TWO-DIMENSIONAL SPECTRAL CLASSIFICATION OF M STARS BY NARROW-BAND PHOTOMETRY

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## 1. INTRODUCTION

To place a star on the HR diagram by means of spectroscopic data alone--i.e., without knowledge of the parallax--one must separate the spectroscopic effects of temperature and luminosity as cleanly as possible. Here we discuss the use of the red and near-infrared bands of TiO, VO, CN, and CaH as classification criteria for M stars. Our eight-color system of filter photometry (Wing 1971; White 1971a) has provided data on the first three molecules.

## 2. TiO: THE PRIMARY TEMPERATURE INDICATOR

The great temperature sensitivity of the TiO bands is well known. Numerical comparisons of the photometric TiO indices that have been given on various systems indicate that the eight-color system measures TiO in the most favorable way, namely, with a filter centered at 7120 Å (full width at half power: 60 Å) within the (0,0) band of the $\gamma$ system, together with a 50 Å continuum filter at 7540 Å. This combination provides good sensitivity throughout the range K4 to M8. The limit at M8 is imposed by the growth of VO bands, such that there are no good continuum regions left anywhere shortward of 1 $\mu$.

Within the useful range of the eight-color TiO index, both the TiO filter and the continuum filter are contaminated by lines of the CN molecule; these filters were, however, chosen to give the



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best separation of the overlapping band systems of TiO and CN. In a recently completed study of 128 M supergiants (White and Wing 1978), we explain the procedure used for correcting our TiO index for CN contamination and show that spectral types based on the corrected TiO index are on the same scale as those of Morgan and Keenan (1973) for supergiants as well as giants.

Even when the luminosity sensitivity of CN is removed from the TiO index, there remains the question of whether the TiO bands themselves are luminosity-sensitive. Wing (1973a) found an appreciable difference between the TiO-color relations for giants and dwarfs; dwarfs have stronger TiO bands than giants of the same temperature in the range K4 to M2, while the reverse is true in the later types. These differences never exceed about 30% in band strength, however, and seem very small in terms of the enormous difference in absolute magnitude. The relations for giants and supergiants appear to be nearly the same, but here it is hard to make a precise statement because of the difficulty of correcting the color temperatures of the supergiants for reddening.

Abundance differences must also affect the TiO index; however, these effects appear to be surprisingly small. Several hundred M giants, including known metal-deficient stars, have been observed on the eight-color system, and the tightness of the relation they define between band strength and color temperature indicates that the TiO band strength depends only weakly on the metallicity.

The Mira variables present a special problem; different TiO bands often indicate different spectral types. The discrepancy is usually in the sense that the (0,0) band is anomalously strong relative to high-excitation bands and to the color temperature (Wing 1974).

## 3. VO: A TEMPERATURE INDICATOR IN VERY COOL STARS

The VO bands in the visible region (Keenan 1963) and in the near-infrared (Cameron and Nassau 1955) have served as temperature criteria for late M stars, and the bands in the one-micron region serve the same purpose on the eight-color system (Wing and Lockwood 1973) for stars cooler than M7. Their temperature sensitivity is demonstrated by their behavior in Mira variables, in which they not uncommonly vary from invisible to very strong, their greatest intensity occurring at the time of minimum light and lowest color temperature.

Unfortunately, since most of our information about VO comes from the Miras, it is difficult to evaluate the sensitivity of the VO bands to luminosity or abundance effects. Boeshaar (1976) was able to detect VO bandheads in several of the coolest M dwarfs, which have TiO types of M5 or M6, and it appears that VO/TiO ratio is nearly the same in dwarfs as in giants. The supergiants tell a different story: Although most M supergiants are too warm to show VO bands, there do exist stars that have all the earmarks of high luminosity together with strong VO bands. Examples of this phenomenon are VX Sgr, NML Cyg, and S Per at minimum. Wing (1973b, 1974) has suggested that high VO/TiO ratio of the stars is a luminosity effect.

## 4. CN: A LUMINOSITY INDICATOR IN HIGH-LUMINOSITY STARS

The strong positive luminosity effect shown by the CN bands has been used often for the recognition of supergiants in low-resolution spectral surveys. However, a considerable spread in CN strength occurs at a given temperature and luminosity among G and K giants (Griffen and Redman 1960) and similarly among M giants (Wing 1967). This spread is presumably attributable to abundance differences, and it limits the usefulness of CN as a luminosity indicator, although giants can almost always be distinguished from dwarfs and supergiants.

Among the M supergiants the situation is more favorable, and the CN measurements on the eight-color system are capable of reproducing the MK luminosity subdivisions Ib, Iab, and Ia, which are based upon atomic line ratios (White 1971a, 1971b; White and Wing 1978). Abundance effects seem to be smaller among supergiants than among giants, perhaps because the M supergiants have more homogeneous population characteristics.

The infrared CN bands are quite insensitive to temperature in the late K and M stars. Whereas Griffin and Redman (1960) found that the bands of the violet system pass through a maximum in the early K's (for any given luminosity class) and fade to invisibility by about M0, the bands of the red system weaken much more gradually and are still measurable in middle-M giants. A single calibration of the eight-color CN index in terms of luminosity class is at least valid throughout the interval K4 to M4 (White 1971b; White and Wing 1978).

## 5. CaH: A LUMINOSITY INDICATOR IN LOW-LUMINOSITY STARS

Although M dwarfs can be recognized by their lack of CN bands, it is obvious that CN cannot be used to define finer luminosity subdivisions among low-luminosity stars. For this purpose we turn to CaH, which has bands in the red region and because of its low dissociation energy is very sensitive to gas pressure.

Measurements of CaH not only distinguish dwarfs from giants

(Jones 1973), but also allow the separation of subdwarfs from normal main sequence stars (Mould 1976; Boeshaar 1976; Wing, Dean, and MacConnell 1976). The recent narrow-band photometry of TiO and CaH by Mould and McElroy (1978) has shown that subdwarfs belonging to the old disk population occupy an intermediate position in the (CaH, TiO) plane between the old disk main sequence stars and the halo subdwarfs.

The temperature dependence of the CaH bands, as indicated by the model-atmosphere calculations of Mould (1976), is rather strong. However, for classification purposes, the CaH bands must be viewed as a luminosity indicator; if they are used for temperature classification, subdwarfs are assigned spectral types that are too late to be consistent with their color temperatures (Wing, Dean, and MacConnell 1976).

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