THE MK CLASSIFICATION AND ITS CALIBRATION

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1. THE STANDARD STARS OF THE SYSTEM.

I have been asked to describe the system of spectral classification as it has developed from the original Yerkes Atlas (Morgan, Keenan, Kellman, 1943) until to-day. I use the word "developed" because any system that is to remain useful must be flexible enough to adapt not only to improved techniques of measurement but also to new theoretical insights into the variables that actually determine the energy spectrum of a star in all its fascinating but sometimes frustrating detail.

The observed criteria on which the classification of normal stars rests are illustrated in detail in the published atlases, of Morgan, Abt and Tapscott (1978) for the stars of early type, and of Keenan and McNeil (1976) for types later than F8. In addition, there are beautiful reproductions of most of the standard stars of solar composition in the atlas prepared in Japan by Yamashita, Nariai, and Norimoto (1977). I shall not consider here the criteria of classification, but confine the discussion to the resulting set of temperature types and luminosity classes, and then look more carefully at a third variable: chemical composition.

Let us start with the first dimension of classification: the temperature types. When the MK system was developed it was decided to retain the basic notation of the Henry Draper Catalogue because of the great usefulness of that work. This is admittedly a somewhat awkward notation, for not all of the decimal subdivisions of the main HD types (F, G, etc.) are equally meaningful. That is not too serious a difficulty, however, if we are consistent in defining our subtypes to represent approximately equal differences in the spectra. Thus, as you know, it was necessary to drop several decimal subdivisions in type G, where the subtypes are G0, G2, G5 and G8. Similarly, there are no full subtypes between K5 and M0; K7, for example, is counted as a half subtype later than K5 and earlier than M0. On the other hand, near B0 and A0 the spectra are changing so rapidly with temperature that we count O9.5 and B9.5 as full subtypes.

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The subtypes in the MK system are not arbitrary, but were developed gradually by experience with standard classification spectrograms with scales of 70 to 120 Å/mm (or resolutions of about 2Å). The ones that we are using now are listed in Table I. Of course, if better resolutions or greater spectral ranges are available, one introduces fractions of the subclasses. Conversely in low-resolution spectral surveys, it is obviously not meaningful to use all of the subtypes. Such surveys thus do not attain the accuracy of the standard MK types, but can be said to be approximately on the same system. This holds true, naturally, for all the dimensions of classification.

It follows, I think, that the standard stars that establish the scale and zero points of the system should have their classification indices defined more precisely than the average observer needs. If we could rely upon the constancy of the stars, we might be satisfied with a small number of basic standards, but in the real universe we cannot count upon any star later than G0 (or upon supergiants of any type) to maintain its spectral features unchanged even over short human time intervals. This is just as true of brightness and color also. Consequently, we need a grid of as many standard stars as possible, well distributed over the sky.

The MK spectroscopic boxes, bounded by full temperature subtypes and luminosity classes, are shown in Table I. Representative standard stars are included, and for types O, B, A and F are taken from the Atlas of Morgan, Abt and Tapscott. For the later types the list of standards furnished to Dr. Pasinetti's IAU Working Group on Standards, and published by Dr. Jaschek in the Bulletin of the Strasbourg Centre de Donnees Stellaires (Keenan 1983) allowed more of the boxes to be filled. For these types the many stars that fall between the boxes (e.g. 46 LMi, K0+ III-IV) have been omitted. I hope that the list of standards can soon be revised and extended, particularly to more stars in the southern hemisphere, if we do not exhaust the patience and funds of the publisher.

Relatively little work has been done on providing comprehensive lists of accurate MK types for faint stars. Some recent catalogs that do reach stars fainter than V = 8 are listed in Table II. The table does not include low-resolution surveys, but only the results of programs designed to give types as accurate as the MK standards that exist for bright stars. Also omitted from Table II are lists of special groups of stars, such as the catalog of types of barium stars by Yamashita and Norimato (1981) and that of S and SC stars by Keenan and Boeshaar (1980).

2. CALIBRATION IN TERMS OF T_e AND M_V.

It will not be necessary to consider the problem of the reduction of MK types to effective temperatures here, for that topic is discussed in the review papers of Hayes (1985), and of Gustafsson (Gustafsson and Graae-Jørgensen 1985). Pending the publication of a really extensive catalog of effective temperatures, on some generally accepted scale, reference can be made to the

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TABLE I

MK TEMPERATURE SUBCLASSES

TYPE	V	IV	III	II	Ib	Iab	Ia
O4	HD 46223						
O5	HD 46150						
O6	HD 199579						
O7	15 Mon						
O8	HD 46149						
O9	HD 46202		ι Ori		19 Cep		
O9.5						BS 7589	
B0	τ Sco				69 Cyg		ε Ori
B0.5			ε Per				
B1	ω^1 Sco			β CMa	ζ Per		κ Cas
B2	β Sco(ft)	γ Peg	π^4 Ori		9 Cep		χ^2 Ori
B3	29 Per	ι Her				o^2 CMa	55 Cyg
B5	HD 36936		τ Ori		67 Oph		η CMa
B7	BS 1029		β Tau				
B8					13 Cep		β Ori
B9							
B9.5	HD 19803						
A0	α Lyr		α Dra		η Leo		BS 1040
A1							
A2	HD 23948	λ UMa					α Cyg
A3	+48°944					BS 641	
A5	HD 23886						

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TABLE I (continued)

Type	V	IV	III	II	Ib	Iab	Ia
A7			θ^2 Tau				
A8							
F0	HD 23585	HD 27397	ζ Leo		α Lep		φ Cas
F2	78 UMa	β Cas			89 Her		ι^1 Sco
F3	BS 1279		20 CVn				
F5	HD 27534	δ Cas			α Per		HD 10494
F7			θ^2 Tau				
F8	HD 27808	BS 8732	υ Peg		γ Cyg		δ CMa
F9	BS 7162						
G0	η Cas A β CVn	ζ Her η Boo			ζ Mon α Aqr	HD 91629	
G2	Sun	φ Vir η Boo			ζ Mon α Aur		
G5	κ Cet	μ Her		β Lep β Cnv	9 Peg	BS 2513	
G8	61 UMa	β Aql	ε Vir 71 Oph	BS 1270	ε Gem		
K0	σ Dra BS 7368	η Cep	κ Per η Cyg	HD 179870			AX Sgr
K2	ε Eri HD 109011		ε CrB κ Oph	π^6 Ori σ Oph	ε Peg		
K3	BS 8832 BS 9038		BS 3751 α Tuc	ι Aur π Her	41 Gem 145 CMa		
K4	HD 160964 HD 216803		17 UMa κ Pyx	V418 Cen	BS 7475		
K5	61 Cyg A		γ Dra N Vel		BS 8726		

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TABLE I (continued)

Type	V	IV	III	II	Ib	Iab	Ia
M0	HD 232979 HD 19305		τ Aqr				
M1			ν Vir BS 5995	BS 3126	BS 6693		
M2	HD 1326		BS 8989 HD 107003		HD 10465		
M3			μ Gem 104 Gem	τ Aur			
M4	γ Leo C		BS 3577	δ^2 Lyr ρ Per	BO Car	HD 91095	
M5			BS 9047			HD 94599	
M6							
M7				BK Vir			
M8				R Dor RX Boo			

diagrams of Keenan (1982) showing how the spectral types vary with photometric indices that are sensitive to temperature.

The calibration of luminosity classes in terms of absolute magnitudes is likewise a continuing problem. For the early-type stars the calibration tables given by Blaauw (1963) remained in use for many years. They were based on a careful evaluation of the data available at that time, and owed much to the work of Schmidt-Kaler on the more luminous stars. It is known, however, that many of the results (and not only the earliest ones) were affected by serious systematic errors. It is not always clear whether the samples averaged were limited by magnitude or by distance (or by both). This hinders the comparison of luminosities for field stars with those for members of clusters. As our surveys go deep enough to reach completeness for at least the stars of higher luminosity classes in the open clusters with best determined distances, their sample space is the volume occupied by the cluster. Consequently, I hope that all future statistical determinations of mean absolute magnitudes for field stars will likewise be reduced to constant volumes of space.

Later improvements included calibration of the four-color photometry and $H\beta$ intensities (cf. Crawford [1978, 1979]), but the results have not all been referred to current MK types. For the O-stars Lesh

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(1979) combined the reclassification and calibration by Walborn (1972) with her own results. Their values for class III are plotted as crosses in Figure 1. More recently a new calibration of Hγ intensities in O- and B-stars has been made by Millward and Walker (1985), and for class V their luminosities are shown by the continuous line in the figure. For types B, A and F, Grenier et al. (1984) have derived new absolute magnitudes from statistical parallaxes. Their calibration curves for classes III and V are shown by the open circles connected by dashed lines. The revised calibration of Schmidt-Kaler (1982) for supergiants of classes Iab and Ib is given by the dotted curves.

The differences between these calibrations, and between them and the old one of Blaauw, rarely exceed a half magnitude except for the F-type stars of class III. The luminosity classification of A- and F-stars is made difficult by the frequent presence of rotation, large magnetic fields, local abundance effects on their surfaces, and the small separation of luminosity classes V, IV, III and II in this part of the HR diagram. The current program of re-classification of A-type stars by Abt (1984) should permit better curves connecting luminosity class and M_V to be constructed.

TABLE II

LISTS OF MK TYPES OF FAINTER STARS

Range of Types	Range of V	Reference
B - G	6.5 - 9.0	Roman, N.G., 1978, A.J., 83, 172.
09 - A3 (In Orion)	To 9.0	Abt, H.A., Levato, H., 1977, Pub. A.S.P., 89, 797.
A - K (In UMa stream)	To 9.0	Levato, H., Abt, H.A., 1978, Pub. A.S.P., 90, 429.
O - A (Near gal. anticenter)		Chromey, F.R., 1979, Astr. Jour., 84, 534.
A3 - M5		Krug, P.A. et al, 1980, Monthly Monthly Notices R.A.S., 190, 237.
167 HD Stars	To 8.5:	Jensen, K.S., 1981, Astr. Astrophys. Suppl., 45, 455.

Turning to later types, we find more published types, but many problems remain. Not even for the cooler dwarfs are there enough nearby stars with individual trigonometric parallaxes good enough to settle all questions about the width of the main sequence.

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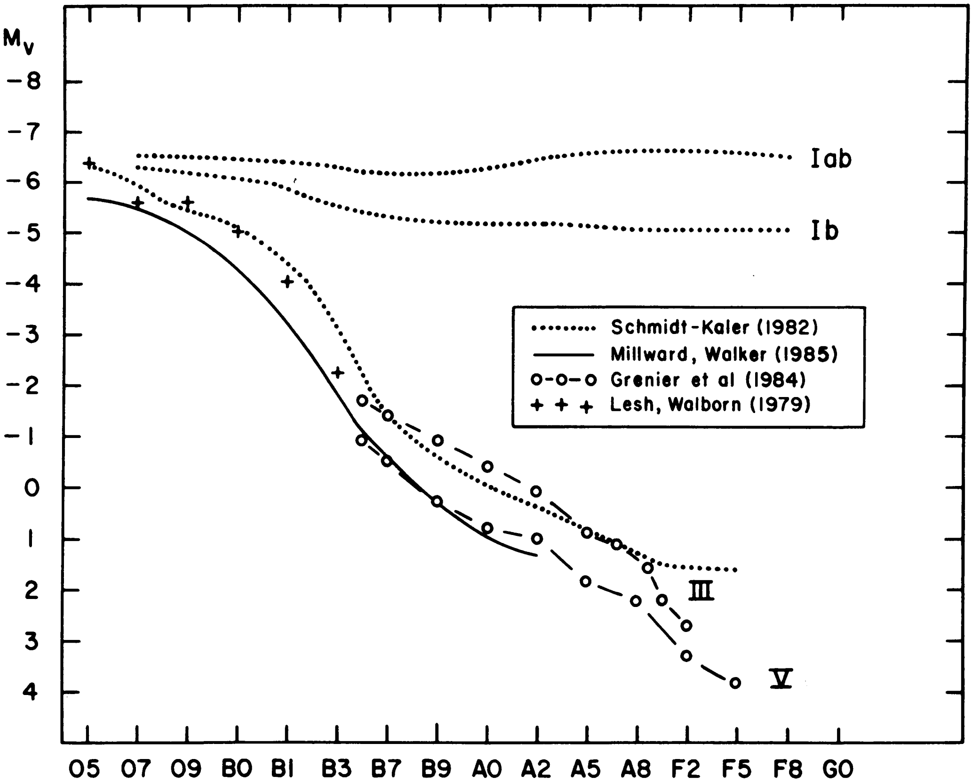

Fig. 1. Published calibrations of luminosity classes for early-type stars.

Mean trigonometrical parallaxes are useful for the yellow and red giants. For class III stars of types G, K and M, and solar composition, meaningful averages have been found if the apparent magnitude is limited to V $\leq$5.0 mag. (Egret, Keenan, Heck, 1982). Some earlier solutions have included stars down to V = 6.5, but when that is done the statistical corrections become large and uncertain. Pending any large improvement in the accuracy of parallaxes that will be coming from space telescopes, the most immediate gains that can be hoped for will come from better parallaxes for southern stars.

For these same giants statistical parallaxes have given equal precision when the samples were extended to stars about two magnitudes fainter - to about V = 7.0. The solutions carried out by Egret at the Centre de Donnees Stellaires at Strasbourg have employed the maximum likelihood formulae developed by Heck (1975), which in turn were based on the earlier work of Rigal (1958) and Jung (1970).

In the immediate future the potential gain in accuracy is greater for the method of statistical parallaxes, since there are many as yet

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unclassified stars brighter than the seventh magnitude which could be used to enlarge the sample. For this purpose approximate classification will not do - we must use a homogeneous set of types.

The calibration curves for Population I giants that we are using are shown in Figure 2, which is based on our 1982 paper. We hope to repeat it with more adequate samples in the near future. It is interesting that our solution gives a distance modulus of 3.42 for the three class III giants in the Hyades, about 0.1 mag. larger than the modulus recommended by Hansen (1980). Four G8-G9 giants in Praesepe also suggest a correction of +0.1 mag. to our calibration if we adopt a modulus of 6.20 (Upgren, Weis and DeLuca 1979) for the cluster. A shift of at least this amount for bright stars will probably result from the use of parallaxes from the revised catalog.

When we move up in luminosity to the bright giants of class II we can still obtain some information from statistical parallaxes, but it is of lower accuracy. From a sample of all types between G0 and K3 the Strasbourg computations gave $M_v = -2.05 \pm 0.60$ for class II. For these stars, however, as for all the supergiants, our best luminosity estimates come from the distances of groups, mainly open clusters, with which they are associated.

Recently Ronald Pitts and I reviewed all the evidence for individual late-type stars of high luminosity that seemed to us to be reasonably good. We tried to use the most recent cluster distances, but in many cases were not able to improve on the values adopted by G. Hagen (1970, 1974). Her spectral types for the bright giants and those of R. M. Humphreys (1970) for the supergiants are on the MK system. There is a more recent and extended catalog of cluster distances by Janes and Adler (1982), but many of their distance moduli are old ones, and the catalog must be used with caution.

We plotted the absolute visual magnitudes for each star (Keenan and Pitts 1984, Fig. 1), and found that the lines of constant luminosity were as nearly horizontal between G0 and about M2 as one can tell in view of the rather large scatter of the points.

The resulting calibration curves for these luminous stars also are shown in Figure 2. The uncertainty of the calibration curves is about $0^m.2$ for the giants but probably approaches one magnitude for the brighter supergiants. It should be emphasized that this calibration applies to Population I stars; for Population II a separate calibration needs to be made.

3. INDICES OF CHEMICAL COMPOSITION

From the early days of the Harvard classification it has been recognized that such objects as the carbon stars display spectra differing so widely from those of stars of solar composition that special indices must be devised for their classification. (For the carbon stars, in fact, the problem has never been satisfactorily solved.)

Especially among the hotter stars the complications mentioned in Section II exist, and in the Ap stars lead to composition differences between the parts of the stellar atmosphere viewed at different times.

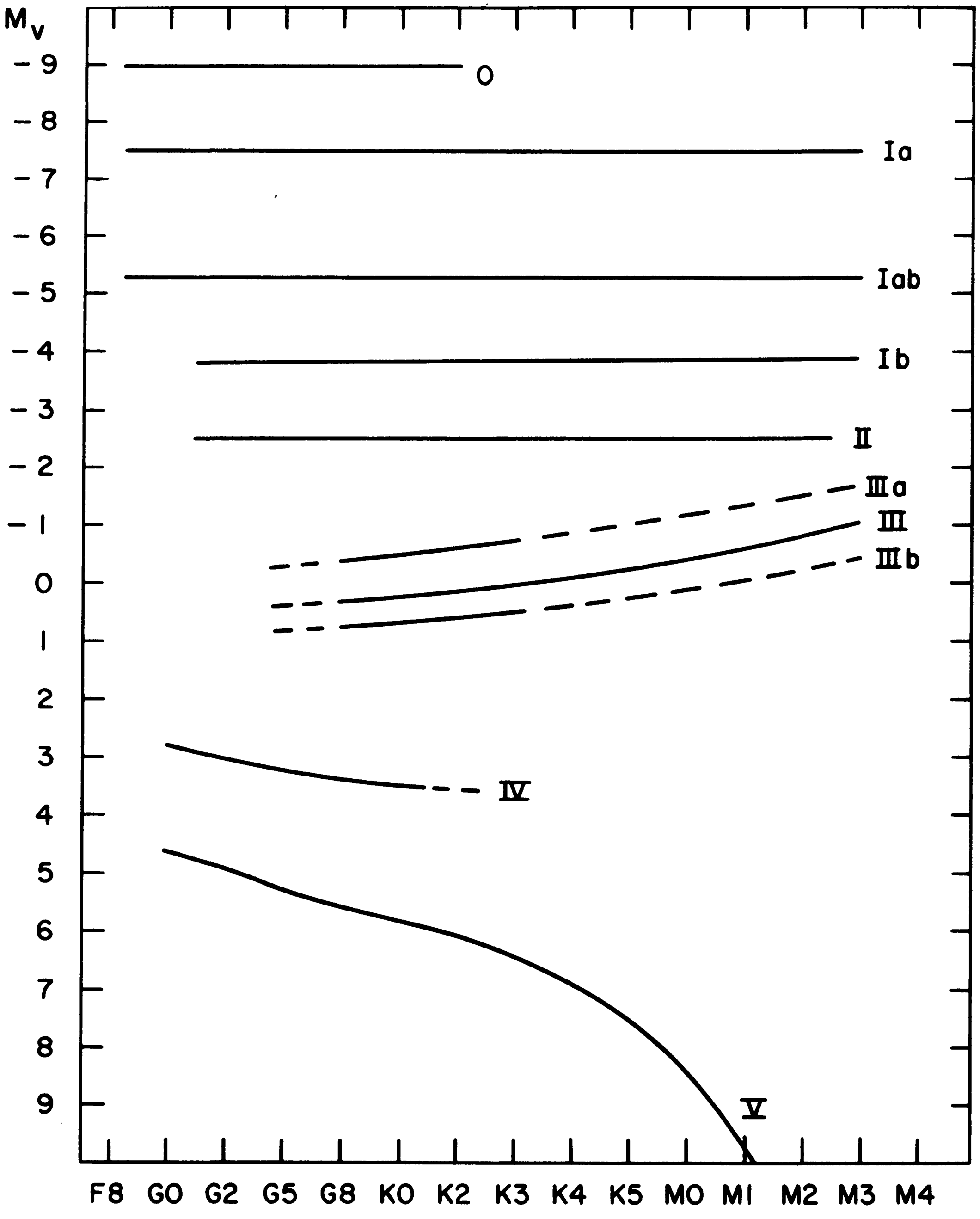

Fig. 2. Calibration of MK luminosity classes for types later than F8. For supergiants the luminosities are based on clusters and binary companions. For classes IIIa, III, and IIIb the mean curves derived by Egret, Keenan and Heck (1982) are shown. For classes IV and V the individual trigonometric parallaxes were plotted and smooth curves drawn through them.

Even among B, A and F stars of more normal atmospheric structure the problem of successfully classifying stars of different populations (defined by their systematic differences in observed composition) is difficult. Morgan reviewed this problem at the Toronto Workshop on the MK Spectral Classification (Morgan, 1984), and expressed the view that it is not feasible to extend the MK system to a multidimensional classification to embrace other populations. Rather, he considers it necessary to set up separate autonomous, systems of classification for each group of "peculiar" stars. Each of these would be set up analogously to the original MK system. This he terms the "MK process". Reference must be made to Morgan's paper for examples.

For the spectral types later than G0 the situation is different and in some ways not so complex. Consider the sample of G5-K5 stars of luminosity classes II, III and IV. The distribution among groups of the 426 stars in my current list of best types is shown in Table III.

TABLE III

SPECTRAL GROUPS, G5 TO K5

Normal solar composition	269 stars	63%
Slightly weak metal lines	33	8
Weak lines (Population II)	53	12
Strong metal lines (SMR)	28	7
Other peculiarities (Ba, strong CH, weak CH, etc.)	44	10

Although the sample is not unbiased, it is evident that if the MK system were limited to stars of "normal" composition, more than one out of every three examined would fall outside the system. The largest fraction of these (20%) are the weak-line (metal-deficient) stars, and it is well known that they form a continuous sequence from halo stars with extremely weak lines to normal solar-composition stars to strong-line stars.

The existence of such continuous transition sequences between population groups naturally suggested the extension of the original MK classification to what I have called the "Revised" system, in which as many as possible of these "peculiar" objects are included and are characterized by abundance indices.

For the spectra with moderate line weakening it has long been known that several of the usual MK criteria can be employed if sufficient care is used (Keenan and Keller, 1953). This conclusion is supported from the theoretical side by the calculations of Foy (1979), based on model atmospheres. He emphasized, however, that the

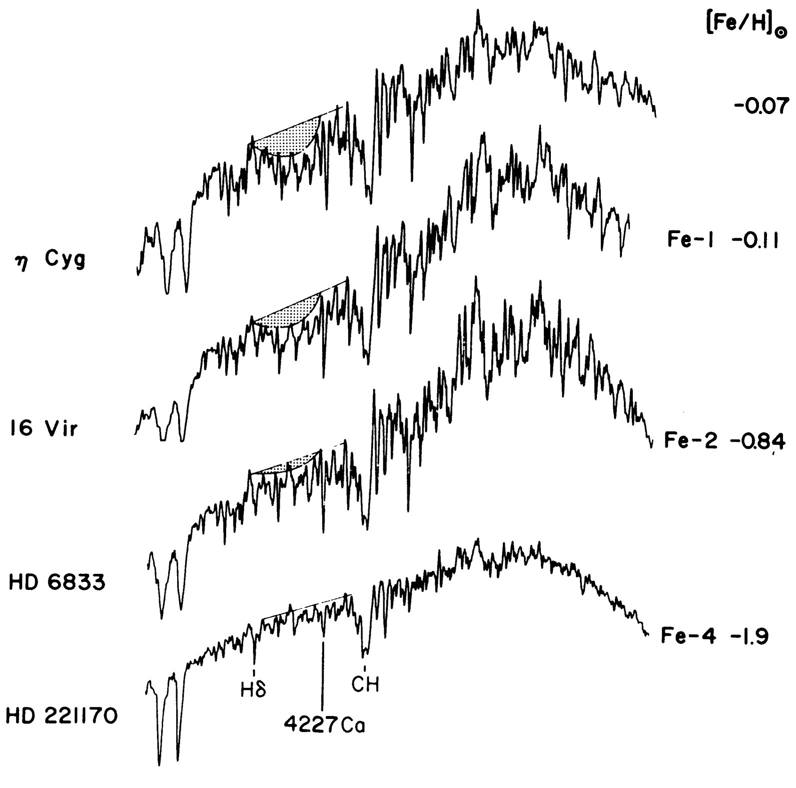

Fig. 3. Effects of metal deficiencies on spectra of KO III stars. The metallicity index is shown at the right, followed by published values of $[Fe/H]_{\odot}$. The dotted areas indicate approximately the absorption by the blue CN band.

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calibration of temperature types and luminosity indices in terms of physical variables must be done separately for stars with markedly different chemical compositions.

In assigning composition indices the classifier must face a problem. He is caught between Scylla and Charybdis. If he uses a separate index for each of the more conspicuous elements or compounds, he can be accused of making the system too complicated. If he tries to simplify things by using only one index he runs the danger of throwing quite different stars into the same spectroscopic box.

In designing the system it seemed safer at the beginning to use several indices whenever there was a suspicion that the abundances were not all closely correlated. As an example, a sequence of linear intensity plots of KO giants with progressively greater metal deficiences is shown in Figure 3. The logarithmic metal deficiencies shown at the right are taken for the most part from the catalog of Morel, Bentolila, Cayrel and Hauck (1981). For η Cyg the determinations published by L. Gratton et al. (1981) and R. G. Gratton (1983) were averaged.

The tracings bring out strikingly the familiar sensitivity of the blue CN depression to even slight metal deficiencies. In contrast, only the strong lines of the iron-peak metals are visible at classification dispersions and do not show clearly visible weakening until the abundances of the metals are reduced several fold.

This behavior holds generally for giants between G8 and K2, and led to the use of the two abundance indices, CN and Fe, for these stars. Now, however, enough types are available to allow us to say that a single metal abundance index, Fe, is sufficient to characterize these stars. Our classification is thus simplified. I should add that Morgan's work on stars of different populations in the main sequence led him to the same conclusion.

This leaves us with another problem. When the lines are weaker than in stars like HD 221170 we can no longer see them well enough to classify the stars on the usual small scale spectrograms. Figure 4 reproduces the photographic spectrum of such a star, BS 5270 = HD 122563. In the upper spectrum all the absorption features except H, K, Hδ, Hγ and the G-band have practically disappeared. When the scale is increased to about 20 Å/mm, however, in the lower spectrum, the lines are visible, even though much weaker than in the comparison star ε Vir. The usual line ratios can be estimated and the star classified, though with somewhat lowered accuracy, on the Revised MK system. This illustrates the flexibility of the classification, for there are few stellar spectra as featureless as that of BS 5270, for which various abundance analyses give $[Fe/H]_o \approx -2.6$. Our metal index for it is Fe -5.

Another small group of chemically peculiar stars is distinguished by spectra with the G-band of CH abnormally weak. The lines of the common metals and of hydrogen, however, are nearly normal for the temperature types of these class III giants. The CN bands are generally weakened in their spectra, but not so much as the CH band. This behavior has been shown by atmospheric analyses of such typical CH-weak stars as 37 Com, BS 6766, and BS 6791 to be due to extreme

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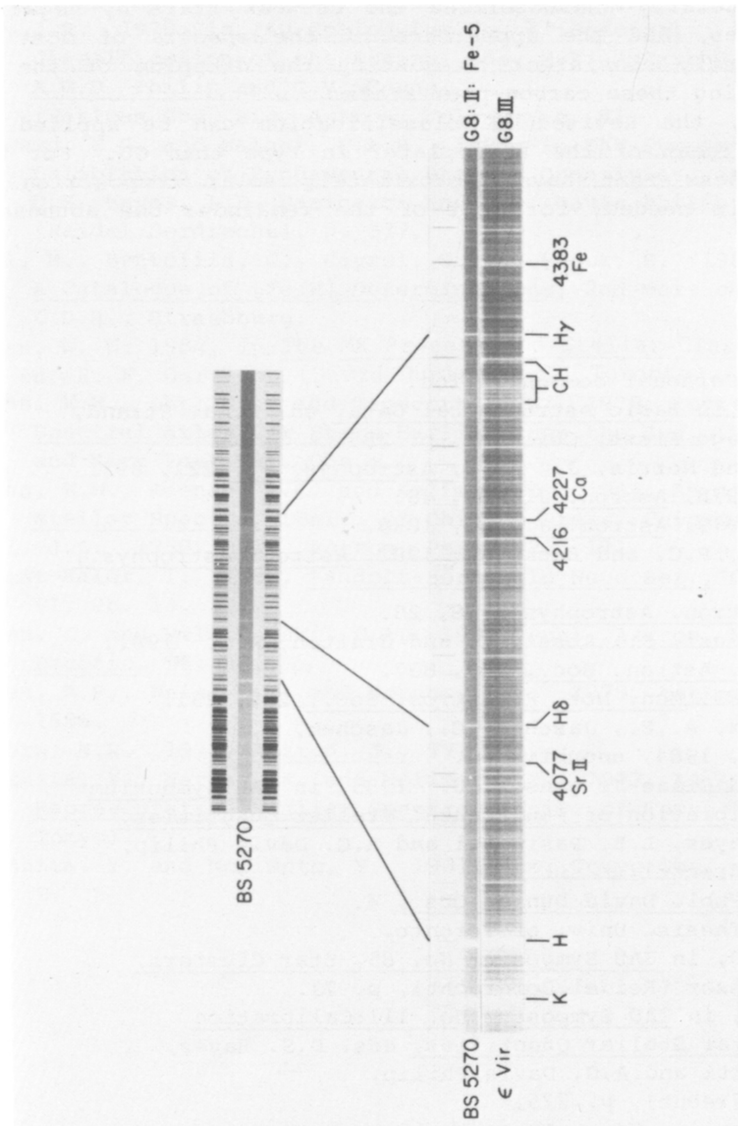

Fig. 4. The extreme metal-deficient star BS 5270 = HD 122563 (G8: II; Fe -5). The upper spectrum shows an ordinary classification plate at 76 Å/mm; the lower one an exposure at 20 Å/mm, taken by Walter Mitchell. The companion star, ε Vir, has essentially solar composition.

deficiency of carbon, coupled with a moderate excess of nitrogen, in their atmospheres (extensive references will be found in the papers of Cottrell and Norris 1978, and of Sneden and Pilachowski 1984).

We have generally characterized the CH-weak stars by negative CH and CN indices, but the appearance of the spectra of most of them is sufficiently consistent to justify the dropping of the CN index in classifying these carbon-poor stars.

In summary, the Revised MK classification can be applied to all but a few percent of the stars later in type than GO. For the two-thirds of these that have approximately solar composition no abundance index is needed; for most of the remainder one abundance index suffices.

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DISCUSSION

GARRISON: I am glad to hear your remarks about the applicability of the MK system to other populations. I have always believed that unusual spectra could be described in terms of the MK system of standards and I have said so in my paper here as well as in other places.

KEENAN: Absolutely.

GARRISON: I am a bit concerned about the suggestion to reduce the peculiar line strength indices to one dimension because of the very few really peculiar objects. Can we agree on a convention that when a type such as Fe-2, or something like that, is given, we can assume that CN is similarly weak; and if it is not, we will give a separate CN index? There may be some confusion, however, for types given previously. How will people know whether an Fe-2 alone (pre 1984) means Fe-2, CN-2 or Fe-2, CN 0? I guess it probably will be so rare that you can republish the few in that category.

KEENAN: Yes, there will be just a few stars so peculiar that the use of several indices is justified.

CAYREL: I am delighted with your classification of the extreme Population II stars.

KEENAN: Thank you!

JASCHEK: Who carried out the calibration for the high-luminosity stars?

KEENAN: Pitts and I are doing that. Schmidt-Kaler did it originally. We are updating his work.