differences between the observed fluxes and the blackbody continua.

The four stars in the left half of Figure 6 are carbon stars. From the relative depressions at the second and third points, it is obvious that HD 52432 has a much higher proportion of C^{13} than X Cnc, which in turn has more than TT CVn or HD 137613. This agrees with what was already known from inspection of the C_2 Swan bands: TT CVn and HD 137613 have no detectable $C^{12}C^{13}$ bands, implying a C^{12}/C^{13} ratio greater than 50 (McKellar, 1960b); X Cnc is a rather typical carbon star whose isotope ratio is probably between 5 and 10 (its CN profile is similar to those of several other carbon stars we have observed); and HD 52432 has outstandingly strong $C^{12}C^{13}$ and $C^{13}C^{13}$ features (Yamashita, 1967). Ultimately we should be able to derive our own C^{12}/C^{13} ratios by comparing the photometric observations to synthetic spectrum calculations, but I would prefer not to give numerical values on the basis of the preliminary com-

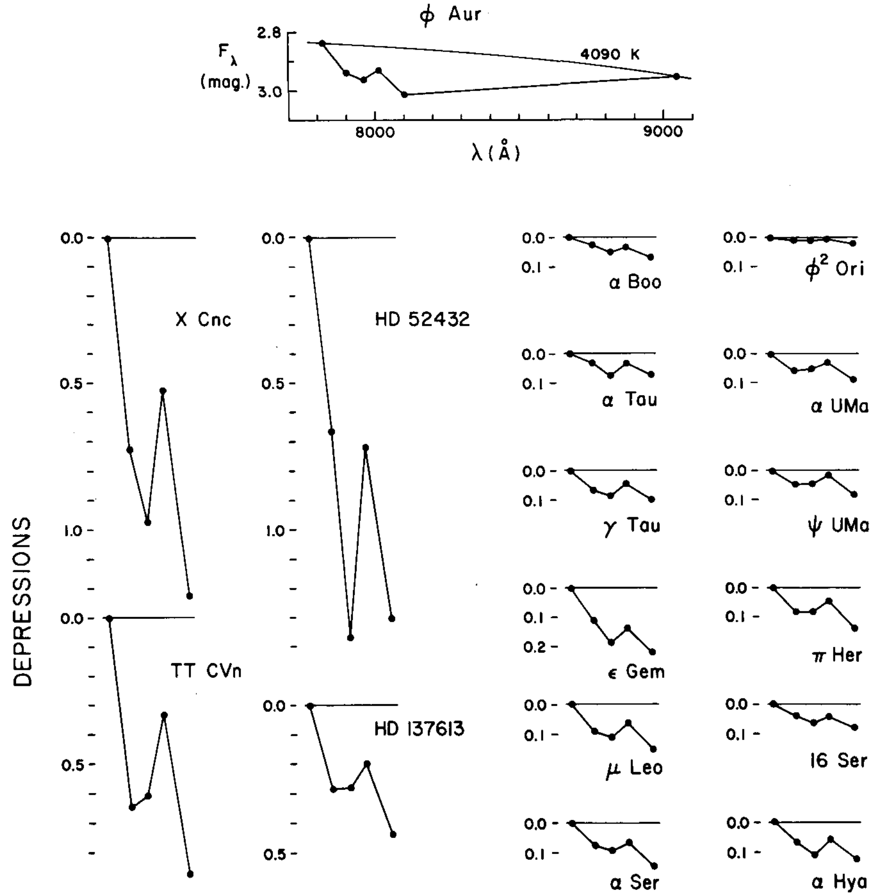

Fig. 6. Results of observations on the CN profile program. The data were obtained with a scanner at Kitt Peak National Observatory on the photometric system defined by the vertical columns in Figure 5. For ϕ Aur (*above*) the fluxes are plotted against wavelength and have been fitted with a blackbody curve. For the four carbon stars (*left*) and 12 G and K stars (*right*), the depressions at the first five wavelengths relative to the blackbody continuum are plotted on the same scale as for ϕ Aur. The relative depressions at the second and third wavelengths are indicative of the carbon isotope ratio.

parisons made to date. It seems safe to conclude, however, that the C^{12}/C^{13} ratio of HD 52432 can hardly be greater than 2, and it may be closer to unity.

Twelve G and K stars are shown in the right half of Figure 6. Again, the relative depressions at the second and third points indicate that their isotope ratios are not all the same. It would appear that α UMa ($K0^-$ IIIa), ψ UMa (K1 III), and π Her (K3 IIab) have very little C^{13}, whereas α Boo (K2 IIIp, weak CN), α Tau (K5 III), ε Gem (G8 Ib), and α Hya (K3 IIIa) are C^{13}-rich. The Hyades G-giant γ Tau and the strong-CN stars μ Leo and α Ser have intermediate C^{12}/C^{13} ratios. There seems to be no correlation between the CN strength and the C^{12}/C^{13} ratio. The barium star 16 Ser is not distinguished from normal giants by either its CN strength or its isotope ratio. The peculiar star ϕ^2 Ori has such weak CN bands that nothing can be said about its isotope ratio.

The synthetic spectrum calculations indicate that, for the observational accuracy achieved here (the probable errors are approximately equal to the sizes of the dots in Figure 6) and for the CN strength of a typical K giant, we should easily be able to distinguish isotope ratios differing by factors of 2, i.e. C^{12}/C^{13} ratios of 2, 4, 8, 16, 32, and >60. Thus we should be able to divide these stars into at least 5 groups – a degree of refinement that we hope will be adequate for a preliminary study of the correlations that may exist between the carbon isotope ratio and other observable parameters.

Acknowledgement

I would like to acknowledge that many of the observations discussed in this paper were made at Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory. Special thanks go to Drs J. H. Baumert, G. W. Lockwood, I. R. Marenin-Little, and N. M. White for permitting me to discuss unpublished results from collaborative efforts. My research has been supported by the U.S. National Science Foundation.

References

Baumert, J. H.: 1972, Ph.D. Dissertation, The Ohio State University.
Baumert, J. H.: 1974, in press.
Baumert, J. H. and Wing, R. F.: 1974, in preparation.
Cameron, D. M. and Nassau, J. J.: 1955, *Astrophys. J.* **122**, 177.
Caswell, J. L. and Robinson, B. J.: 1970, *Astrophys. Letters* **7**, 75.
Connes, P., Connes, J., Bouigue, R., Querci, M., Chauville, J., and Querci, F.: 1968, *Ann. Astrophys.* **31**, 485.
Fujita, Y.: 1973, 'Identification of Spectra in Violet and Infrared Regions of Carbon Stars' (read at 15th IAU General Assembly).
Glass, I. S. and Feast, M. W.: 1973, *Monthly Notices Roy. Astron. Soc.* **163**, 245.
Griffin, R. F. and Redman, R. O.: 1960, *Monthly Notices Roy. Astron. Soc.* **120**, 287.
Herbig, G. H. and Zappala, R. R.: 1970, *Astrophys. J.* **162**, L15.
Humphreys, R. M. and Lockwood, G. W.: 1972, *Astrophys. J.* **172**, L59.
Humphreys, R. M., Strecker, D. W., and Ney, E. P.: 1972, *Astrophys. J.* **172**, 75.
Johnson, H. L.: 1967, *Astrophys. J.* **149**, 345.
Johnson, H. L., Coleman, I., Mitchell, R. I., and Steinmetz, D. L.: 1968, *Comm. Lunar Planet. Lab.* **7**, 83.
Joy, A. H.: 1947, *Astrophys. J.* **105**, 96.
Keenan, P. C.: 1950, *Astron. J.* **55**, 74.

Keenan, P. C.: 1963, *Stars and Stellar Systems* **3**, 78.
Keenan, P. C.: 1966, *Astrophys. J. Suppl.* **13**, 333.
Krupp, B. M.: 1973, *Bull. Am. Astron. Soc.* **5**, 336.
Lambert, D. L. and Dearborn, D. S.: 1972, *Mem. Soc. Roy. Sci. Liège, 6th Ser.* **3**, 147.
Lockwood, G. W.: 1972, *Astrophys. J. Suppl.* **24**, 375.
Lockwood, G. W.: 1973, *Astrophys. J.* **180**, 845.
Lockwood, G. W. and McMillan, R. S.: 1971, in G. W. Lockwood and H. M. Dyck (eds.), *Proc. Conf. on Late-Type Stars*, Kitt Peak National Observatory Contr. 554, p. 171.
Lockwood, G. W. and Wing, R. F.: 1971, *Astrophys. J.* **169**, 63.
Maehara, H.: 1968, *Publ. Astron. Soc. Japan* **20**, 77.
McKellar, A.: 1960a, *J. Roy. Astron. Soc. Canada* **54**, 97.
McKellar, A.: 1960b, *Stars and Stellar Systems* **6**, 569.
Merrill, P. W. and Greenstein, J. L.: 1958, *Publ. Astron. Soc. Pacific* **70**, 98.
Merrill, P. W., Deutsch, A. J., and Keenan, P. C.: 1962, *Astrophys. J.* **136**, 21.
Neugebauer, G. and Leighton, R. B.: 1969, *Two-Micron Sky Survey – A Preliminary Catalog*, NASA SP-3047.
Pesch, P.: 1972, *Astrophys. J.* **174**, L155.
Ridgway, S. T.: 1974, this volume, p. 327.
Schild, R., Peterson, D. M., and Oke, J. B.: 1971, *Astrophys. J.* **166**, 95.
Smith, M. G. and Wing, R. F.: 1973, *Publ. Astron. Soc. Pacific* **85**, 659.
Spinrad, H. and Taylor, B. J.: 1969, *Astrophys. J.* **157**, 1279.
Spinrad, H. and Wing, R. F.: 1969, *Ann. Rev. Astron. Astrophys.* **7**, 249.
Upson, W. L.: 1973, Ph.D. Dissertation, University of Maryland.
Wallerstein, G.: 1971, *Astrophys. Letters* **7**, 199.
White, N. M.: 1971, Ph.D. Dissertation, The Ohio State University.
White, N. M.: 1972, in M. Hack (ed.), *Colloquium on Supergiant Stars*, Trieste, p. 160.
Whitford, A. E.: 1972, *Bull. Am. Astron. Soc.* **4**, 230.
Whitford, A. E.: 1974, in J. R. Shakeshaft (ed.), 'The Formation and Dynamics of Galaxies', *IAU Symp.* **58**, in press.
Wing, R. F.: 1967a, in M. Hack (ed.), *Colloquium on Late-Type Stars* Trieste, p. 205.
Wing, R. F.: 1967b, in M. Hack (ed.), *Colloquium on Late-Type Stars*, Trieste, p. 231.
Wing, R. F.: 1967c, Ph. D. Dissertation, University of California, Berkeley.
Wing, R. F.: 1971a, in G. W. Lockwood and H. M. Dyck (eds.), *Proc. Conf. on Late-Type Stars*, Kitt Peak National Observatory Contr. 554, p. 145.
Wing, R. F.: 1971b, *Publ. Astron. Soc. Pacific* **83**, 301.
Wing, R. F.: 1972, *Mem. Soc. Roy. Sci. Liège, 6th Ser.* **3**, 123.
Wing, R. F.: 1973a, in Ch. Fehrenbach and B. E. Westerlund (eds.), 'Spectral Classification and Multicolour Photometry', *IAU Symp.* **50**, 209.
Wing, R. F.: 1973b, in J. D. Fernie (ed.), *Variable Stars in Globular Clusters and in Related Systems*, D. Reidel Publ. Co., Dordrecht, p. 165.
Wing, R. F.: 1973c, in H. R. Johnson, J. P. Mutschlecner and B. F. Peery, Jr. (eds.), *Proc. Conf. on Red Giant Stars*, Indiana Univ., p. 52.
Wing, R. F. and Ford, W. K., Jr.: 1969, *Publ. Astron. Soc. Pacific* **81**, 527.
Wing, R. F. and Lockwood, G. W.: 1973, *Astrophys. J.* **184**, 873.
Wing, R. F. and Spinrad, H.: 1970, *Astrophys. J.* **159**, 973.
Wing, R. F. and Stock, J.: 1973, *Astrophys. J.* **186**, 979.
Wing, R. F. and Warner, J. W.: 1972, *Publ. Astron. Soc. Pacific* **84**, 646.
Wing, R. F., Baumert, J. H., Strom, S. E., and Strom, K. M.: 1972, *Publ. Astron. Soc. Pacific* **84**, 646.
Wing, R. F., Spinrad, H., and Kuhi, L. V.: 1967, *Astrophys. J.* **117**, 147.
Wing, R. F., Warner, J. W., and Smith, M. G.: 1973, *Astrophys. J.* **179**, 135.
Wyckoff, S.: 1970, *Astrophys. J.* **162**, 203.
Yamashita, Y.: 1967, *Publ. Dominion Astrophys. Obs.* **13**, No. 5.

DISCUSSION

Fujita: Have you any comments regarding the comparison of the abundances of ^{12}C and ^{13}C compared with other determinations?

Wing: No. I really cannot compare the relative accuracy of this technique of measuring carbon isotope ratios with spectroscopic measurement. I have not actually determined any numbers. We are hoping to be able to do that. It is a question of how realistic the synthetic spectrum predictions are which is difficult to evaluate. I can say that narrow band photometry is a much easier observation to make and can be applied equally to faint stars, but it will depend critically on accurate determinations from high resolution work in order to calibrate the photometric ratios.

Schwarzschild: May I say not just to the present speaker but certainly to all of this morning's speakers that the input you are making to the theories of stellar structure and evolution is rather larger than I think you realize, and it is not just the one point that was emphasized several times on the relative abundances both isotopic and otherwise. It is also that one feels implicitly underlying many of your comments that the structure of the outermost layers is after all only a boundary condition and a very nasty type of boundary condition for stellar models. I sort of hope that by and large the interests of at least several of you will switch to the dynamical state of the very layers that you are observing. There are several comments that came up. Firstly the microscopic turbulent velocity, then there was this beautiful doubling that is quite hair-raising dynamically where other types of dynamical problems come up. One point that I do not remember that I have heard this morning mentioned is that whenever you want velocity differences or temperature differences I would suggest one might not want to always stick in very stratified layers, you know everything constant on spheres, could it not very well be, particularly for the supergiants, that they really have a violently mottled appearance for all we know? And therefore whenever you get into trouble, instead of only looking into models with vertical stratification, might the time not be right to think (whenever you are in trouble, and only then) to make the surface the superposition of two different atmospheres and see whether that might be another potential possibility of getting out of trouble?

Townes: It clearly will get you out of trouble and one would be able to have more variables and fit things more, but then what do you know?

Schwarzschild: Sir, the astronomers always first find possibilities, and then try to sort out the true ones.