THE SPECTRAL CLASSIFICATION
OF M-DWARF STARS

By

Patricia C. Boeshaar, Ph.D.
The Ohio State University

Professor Philip C. Keenan and
Professor Terry P. Roark, Advisers

A spectral classification scheme is presented for M-dwarf stars based on a study of the visual region (λ4400- 6800) in the spectra of 75 M dwarfs and late-type K dwarfs. Trailed Carnegie Image Tube spectrograms of low dispersion (110 Å/mm and 250 Å/mm at the Na "D" lines) were obtained for this purpose. The temperature classification of the early M dwarfs depends on the appearance (i.e. which bands are visible) of different TiO bands rather than the absolute strength of a particular band. For dwarfs M5 and later the spectral types depend on visual estimates of the ratio of the VO λ5736 to TiO λ5759 band strengths plus the rapid increase in the strength of the λ5530-60 band of CaOH. This CaOH feature first becomes marginally visible near type M3.5. The strengths of the TiO bands appear to change very slowly after type M5, whereas the change in λ5530-60 band of CaOH is easily seen. The New Spectral types are compared

to those of the Mt. Wilson system, Kuiper, and the near infrared photoelectric types of Wing and Dean. A few M dwarfs were found where the CaOH band was a better temperature criterion than the TiO bands, which were abnormally weak, though this is not always the case among the few stars with weak TiO bands. Not all stars with weak TiO bands appear to be subdwarfs.

Separation of luminosity classes III and V was not found to be difficult. In general, known subdwarfs were found to exhibit enhanced bands of MgH and CaH plus a strengthening of the resonance lines of neutral metals as compared to dwarfs. The latter feature appears to be particularly sensitive to changes in surface gravity.

An H-R diagram for all program stars with trigonometric parallaxes excluding known subdwarfs, spectroscopic binaries and those with uncertain types yields a dispersion of ± 0.46 in M_V, with a mean range of one magnitude at any one subclass. Flare stars without Balmer emission in the quiescent state are found both above and below the mean main sequence.

TABLE OF CONTENTS

Page

Chapter

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

Chapter 1

INTRODUCTION

General Considerations

The M-dwarf stars are probably the most numerous objects in our Galaxy, yet less is definitely known of their physical properties than is known for main sequence stars of earlier spectral type. A renewed astrophysical interest in these inherently faint objects is due in part to improved spectroscopic and photometric techniques for observing them. Physical parameters have been determined more reliably from observational data rather than from theoretical models. Improvement in late type dwarf model atmospheres has been difficult due to the complicated temperature dependence of the opacity. Recent models include one or more, but not all, of the effects on the opacity due to the extensive absorption features of the various molecules and the atomic absorption lines found in these stars (Auman 1969, Tsuji 1969). Fair agreement with observations has been found in the emergent flux of early M dwarfs by Mould (1975) using the standard ATLAS continuous opacities, H_2^- free-free and pressure induced dipole absorption of molecular hydrogen, plus the opacity distribution function treatment of TiO and H_2O.

A brief general description of the physical properties of M dwarfs based on observational results follows. These stars occupy the lower end of the main sequence from $M_V \sim 8.5$ to $M_V \sim 16.5$. The fainter value is set by the limiting mass necessary to initiate hydrogen burning, somewhere in the range from $0.075M_\odot$ to $0.10M_\odot$ according to Grossman (1970), but depending strongly on the assumed initial composition in theoretical model calculations. The mass of an MO dwarf is on the order of $0.6\ M_\odot$ (Veeder 1974). Veeder has calculated effective temperatures using the method of Greenstein *et. al*. (1970). For an MO dwarf he obtains $T_e \sim 3900°K$. The intrinsically faintest stars on his list with known masses which indicate that they are capable of settling on the main sequence are UV Ceti and its companion (Gliese 65AB). The T_e of the companion, Gliese 65A, was determined to be 2700°K ± 150°K. The coolest star studied by Veeder is G51-15 with a T_e of 2450°K ± 150°K. A comparable range of effective temperatures for the M dwarfs, 3900°K to 2650°K, was found by Johnson (1965). Johnson also determined the range of radii for these stars to be on the order of $0.6R_\odot$ to $0.18R_\odot$. The mass-luminosity relation found by Veeder for the lower main sequence is:

$$\frac{L}{L_\odot} \propto \left(\frac{M}{M_\odot}\right)^{2.2\pm0.2} .$$

This may be compared to

$$\frac{L}{L_\odot} \propto \left(\frac{M}{M_\odot}\right)^{3.5}$$

found by Harris *et*. *al*. (1963) for brighter stars.

Principal Spectral Features Used in the Classification of Cool Dwarfs

The spectral energy distributions of M dwarfs peak near 1μ and scanner observations from 4500 Å to 10000 Å (Greenstein et al. 1970; Fay et al. 1973) show that these stars are heavily blanketed by TiO. The TiO bands have been shown to be good temperature indicators (Morgan 1938, 1939; Joy 1947; Spinrad 1973). For these reasons most classification done at low dispersion has utilized only visual estimates of TiO band strength to indicate temperature type. The VO band at λ5736 can be seen only in the coolest M dwarfs. The ratio of the intensity of this VO band to the λ5759 TiO band (Merrill et al. 1962) has been used to classify MK giants of types M5 and later. In the giants, the VO band increases in intensity until it is equal to that of the λ5769 TiO band at type M7. However, this ratio has not been previously used for the M dwarfs. Pesch (1972a) identified the CaOH bands (a sharp feature at λλ5530-5560 and another more diffuse feature with a maximum at λ6230) and found them to exhibit negative luminosity and temperature effects. Both bands were absent in the spectrum of RX Boo (M8 III), easily seen in Barnard's star (Gliese 699), and strongest in the very late type dwarf Wolf 359 (Gliese 406). The intensity of the λ5530 CaOH band increases more noticeably than the intensity of the TiO bands with decreasing temperature in the coolest M dwarfs.

The Na "D" lines (Luyten 1923), the Ca I lines at λλ6103, 6122, and especially 6162 (Burwell 1930), the Mg "b" lines λλ5167-5184 (Fitch and Morgan 1951), the MgH band at λ5211, the CaH B- and A-bands at λ6385 and near λ6900, respectively, (Ohman 1934, 1936a,b) are several luminosity criteria commonly used to separate M-type giants from dwarfs. The differences in the visual region between stars in these two luminosity classes are so striking as to be noticeable even on very low dispersion objective prism spectra (Iwanowska and Wayman 1952). Moreover, some of the features exhibiting negative luminosity effects are useful in identifying subdwarf candiates. The resonance lines of neutral metals are sensitive to both temperature and luminosity changes. Spectra of Kapteyn's star (Gliese 191), a known subdwarf, in the blue and red indicate that the resonance line of CaI at λ4226 and those of AℓI at λλ3944, 3961 and NaI at λλ5889, 5895 appear as strong as in a much cooler star. Unfortunately, the Na "D" lines are rendered unreliable due to strong and time-variable night sky emission on the image tube spectra used in the present study.

The relative effects of temperature, luminosity, and abundance on the metallic hydride bands have been argued in the literature. The MgH bands producing a sharp, narrow band at λ4788 (Davis 1937) and another feature with a band head at λ5211 and extending over 200 Å blueward (Ohman 1936a, Spinrad and Wood 1965) are present in early K dwarfs. They increase rapidly in strength near K5V, reaching maximum intensity near MOV, and then appear to remain constant in later types. The CaH B-band at λ6385 (Ohman 1936b) can be seen on low dispersion spectra of dMO stars and increases in intensity until about type dM4.

The bands of both MgH and CaH appear marginally at best in giant stars. In comparison, the bands of AlH at λ4241 and λ4249 (Davis 1947, Ohman 1936b) appear weaker than either of the other metallic hydrides observed, and seem to have the same intensity in giants and dwarfs.

The increase in the strength of the metallic hydride bands relative to TiO has been found to be a characteristic anomaly of high velocity dwarfs by Eggen and Greenstein (1965b, 1966). Smethells (1974), in an objective prism survey of southern M dwarfs, has used visual estimates of variations in the strength of the CaH B-band to conclude that the stars represent a mixture of population types. The question is whether the enhanced appearance of the metallic hydrides is due to the relatively weaker TiO bands used for comparison or an increase in surface pressure. Greenstein (1965) pointed out that in metal-weak stars, the metal underabundance factor is squared for the TiO molecule while both the metallic hydride molecules and the continuous opacity are reduced only by the first power of the metal underabundance (assuming that H^- is the opacity source and that the metals are the source of the electrons). Thus, the metallic hydride bands may appear strengthened relative to the TiO bands. Bidelman (1975), on the basis of Smethells' work, has suggested that the CaH B-band is a better indicator of temperature than the TiO bands. The results of Wing et al. (1976) do not support this hypothesis in the case of Kapteyn's star. They find a discrepancy of one subtype between the TiO spectral type and the color temperature equivalent type, indicating that stars with halo type motions probably do exhibit some degree of metal deficiency. However, the CaH strength would suggest a much later type than the color temperature, M3 compared to M1. Therefore Wing _et_ _al_. recommend that TiO be used as the temperature indicator, and the metallic hydride bands as the luminosity indicators.

The negative luminosity effect of the metallic hydrides in M subdwarfs may be further tested by investigating the behavior of the uncontaminated CaOH band at λ5530 in high velocity stars. The temperature dependence of CaOH bands is more striking than that of the metallic hydrides, but the effect of surface pressure (at least in the case of giants and dwarfs) is even greater. The formation of triatomic molecules is not well understood for late type stellar atmospheres; however, in M-dwarfs showing enhanced CaH relative to TiO (assuming the suggestion of Greenstein is correct), one might expect similar behavior between the CaOH and TiO molecular features. In at least one star (GL754.1B), a companion to a white dwarf, this is not found to be the case.

The majority of the "subdwarfs" identified by Eggen and Greenstein are not cool enough for the CaOH band to be present in their spectra. This includes G95-59, the only subdwarf known to exhibit strong bands of MgH, CaH and AlH. No TiO is seen in this star. Enhancement of the MgH and CaH bands is more commonly noted than that of the AlH bands. Also, the usefulness of the MgH bands as luminosity criteria appears to be limited to the early M dwarfs, as these bands are complicated by the presence of TiO at λ4761 and λ5000 after spectral type M1.

Kron (1956), Eggen (1973), and Veeder (1974), in absolute magnitude vs. R-I diagrams, find that the K and M dwarfs with old disk space motions tend to be less luminous than those with young disk motions. Dwarfs with halo-type motions appear to be the most subluminous group, though the overlap in population groups is considerable. If the high-velocity M dwarfs are analogous to the G-type subdwarfs which have high velocity and a large metal deficiency, then their position in the HR diagram may be explained by the effect of the metal deficiency on the TiO band strengths. Since the TiO contaminates the R-filter more strongly than the I-filter, the high velocity stars would appear too blue. Although extremely metal-poor stars have not been recognized later than G8, the effect required is small enough that many stars indicated as subluminous in absolute magnitude-color diagrams may not be true subdwarfs and differential line blanketing may explain the position of these stars. However, in scanner observations of TiO band strengths in low and high space motion K and M dwarfs, Jones (1968) discovered no significant difference between the two groups.

Statement of the Problem

From the previous discussion, it can be seen that a variety of atomic and molecular features are available to serve as temperature and luminosity criteria for the spectroscopic classification of cool dwarfs. The problem lies not in the availability of criteria, but in the dependence of several of these features on more than one parameter and the inability of existing classification systems to define their criteria clearly. Of the two systems most commonly used for main sequence stars, the MK and Mt. Wilson systems, the former was never really defined for types later than M2, and the latter provides no standard scale representative of its different spectral subdivisions. As the situation exists presently, an observer can attribute his classification to either of the above two systems and still show results inconsistent with other observers using the same system. The problem was described well by Wing (1973) in a paper given at the 1971 meeting of the I.A.U. Commission on Spectral Classification and Multicolor Photometry:

> The scale differences of these systems are well known to those who assign the types, but less well known to other kinds of astronomers who have to *use* them. Not infrequently, one finds types on all three systems in the same catalogues or lists, and if the types are not individually referenced, the uncertainty in their meaning is much greater than the half-subclass accuracy of the original classifications.

In the same paper Wing proposed a photoelectric technique for determining spectral types based on the measurement of a single TiO band strength. Though a small sample of M dwarfs was used to demonstrate the potential of this technique, additional observations are currently in progress (Wing and Dean 1975).

The spectroscopic criteria distinguishing the M subdwarfs from main sequence stars need to be explored in more detail. There is some question as to whether the color-luminosity diagrams have correctly indicated the width of the main sequence precisely or the existence and position of subdwarfs. The possibility exists that abundance anomalies in TiO between stars could affect the R-I color which is generally used as a temperature indicator (Kron, Gascoigne, and White 1957; Veeder 1974). In addition, some widely quoted criteria used to identify subdwarfs, such as the weakening of atomic lines, may not always be applicable, as in Kapteyn's star, where no obvious weakening is observed. Veeder found in his M_{bol} vs. T diagram subluminous stars that have been classified on the Mt. Wilson system both as sdM's and as dM's.

For the reasons cited above and because of the faintness of the stars involved, it was decided to use low dispersion image tube spectrograms of a large enough number of dwarf stars, M2 and later, to develop a consistent and well-defined spectral classification scheme. This system was developed independently of the narrow-band near-infrared system of Wing with the intention of looking at a range of spectral features as temperature and luminosity criteria. It also allows the observation of the strength of Balmer emission, severe abundance anomalies, plus other spectral peculiarities. The standard stars from my system may then be useful in providing a clearer definition of the lower main sequence and in differentiating those stars that may truly be subluminous.

Chapter 2

SYSTEMS OF CLASSIFICATION BASED ON SLIT SPECTROGRAMS

The Mt. Wilson System as defined by Joy (1947) is probably the most commonly employed scheme for two reasons. First, the catalog of spectral types for M dwarfs by Joy and Abt (1974) (hereafter referred to as JA (1974)) lists over 400 of these stars distributed over all of the sky visible from the northern hemisphere. Second, the classification by Joy appears to be consistent, based primarily on the intensity of the various blue TiO band systems.

A program to obtain slit spectra of stars with high proper motions and good parallaxes began in the early 1900's at Mt. Wilson. This program was limited to objects brighter than 8th magnitude, and resulted in the discovery by Adams and Kohlschutter of the two M dwarfs, Groombridge 34A (Gliese 15A) and Lalande 21185 (Gliese 411), in 1913 (Joy 1971a). In 1914, the first spectrogram (of BD-8°4352AB = Gliese 644AB) to show Balmer emission was taken by Adams. Originally stars with spectra showing the blue TiO bands were designated M, and those with Balmer emission were denoted by the suffix d, a procedure adopted from the Harvard system (which utilized objective prism spectrograms). In the latter system, the HD types for class M stars provided for TiO band variations by noting increased band strength with the suffixes a, b, or c. Initially, the Mt. Wilson system made no attempt to indicate the intensity of the TiO absorption bands. At the first meeting of the I.A.U. in 1922, the decimal subdivisions M0 to M10, were adopted as a measure of TiO band strength and the letter e was introduced to indicate emission instead of d.

In 1926, Adams, Joy, and Humason published a list of 410 M stars (of which 97 were dwarfs) classified by decimal subdivision. The same temperature scale was used for stars in different luminosity classes. The list was extended by Adams *et al.* (1935) when they published the spectroscopic absolute magnitudes (estimated from atomic line ratios) for 4179 stars. Later, low dispersion slit spectra were taken by Dyer for M dwarfs initially discovered by Vyssotsky and his co-workers with objective prism surveys. Joy (1947) felt the accuracy of the classification justified the addition of a decimal half subdivision to the spectral type. Spectra of 97 large-proper-motion dwarfs and subdwarfs taken prior to 1940 were then classified in this way and the mean absolute visual magnitude per spectral subdivision was found. The M dwarfs and subdwarfs listed in this 1947 paper, along with over 300 others, were uniformly reclassified by Joy, with the complete list published as JA (1974). No systematic differences between the mean absolute visual magnitudes in this larger sample and the 1947 dwarfs were found.

The latest spectral type assigned to a star by JA (1974) is dM6.5e, in contrast to the 1947 list where the same star was called a dM6e. Several other stars have been reclassified, usually by only one half of a subtype, and five of the ten original sdM's (subdwarfs) have become dM's. The spectral characteristics distinguishing the scale division of this system were well known to Joy and the other Mt. Wilson astronomers assigning the types, but they failed to define the system clearly for the use of others. One may ask, for example, whether all of the 41 dM3 stars, if classified by someone familiar directly with this system, would still comprise a single set of dM3 stars. Moreover, there is nothing to indicate the relative quality of the spectra used to estimate the spectral types of these stars, or the relative reliability of the type of one star over another. Generally, the brighter a star is, the more reliable is its spectral type. But even this is not always so, as an inspection of several visual-region TiO bands in the spectrum of one bright dM3 star (HD 36395 = Gliese 205) indicates that this object should have been classed much earlier by Mt. Wilson standards.

Another possible cause of non-uniformity within the spectral subclasses arises from the reclassification of plates taken 35 or more years ago. The quality of the emulsion on many of the earlier plates appears to have deteriorated (Kraft 1974). As to the actual quality of the spectrograms, Wilson (1962), while investigating the spectra of late main sequence stars observed at Mt. Wilson, had this comment:

> . . . it quickly became apparent that many of the Mount Wilson types were indeed seriously inaccurate. The reasons for these inaccuracies also became obvious upon inspection of some of the old plates, most of which were obtained during the period 25-40 years ago with spectrographs and emulsions very much less

efficient than those available today. Many of the spectra are extremely narrow and underexposed and are really only capable of revealing only a rough indication of the true spectral type.

According to Morgan (Morgan and Keenan 1973), "The MKK system is defined, in effect by the list of standard stars published by Johnson and Morgan (1953). The criteria for classification in 1953 were, in general, those described in the 'MKK' Yerkes Atlas of Stellar Spectra (Morgan, Keenan, and Kellman 1943)." The criteria in the latter have been given to M2 V. Of the few MV's listed by Morgan and Johnson, at least three (Gliese 15 A and B, and Barnard's Star) appear to be subluminous in absolute magnitude-color diagrams (Spinrad 1973; Veeder 1974), and all of the remaining dwarf M stars have been classified on the system of Kuiper. The criteria used by Kuiper (1938a, 1942) are essentially the same as those of Morgan (1938) (the red TiO bands between λ5800 and λ6500) applied to much lower dispersion spectra (340 Å/mm). Both assigned M8 as the latest type, with Kuiper using half decimal classes as indicated by a suffix +. More specific criteria have not been enumerated, in contrast to the situation for the MK giants.

Unlike the Mt. Wilson system, there is some question here as to the relation between the classification of the dwarfs and giants. Morgan (1938) uses three Mt. Wilson gM0's as standards of the M0 type for the dwarfs. It is interesting to note that two of these three giants have since been called M0.5 III and M1.5 III by Keenan (Morgan and Keenan 1973). Kuiper (1938b) finds that his dwarfs differ from the giants by -0.1 class at M0 and are in agreement by M4, while his giants show excellent systematic agreement with the Mt. Wilson scale. However, while the red TiO bands for a Kuiper M4 dwarf correspond in strength to those in an M4 giant, the blue, green, and yellow TiO bands are weaker in the former (Kuiper 1938c). Morgan noticed the same effect to a greater degree in the cooler dwarf Barnard's star. This non-uniform behavior of the TiO bands can be explained by the contamination of the red (γ'o,o) system by a broad band of CaOH in late dwarfs (Pesch 1972a), which itself appears to exhibit a negative temperature effect. Thus, the resulting classification is not a function solely of TiO strength as had been the original intent.

Comparison of stars in common to both Johnson and Morgan (1953) and JA (1974) finds the two systems in general agreement at type M3. The differences at earlier and later types have been noted in the literature. For example, Iwanowska and Wayman (1952) show that the Mt. Wilson types are later than those of the MK system in the K5 to M2 range, while the reverse holds true for types later than M3. Quantitatively, the mean absolute magnitudes of JA (1974) can be compared with those of Keenan (1963) and are found to vary from being 0.8 of a magnitude brighter at M0 to being fainter by 2.4 magnitudes at M6. This latter large deviation is probably due to the contamination of the λ6157 TiO system (used by Morgan and Kuiper to assign types) by CaOH as previously mentioned.

Very few of the MV stars of Johnson and Morgan have been investigated for temperature criteria in other spectral regions. Abt *et al.*(1968) in *An Atlas of Low-Dispersion Grating Stellar Spectra* discuss only two of these stars: HD 95735 (M2 V) and Barnard's star (M5 V). Here a comparison is made of the blue TiO bands at λ4761 and λ4955. The behavior of several near infared atomic features (the CaII triplet at λ8498, 8543, 8662; the KI lines at λ7665 and λ7699; the NaI lines at λ8183 and λ8195) along with some TiO band systems in the λλ7000-9000 region are discussed by Sharpless (1956) with respect to the spectra of HD 95735 and AD Leo (M4.5 : V). Recently, Gahm (1970) proposed a quantitative classification scheme based on the measured depth and area of the TiO bands from λλ6150-6400 and λλ6600-6750, derived from microdensitometer tracings of 185 Å/mm spectrograms.

No mention is made by Morgan or Kuiper of the spectral criteria which distinguish those stars falling below the main sequence - the subdwarfs. Joy (1947) assigned an <u>sd</u> prefix to M stars based on the strengthening of the Lindblad depression in the neighborhood of λ4226 and a weakening of the emission lines. In JA (1974), a general weakening of the atomic absorption lines in the subdwarfs is noted as the defining characteristic. However, Greenstein (1960) says that weak lines behave differently in F and M subdwarfs, and that M subdwarfs do not seem to have very weak lines. Eggen and Greenstein (1965b, 1966), investigating halo motion dwarfs discovered in surveys for white dwarfs, remark on the anomalously strong metallic hydride bands found in those stars that they classify as sdK and sdM. As they note, however, we do not know what the exact spectral attributes of a genuine halo population subdwarf should be. These stars are generally discovered from parallax programs, rather than spectroscopically.

With the development and improvement of image intensitification systems, slit spectra of the faintest M dwarfs in the solar neighborhood and in some nearby open clusters can be obtained in reasonable exposure times. McCarthy demonstrated the efficacy of using a Carnegie Image Tube System in his low dispersion (135 to 360 A/mm) investigation of the lower main sequence of the Pleiades. Pesch (1972b) has also used low dispersion (250 A/mm) visual-red region image tube spectra to check the luminosity class of M stars discovered in an objective prism survey. A comparison of the results of these two studies shows the need for a well defined classification scheme. As Pesch points out, his stars are classified and labeled only with *g*- and *d*-prefixes, so that his types should not be considered on the MK system. McCarthy states that he observed 33 stars with "well-known" types to control the classification. The problem of defining a standard sequence of M dwarfs for the classification of slit spectra was considered by Vatican Observatory astronomers five years ago, but was frustrated by equipment problems (McCarthy 1971).

Chapter 3

OBSERVATIONS

The observations for this program were carried out using the Department of Terrestrial Magnetism Image Tube Spectrograph on the Perkins 72-inch telescope of the Ohio State and Ohio Wesleyan Universities at Lowell Observatory and a spectrograph of similar design on the 84-inch telescope at Kitt Peak National Observatory. Image tube spectroscopy was deemed the most suitable method because of its greater speed compared to conventional means. This has led to its widespread use in faint star work.

Both of the spectrographs used have an S-20 tube with useful sensitivity to about 8500 Å and one-to-one transfer optics so that the image on the phosphor, whose peak output is near 4400 Å, can be photographed. The camera, transfer optics, and tube voltage require individual focusing. Most of the observations at Lowell Observatory were made during 40 nights in the period October through February in 1972, 1973, and 1974. A 600 line/mm grating blazed at λ7200 in the first order giving a reciprocal dispersion of 110 Å/mm at the Na "D" lines (hereafter referred to as the high dispersion) was employed here; and, spectra from approximately λ4400 to λ6800, widened from 0.5 mm to 1 mm, were taken on baked IIa-O plates. The resulting resolution is about 7 Å for atomic lines and weak blends not overlaid by TiO. The fainter program stars were observed at KPNO on eleven nights in October and November of 1973 and 1974. A lower dispersion of about250 Å/mm obtained using a 300 line/mm grating blazed at λ6750 in the first order (hereafter referred to as the low dispersion) gave an increased spectral range of λλ4000-8000 on the plate. To compensate for this lower dispersion, N_2-baked IIIa-J Plates were used instead of IIa-O plates and the f-stop on the transfer lens was closed down to f/2.8 (compared to f/1.5 used at Lowell Observatory). The latter change was also necessary because of the increased thermal noise encountered using a higher operating voltage on the image tube at KPNO. A comparable resolution of about 8 to 10 Å resulted on spectra widened only 0.4 mm on the plates. For this study, a minimum of two spectra were obtained for most of the program stars.

The stars included in the program were taken from Gliese (1969), Veeder (1973), Joy (1971b), Eggen and Greenstein (1965a,b), and Dahn (1973). With the exception of the subdwarfs, only stars brighter than apparent visual magnitude 15 and having a parallax larger than 0".050 were considered here. The general criteria that favored stars for inclusion were as follows:

(1) M dwarfs with parallax > 0".100

(2) dM's with a large number of observations on the Mt. Wilson program

(3) spectral type of dM5 or later (JA(1974)) and dM6 or later (Kuiper 1942)

(4) stars classed as sdM by Joy (1947) or by Eggen and Greenstein

(5) color class +4 stars from the Lowell Proper Motion Survey

(6) stars with faint M_V's.

Of particular interest were dwarfs M2 and later, so that standard spectra might be identified for these types; however, additional stars were included in the final list in order to represent all spectral types later than M0. A few K dwarfs were added for comparison. Most stars in the program are fall and winter objects as this investigation began as a study of the Hyades lower main sequence. The diversity noted in the appearance of the spectra of dM's classified as having the same temperature type by Joy and chosen as my initial standard stars prompted a change of thesis topic.

For consistency, stars will be referred to by their number in Gliese's catalog (Gliese 1969) whenever possible, e.g. GL 406. Otherwise, stars which do not appear in this catalog will be referred to by their Giclas (G) number in the Lowell Proper Motion Survey. If a star's common name is frequently used in the literature, this will also be given, particularly in the case of stars from the lists of Ross and Wolf.

Chapter 4

DISCUSSION

MK M III Standard Stars

MK giant standards were used as a check on the temperature criteria in the spectra of the M-dwarf standard stars chosen in this investigation. These MK standard stars are listed in Table 1. The present system was developed along the lines of the MK giant scale for several reasons. Joy's classification of M dwarfs is on the same scale as the Mt. Wilson M giants, which is similar to that of the MK giants (Blanco 1964). On the MK system, a list of well determined giant standard stars is available (Morgan and Keenan 1973) and classification criteria in the blue and visual regions have been defined. Johnson and Morgan (1953) state that MK types for M dwarfs should be expressed on the system of Kuiper (1942). Kuiper (1938b,c) found close agreement between the spectral types of his M dwarfs and the Mt. Wilson giants from M0 to M4. The use of the MK giants not only relates the present system to a well defined system commonly used for all spectral types except the M-dwarf stars, but also facilitates comparison with M dwarfs classified on the systems of Kuiper and Mt. Wilson.

At the dispersions chosen for this thesis work, the visual spectral region offers a variety of criteria as temperature and luminosity discriminators. In addition, the visual region is closer to the peak of the energy distributions of these stars than the faint photographic blue. Of course, the most useful criteria of spectral type are a function of the dispersion employed and the best criteria here were selected by inspecting the spectra of the standard stars. On Plate I are image tube spectra (110 Å/mm) of some of the MK giants from Table 1. The MK criteria applicable to spectra of this scale and in this wavelength range are listed in Table 2. The blue TiO bands at λλ4352, 4395, and 4422 which characterize the later spectral types, and were probably used by Joy in the Mt. Wilson classification, are beyond the limit of the effective spectral range of the system used here.

Table 1

THE MK GIANTS

Star	V	Spectral Type
β Cnc	3.52	K4 III
76 Gem	5.40	K4.5 III
α Tau	0.86	K5 III
α Lyn	3.13	K7 IIIab
HR 3850	5.91	M0 III
55 Peg	4.50	M1 IIIab
α Cet	2.53	M1.5 III
83 UMa	4.66	M2 IIIab
8 And	4.86	M2.5 III
μ Gem	2.97	M3 IIIab
51 Gem	5.08	M4 III
HD 11961	7.21	M5 III
56 Leo	6.05	M5.5 III
45 Ari	5.94	$M6^-$ III
EU Del	6.2-6.9	M6 III
HD 207076	7.2	M7 III

Table 2

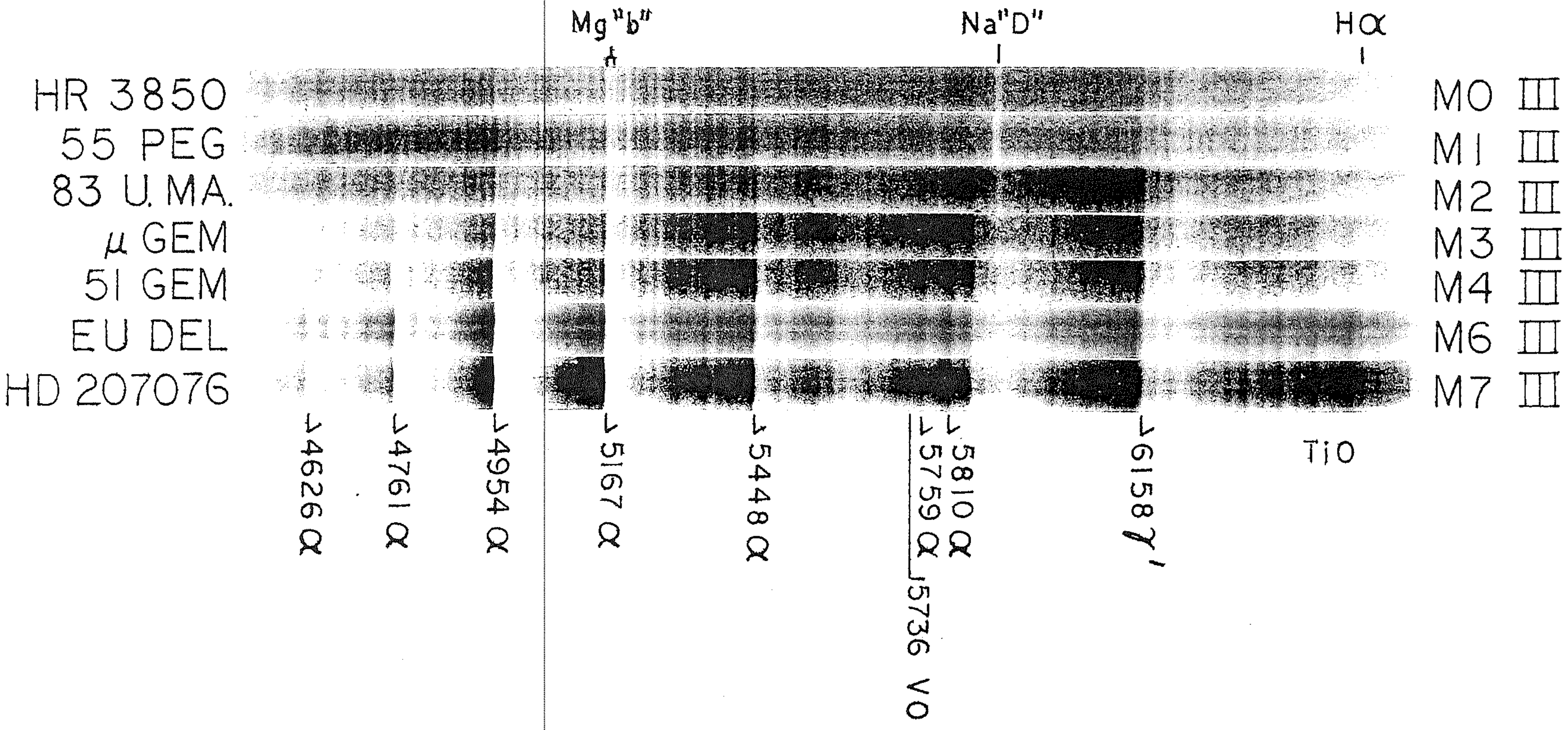
MK CRITERIA FOR CLASSIFICATION

TYPE M GIANTS

M0	λ4954(1,0), λ6159(γ'0,0) clearly seen. λλ5448(0,1), 5167(0,0) present.
M1	λ4761(2,0) present. λ5448 clearly seen. λ5167 is now strong enough to form a distinct break in spite of the strong atomic lines nearby.
M2	λ4804(3,1) present. λλ5448, 6159 stronger.
M3	λ4584(3,0) present. λλ5597(0,0), 5849(γ'1,0) present.
M4	λλ4626(4,1), 4667(5,2) distinct. λλ5759(0,2), 5810(1,3) distinct. λ4848(4,2) present.
M5	VO λ5736 present.
M6	VO λ5736 slightly weaker than λ5759.
M7	VO λ5736 = λ5759. λ5615(γ'3,1) fairly strong.

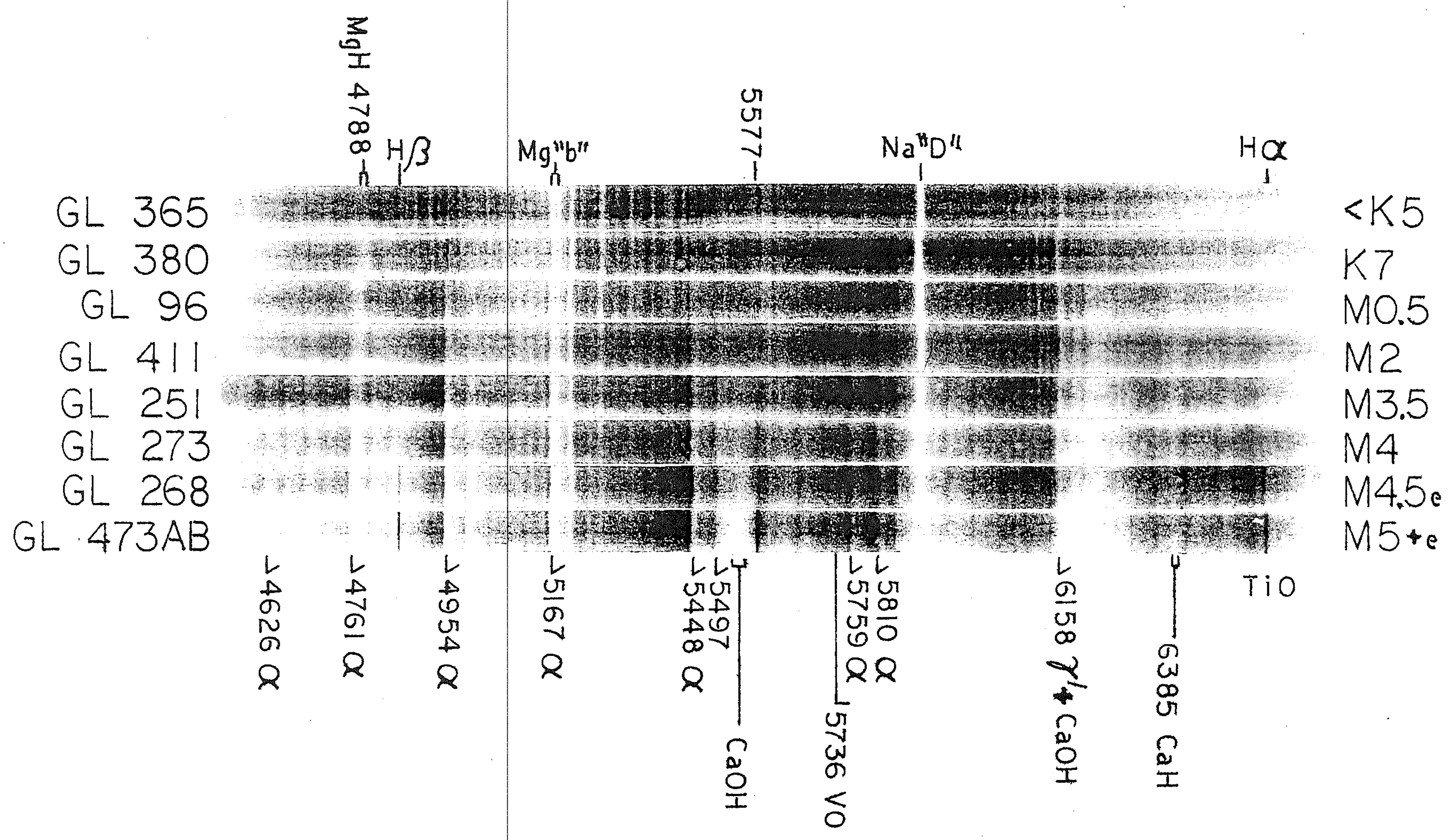
CAPTION FOR PLATE I

110 A/mm Image Tube Spectra of Some MK Giant Standard Stars in Table 1.

Mg"b"
Na"D"
Hα
HR 3850
55 PEG
83 U. MA.
μ GEM
51 GEM
EU DEL
HD 207076
M0 III
M1 III
M2 III
M3 III
M4 III
M6 III
M7 III
4626 α
4761 α
4954 α
5167 α
5448 α
5759 α
5736 VO
5810 α
6158 γ'
TiO

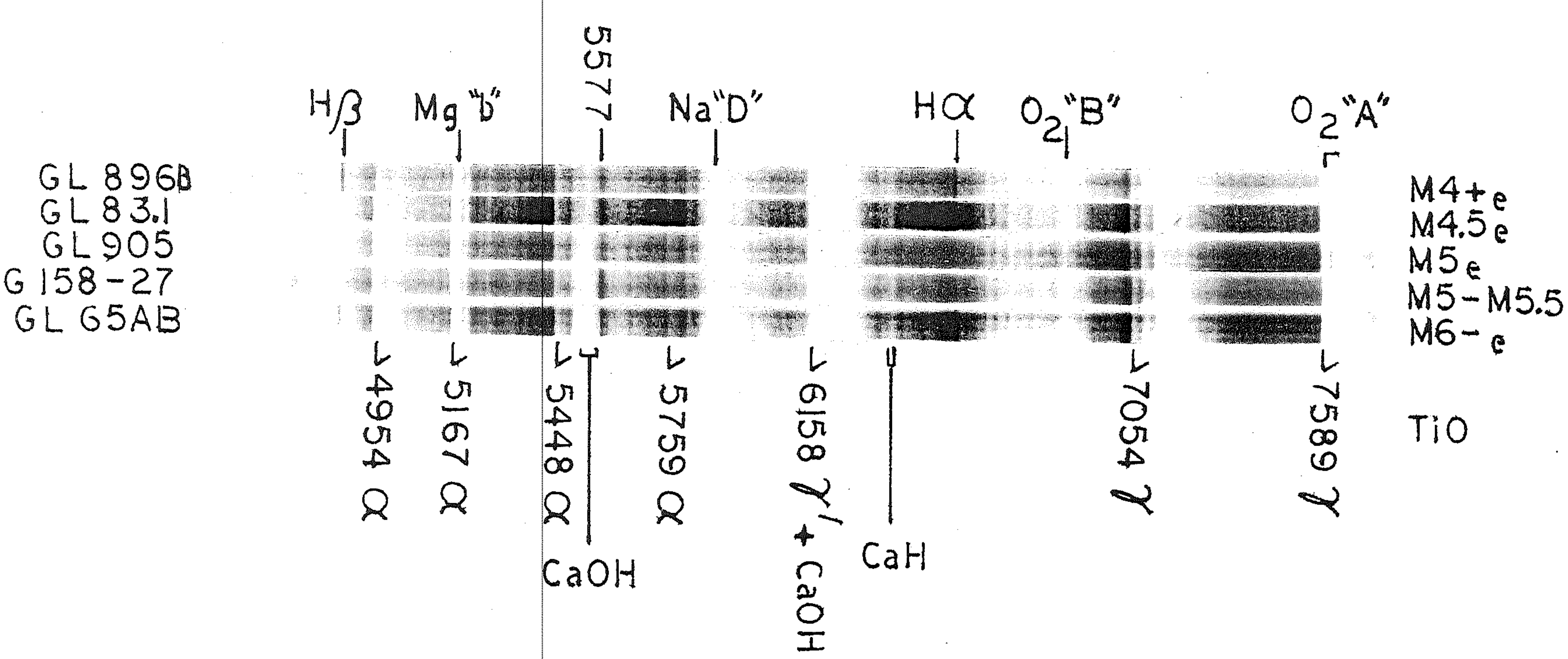
CAPTION FOR PLATE II

110 A/mm Image Tube Spectra of Late-Type K Dwarfs and M Dwarfs Arranged in a Sequence of Decreasing Temperature.


MgH 4788
Hβ
Mg "b"
5577
Na "D"
Hα
GL 365
GL 380
GL 96
GL 411
GL 251
GL 273
GL 268
GL 473AB
<K5
K7
M0.5
M2
M3.5
M4
M4.5e
M5+e
4626 α
4761 α
4954 α
5167 α
5448 α
5497
CaOH
5736 VO
5759 α
5810 α
6158 γ' + CaOH
6385 CaH
TiO

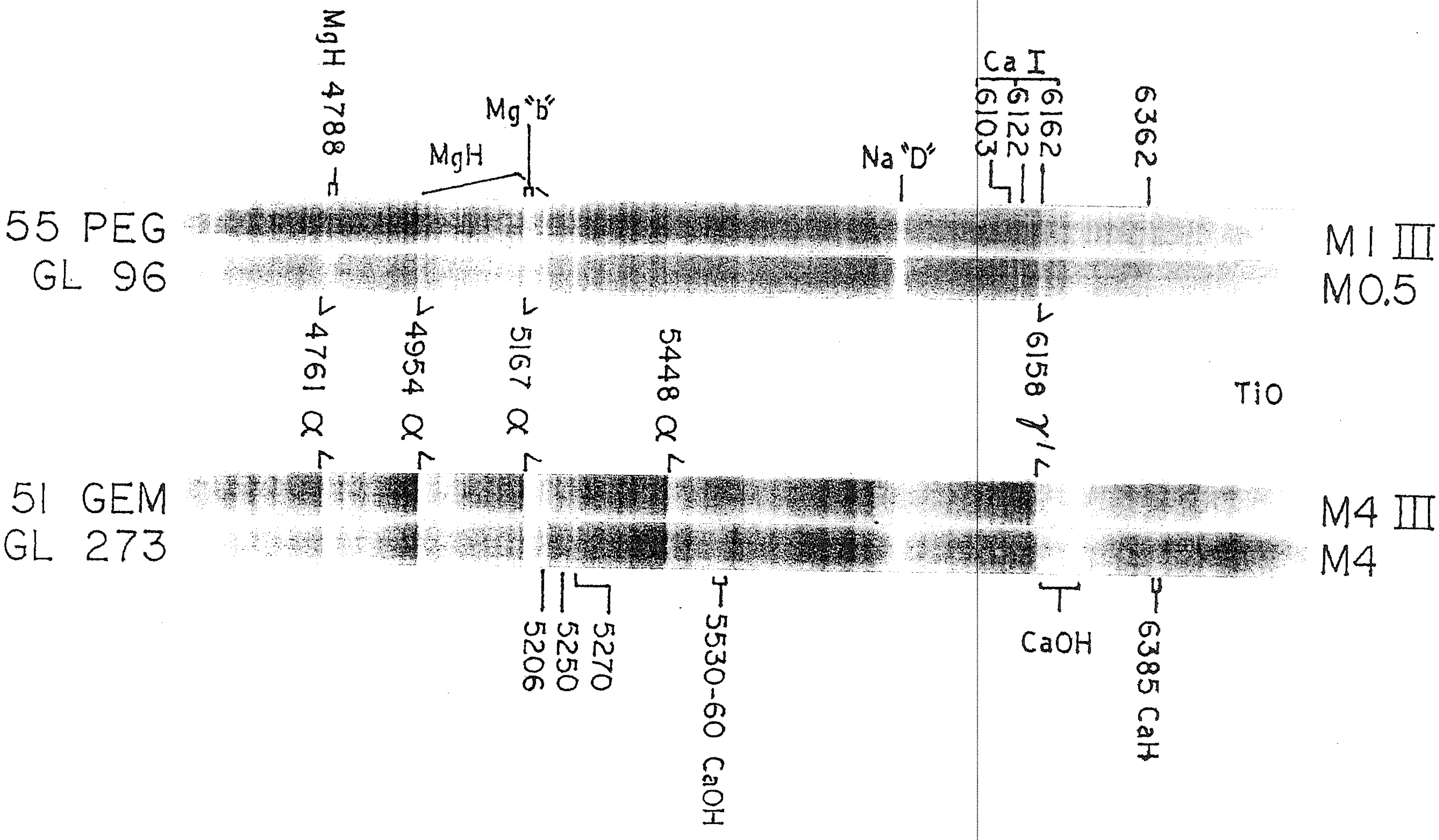
CAPTION FOR PLATE III

110 A/mm Image Tube Spectra of Some of the Latest Type M Dwarfs. (These spectra were widened half as much as those seen in Plate II).


GL 896B
GL 83.1
GL 905
G 158-27
GL 65AB
Hβ
Mg "b"
5577
Na "D"
Hα
O2 "B"
O2 "A"
M4+ e
M4.5 e
M5 e
M5-M5.5
M6- e
4954 α
5167 α
5448 α
CaOH
5759 α
6158 γ' + CaOH
CaH
7054 γ
7589 γ
TiO

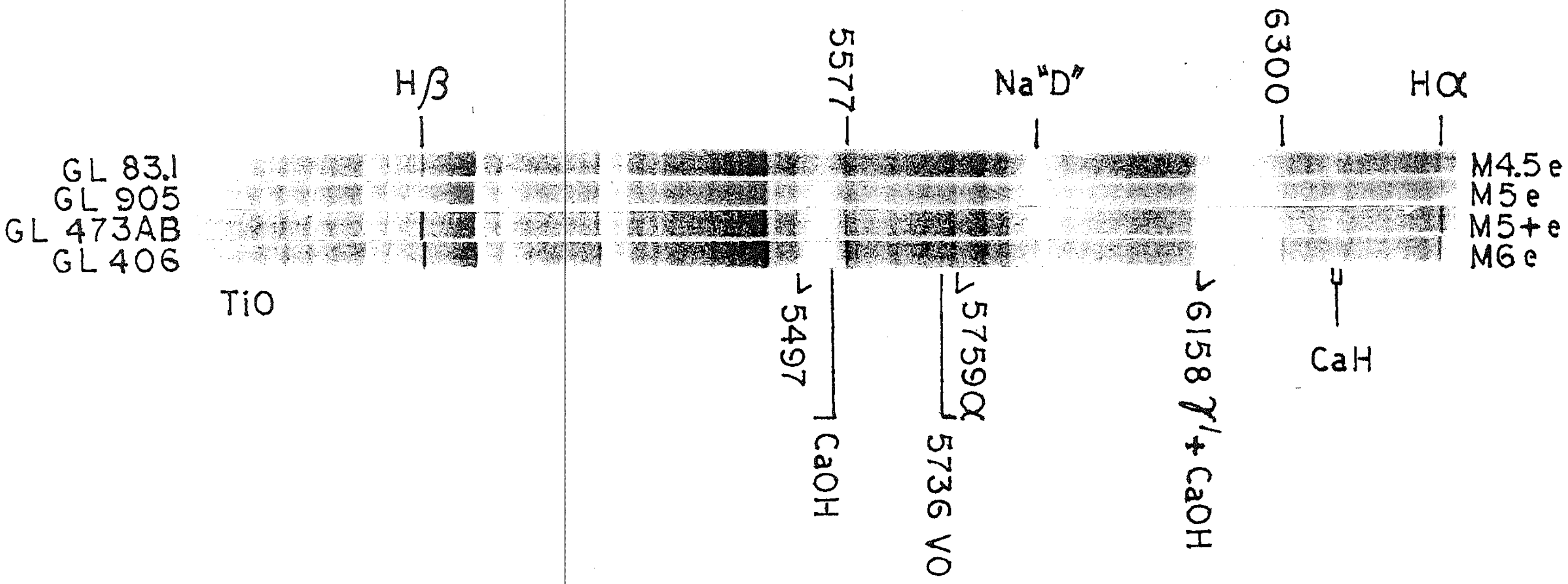
CAPTION FOR PLATE IV

250 A/mm Image Tube Spectra of Late Type M Dwarfs. (G158-27 is the only M dwarf later than M4.5 found to exhibit no Balmer emission.)


55 PEG
GL 96
51 GEM
GL 273
M1 III
M0.5
M4 III
M4
TiO
MgH 4788
MgH
Mg "b"
Na "D"
Ca I
6103
6122
6162
6362
4761 α
4954 α
5167 α
5448 α
6158 γ′
5206
5250
5270
5530-60 CaOH
CaOH
6385 CaH

CAPTION FOR PLATE V

Illustration of Spectral Features Sensitive to Luminosity Changes on Image Tube Spectra of 110 A/mm.


GL 83.1
GL 905
GL 473AB
GL 406
TiO
Hβ
5577
Na"D"
6300
Hα
M4.5e
M5e
M5+e
M6e
5497
CaOH
5759α
5736 VO
6158 γ′+ CaOH
CaH

Adopted Classification Criteria

Spectra were obtained for 70 M-dwarf and 4 K-dwarf stars. Plates II and III contain representative spectra that illustrate the appearance of the molecular features defining the dwarf M subclasses, these spectra being arranged in order of decreasing temperature. In general, the classification is similar to that of the M giants, with standards chosen so that differences between the spectral subdivisions would be recognizable on plates of comparable scale and quality to those employed here. Since a wide spectral range is covered on the image tube plates and the bands of the TiO present do not all vary with temperature in the same way, the spectra have been classified on the appearance (i.e., which bands are visible) of different TiO bands rather than the absolute strength of a particular band. Merrill _et al_. (1962), using coude spectrograms of M3 to M8 giants, show the non-uniformity in the behavior of different TiO bands in the λλ5600-5900 region. They demonstrate that ratios of certain molecular features in this region can be used as temperature indicators even on spectrograms with dispersions as low as 150 to 200 Å/mm.

Dwarfs earlier than K5 are recognizable by the weak appearance of the MgH λλ4788, 5211 bands, as can be seen in GL 365. Hα appears in absorption through the K dwarfs down to type M0, after which it is too weak to be seen. In the M giants by contrast (because of the marked positive luminosity effect of the Balmer absorption), Hα is visible in the spectrum of 51 Gem (M4 III), even through the overlaying TiO absorption. For the M dwarfs, the temperature criteria are as follows:

M0: The TiO α(1,0) band at λ4954 is clearly discernible over the blend of Fe I lines in this region. The MgH band at λ5211 extends over 200 Å blueward, giving the appearance of a continuous absorption feature from λ4954 to the Mg "b" lines. The γ'(0,0) λ6159 band can be clearly seen over the Ca I λ6162 line.

M1: The λ4761 α(2,0) band is present and can be seen to form a break blueward of the MgH λ4788 band. λ5448 α(0,1) can be clearly seen.

M2: λ4804 α(3,1) is present. λ5000 α(2,1) can be clearly seen through the overlaying MgH absorption. GL 411 (HD 95735) is an M2 V standard.

M3: λλ5597 β(0,0), 5629 β(1,1) present a blended appearance. λλ5759 α(0,2), 5810 α(1,3) are present and CaOH λ5530 is present at M3.5.

M4: λλ4584 α(3,0), 4626 α(4,1), 4667 α(5,2) are distinct, with λ4848 α(4,2) present. CaOH λ5530 is slightly stronger than neighboring TiO bands.

M5: VO λ5736 is present and CaOH λ5530 forms a sharp depression between the surrounding TiO bands.

M6: VO λ5736 is slightly weaker than λ5759. The region from λ5500 to λ5560 gives the appearance of a single broad depression.

M7: VO λ5736 equals λ5759 in strength.

The relative strengths of the TiO bands appear to change very slowly after type M5. For these stars, a more accurate temperature sequence is given by the ratio of VO λ5736 to TiO λ5759 (Merrill et al. 1962) and by the rapid increase in the strength of the λ5530 band of the CaOH molecule, present only in the late M dwarfs. There is a good correlation between the increase in the VO/TiO ratio and the strengthening of the λ5530 band, though the change in the former is not as striking as the behavior of the CaOH band. On the 250 Å/mm spectrograms, the change in the VO/TiO ratio is not as easily discernible. The VO λ5736/λ5759 ratio appears greatest in G51-15 (where it is near unity), making this star the latest dwarf classified in this program. Plate IV contains a sequence of the latest dwarfs taken at low dispersion. The change in the strength of CaOH is the most notable characteristic. The effect of the CaOH contamination on the $\gamma'(0,0)$ band makes this feature appear stronger than any other TiO band.

Spectral features sensitive to luminosity changes are illustrated in Plate V. In the upper set, the MgH bands at λ4788 and the one extending blueward from the Mg "b" lines are evident in GL 96, an M0.5 dwarf, but not in 55 Peg, an M1 III. The strength of the blend at λ5250 (due primarily to one or more members of the $a^5D-z^7D^o$ multiplet of FeI) in comparison to the blends at λ5270 and λ5206 can be seen to increase in the giants (Fitch and Morgan 1951; Scarfe 1966). The λ5250 blend increases in strength with decreasing temperature in the M dwarfs until it is equal in strength to the λ5270 blend near type M4.5. The blended feature near λ6362 seen in M giants appears to be a composite of the following intersystem lines (Davis 1947):

Fe	13	λ6358.692	$a^5F-z^7F^o$
Ti	1	λ6359.896	$a^3F-z^5G^o$
Cr	6	λ6362.874	$a^5S-z^7P^o$
Ti	1	λ6364.920	$a^3F-z^5G^o$

and

Ti	103	λ6366.354	$b^3F-x^3D^o$.

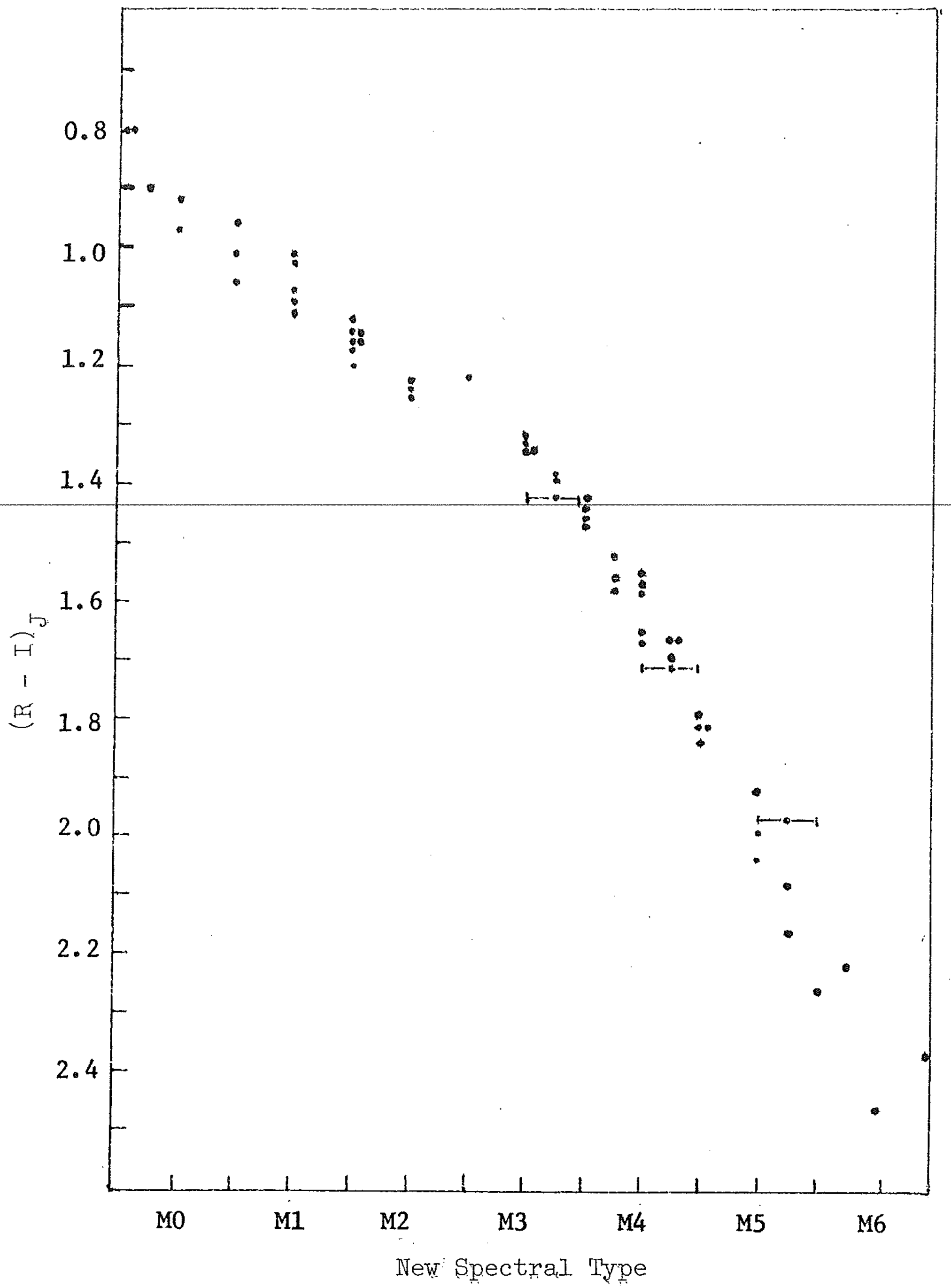


Fig. 1 - (R-I) Color on the Johnson system vs. the New Spectral Types for Stars in Table 3.

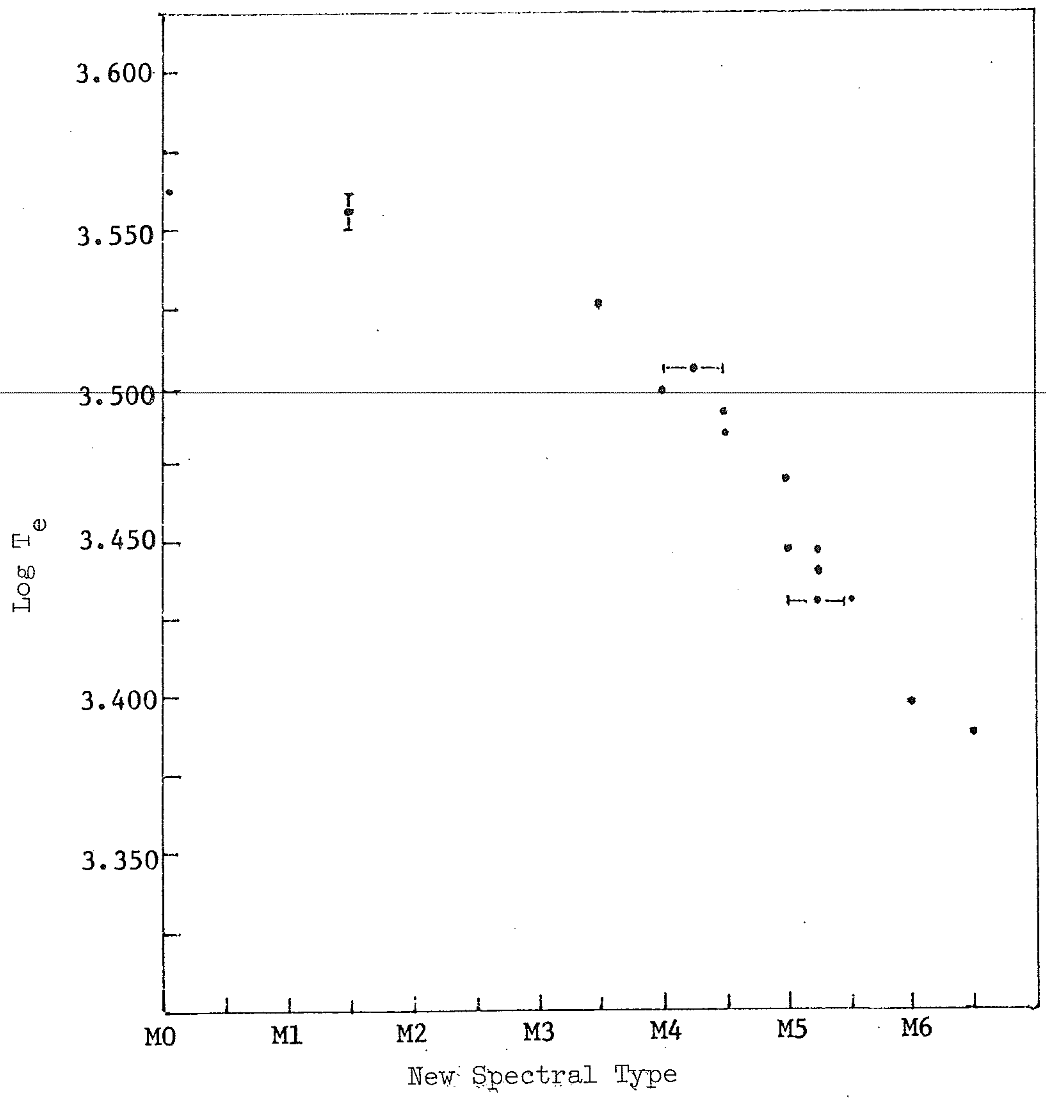


Fig. 2 - Effective Temperature (T_e) ± 150°K vs. the New Spectral Types for Stars in Table 5.

Table 5

THE EFFECTIVE TEMPERATURES OF VEEDER (1974) FOR SOME M DWARFS FROM TABLE 3

GL	SP. T.	T_e ($\pm$150°K)	log T_e
G158-27	M5-M5.5	2700	3.431
15B	M4.0	3150	3.498
51	M5.0	2950	3.470
65A	- - -	2700	3.431
205	M1.5	3600	3.556
234A	M4.5	3050	3.484
239	M0.0	3650	3.562
285	M4.5	3100	3.491
299	M4-M4.5	3200	3.505
G51-15	M6.5	2450	3.389
406	M6.0	2500	3.398
473	M5$^+$	2800	3.447
551	M5.5	2700	3.431
860A	M3.5	3350	3.525
866	M5$^+$	2750	3.439
905	M5	2800	3.447

The spectral types of M-dwarfs classified by JA (1974), Kuiper, and Wing and Dean (1975) are compared to the new types of this study. Figure 3 illustrates the scatter between the Mt. Wilson and Kuiper types for these stars. The standard deviation obtained from a linear least squares fit to the data is greater than 0.8 subtype. For types earlier than M3, the Mt. Wilson classification is systematically later than Kuiper's, the reverse being true for types later than M3. In Figures 4 and 5, the dispersion is approximately $\frac{1}{2}$ subtype for the correlations between the new spectral types and those of JA (1974) and of Kuiper. Specifically, my types are systematically earlier than Kuiper's, with the deviation increasing toward the later types. This effect may be explained by Kuiper's use of the intensity of CaOH-contaminated λ6159 TiO band as the sole temperature criterion. The new types are systematically earlier than those of Joy, with the deviation decreasing with increasing type.

The new types are compared in Figure 6 to some provisional unpublished data kindly supplied by Wing and Dean (1975). Wing's (1973) classification is based upon narrow-band near-infrared photoelectric photometry with spectral types assigned on the basis of the depth below the continuum of TiO features measured at λ7120 (in the γ(0,0) band) and at λ7810 (in the γ(3,4) band). Here, the agreement is quite good with a deviation on the order of $\frac{1}{4}$ subtype from the mean. This is not surprising, since Wing's system was also calibrated using the MK giants. The largest deviation occurs in the early dwarf M's. This may be explained by the difficulty encountered here in estimating the strength of the TiO bands close to those of MgH (TiO λ4761 and λ4951 are blue-

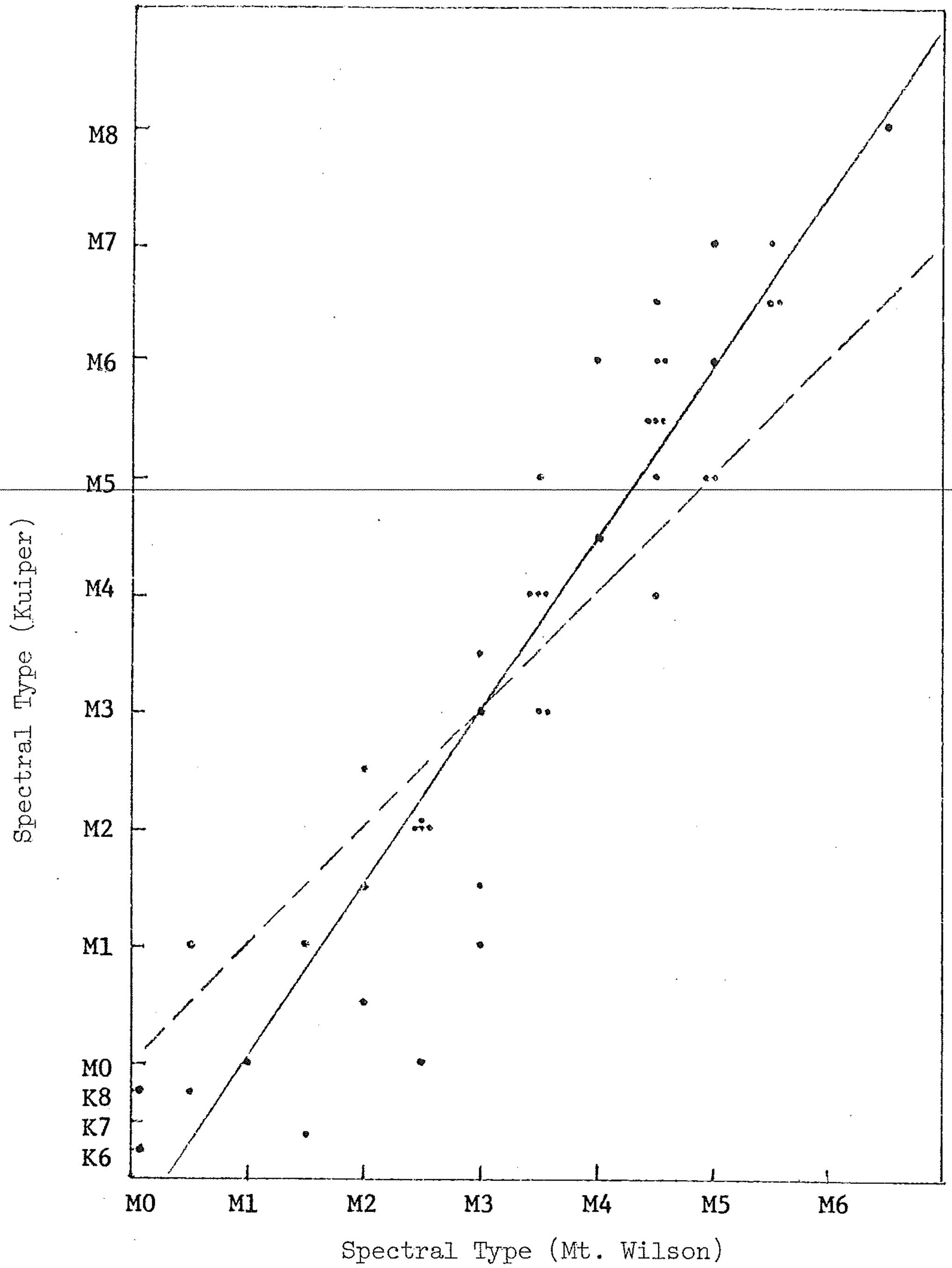


Fig. 3 - Mt. Wilson vs. Kuiper Spectral Types for Stars in Table 3. The dashed line represents a one to one relation and the solid line, a linear least squares fit to the data points.

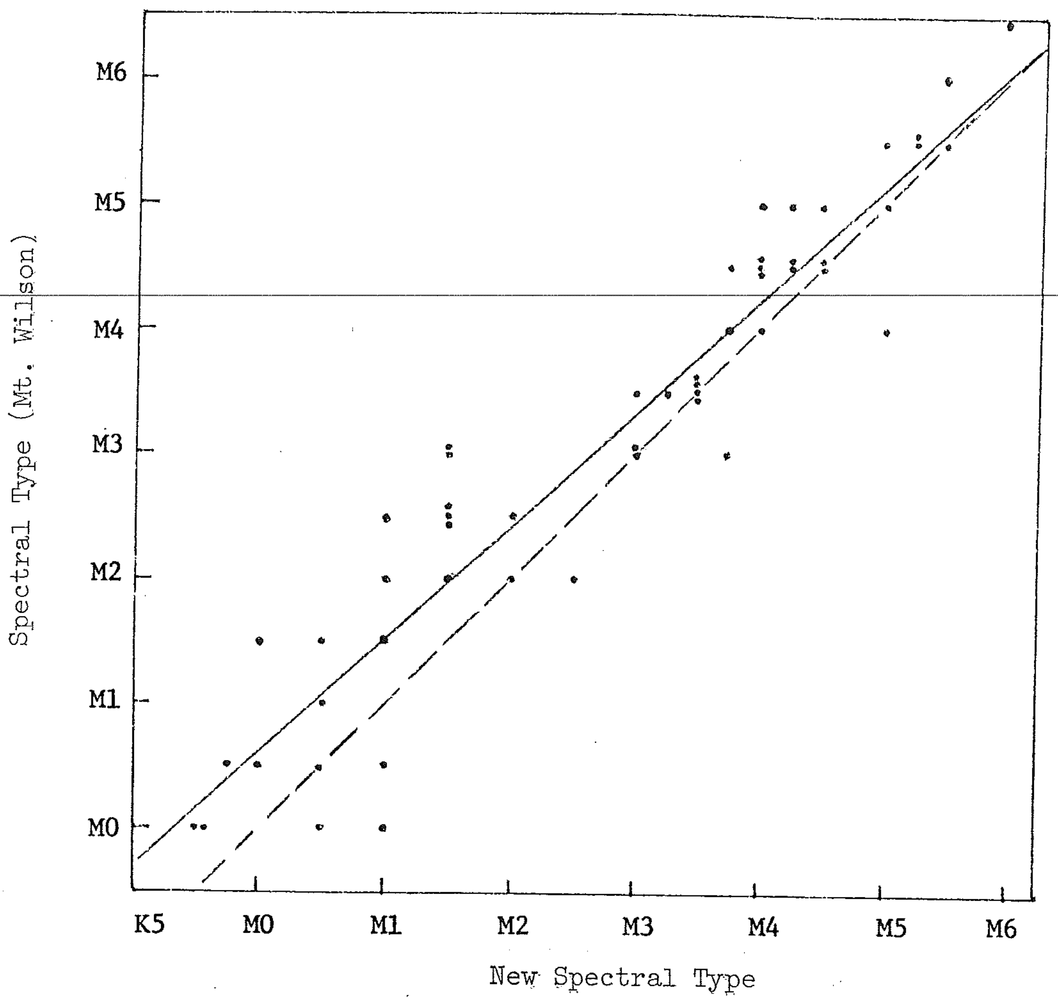


Fig. 4 - Mt. Wilson vs. New Spectral Types for Stars in Table 3. The dashed line represents a one to one relation and the solid line, a linear least squares fit to the data points.

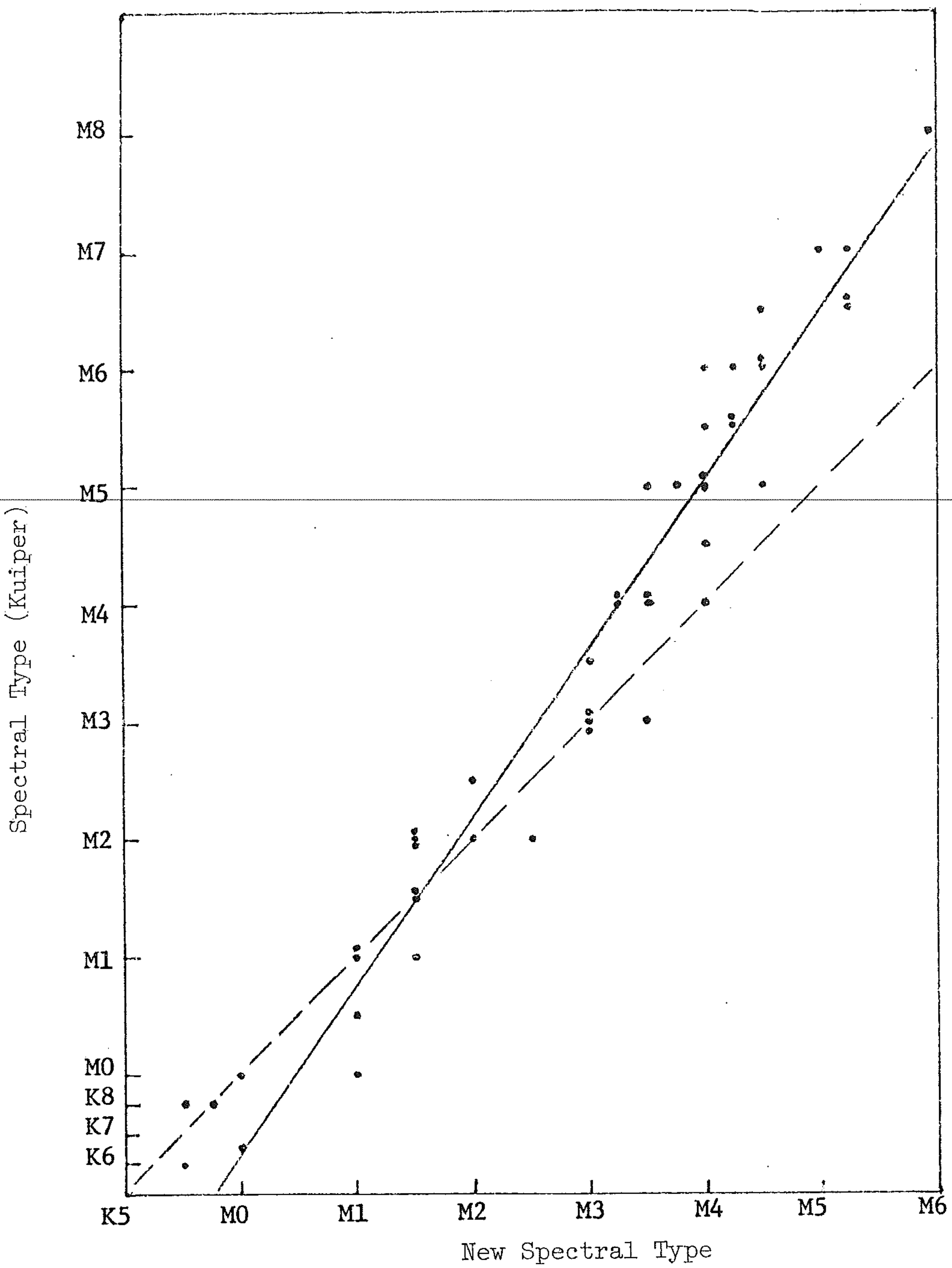


Fig. 5 - Spectral Types by Kuiper vs. the New Spectral Types for Stars in Table 3. The dashed line represents a one to one relation and the solid line, a linear least squares fit to the data points.

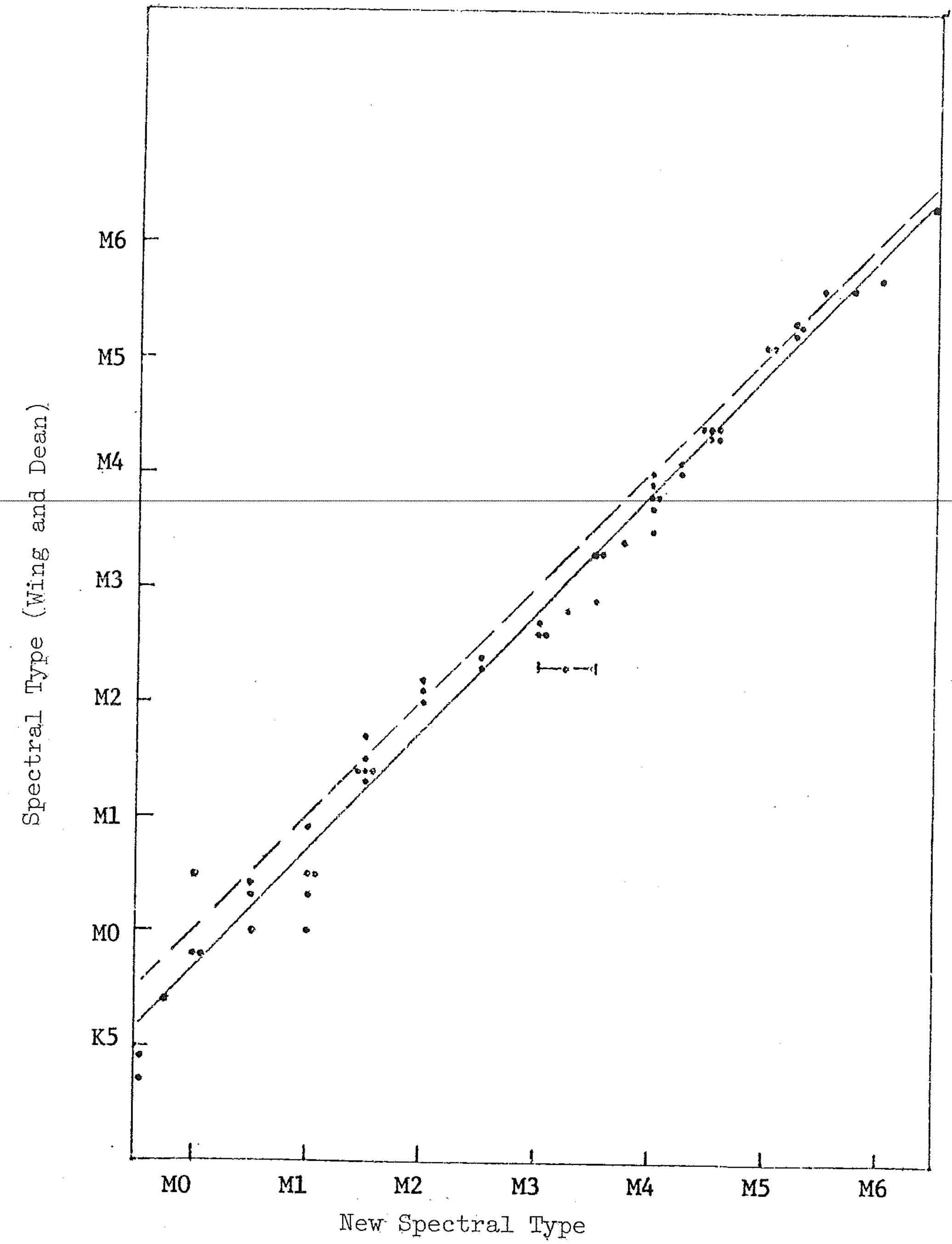


Fig. 6 - Spectral Types Obtained by Narrow-band Infrared Photometry by Wing and Dean (unpublished) vs. New Spectral Types for Stars in Table 3. The dashed line represents a one to one relation, and the solid line, a linear least squares fit to the data points.

ard of MgH λ4788 and λ5211). The λ4951 region also contains many blends of atomic lines. For these early M stars, the exposures on the high dispersion plates had to be of comparable density to estimate reliably the strength of the λ6159 band. In a few cases, the blue and red TiO bands appeared to indicate different types, but this is most likely a function of hydride and blend features complicating the TiO.

Hertzsprung-Russell Diagrams

Several H-R diagrams were constructed in order to examine the observed intrinsic dispersion in the main sequence. For comparison, a luminosity-color diagram for all program stars with available photometry is plotted in Figure 7. A linear least squares fit to the data for all single stars yields the mean relation:

$$M_V = 5.28(R-I) + 3.88. \qquad (3)$$

The line drawn through Figure 7 represents this relation, excluding all known spectroscopic binaries (which are indicated by open circles). The observed dispersion of the stars in this figure is approximately ± 0.53 magnitudes in M_V. GL 154 has the largest listed probable error for the parallax of any star plotted in this M_V vs. R-I diagram. The resulting error in the absolute magnitude of this star is

$$\Delta M_V = 2.17 \frac{\Delta\pi}{\pi} = 2.17 \times \frac{0.013}{0.087} = \pm\, 0.32. \qquad (4)$$

For all other stars, ΔM_V is less than $\pm\, 0.25$. If the uncertainty in the photometry is small ($\sim$0.01 magnitudes), then the dispersion

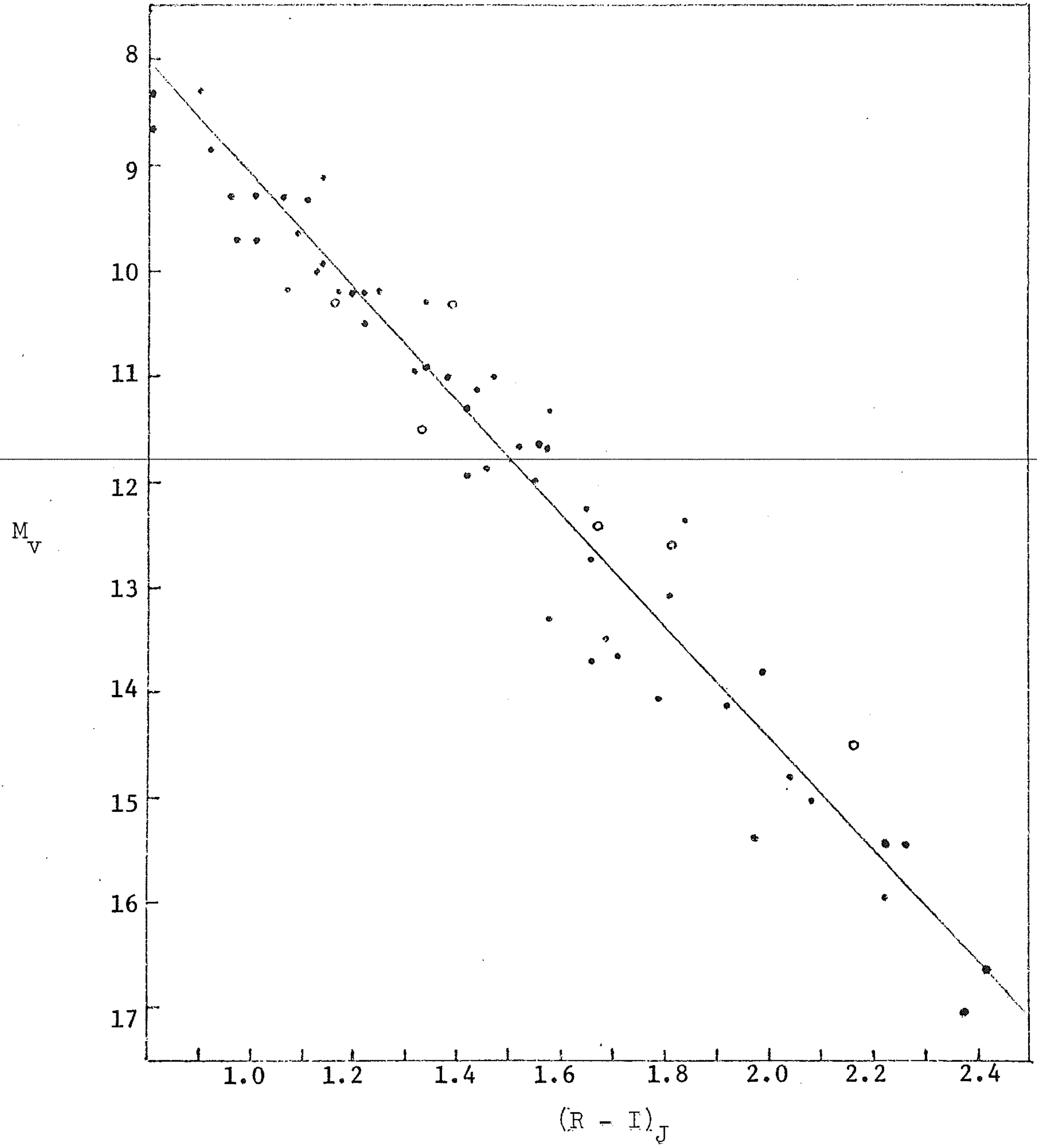


Fig. 7 - Absolute Visual Magnitude vs. (R-I) Color on the Johnson System for Stars in Table 3. The straight line represents the mean relation $M_V = 5.28\ (R-I) + 3.38$ obtained from a linear least squares fit to the data points. The open circles represent spectrocopic binaries which were excluded in calculating the mean relation.

cannot be totally accounted for by errors in observation. A star that is 0.5 magnitudes from the mean relation would require either a change in R-I of 0.10 magnitudes or a change in the stellar parallax of more than 0″.025. Several stars are even farther than 0.5 magnitudes from the mean relation. Similar results have been found by Upgren (1973) for dwarfs from K3 to M2, by Spinrad (1973) for M dwarfs within 10 parsecs of the sun, and by Veeder (1974) in his bolometric magnitude vs. color diagrams for 145 M dwarfs of mixed population groups.

The absolute visual magnitudes of all program stars are plotted against the new spectral type in Figures 8 and 9. Spectroscopic binaries are denoted as open circles and flare stars as crosses. Data from Veeder (1974), who has determined the population group of many of these stars from their space motions, indicates that they represent young disk plus old disk and halo populations. The sample does not appear to be biased toward high velocity stars and should be representative of the solar neighborhood. The line drawn in Figure 8 represents the mean relation

$$M_V = 8.88 + 0.24\ (\mathrm{Sp.T.}) + 0.16\ (\mathrm{Sp.T.})^2, \qquad (5)$$

which was obtained by a quadratic least squares fit to the data for all single stars. Due to the non-linear form of the plot, the quadratic solution allowed a more reasonable estimate of the dispersion in absolute magnitude utilizing all data points. The observed dispersion in absolute magnitude is ∿ ± 0.46 magnitudes, with a mean range of about one magnitude at any one subclass.

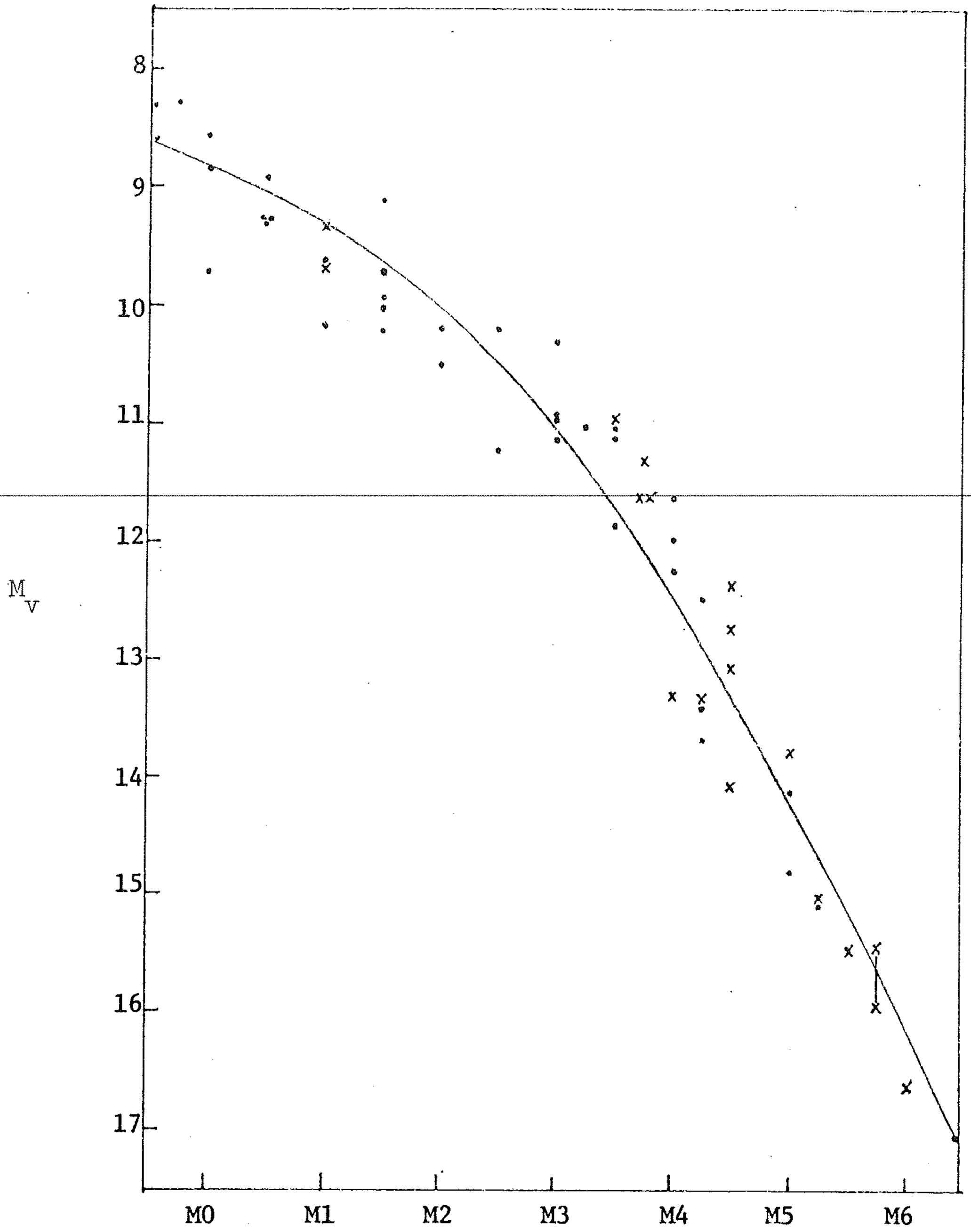


Fig. 8 - H-R Diagram for M Dwarfs in Table 3, Excluding Stars with Uncertain Spectral Types, Known Subdwarfs, and Spectroscopic Binaries. The curve represents the mean relation $M_V = 8.88 + 0.24\ (Sp.T.) + 0.16\ (Sp.T.)^2$. Non-flare stars are represented by dots; flare stars, by crosses.

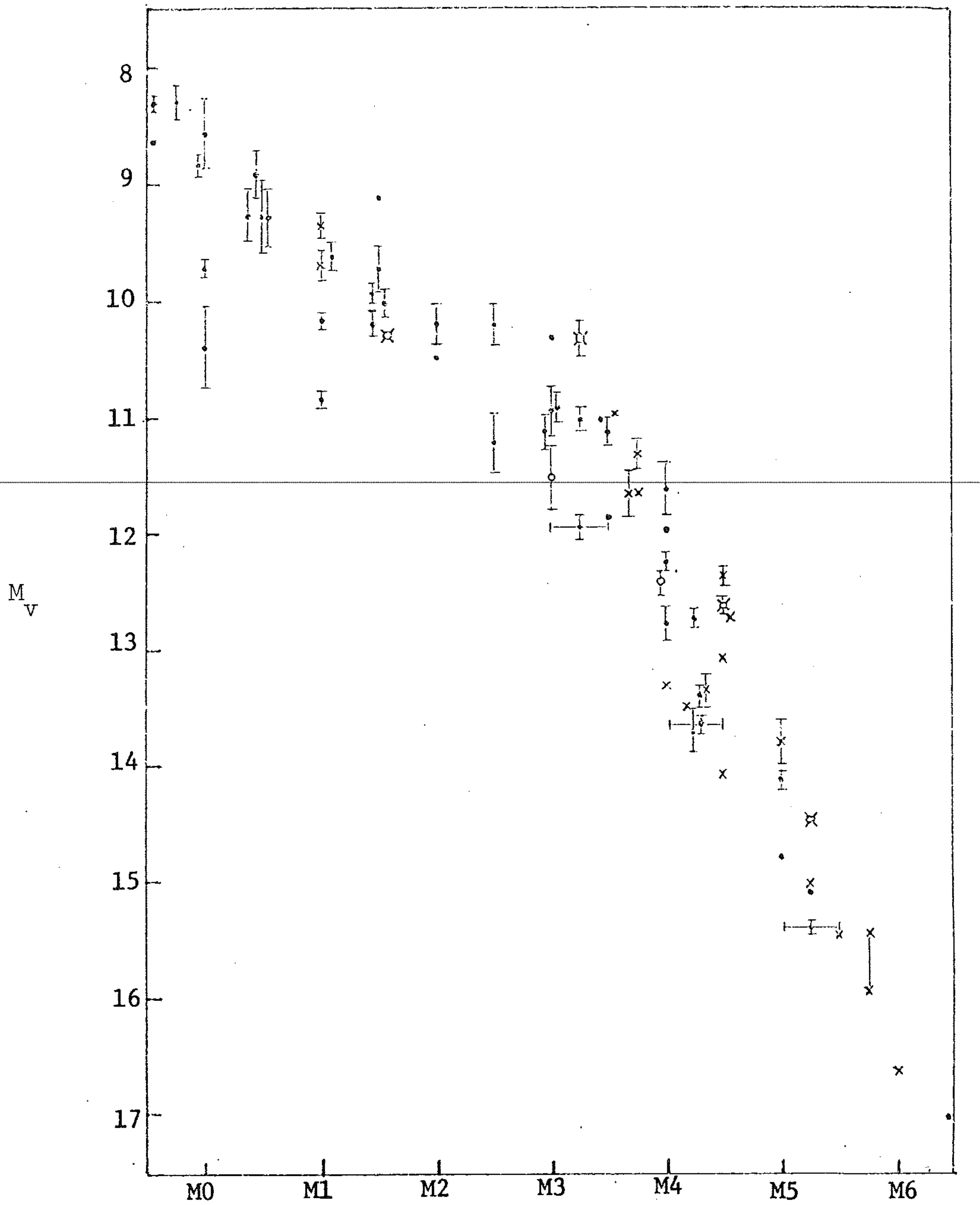


Fig. 9 - H-R Diagram for All Stars with Trigonometric Parallaxes Found in Table 3. Error bars represent probable errors in the absolute magnitude calculated from the probable errors in the trigonometric parallax. If no error bar drawn, the p.e. in the absolute magnitude is ≲ $0^m.05$. The dots represent non-flare stars; the crosses, flare stars; and the open circles, spectroscopic binaries.

Figure 9 is essentially the same as Figure 8 with error bars in M_V included to represent the uncertainties in the parallaxes of the individual stars. The largest error in absolute magnitude results for the subdwarf G95-59 (± 0.35 magnitude), primarily because of its small parallax ($0''.020$). Typically, the ΔM_V's from this source of error range from less than $0^m.05$ up to $0^m.25$. A combination of classification and parallax errors could conceivably account for the observed dispersion, as pointed out by JA (1974). The mean dispersion in M_V for the 426 dwarfs on the Mt. Wilson system was 0.57 magnitudes, which was explained as resulting from a combination of errors in photometry, parallax determination, spectral classification, and the presence of undetected spectroscopic binaries - perhaps 10 per cent of the sample. While these errors may contribute considerably to the spread about the mean relation for the M-dwarf main sequence, there exist stars below the mean which would require large changes in parallax or spectral type in order to move them back to the mean relation. For example, GL 15A is a spectroscopic binary. The true position of the star is probably much lower than an M_V of 10.32 magnitudes indicates. Yet the spectral type of GL 15A is clearly not as late as GL 411 or GL 382. In general, stars that fall below the mean relation in the M_V vs. spectral type diagram behave similarly in the M_V vs. R-I plot. Also, many of these stars exhibit slightly enhanced hydride bands in comparison to stars lying above the mean relation. In spectral types later than M3, a strengthening of the CaOH λ5530 band in comparison to the TiO bands is sometimes noticeable. In two extreme cases, the

TiO appears very weak compared to the CaOH. For GL 754.1B and G 158-27, the temperatures calculated by Wing and Dean (1975) and by Veeder (1973), respectively, appear to correspond more closely to the CaOH type (See Figure 1).

Similar anomalous behavior between the TiO and CaOH bands is seen in GL 15B, GL 203, and GL 299. However, the effective temperature calculated by Veeder for GL 299 is higher than that of GL 15B. On the other hand, GL 299 is 0.1 magnitude redder in R-I than GL 15B. The spectra of these two stars also suggests that GL 299 is cooler, both in the appearance of the green-yellow TiO bands and because of the CaOH band strength. The blue TiO bands are weaker in GL 299.

An attempt was made to see if the scatter in the HR diagram was considerably reduced by using the strength of the CaOH λ5530 band as the sole temperature criterion. The resulting dispersion in M_V for the M3.5 and later dwarfs was reduced by less than $0\overset{m}{.}05$. The majority of stars which assumed a later spectral type were of the old disk or halo population. Stars such as GL 15B, GL 299, GL 102, and GL 447 still fall below the mean relation.

No definite conclusion can be reached as to whether the CaOH is a better temperature indicator than TiO in all cases. Since CaOH is sensitive to changes in surface gravity (it is not seen in M giants), this band may be enhanced in subdwarfs. The observation that a weakening of TiO bands does not appear to be accompanied by a weakening of CaOH bands would tend to support this statement. Simplistically, one might expect that Ca is affected by depletion to the same extent as Ti. Then, bands of both molecules should indicate a similar temperature.

However, the sensitivity of CaOH to temperature changes is much more striking than either TiO or the luminosity sensitive CaH bands for M3.5 and later dwarfs. So CaOH may prove to be the better temperature indicator, as in the case of G 158-27 and GL 754.1B. The problems associated with a discussion of the effects of abundance differences on the spectra of disk and halo population K and M dwarfs have been pointed out by Rogers and Eggen (1974). The ratios of O/H and (heavier metals)/H are probably different between the two populations. The same may be true for the C/O ratio, which determines the abundance of free oxygen in these stars. However, a detailed discussion of the effects of varying abundance, temperature, and pressure on the formation rates of TiO and CaOH is beyond the scope of this study.

Veeder (1973, 1974) has found that the blocking by atomic lines and molecular bands in different portions of the spectra of M dwarfs are related. He reduced the scatter in the absolute K-magnitude vs. color diagrams to within the observational errors in the photometry by correcting the U, B, R, and I magnitudes for differential blanketing. The same blanketing function appears to apply to all population groups. His results rather strongly imply that the scatter in his uncorrected HR diagrams is due to differences in blanketing rather than scatter in absolute magnitude. He cautions further that excessive blanketing in an M dwarf may result in the calculation of a lower effective temperature by strongly depressing the region blueward of 9000 Å relative to the peak of the energy distribution in these stars (well beyond 1μ).

Jones (1968) has suggested that the difference in the HR diagram positions of high and low velocity M dwarfs may be due to differences in age rather than differential blanketing. His scanner observations indicate no significant difference in TiO intensities between stars in these groups. He suggests that the stars are still evolving along their Hayashi tracks to the main sequence. Stars on the same Hayashi track will have the same temperature, but the older stars will have lower luminosities. However, stars of the old disk and halo population with ages > 10^9 years have had sufficient time to reach the main sequence. Grossman (1970) finds contraction times of 10^8 to 10^9 years for M dwarf stars.

According to the models of Iben (1967), M dwarfs have not had sufficient time to complete their main sequence phase of evolution and are still in the process of evolving up the main sequence. Displacement of the main sequences of stars with differing compositions (Copeland _et al_. 1970) may account for some of the scatter in the HR diagram. There are certain high velocity objects, e.g. GL 299, which fall farther below the mean main sequence than can be explained by theoretical models, however. Motions of other stars with large displacements (e.g. GL 15A and B) are not indicative of the halo population and there exist halo population stars that are not near the faint extreme of their spectral type (e.g. GL 213).

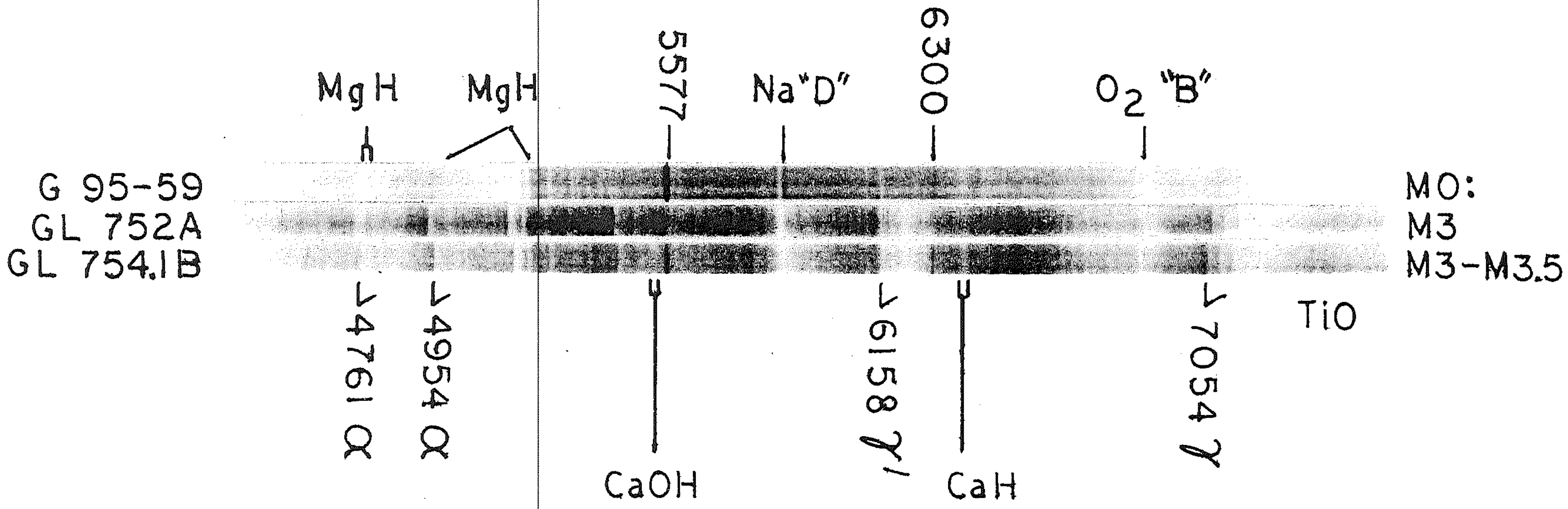
Unresolved binaries may also contribute to the observed scatter, though all known binaries were excluded from the calculation of the mean main sequence and the mean dispersion. A maximum upward displacement of $0\overset{m}{.}75$ in a star's M_V is possible for equally luminous components. Woolley, Pocock, Epps, and Flinn (1971) find that 6% of the dM stars and 24% of the dMe stars are spectroscopic binaries. The percentages are larger for resolved multiples. Therefore, the M dwarfs with Balmer emission have a higher probability of being multiple systems. It is interesting to note that some of the stars farthest above the mean relation in Figure 7 and 8 are not emission stars and that several of the identified spectroscopic binaries (e.g. GL 15A, GL 157 B) fall below.

Errors in the parallaxes and classification could certainly account for a large portion of the scatter, though large changes would be required to move the stars with the most extreme deviations back onto the mean main sequence. These extreme cases may be due to the binary nature, low luminosity, or differential blanketing for the star in question. Detection of a weakening of the TiO bands was possible in a few cases and this may account for the downward displacement in the M_v vs. R-I diagram for some stars.

Stars which still fall below the main sequence when classified using the CaOH $\lambda5530$ band strength are probably subluminous. In stars earlier than M3.5, where the CaOH band is not present, enhancement of the CaH band appears to be the best indication that the star may be subluminous. In dwarfs later than M4.5, an enhancement of the CaH band was not easily detected, possibly because it has reached maximum intensity near this spectral type.

CAPTION FOR PLATE VI

250 A/mm Image Tube Spectra of the Subdwarf, G95-59, the Peculiar M Dwarf, GL 754.1B, and the Normal M Dwarf, GL 752A.

MgH
MgH
5577
Na"D"
6300
O_2 "B"
G 95-59
GL 752A
GL 754.1B
MO:
M3
M3-M3.5
4761 α
4954 α
CaOH
6158 γ'
CaH
7054 γ
TiO

Comments on Individual Stars

Plate VI contains the spectrum of the peculiar subdwarf G95-59, the normal M3 dwarf GL 752A, and GL 754.1B (L923-22), the common proper motion companion to the DA star L923-21. The peculiar spectrum of G95-59 was first noted by Greenstein and Eggen (1965b), who found an extremely red B-V of $2^{m}.05$ for this star. Dahn and Priser (1973) measured a B-V of $1^{m}.57$, approximately the color of an M2 dwarf. They also list the V-I color on the Kron system as $1^{m}.66$, a value similar to that of GL 488 (M0^{-}). An inspection of the spectrum of G95-59 indicates that the TiO bands are absent (or extremely weak, at best), while the hydride bands of Mg and Ca are quite strong. In a normal dwarf of type K7 (see Plate I), the TiO λ6159 band already is easily seen. Finally, the strength of the hydride bands would indicate a spectral type of at least M0, which must be considered an estimate because of the sensitivity of these bands to changes in luminosity.

Spectra of similar density are compared for GL 752A (M3), and GL 754.1B. The TiO bands appear to be weaker in GL 754.1B, implying a spectral type of M2.5 based on their strength alone. However, on spectra of longer exposures, the TiO bands at λλ4584, 4626, and 4667 are and λ4848 is marginally present. These bands, together with the presence of CaOH at λ5530, indicate a type of M3.5. This is consistent with the R-I color. The strength of the CaH band at λ6385 is at least that of an M4 dwarf, and is much stronger than in GL 752A.

Four additional subdwarfs from the lists of Eggen and Greenstein (1965a, b) were observed in order to compare the behavior of CaH and CaOH bands with those of the main sequence dwarfs. The criteria for subdwarf classification by Eggen and Greenstein include weak TiO and enhanced hydride bands. Inspection showed that the spectrum of G111-72 (sdM2) resembles that of GL 908 and was thus classified as a dwarf M1.5. G5-43 (sdM3) is similar to GL 754.1B. G5-43 has weak TiO bands and enhanced CaH, but no CaOH is observed in its spectrum. The appearance (but not the strength) of the TiO bands in G5-43 are similar to those in GL 752A. G107-69 is the only star of the four which has a trigonometric parallax. The overall spectrum of this object gives the impression of an M4 to M4$^+$ dwarf. Compared to GL 299 (M4$^+$:) which also falls below the mean main sequence, the TiO bands in the blue are stronger. The entire remaining spectrum of G107-69, though, is of an earlier type with enhanced CaH.

Eggen and Greenstein note that G43-53 has very weak TiO for its color (B-V = $1^{m}.40$) and must be similar to G95-59. However, G43-53 more closely resembles GL 488. Unlike G95-59, the TiO bands at λ4954 and λ6159 are easily seen for G43-53. B-V = $1^{m}.40$ is approximately the color of an M0 V star.

Five of the flare stars included in this study do not show Balmer emission in the quiescent state (GL 15 A and B, GL 229, GL 424, GL 447). All of these stars have been found to exhibit some degree of Ca II emission, but only GL 229 lies above the mean main sequence in Figures

7 and 8. Both GL 229 and GL 447 are young disk objects according to Veeder, and appear to have normal spectra for their respective temperature classes. However, GL 15 A and B and GL 424 show slightly enhanced CaH and belong to the old disk population.

Summary and Conclusions

The primary purpose of this study was to define a classification system for the M dwarfs using image tube spectra of the visual region. The MK M-giant criteria served as a reference scale for defining the temperature subclasses of the dwarfs. However, the criteria for the M dwarfs differ in some ways due to the effects of the large differences in surface gravity between the two luminosity classes. Classification based on the appearance rather than strength of the TiO bands reduced the scatter in the HR diagram by a small amount.

The distinction between an M dwarf and a true M subdwarf, i.e. a star that is underluminous for its effective temperature, is not easily made here. M dwarfs which exhibit weak metallic lines and TiO bands may not be true subdwarfs, and their underluminous position in color-magnitude diagrams may only reflect differential blanketing effects. On the other hand, in Kapteyn's star (a known subdwarf), the metallic lines do not appear abnormally weak. The Ca I λ4226 and neutral Al lines at λλ3944, 3961 however, appear as strong as in an M4 dwarf. Because of night-sky Na emission, present on image tube spectrograms, a negative luminosity effect in the Na "D" lines cannot be used reliably to identify subluminous stars. Wing *et al.* (1976) find that the hydride bands in Kapteyn's star are enhanced due to an increase in surface gravity. This is also seen in G95-59. However, the positioning of other M dwarfs with enhanced CaH relative to TiO just below the main sequence cannot be definitively taken as a pure luminosity phenomenon. The effect of small changes in log g on the appearance of the metallic hydride bands is not known. A difference of more than 3.0 in log g between the M dwarfs and M giants can account for the weakness of the MgH and CaH features in the giants. The log g change between G8 to K1 subdwarfs and their main sequence counterparts is on the order of 0.25 (Hearnshaw 1975). The apparent slight subluminosity of some M stars may reflect either differences in initial composition (and hence evolution) or differential blanketing between these objects and stars which lie on or above the mean main sequence. Eggen and Rogers (1974) have estimated that a minimum abundance difference of a factor of 10 is required to be noticeable in spectra of similar scale (and higher resolution) to that (110 Å/mm) used in this study. This would correspond to those cases (e.g. GL 203, GL 754.1B, etc.) where the TiO bands are extremely weak for the overall spectral appearance.

The effect of small temperature changes in late M dwarfs is more evident in the appearance of the CaOH λ5530 band than in the TiO bands. However, variations in log g may alter the strength of this band in a manner similar to that of the metallic hydrides. In stars which show both enhanced CaH and CaOH relative to TiO, the CaH strength usually indicates a later type than CaOH. A few M dwarfs were found where the CaOH band was a better temperature criterion than the TiO bands, which were abnormally weak. Nevertheless, using the CaOH strength as the sole temperature indicator did not reduce the scatter in the lower main sequence by a significant amount.

The importance of this study lies in the use of the visual region of the spectrum for the study of cool dwarf stars. Definite advantages over classification systems based on the blue TiO bands include working nearer the peak of the energy distribution plus the variety of temperature criteria spread across the visual region. The presence of uncontaminated Na "D" lines or Ca I λ4226 would be useful, though, in resolving the question of marginal hydride enhancement. New image intensification systems are now in existence which offer higher resolution than that obtainable from the spectrograph used for the high dispersion observations in this study. Such instrumental advances should enable classification of the M dwarfs to accuracies of one quarter of a subtype.

LIST OF REFERENCES

Abt, H. A., Meinel, A. B., Morgan, W. W., and Trapscott, J. W. 1968, An Atlas of Low-Dispersion Grating Stellar Spectra.

Adams, W. S., and Joy, A. H. 1924, Pub. A.S.P., 36, 141.

Adams, W. S., Joy, A. H., and Humason, M. L. 1926, Ap. J., 64, 225.

Adams, W. S., Joy, A. H., Humason, M. L., and Brayton, A. M. 1935, Ap. J., 81, 187.

Auman, J. R. 1969, Ap. J., 157, 799.

Bidelman, W. P. 1975, I.A.U. Symposium No. 72, in press.

Blanco, V. M. 1964, A. J., 69, 730.

Burwell, C. G. 1930, Pub. A. S. P., 42, 351.

Copeland, H., Jenson, J. O., and Jorgensen, H. E. 1970, Astr. and Ap., 5, 12.

Dahn, C. C. 1973, private communication.

Dahn, C. C., Behall, A. L., Guetter, H. H., Priser, J. B., Harrington, R. S., Strand, K. Aa., and Riddle, R. K. 1972, Ap. J. (Letters), 174, L87.

Dahn, C. C., and Priser, J. B. 1973, A. J., 78, 253.

Davis, D. N. 1937, Ap. J., 86, 109.

__________. 1947, ibid., 106, 28.

Eggen, O. J. 1968, Ap. J. Suppl., 16 (No. 142), 49.

__________. 1973, Ap. J., 182, 821.

Eggen, O. J., and Greenstein, J. L. 1965a, Ap. J., 141, 83.

______________________________. 1965b, ibid., 142, 925.

______________________________. 1966, Vistas Astr., 8, 63.

Eichhorn, H. 1975, M.N.R.A.S., 173, 619.

Fay, T. D., Stein, W. L., and Warren, Jr., W. H. 1974, Pub. A.S.P., 86, 772.

Fitch, W. S., and Morgan, W. W. 1951, Ap. J., 114, 548.

Gahm, G. F. 1970, Astr. and Ap., 4, 268.

Gliese, W. 1969, Catalogue of Nearby Stars, Veroff. Astr. Rechen. - Inst. Heidelberg, No. 22.

Greenstein, J. L. 1960, in Stellar Atmospheres, ed. J. L. Greenstein (Chicago: University of Chicago Press), p. 676.

________________. 1965, in Galactic Structure, ed. A. Blaauw and M. Schmidt (Chicago: University of Chicago Press), p. 361.

Greenstein, J. L., Neugebauer, G., and Becklin, E. E. 1970, Ap. J., 161, 519.

Grossman, A. S. 1970, Ap. J., 161, 619.

Harrington, R. S., and Behall, A. L. 1973, A. J., 78, 1096.

Harrington, R. S., Dahn, C. C., and Guetter, H. H. 1974, Ap. J., (Letters), 194, L87.

Harris, D. L., Strand, K. Aa., and Worley, C. E. 1963, in Basic Astronomical Data, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 273.

Hearnshaw, J. B. 1975, Astr. and Ap., in press.

Iben, Jr., I. 1967, Ann. Rev. Astron. Astrophys., 5, 571.

Iwanowska, W., and Wayman, P. A. 1952, Ap. J., 115, 129.

Johnson, H. L. 1965, Ap. J., 141, 170.

Johnson, H. L., and Morgan, W. W. 1953, Ap. J., 117, 313.

Jones, D. H. P. 1968, M.N.R.A.S., 139, 189.

Joy, A. H. 1947, Ap. J., 105, 96.

__________. 1971a, A.S.P. Leaflet No. 502.

__________. 1971b, private communication.

Joy, A. H., and Abt, H. A. 1974, Ap. J. Suppl., 28 (No. 252), 1 (JA (1974)).

Keenan, P. C. 1963, in *Basic Astronomical Data*, ed. K. Aa. Strand (Chicago: University of Chicago Press), p. 78.

Kerridge, S. J., and Upgren, A. R. 1973, *Pub. A. S. P.*, *85*, 721.

Kraft, R. P. 1974, private communication.

Kron, G. E. 1956, in *Proc. Third Berkeley Symp. on Math. Stat. and Prob.*, *3*, ed. J. Neyman (Berkeley: University of California Press), p. 39.

Kron, G. E., Gascoigne, S. C. B., and White, H. S. 1957, *A. J.*, *62*, 205.

Kuiper, G. P. 1938a, *Ap. J.*, *87*, 592.

____________. 1938b, *ibid.*, *88*, 429.

____________. 1938c, *ibid.*, *88*, 472.

____________. 1940, *ibid.*, *91*, 269.

____________. 1942, *ibid.*, *95*, 201.

Kunkel, W. 1975, preprint.

Lippincott, S. L. 1973, *A. J.*, *78*, 426.

________________. 1974, *ibid.*, *79*, 974.

Luyten, W. J. 1923, *Pub. A. S. P.*, *35*, 175.

Martin, G. E., and Ianna, P. A. 1975, *A. J.*, *80*, 321.

McCarthy, M. F. 1969, in *Low Luminosity Stars*, ed. S. S. Kumar (New York: Gordon and Breach), p. 83.

McCarthy, M. F. 1971, private communication.

Merrill, P. W., Deutsch, A. J., and Keenan, P. C. 1962, *Ap. J.*, *136*, 21.

Morgan, W. W. 1938, *Ap. J.*, *87*, 589.

____________. 1939, *ibid.*, *89*, 310.

Morgan, W. W., and Keenan, P. C. 1973, *Ann. Rev. Astron. Astrophys.*, *11*, 29.

Morgan, W. W., Keenan, P. C., and Kellman, E. 1943, *An Atlas of Stellar Spectra* (Chicago: University of Chicago Press).

Mould, J. R. 1975, Astr. and Ap., 157, 799.

Öhman, Y. 1934, Ap. J., 80, 171.

________. 1936a, Stockholms Obs. Ann., 12, No. 3.

________. 1936b, ibid., 12, No. 8.

Pesch, P. 1972a, Ap. J. (Letters), 174, L155.

________. 1972b, Ap. J., 177, 519.

Riddle, R. K., Priser, J. B., and Strand, K. Aa. 1970, Pub. U.S.N.O., XX, part III.

Rogers, A. W., and Eggen, O. J. 1974, Pub. A.S.P., 86, 742.

Routly, P. M. 1972, Pub. U.S.N.O., XX, part VI.

Scarfe, C. D. 1966, M.N.R.A.S., 133, 99.

Sharpless, S. 1956, Ap. J., 124, 342.

Smethells, W. G. 1974, thesis, Case Western Reserve University.

Spinrad, H. 1973, Ap. J., 183, 923.

Spinrad, H., and Wood, D. M. 1965, Ap. J., 141, 109.

Tsuji, T. 1969, in Low Luminosity Stars, ed. S. S. Kumar (New York: Gordon and Breach), p. 457.

Upgren, A. R. 1973, A. J., 78, 79.

____________. 1974, Pub. A. S. P., 86, 294.

van Altena, W. F., and Stone, R. C. 1973, A. J., 78, 781.

van Altena, W. F., and Vilkki, E. U. 1973, A. J., 78, 201.

____________________________________. 1975, ibid., 80, 647.

Veeder, G. J. 1973, thesis, California Institute of Technology.

____________. 1974, A. J., 79, 1056.

Wilson, O. C. 1962, *Ap. J.*, *136*, 793.

Wing, R. F. 1973, in I.A.U. Symposium No. 50: *Spectral Classification and Multicolour Photometry*, ed. C. Fehrenbach and B. E. Westerlund (Dordrecht: Reidel), p. 209.

Wing, R. F., and Dean, C. A. 1975, private communication.

Wing, R. F., Dean, C. A., and MacConnell, D. J. 1976, *Ap. J.*, in press.

Woolley, R., Pocock, S. B., Epps, E. A., and Flinn, R. 1971, *Roy. Obs. Bull.*, No. 166.