COMPARISONS OF TEMPERATURE CLASSES OBTAINED BY SPECTROSCOPIC AND PHOTOMETRIC TECHNIQUES: M-TYPE DWARFS, GIANTS, AND SUPERGIANTS

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ABSTRACT

Temperature classes based on photometric measurements of the 7100 Å band of TiO are compared with published spectroscopic classifications by various investigators. Dwarfs, giants, and supergiants are treated separately. The photometric types are in excellent agreement with types given by P. C. Boeshaar for M dwarfs and by P. C. Keenan and Y. Yamashita for M giants. In all other cases the scatter is larger. The usefulness of the types given by various authors for dwarfs and giants is tested by examining their correlation with color temperature determined by narrow-band photometry.

1. INTRODUCTION

Since 1969, a large number of M stars of all luminosity classes have been classified by photoelectric photometry on an eight-color narrow-band system in the near infrared. These results are used here as a basis of comparison for several bodies of classification data.

In Figs. 1-5, spectral types on various systems are plotted against the types determined photometrically. Dwarfs, giants, and supergiants have been plotted in separate diagrams. These comparisons reveal the systematic differences that exist among the various systems as well as their different degrees of observational scatter.

The TiO band strength is the primary temperature criterion on all of the systems considered here, including the eight-color photometry. Historically, the relations between TiO strength and spectral type have been established independently for dwarfs, giants, and

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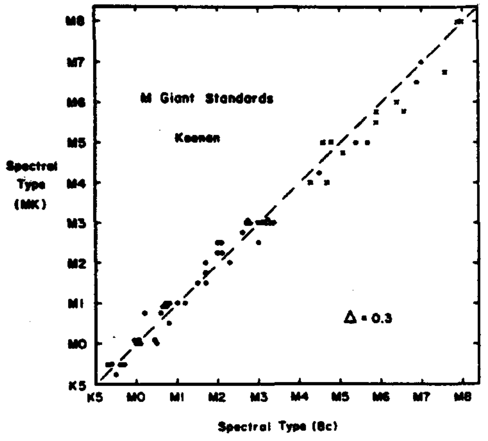

Fig. 1 - Temperature classes by Keenan for class III giants plotted against temperature classes from the eight-color photometry, which are based on the strength of the TiO γ(0,0) band near 7100 Å. In Figs. 1-5, the dashed line is the one-to-one relation, and Δ is the mean deviation from this line in units of spectral subtypes. Mira variables have been excluded from all diagrams; small-range variables are plotted as crosses (X).

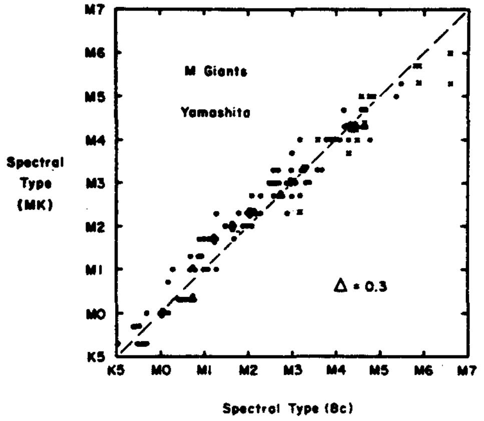

Fig. 2 - Temperature classes by Yamashita (1967) plotted against eight-color types. Class III giants only.

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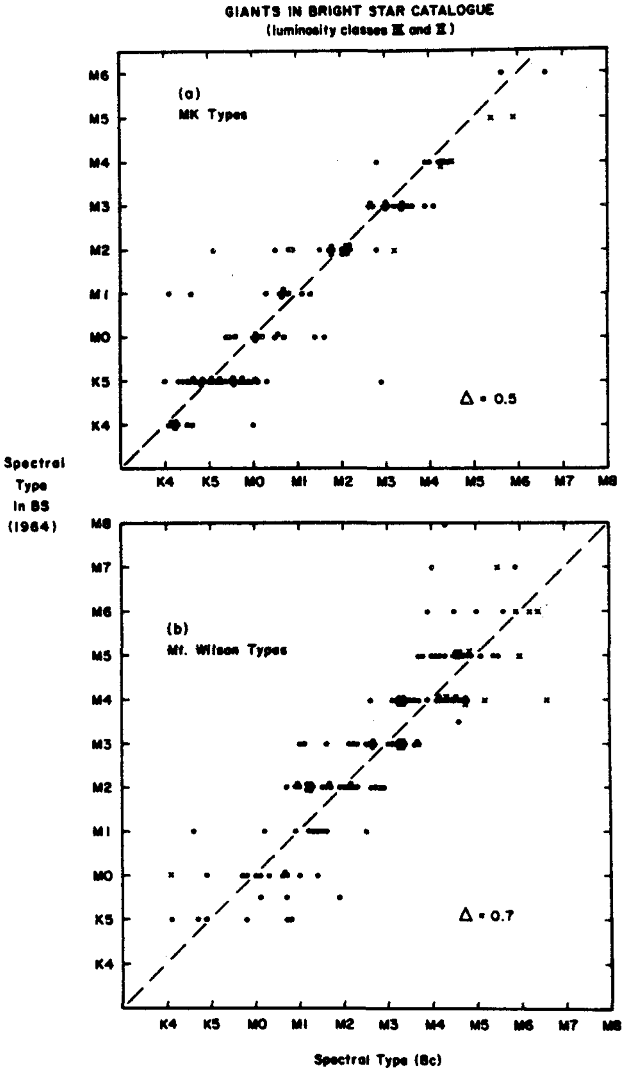

Fig. 3 - Spectral types as listed in the third edition of the *Bright Star Catalogue* (Hoffleit 1964) plotted against the eight-color type. Giant stars only. (*a*) Types listed in the MK notation. (*b*) Types listed in the Mount Wilson notation. Again, crosses indicate variable stars.

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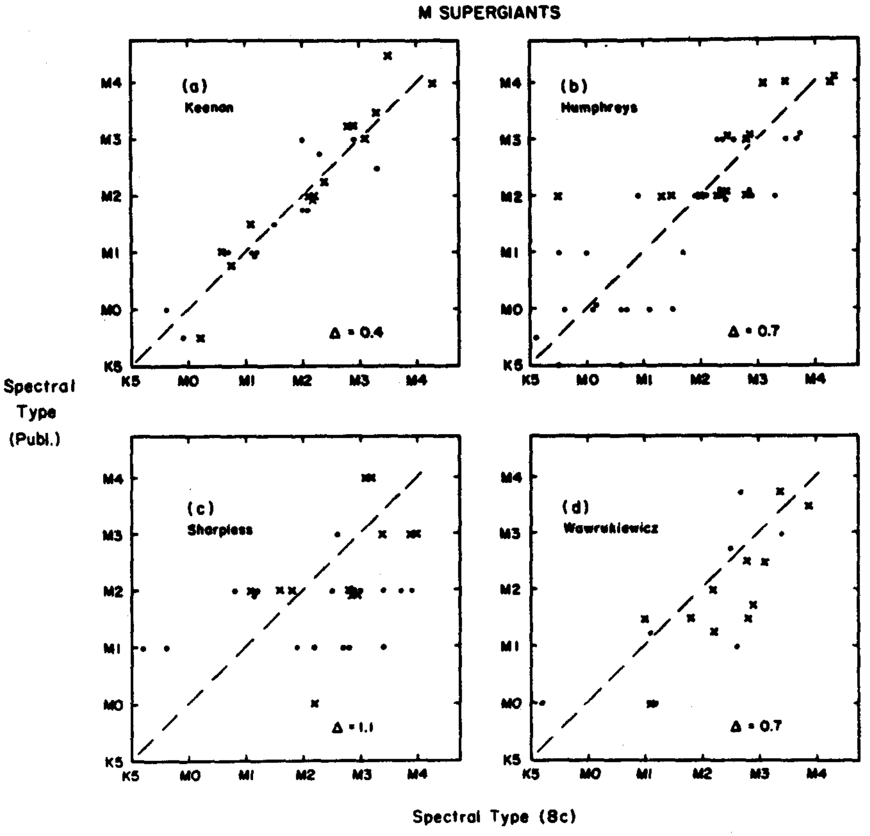

Fig. 4 - Published spectral types for M supergiants plotted against the eight-color type. The types by Wawrukiewicz were determined from filter photometry; those by Keenan, Humphreys, and Sharpless were obtained spectroscopically.

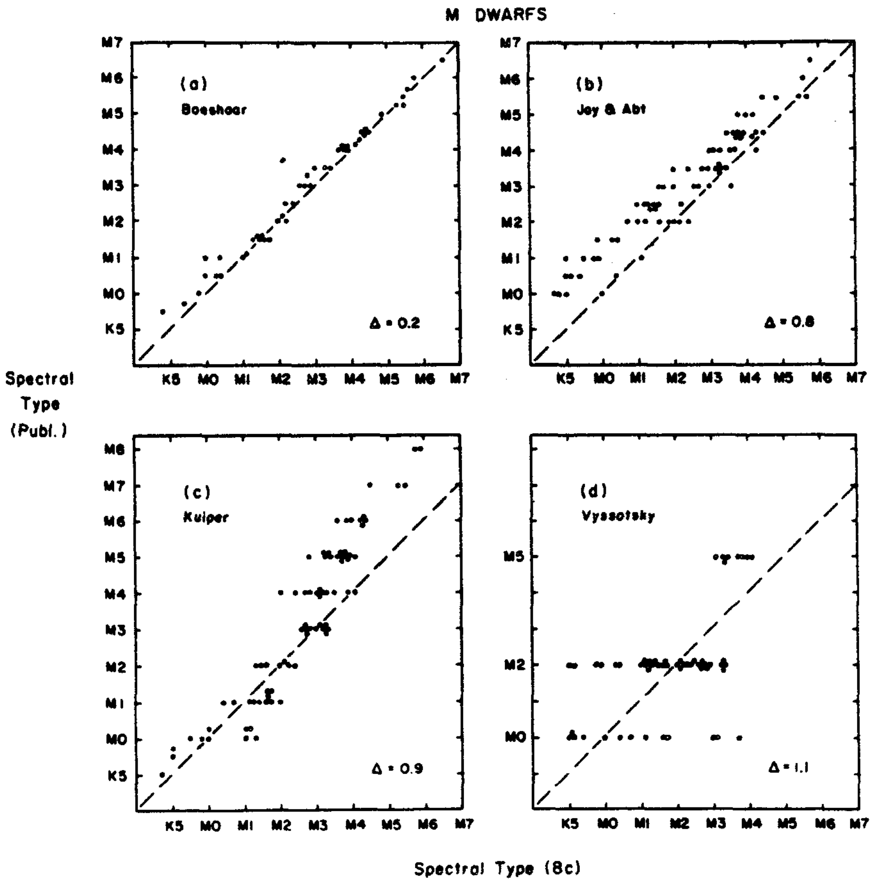

Fig. 5 - Published spectral types for M dwarfs plotted against the eight-color type. Vyssotsky used objective-prism spectra; Joy and Kuiper used photographic spectrograms, mostly unwidened; and Boeshaar used widened image-tube spectrograms.

supergiants, and significant differences in the spectroscopic scales have existed until very recently. The eight-color system, on the other hand, uses the same numerical relation between the TiO index and spectral type for stars of all luminosities. In fact, one of the original objectives of the eight-color photometry was to establish a unified system of spectral classification for all M stars (Wing 1973).

Since the purpose of the spectral types is to distinguish stars of different temperature, we may test the usefulness of the types on various systems by plotting them against a color index or color temperature. In Figs. 6 and 7 we plot the types for giants and dwarfs given by various investigators against the color temperature determined from the eight-color photometry. We cannot apply this test to the supergiants since most of them are appreciably affected by interstellar reddening.

2. THE EIGHT-COLOR SYSTEM

The characteristics of the interference filters defining the eight-color system of classification photometry are given by Wing (1971). The filters range in wavelength from 7120 to 10975 Å and in width from 40 to 70 Å. They serve to measure strong bands of TiO, VO, and CN as well as the best near-infrared continuum points.

The procedures used for deriving spectral classifications from the photometric data are described by Wing, Dean, and MacConnell (1976) and White and Wing (1978). Briefly, the photometric readings are reduced to an absolute flux scale to form an eight-color "spectrum"; the continuum is defined as the blackbody curve passing through the best continuum points (generally 7540 and 10540 Å for M stars); the TiO index is then the magnitude difference between the observed flux and the continuum at 7120 Å; and finally, the spectral type is obtained from a calibration of this TiO index based on giant stars which have been classified by Keenan. Small corrections are applied for the effect of CN lines in the TiO filter and in one of the continuum points; without these corrections, the types for dwarfs, giants, and supergiants would not be on precisely the same scale. The color temperature is simply the temperature of the blackbody curve which passes through the best continuum points, after CN corrections.

The probable errors in the photometric spectral types seldom exceed ±0.1 subtype for single observations. Most of the stars considered here have been observed 3 or more times, and the averaged data have been used. In the diagrams for giant and supergiant stars, known variables have been plotted as crosses; Mira variables have been excluded from all diagrams. We have not distinguished variables

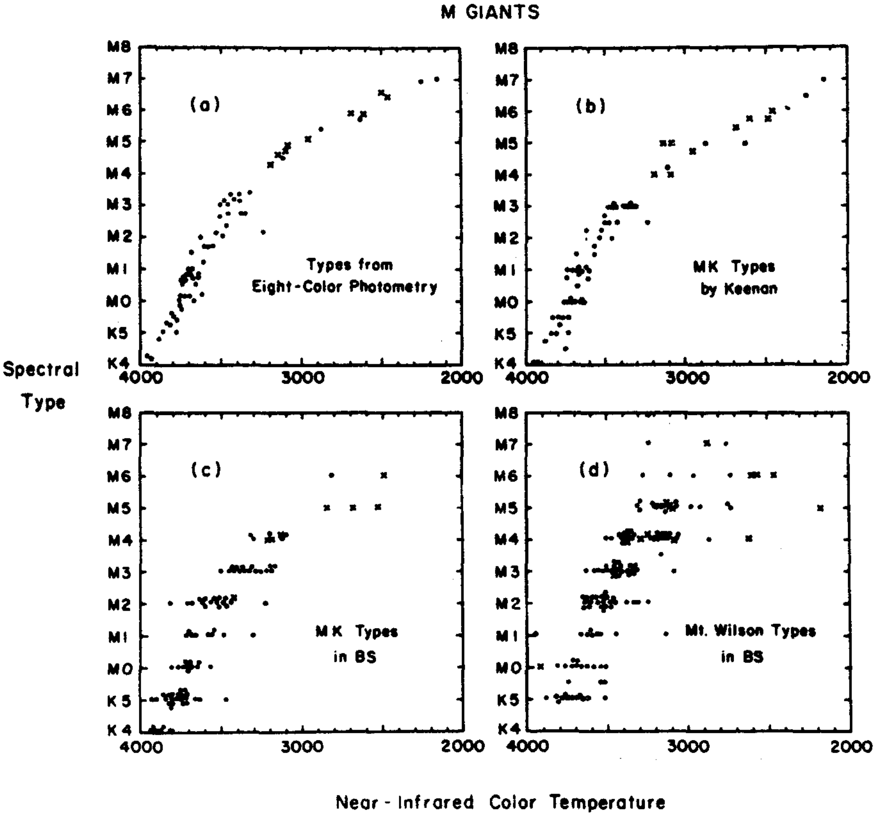

Fig. 6 - Spectral types for giant stars from four sources including the eight-color photometry plotted against the color temperature measured in the near-infrared continuum.

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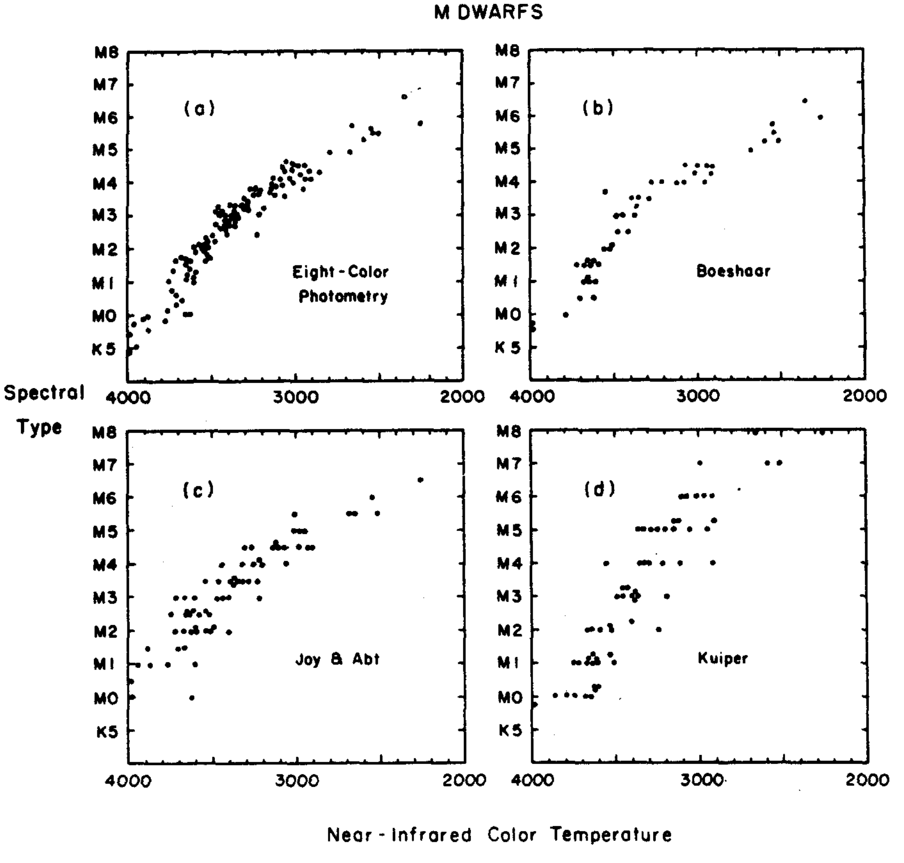

Fig. 7 - Spectral types for dwarf stars from four sources plotted against the color temperature measured on the eight-color system.

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from non-variables in the diagrams for dwarfs since it has not been shown that the flare activity of these stars has an appreciable effect upon their spectral types and color temperatures measured in the near infrared.

It is important to emphasize that the photometrically determined spectral types are based on the measurement of a spectral feature -- a TiO band -- and not on a color index. In fact the TiO index is defined in such a way that it is completely independent of the slope of the continuum; as a result, it is also independent of reddening. Thus there is no important difference in the meaning of the spectral types determined photometrically and spectroscopically, but only a difference in instrumentation and method.

3. SOURCES OF EIGHT-COLOR DATA

For the supergiants, the available eight-color photometry has been published by White and Wing (1978).

For the giants, the photometric spectral types and color temperatures used here are from an unpublished tabulation by Wing (1978), which is available on request.

For the dwarfs, the main body of eight-color photometry will be published by Wing and Dean (in preparation). Some preliminary results from this program have been published by Wing (1973), and some of the material has been discussed by Wing, Dean, and MacConnell (1976).

4. RESULTS FOR GIANTS

Spectral types by Keenan are plotted against the eight-color types in Fig. 1. Most of these stars are from Morgan and Keenan (1973), but a few have been added from the lists of Keenan (1963) and Landi Dessy and Keenan (1966). These 57 stars, all of which have been classified as class III giants, have been adopted as "standards" in the sense that they were used to establish the calibration of the photometric TiO index in terms of spectral type. It is therefore not surprising that the points in Fig. 1 are approximately evenly distributed about the one-to-one relation. What is significant is the fact that the scatter is quite small, since the two sets of classifications were obtained from completely independent data. The mean deviation Δ from the one-to-one relation is 0.3 subtype, which agrees well with the sum of the quoted errors in the spectroscopic and photometric classifications, which are 0.25 and 0.1 subtype, respectively.

A small systematic displacement from the one-to-one relation is shown by the M6-M7 stars in Fig. 1. This was introduced in order to have the smoothest possible relation between band strength and spectral type while at the same time agreeing with Keenan at M8.

The types given for giants by Yamashita (1967) are shown in Fig. 2. Again the agreement with the eight-color types is excellent (Δ = 0.3). Some curvature is evident in Fig. 2: Yamashita's types are systematically about one-third of a subtype later than the adopted scale between types M1 and M2, and they are about the same amount earlier near M6. For each of the spectral types used by Yamashita (who subdivides each subtype into three parts, whereas Keenan uses four) we show in Table I the reduction to the MK scale defined by Keenan's giants and the eight-color photometry. [The results are expressed in the decimal notation, since this is the most manageable way to apply small systematic corrections to pluses and minuses].

We have also examined the classifications of M giants listed in the Bright Star Catalogue (Hoffleit 1964). In Fig. 3, the BS types have been segregated according to whether they are expressed in the MK notation (luminosity class III) or in the Mt. Wilson notation (gM stars). In both plots the scatter is much larger than in Figs. 1 and 2, but only the latest Mt. Wilson types show systematic differences from the adopted scale.

5. RESULTS FOR SUPERGIANTS

Supergiant classifications from four sources are compared to the eight-color classifications in Fig. 4. The types by Keenan in Fig. 4a are taken from Keenan (1963, 1970), Morgan and Keenan (1973), and Keenan and McNeil (1976). The scatter, Δ = 0.4 subtype, is encouragingly small; the slight increase in scatter relative to that shown by Keenan's giants can no doubt be attributed to the greater incidence of variability among the supergiants. Most important is the fact that the supergiants of Fig. 4a do not depart systematically from the one-to-one relation; this demonstrates that Keenan's modern supergiant classifications are on the same scale as his giant types. On the other hand, it is not possible to include his supergiant classifications from the 1940's without increasing the scatter greatly.

The types by Humphreys in Fig. 4b are from Humphreys (1970), Humphreys, Strecker, and Ney (1972), and Humphreys and Ney (1974); they are all from classification-dispersion spectrograms in the blue. Since no systematic departure from the one-to-one relation is evident, we conclude that Humphreys' types are indeed on the MK scale. The scatter, however, is larger (Δ = 0.7) than in the case of Keenan's types, especially among the K5-M1 stars, and it does not seem to

TABLE I

REDUCTION OF YAMASHITA'S TYPES FOR M GIANTS
TO THE MK SYSTEM

Yamashita Type	Change	MK Type
K5+	0	K5.3
M0-	0	K5.7
M0	0	M0.0
M0+	0	M0.3
M1-	-0.1	M0.6
M1	-0.2	M0.8
M1+	-0.3	M1.0
M2-	-0.4	M1.3
M2	-0.3	M1.7
M2+	-0.1	M2.2
M3-	0	M2.7
M3	0	M3.0
M3+	0	M3.3
M4-	0	M3.7
M4	0	M4.0
M4+	0	M4.3
M5-	0	M4.7
M5	0	M5.0
M5+	+0.2	M5.5
M6-	+0.3	M6.0
M6	+0.5:	M6.5

correlate with declination, magnitude, or variability. The types by Sharpless (1966) in Fig. 4c, from near-infrared spectra, show still larger scatter (Δ = 1.1). At least part of this can be explained in terms of the relative faintness of the stars he studied, his lower dispersion (200 Å mm^{-1}), and the fact that his work was carried out before there existed an adequate set of supergiant standards.

In Fig. 4d we show classifications by Wawrukiewicz (1971), who used photoelectric filter photometry of the TiO absorption near 7100 Å. Although his types are strongly correlated with the eight-color types, there is a clear systematic difference between the two scales. The main reason that Wawrukiewicz' types do not agree better with the eight-color types is that his TiO index is seriously affected by CN absorption, particularly in his wide reference band (see White and Wing 1978).

6. RESULTS FOR DWARFS

Spectral types for M dwarfs from four spectroscopic programs are compared in Fig. 5. The agreement with the eight-color types is excellent in the case of the types recently given by Boeshaar (1976) in her dissertation at Ohio State University, which was supervised by Keenan. For the three other bodies of data, all of which have roots going back at least 35 years, we find larger scatter as well as systematic differences.

Kuiper's types in Fig. 5c are mostly from Kuiper (1942), but we have added some types from the General Catalogue of Trigonometric Stellar Parallaxes (Jenkins 1952) that are specifically attributed to Kuiper. They are on a scale defined by the work of Morgan (1938), which agrees with the adopted scale through type M3 but diverges in the later types. In Fig. 5b we show types determined by Joy at Mt. Wilson; although many of these types were revised prior to their recent publication by Joy and Abt (1974), they are on the same scale as was used in Joy's (1947) earlier compilation. Joy's scale is clearly different from Kuiper's, and his types are systematically later than the eight-color types by amounts ranging from a full subtype near M0 to one-half a subtype near M5. The systematic corrections that reduce the types by Joy and Kuiper to the modern MK scale defined by Boeshaar and the eight-color photometry are given in Table II.

Vyssotsky's types, which were published in four lists (Vyssotsky 1943, 1956; Vyssotsky et al. 1946, Vyssotsky and Mateer 1952), are from an objective-prism survey. Although subsequent work has generally confirmed that Vyssotsky's stars are indeed dwarfs, the scatter in Fig. 5d is very large: the M0 and M2 groups both contain stars ranging from K5 to about M3.5. The M5 group seems better defined and corresponds to M3-M4 stars on the modern scale.

Because of the several different scales that have been used concurrently for M dwarfs, Wing (1973) suggested starting all over with a new set of dwarf standard stars, based on the eight-color photometry, which would place their types on the same scale as giants. Boeshaar (1976) followed this recommendation, and Fig. 5a shows that she succeeded in matching the giant scale. The only star showing a significant discrepancy is HD 214479A, and we suggest that this is simply a misidentification, since we can remove the discrepancy completely by assuming that Boeshaar actually observed component B.

TABLE II

REDUCTION OF PUBLISHED TYPES FOR M DWARFS
TO THE MK SYSTEM

Joy & Abt Type	Change	MK Type	Kuiper Type	Change	MK Type
-	-	-	K5	0	K5.0
-	-	-	K5+	0	K5.5
M0	-1.0	K5.0	M0	0	M0.0
M0.5	-1.0	K5.5	M0+	0	M0.5
M1	-1.0	M0.0	M1	0	M1.0
M1.5	-1.0	M0.5	M1+	0	M1.5
M2	-0.8	M1.2	M2	0	M2.0
M2.5	-0.7	M1.8	M2+	0	M2.5
M3	-0.5	M2.5	M3	0	M3.0
M3.5	-0.5	M3.0	M3+	-0.3	M3.2
M4	-0.5	M3.5	M4	-0.7	M3.3
M4.5	-0.5	M4.0	M4+	-1.0	M3.5
M5	-0.5	M4.5	M5	-1.3	M3.7
M5.5	-0.5	M5.0	M5+	-1.7	M3.8
M6	-0.5	M5.5	M6	-2.0	M4.0
M6.5	-0.5	M6.0	M6+	-2.0	M4.5
-	-	-	M7	-2.0	M5.0
-	-	-	M7+	-2.0	M5.5
-	-	-	M8	-2.0	M6.0

7. COMPARISON WITH COLOR TEMPERATURE

Since each observation on the eight-color system provides a color temperature measured in the near-infrared continuum in addition to the spectral type, we can examine the correlations between spectral type and color temperature for the various bodies of data. These correlations show the extent to which the types succeed in indicating the temperature. Since this test breaks down when the color is affected by interstellar reddening, we have not attempted to apply it to the supergiants. Other factors which can cause an imperfect correlation between spectral type and temperature are observational errors in the spectral types and real scatter in the relation arising from differences in chemical composition, which can cause the TiO strength to be abnormal for the temperature. Random errors in the color temperatures should be unimportant for the stars included here.

These comparisons are shown in Figs. 6 and 7 for giants and dwarfs, respectively. Note that we can now test not only the several sets of published classifications considered earlier, but also the eight-color types which have been used as the abscissae of previous figures, since the eight-color types and color temperatures are independent of one another.

The eight-color types for giants [Fig. 6a] display a smooth dependence on temperature that could be well fitted by a second-degree polynomial. Keenan's types for giants [Fig. 6b] would be better represented by two straight lines with a change of slope at M3. Exactly the same stars have been plotted in these two figures so that they can be compared closely.

The scatter among the K5-M3 giants in Figs. 6a and 6b, while smaller than in the other diagrams shown for comparison, is larger than expected from the observational errors in these sets of data. Since it is unlikely that reddening has a significant effect upon this sample of bright stars, the scatter is probably mostly the result of composition differences. The most discrepant star in both figures, displaced to the right at type M2, is HR 6128; reddening cannot be ruled out in any specific case such as this, but it seems likely that the TiO bands are weak for the temperature. Some of the scatter shown by the dwarfs in Fig. 7a is definitely intrinsic: the reddest M0 star is Kapteyn's star, a high-velocity subdwarf (Wing, Dean, and MacConnell 1976).

The larger scatter in Figs. 6c, 6d, 7c, and 7d simply confirms our conclusion that observational errors are larger in these sets of data.

8. SUMMARY

Spectral types from eight-color photometry, which have high internal precision and are on the same scale for all luminosity classes, have been used to compare the scales and accuracy of several other sets of spectral types for M stars. Our principal conclusion is that there now exist spectroscopically-determined types of M stars of all luminosity classes that have good accuracy and, for the first time, are on the same scale. These are Keenan's types for supergiants, Keenan's types for giants, and Boeshaar's types for dwarfs. Representatives from all three of these data sets are included in the Atlas of Keenan and McNeil (1976).

The types by Yamashita (1967) also have good internal precision and can be brought into better agreement with the scale of the Keenan-McNeil Atlas by the application of the small systematic corrections given in Table I. The types for 426 M dwarfs by Joy and Abt (1974), although of lower precision than Boeshaar's types, will continue to be extremely valuable because it is not likely that improved classifications for so many faint stars will become available in the foreseeable future. It is therefore important to know how the Joy-Abt types relate to the MK scale, and these differences are given in Table II.

The work of Boeshaar (1976) has shown that accurate classifications can be obtained for the M dwarfs, despite their relative faintness. It is noteworthy that of the authors considered here, only Boeshaar used image-tube spectrograms. The greater dispersion and widening made possible by the higher efficiency of the image tube more than compensate for its loss of resolution.

The best sets of spectral types are well correlated with color temperature, indicating that the TiO strength is indeed a good temperature indicator. However, it is apparent that composition differences that affect the TiO strength are limiting the usefulness of TiO as a temperature indicator. If future measurements of TiO strength achieve still greater accuracy, they will not provide more accurate temperatures but may be useful as composition indicators if accompanied by measurements of color temperature.

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