SPECTRAL CLASSIFICATION ❖ 2042

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INTRODUCTION

This chapter is divided into two parts: the first is concerned with a reexamination of the validity of the MK system of spectral classification, and gives a revised frame of reference for the early-type stars; the second gives a revision of the MK system for giants and supergiants of classes G, K, and M. Part I was prepared by Morgan; Part II by Keenan.

In Part I we will be concerned with the following subjects: (1) the present state of the MK system; (2) the validity of the MK system; (3) a revised list of fundamental MK standards for the O4–G2 spectral range; (4) the problem of a third dimension; and (5) the practical limits in visual spectral classification.

PART I

1. The Present State of the MK System

The MK system is defined, in effect, by the list of standard stars published by Johnson & Morgan (1953). The criteria for classification in 1953 were, in general, those described in the "MKK" Yerkes *Atlas of Stellar Spectra* (Morgan, Keenan & Kellman 1943). In the period from 1953 to the present, a large number of spectral types on the MK system have been published by a variety of observers using a variety of spectrograms. This has greatly expanded the problem of evaluating the systematic and accidental errors in the types of the various investigators, since the earliest MK types were the work of a rather closely knit group at the Yerkes Observatory. In some instances the scatter in derived types is considerable, and discrepancies of two luminosity classes or spectral subdivisions are not particularly uncommon. This can be considered to be due principally to the great range in characteristics of the spectrograms used.

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In recent years there has been a progressive improvement in the quality and suitability of spectrograms for classification. This development has brought to light discrepancies in the earlier types; it also makes possible a more precise definition of the frame of reference of the MK system. The latter subject is discussed below.

There is an additional source of difficulty in the use of the MK system: the rapidly growing acceptance of the use of what has been described as quantitative classification methods, through intermediate and narrow-band photoelectric techniques. Some of the results of the application of these methods have been described in terms of the nomenclature of the MK system. When this is done, a conclusion can be reached that such derived types are of considerably greater precision than those obtainable from direct examination of stellar spectrograms; it is thus possible to arrive at a general conclusion that quantitative methods have displaced visual ones—and, specifically, that the MK system has lost its usefulness. This conclusion is false.

2. *The Validity of the MK System*

CHARACTERISTICS OF THE MK SYSTEM The MK system is a phenomenology of spectral lines, blends, and bands, based on a general progression of color index (abscissa) and luminosity (ordinate). It is defined by an array of standard stars, located on the two-dimensional spectral type vs luminosity-class diagram. These standard reference points do not depend on values of any specific line intensities or ratios of intensities; they have come to be defined by the appearance of the totality of lines, blends, and bands in the ordinary photographic region.

The definition of a reference point, then, is the appearance of the spectrum "as in" the standard star. For example, a star located at A2 Ia would have a spectrum having a total appearance as in the standard α Cygni; a star of spectral type G2 V would have a spectrum whose appearance is similar to that of the Sun.

The use of such a frame of reference makes the process of spectral classification a differential one, which makes possible a considerably higher precision than could be achieved without such a reference frame. The use of the standard frame of reference serves another important purpose: it minimizes the possibility of localized distortions of the MK system. If the reference-frame standard-stars are not respected, and their types are allowed to fluctuate in use, such localized distortions will appear; and the overall systematic accuracy of the deduced spectral types will be less than that of the reference system itself.

In the course of the program of classification, it is found that when a number of spectra are classified in a single cell (for example, B2 V), a careful examination, on plates of optimum quality, reveals that such spectra are not identical in appearance. *This is a fundamental characteristic of the MK system*; we are, in fact, substituting a finite array of discrete cells for what is in fact a continuum. Without such a procedure, visual spectral classification would be impractical—and for that matter, *any* two-dimensional classification would be in serious difficulties, since the spectral phenomena are not confined to two dimensions. We discuss these questions more fully below.

THE ROLE OF SPECTRAL CLASSIFICATION: STATEMENT BY DIMITRI MIHALAS We are fortunate in being able to present the following statement by Dr. Mihalas on the relationship between spectral classification and stellar atmospheres:

> By constructing a model, we have the opportunity to carry out two kinds of interesting activity. First, by comparison of the computed observables with the observations themselves, we can (with luck) find a model that fits the observations more or less satisfactorily. Having done this, we may then use the model to infer physical properties that are not in themselves observable, and by examining the relations among the relevant properties from a physical standpoint we ultimately construct some kind of word-picture which we use to "describe" the atmosphere. When this picture is very well-developed, seemingly consistent, and sufficiently detailed, we feel we "understand" what occurs in the real stellar atmosphere under study.
>
> The second activity is more important. Here we construct perhaps many models according to the basic physical ground rules we have chosen. Then by comparing these with the totality of observations we attempt to find the strengths and weaknesses of the theory itself. Thus we try to exploit the fundamentally reflexive nature of the abstracting process and close the circle of abstraction by using the objects to be explained as reference points against which we measure the worth of the explanation.
>
> One of the most insidious problems that can arise is when we deal with a theoretical system that is seemingly self-consistent *and yet incorrect*. Here we may, for example, make diagnoses of (say) the temperature and gravity of a star which follow with small error (of comparison) from the theory, and *yet are systematically wrong*! A classic example of this problem arises in discussions of whether departures from LTE are of sensible importance in the atmospheres of stars. If one works only *within* the framework of the LTE hypothesis, one can "show" that LTE is "almost" self-consistent, and that the departures are seemingly "small." *Yet analysis shows this conclusion to be false.* A truly consistent analysis shows that while the "fractional error" predicted by LTE is, say, ϵ, if the predictive process is *iterated* to conclusion, of order $1/\epsilon$ iterations are required; and the final result bears little resemblance to the initial inference (except in certain asymptotic limits).
>
> In the final analysis there is only one meaningful approach we can adopt in the empirical system: to *define it in terms of real objects*, *without comment*. For example, the most valid way to "describe" a stellar spectrum is to *refer* it to spectra of prechosen *standards* which in themselves contain the entire information content and ultimately provide the Supreme Court to adjudicate any question pertaining to some other spectrum.
>
> At this juncture the fundamental role of the standards must be recognized and emphasized. In particular, it should be noted that *once we establish an autonomous system in terms of certain reference objects*, *we are not free to alter the framework for external reasons*. For if we do so, either we must reconstruct the empirical system, which then becomes a *different system*, or, failing that, we must note quite candidly that we have imposed some *other* structure on the system, based on precepts which may be inconsistent with the information actually present in the original system.

THE ROLE OF THE MK CLASSIFICATION SYSTEM: GENERAL SUMMARY The general situation can be summarized as follows:

(a) A spectral classification system having general properties similar to those of the MK system is necessary for the orderly preservation of the wide range of phenomena encountered among the lines and bands in stellar spectra; this includes both information that we think we understand as well as information that we do not.

(b) Such a system is defined by the spectra of an array of standard stars.

(c) With a two-dimensional structure defined by such standard stars, the process of classification becomes a differential one, based on the appearance of the various spectral lines, bands, and blends, as observed in the ordinary photographic region. The revised MK system is well-suited to the incorporation of additional dimensions. Some possibilities are mentioned in Section 4 of Part I, and in Part II.

(d) Such a system is autonomous and self-consistent with regard to the various lines, bands, and blends in the ordinary photographic region.

(e) When types are determined from other spectral regions, they must be collated with results from the ordinary photographic region.

3. *A Revised List of Fundamental MK Standards for the O4–G2 Spectral Range*

During the past few years, Dr. Helmut Abt and the writer have been engaged on a critical reexamination of the stellar spectra that define the MK system from two points of view: (1) to achieve the highest practicable degree of internal self-consistency, and (2) to improve the self-consistency and autonomy of various categories of peculiar spectra requiring an implicit third dimension for satisfactory classification. This program is still not completed; in what follows, we give certain partially completed sections. The writer is greatly indebted to Dr. Abt for permission to publish the results incorporated in this and the following sections.

THE "DAGGER TYPES" In order to discriminate clearly between earlier MK types and those which have undergone reexamination for self-consistency, we prefix the latter with a dagger. The types already reexamined are listed in Table 1. The columns give: (1) the HR number, (2) the star name, (3) the MK dagger type.

While the number of stars included in the table is rather small, it can be considered to define the MK system in a fairly satisfactory manner from O9 to F8. In particular, the high internal accuracy of the array makes possible precise interpolation—except for spectra of types Ia–III in the ranges O5–O8, A0–A7, and for the supergiants of class F.

The revision of the types between O5 and B9 was carried out principally from spectrograms in the Yerkes spectral classification collection. A new series obtained by Mr. Richard White with the Yerkes 24-inch reflector and a small grating spectrograph designed by Dr. W. A. Hiltner has been of special importance; the scale of these spectrograms is 84 Å/mm, and their width is 1.3 mm. For the

A3–G2 spectrograms, the principal weight for the reclassification is from a series of grating spectrograms obtained by Dr. Abt with the Kitt Peak Observatory 36-inch telescope #1, together with a spectrograph giving a scale of 125 Å/mm.

SOME CHARACTERISTICS OF THE TYPES GIVEN IN TABLE 1 The fragmentary structure defined by the dagger types in Table 1 gives a clean representation of the two-dimensional MK system; except for differences in line-broadening, there are no obvious cases where spectral peculiarities would indicate the need for a third

Table 1 Revised standards for MK system

HR	Name	† MK	HR	Name	† MK
HD 46223		† O4	1713	β Ori	† B8 Ia
HD 46150		† O5	7906	α Del	† B9 IV
3165	ζ Pup	† O5f	7001	α Lyr	† A0 V
2456	15 Mon	† O7	4554	γ UMa	† A0 V
8622	10 Lac	† O9 V	7924	α Cyg	† A2 Ia
1899	ι Ori	† O9 III	8728	α PsA	† A3 V
2782	τ CMa	† O9 Ib	6081	ο Sco	† A5 II
1931	σ Ori	† O9.5 V	3569	ι UMa	† A7 IV
6165	τ Sco	† B0 V	1412	θ^2 Tau	† A7 III
1855	υ Ori	† B0 V	7876		† A9 II
1903	ε Ori	† B0 Ia	1351	57 Tau	† F0 IV
5953	δ Sco	† B0.3 IV	4031	ζ Leo	† F0 III
1220	ε Per	† B0.5 III	292		† F0 II
2004	κ Ori	† B0.5 Ia	1865	α Lep	† F0 Ib
5993	ω Sco	† B1 V	4931	78 UMa	† F2 V
1892	42 Ori	† B1 V	2107	1 Mon	† F2 IV
1131	ο Per	† B1 III	21	β Cas	† F2 III-IV
1203	ζ Per	† B1 Ib	1279		† F3 V
6141	22 Sco	† B2 V	HD 27524		† F5 V
39	γ Peg	† B2 IV	856		† F5 III
153	ζ Cas	† B2 IV	7495		† F5 II
1790	γ Ori	† B2 III	1017	α Per	† F5 Ib
2135	χ^2 Ori	† B2 Ia	1543	π^3 Ori	† F6 V
7121	σ Sgr	† B2.5 V	544	α Tri	† F6 IV
5191	η UMa	† B3 V	6577		† F6 III
1641	η Aur	† B3 V	HD 27808		† F8 V
2653	o^2 CMa	† B3 Ia	HD 27383		† F9 V
1749	ρ Aur	† B5 V	4540	β Vir	† F9 V
6092	τ Her	† B5 IV	4983	β Com	† G0 V
2827	η CMa	† B5 Ia	4883	31 Com	† G0 III
1145	19 Tau	† B6 IV	339	ψ^3 Psc	† G0 III
1165	η Tau	† B7 III	HD 27836		† G1 V
1144	18 Tau	† B8 V	6212	ζ Her	† G1 IV
1178	27 Tau	† B8 III	Sun	(Jupiter IV)	† G2 V

dimension. These stars are fundamental reference points for the revised MK system; and any future changes in their values will effectively alter the MK system itself.

RECENT REFERENCE CATALOGUES CLOSE TO THE MK DAGGER SYSTEM Among recent publications, there are two catalogues of MK types of O and B stars which define a system effectively that of the above-listed dagger types. They are contained in papers by Hiltner, Garrison & Schild (1969) and by Lesh (1968). Until a more complete catalogue of dagger types has been finished, it is recommended that additional standards be taken from these lists as needed. We refer below to several investigations of the O4–B1 stars by N. R. Walborn.

4. The Problem of a Third Dimension

The concept of a third dimension—or additional dimensions—flows naturally from the preceding discussion of the phenomenology of spectral classification. Here again, the "language" is in terms of spectral lines, bands, and blends, observed "as in" the spectra of certain standard stars. We consider a basically two-dimensional system (the MK diagram), with a number of third dimensions protruding from various points or localized regions.

We are not yet in a position to present a unitary picture of such a structure, and must content ourselves with two rather simple examples. Figure 1 shows spectrograms of the O stars θ' Ori (br) and 15 Mon. The stars are of very nearly the same spectral type, and the helium lines have similar line quality; the absorption Hγ, however, is strikingly broader in θ' Ori (br) than in 15 Mon. This phenomenon of abnormally broadened Balmer lines has been observed in the Orion Nebula cluster over the spectral range O6–B2; it is encountered very infrequently; the faint B0.5 star, whose spectrum was observed by Garrison (1968) in NGC 2024, has the same peculiarity—as does the star Herschel 36, located near the "hour glass" in M 8 (Hiltner & Morgan 1962).

Figure 2 illustrates another possible dimension for the classification of O and B stars: the intensity of the He I lines. The stars CPD-31°1701 (Garrison & Hiltner 1972) and HD 144941 (MacConnell, Frye & Bidelman 1970) can be considered extreme examples of abnormally strong He I lines. We are greatly indebted to Drs. Garrison and Hiltner and to Drs. Bidelman and MacConnell for permission to show the spectra of these remarkable objects.

THE PRACTICAL ESTABLISHMENT OF ADDITIONAL DIMENSIONS: THE OPTIMUM DISPERSION In the case of the two-dimensional MK diagram, there are two limiting considerations in the selection of spectrograms for classification: (1) the scale and spectrum width must be large enough to permit the determination of accurate two-dimensional MK types; and (2) the scale of the spectrogram must be as low as possible, to permit faint stars to be classified without systematic error depending on magnitude.

For normal stars of types O4–G2, the optimum characteristics of spectrograms that satisfy the two above-mentioned conditions are a scale of 60–125 Å/mm and

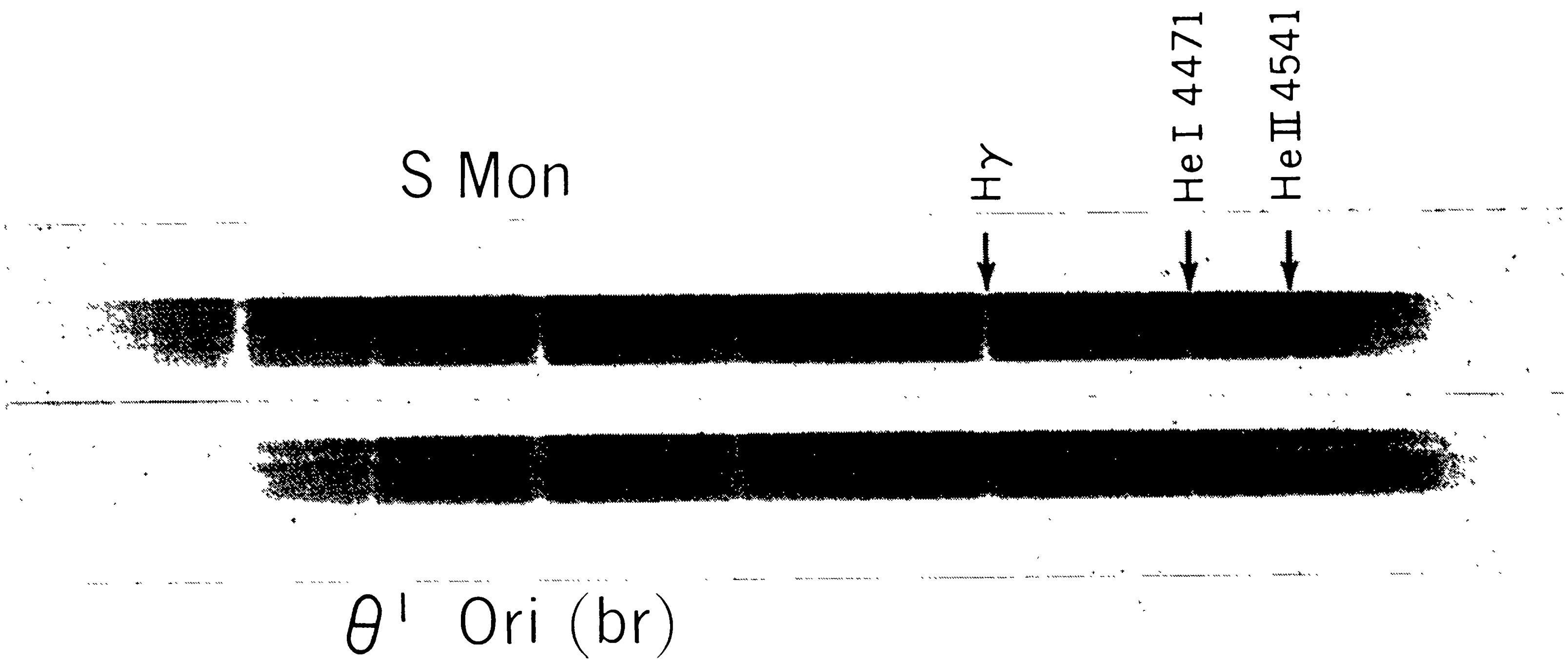

Figure 1 Spectrograms of 15 S Mon and θ' Ori. The lines of He I and He II are of similar quality and indicate similar types near 06–07. The line Hγ is much broader in θ' Ori than in S Mon. Yerkes 40-inch spectrograms with classification spectrograph, on Eastman Process emulsion.

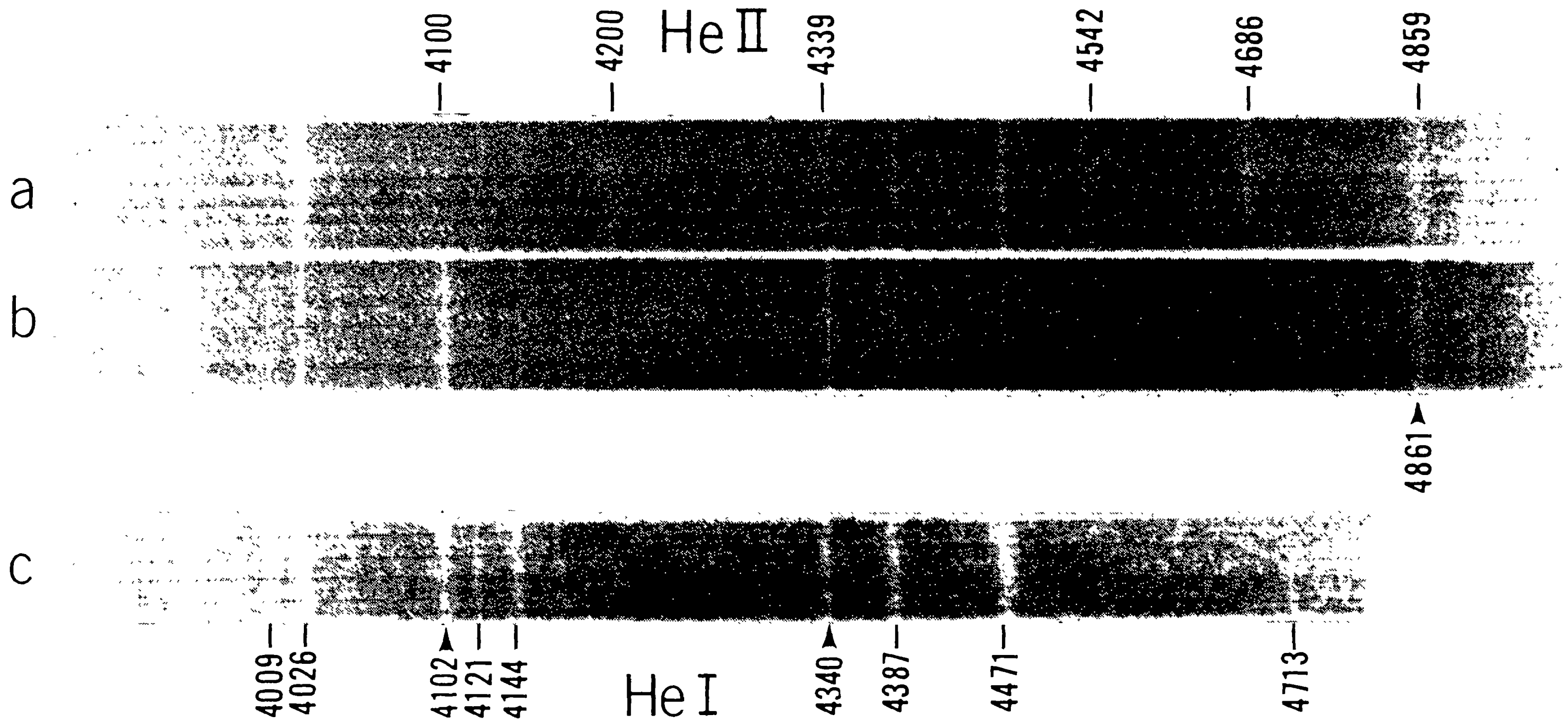

Figure 2 Two helium-rich stars: (a) the Garrison–Hiltner star CPD −31°1701 (*Bull. AAS* 4:312, 1972); (b) τ Sco (B0 V); (c) the MacConnell–Frye–Bidelman star HD 144941 (*PASP* 82:734, 1970). Spectrum (a) is of class O, with well-marked lines of He II, and very strong lines of He I. Spectrum (c) contains outstandingly strong absorptions of He I, and probably abnormally weak Balmer lines.

greatly widened spectra. The requirements may be different, however, for the introduction of additional dimensions—or descriptions of peculiarities—in the case of the O–F0 stars. Here, spectrograms of dispersions ranging from 40 Å/mm to 10 Å/mm may be required in some instances; on the other hand, the recognition and cataloguing of the Orion Nebula cluster type of wide hydrogen lines referred to above requires low dispersion combined with high-contrast emulsions.

5. *The Practical Limits in Visual Spectral Classification*

As in all structurings, there is a limit beyond which it is not useful to go in the case of the MK classification. This limit depends on the degree of precision with which the reference frame of standard stars can be defined—and on the degree of interest shown by users of the system in respecting the fundamental frame of reference; on this latter factor depends the degree to which the classification operation can be made differential rather than absolute.

Perhaps the best example of a successful attempt to carry visual spectral classification to a point near the practical limit is given in a series of papers by Walborn (1970, 1971a,b). These observations, which were obtained at the Kitt Peak and Cerro Tololo Observatories, made use of a dispersion of about 60 Å/mm and greatly widened spectra. Using the classification methods developed at the Yerkes Observatory, Walborn was able to present the behavior of certain emission and absorption features in the O stars in a rigorously self-consistent manner that has made possible major theoretical advances by Mihalas and others. The tie-in of Walborn's types with the MK system is not complete; however, this does not lessen their importance for astrophysical investigations, and for preserving implicit spectral characteristics not yet completely understood.

The preceding leads directly into a most important final subject: the plurality of visual classification systems. The MK system has, by the way in which it is defined, a basic limitation. This definition represents a compromise between degree of systemic resolution on the one hand, and avoidance of systematic errors depending on stellar magnitude on the other; and the optimum range in spectral dispersion (60–125 Å/mm) is a result of that compromise.

It has been noted by Osawa (1959, 1965) that a dispersion of around 60 Å/mm is necessary for highly accurate classification of the B8–A2 stars. A similar dispersion was used by Walborn for his work on the OB stars referred to above; and Conti & Alschuler (1971) have carried out a redetermination of the spectral types of all the brighter known O stars on coudé plates having a scale of 16 Å/mm. The revised spectral types of the latter depend solely on the ratio of He I 4471/He II 4541, and were reduced in a statistical fashion to the MK system. It is interesting and instructive to compare the two approaches used for these reclassifications of the O stars.

It is now clear that localized classification structures possessing autonomy and inner self-consistency of a high order can be devised for a number of regions of the HR diagram; and, where limiting magnitude does not present a problem, these local structures may have a precision higher than that of the MK system.

It seems to the writer that the practical limit of precision in the classification of the spectra of O and B stars might be most closely approximated through use of spectrograms similar to those in a remarkable series obtained by Dr. Arne Slettebak with the Perkins reflector at the Lowell Observatory. These spectrograms have a dispersion of around 20 Å/mm and a width of 1.5 mm. It is clear that such spectrograms could only be obtained for the brighter stars.

PART II

1. Normal Stars

For stars later than about F8, where rotation ceases to be important, the physical variables that determine their spectral features appear to consist essentially of temperature and pressure and the abundances of the chemical elements. Fortunately the abundances are usually coupled into a few groups (such as metals/hydrogen) so that the description of their spectra can be given by the few shorthand symbols that we know as spectral types. The classification could be carried out by multivariate analysis (Deeming 1964) into as many parameters as are found necessary to eliminate significant variance among the measured features. Since, however, the stronger spectral features are practically all identified and arise from known states of excitation and ionization (or molecular association), it has usually been found more convenient to make use of this physical information by directly estimating temperature types, luminosity parameters, and one or more abundance classes. In this chapter only the latter procedure will be considered.

In the MK system the first two symbols give the temperature type and the luminosity class, and represent the projection on the luminosity-temperature plane (H-R diagram) of whatever multidimensional surface is described by the stars having a particular composition. The group abundances can then be represented by additional symbols determined by relative intensities of the lines or bands that reveal the composition variations. If the composition is essentially that of the Sun, we omit the additional symbols. Thus to distinguish a Population I giant of type K0 III from a Population II giant with a lower ratio of metals/hydrogen, the type for the latter becomes K0 III CN-1, or K0 III CN-2, etc.

The greatest precision of classification has been achieved for the stars of roughly solar composition, which can conveniently be called "normal" stars, and fortunately there are enough of them in our parts of the galaxy to provide a good network of standards for all but the most luminous supergiants. Table 2 includes the normal stars that we judge to be the best-determined standards of temperature type and luminosity class, and their types are preceded by the symbol † as in Table 1. Their classification has been carefully reviewed by intercomparison on well-matched spectrograms of the blue region, most of which have a scale of close to 80 Å/mm. In addition to the fundamental standards, Table 2 lists all the stars with revised MK types later than F8, including those of differing composition. The stars below the giant branch are only incompletely represented in the tables, and additional standards should be added later. For the main sequence in the Hyades to type K4 the tables given by Morgan & Hiltner (1965) can be used.

The separation of stars with spectra that differ appreciably from those of the

Table 2 Revised types, G0 to M8

Name	BS = HR	HD	1900	V	Type	Remarks
χ Peg	45	1013	$0^h09^m.4$ +19°39′	4.80	† M2$^+$III	
ι Cet	74	1522	0 14.3 − 9 23	3.55	† K1.5 III	
δ And	165	3627	0 34.0 +30 19	3.28	† K3 III	
α Cas	168	3712	0 34.8 +55 59	2.23	K0$^-$ IIIa	
		4404	0 41.3 +59 44	7.6:	G9 II	
	237	4817	0 45.2 +61 16	6.07	K2 Ib-II CN-2	
θ Cet	402	8512	1 19.0 − 8 42	3.60	K0 IIIb	
β And	337	6860	1 04.1 +35 05	2.05	† M0 IIIa	
		10465	1 37.0 +48 01	(7.00)	† M2.5 II	
ο Psc	510	10761	1 40.1 + 8 39	4.26	G8 III	
		11092	1 44.0 +64 22	6.56	† K4+Ib-IIa	
γ And A	603	12533	1 57.7 +41 51	2.10	† K3$^-$ IIb	
α Ari	617	12929	2 01.5 +22 59	2.00	† K2 IIIab	
65 ξ^1 Cet	649	13611	2 07.7 + 8 23	4.36	G8 II CN-2	
SU Per		14469	2 15.1 +56 09	7.6:	† M3-M4 Iab	
η Per A	834	17506	2 43.4 +55 29	3.76	† K3$^-$ Ib-IIa	
17 Per	843	17709	2 45.3 +34 39	†4.53	K7 III	
45 RZ Ari	867	18191	2 50.2 +17 56	5.9 var	† M6$^-$ III:	
α Cet	911	18884	2 57.1 + 3 42	2.53	† M1.5 III	Type sl. var.
ρ Per	921	19058	2 58.8 +38 27	3.2–4.1	† M4 IIb-IIIa	
κ Per	941	19476	3 02.7 +44 29	3.80	K0 III	
	1016	20894	3 17.0 −24 00	5.50	G7 IIb	
	1155	23475	3 40.4 +65 13	4.42:	† M2$^+$ IIab	
	1286	26311	4 04.6 +33 19	5.72	K1 II-III	Hδ sl. wk?
μ Per	1303	26630	4 07.6 +48 09	4.12	† G0 Ib	
	1327	27022	4 11.2 +64 54	5.28	G4 III	
γ Tau	1346	27371	4 14.1 +15 23	3.65	† K0$^-$ IIIab	
α Tau	1457	29139	4 30.2 +16 18	0.86	† K5 III	
R Dor	1492	29712	4 35.6 −62 16	5.0–6.0	M8e	SRb var
ι Aur	1577	31398	4 50.5 +33 00	2.68	† K3 II	
10 π^6 Ori	1601	31767	4 53.4 + 1 34	4.46	† K2 II	
		268757	4 54.6 −69 14	10.2	† G7 0	LMC
θ Dor	1744	34649	5 13.8 −67 18	4.82	† K2.5 III	
		271182	5 20.9 −65 52	9.7	† F8 0	LMC
119 Tau	1845	36389	5 26.4 +18 31	(4.73)	† M2 Iab-Ib	
40 ϕ^2 Ori	1907	37160	5 31.4 + 9 14	4.09	G8 IIIb	CN-2
	1909	37192	5 31.6 −33 09	5.74	K2 IIIa	
		269723	5 32.0 −67 44	9.9	G4 0	Prob. var. type LMC
		269953	5 40.7 −69 43	9.9	† G0 0	LMC
56 Ori	2037	39400	5 47.2 + 1 50	4.75	† K1.5 IIb	
α Ori	2061	39801	5 49.8 + 7 23	0.1–1.2	† M1-M2 Ia-Ib	
π Aur	2091	40239	5 52.5 +45 56	4.25	† M3 II	
TV Gem		42475	6 05.8 +21 53	7.0–7.8	† M0-M1 Iab	
6 BU Gem		42543	6 06.2 +22 56	6.1–7.5	† M1-M2 Ia-Iab	
η^2 Dor	2245	43455	6 11.0 −65 34	5.00	M2.5 III	
		44362	6 16.3 −50 19	7.03	† G2 Ib	
μ Gem	2286	44478	6 16.9 +22 34	2.97	† M3 IIIab	
46 ψ^1 Aur	2289	44537	6 17.2 +49 20	4.95 var	† K5-M0 Iab-Ib	
ε Gem	2473	48329	6 37.8 +25 14	2.99	† G8 Ib	
o^1 CMa	2580	50877	6 50.0 −24 04	3.8:	K2.5 Iab	In Cr 121?
41 Gem	2615	52005	6 54.5 +16 13	5.68	† K3 Ib	
		52220	6 55.2 −32 35	6.9:	† G1 Ib	
σ CMa	2646	52877	6 57.7 −27 47	3.46	† K7 Ib	
		52938	6 58.0 − 8 19	7.8:	† K3.5 IIb	In NGC 2323 =M50

1973ARA&A..11...29M

Table 2—(*Continued*)

Name	BS = HR	HD	1900	V	Type	Remarks
145 CMa	2764	56577	$7^{h}12^{m}.4$ −23°08′	4.82	† K3 Ib	In o^1 CMa group ?
	2786	57146	7 14.8 −26 25	5.27	† G1 Iab-Ib	H & K shallow
		58134	7 19.1 −29 34	7.7:	† G5 Ib	H & K sl. shallow
ι Gem	2821	58207	7 19.5 +28 00	3.79	† G9 IIIb	
υ Gem	2905	60522	7 29.8 +27 07	4.06	M0 III	
R Pup	2974	62058	7 37.0 −31 26	7.5:	G1 0-Ia	In NGC 2439 ?
CPD-31°1790			7 37.2 −31 27	8.3:	M3 Iab-Ib	In NGC 2439
76 Gem	2983	62285	7 38.0 +26 01	5.30	K4.5 III	
κ Gem	2985	62345	7 38.4 +24 38	3.56	† G8 IIIa	
β Gem	2990	62509	7 39.2 +28 16	1.14	† K0 IIIb	
	3026	63302	7 43.1 −15 44	6.34	† K1 Ia-Iab	
	3153	66342	7 57.9 −60 19	5.16	M1 IIa	In NGC 2516
29 ζ Mon	3188	67594	8 03.6 − 2 42	4.34	† G2 Ib	
β Cnc	3249	69267	8 11.1 + 9 30	3.52	† K4 III	
31 Lyn	3275	70272	8 16.0 +43 31	4.25	† K7 III	
		73884	8 35.5 −47 26	7.8:	K2 Ib Ba 0	CN sl str.
(31 Mon)	3459	74395	8 38.8 − 6 52	4.62	† G1 Ib	
		75022	8 42.4 −29 23	7.6	K2$^+$ II	
ζ Hya	3547	76294	8 50.1 + 6 20	3.11	† G9 II-III	
	3612	77912	9 00.1 +38 51	4.56	† G7 Ib-II	
α Lyn	3705	80493	9 14.9 +34 49	3.13	† K7 IIIab	
α Hya	3748	81797	9 22.7 − 8 14	1.98	K3 II-III	
24 UMa	3771	82210	9 25.6 +70 16	4.56	G4 III-IV	
10 LMi	3800	82635	9 28.1 +36 50	4.55	† G8.5 III	
N Vel	3803	82668	9 28.3 −56 36	3.13	† K5 III	
ε Leo	3873	84441	9 40.2 +24 14	2.97	G1 II	
μ Leo	3905	85503	9 47.1 +26 29	3.88	K1.5 CN1, Ca Str.	
π Leo	3950	86663	9 54.9 + 8 31	4.70	† M2$^-$ IIIab	
		88009	10 03.7 +19 01	7.1:	G8$^+$ IIIa CN 1	
μ UMa	4069	89758	10 16.4 +42 00	3.03	† M0 III H & K em	
EV Car		89845	10 16.9 −59 57	7.7–7.9	† M4.5 Ia	
β LMi	4100	90537	10 22.1 +37 13	4.20	† G9 IIIab	
		91629	10 29.7 −58 54	7.9	† G0 Iab	
CPD-57°3502			10 31.9 −57 44	7.3–7.4	M1.5 Iab-Ib	
37 LMi	4166	92125	10 33.1 +32 20	4.67	† G3 Ib-II	
RT Car			10 40.9 −58 54	8.6:	† M2$^+$ Ia-0	
BO Car		93420	10 41.9 −58 58	7.2–8.5	† M4 Ib	
BZ Car		94613	10 50.2 −61 30	7.7:	† M3$^+$ Ib	
56 VY Leo	4267	94705	10 50.8 + 6 43	6.0 var	† M5.5 III	Prob. sl. var.
α UMa	4301	95689	10 57.6 +62 17	1.79	† K0$^-$ IIIa	
		96746	11 03.5 −31 33	9.1:	† G2 Iab	
ψ UMa	4335	96833	11 04.1 +45 02	3.01	K1 III	
ν UMa	4377	98262	11 13.0 +33 38	3.49	K3 III Ba 0:	
		98817	11 17.2 −60 26	8.3:	M1 Iab-Ib	
56 UMa	4392	98839	11 17.3 +44 02	4.98	† G8 IIb	
o^1 Cen	4441	100261	11 27.1 −58 53	5.10	G2 Ia	
		100930	11 31.8 −60 46	8.1	† M2.5 Iab-Ib	N. of NGC 3766
		101007	11 32.3 −60 37	7.9:	M3$^-$ Ib+B	VV Cep type
ν Vir	4517	102212	11 40.7 + 7 05	4.05	† M1 IIIab	
BK Vir		108849	12 25.2 + 4 58	7.9–8.7	M7$^-$	
β CVn	4785	109358	12 29.0 +41 54	4.27	G0 V	
31 Com	4883	111812	12 46.8 +28 05	4.94	† G0 III	
CPD-59°4547			12 47.3 −59 40	7.58	† M2$^-$ Iab	Star D in NGC 4755
		112127	12 49.1 +27 19	6.92	K2 III: CN+3	

Table 2—(*Continued*)

Name	BS=HR	HD	1900	V	Type	Remarks
ψ Vir	4902	112142	$12^h49^m.2$ − 9°00′	4.80	M3 III	
TU CVn	4909	112264	12 50.4 +47 45	6.1 var	M5$^-$ III	
δ Vir	4910	112300	12 50.6 + 3 56	3.38	† M3 III	High vel.?
36 Com	4920	112769	12 54.0 +17 57	4.78	† M1$^-$ IIIb	
ε Vir	4932	113226	12 57.2 +11 30	2.83	† G8 IIIab	
41 Com	4954	113996	13 02.4 +28 10	4.82	K5$^-$ III	
	4991	114873	13 08.2 −42 37	6.15	K4 III	
83 UMa	5154	119228	13 37.0 +55 11	4.66	† M2 IIIab	
	5171A	119796	13 40.2 −62 05	6.80	G8 Ia-0	
87 Vir	5181	120052	13 42.0 −17 22	5.44	M2 IIIab	High vel.
υ Boo	5200	120477	13 44.6 +16 18	4.06	K5$^+$ III	
θ Aps	5261	122250	13 55.6 −76 19	5.8–6.7	M6.5 III:	
V 418 Cen		125332	14 13.6 −63 47	8.0 var	K4 II	
RX Boo		126327	14 19.7 +26 09	7.0–9.1	M8	Note 1
ρ Boo	5429	127665	14 27.5 +30 49	3.57	† K3 III	
		130705	14 44.6 +10 28	6.7:	† K3 IIIb CN 2	
β UMi	5563	131873	14 51.0 +74 34	2.07	† K4 III	
ω Boo	5600	133124	14 57.7 +25 24	4.80	K4 IIIab	
δ Boo	5681	135722	15 11.5 +33 41	3.49	† G8 III CN −1	
ι Dra	5744	137759	15 22.7 +59 19	3.29	K2 III	
γ Lib	5787	138905	15 29.9 −14 27	3.90	G8 III CN −1	
	5831	139862	15 35.4 +12 23	6.3:	G8 II-III:	
α Ser	5854	140573	15 39.4 + 6 44	2.64	† K2 III CN 1.5	
λ Ser	5868	141004	15 41.6 + 7 40	4.43	G0 V	
κ Ser	5879	141477	15 44.2 +18 27	4.10	† M1$^-$ IIIab	
ρ Ser	5899	141992	15 46.9 +21 17	4.78	† K4.5 III	
κ CrB	5901	142091	15 47.5 +35 58		K1 IVa	
	5924	142574	15 50.2 +20 36	5.44	M0 III	High vel.
ε CrB	5947	143107	15 53.5 +27 10	4.14	† K2 IIIab	
δ Oph	6056	146051	16 09.1 − 3 26	2.75	† M0.5 III	
ε Oph	6075	146791	16 13.0 − 4 27	3.23	K0$^-$ III	Note 2
	6128	148349	16 22.3 − 7 23	5.24	M2.5 III	High vel.
α Sco	6134	148478	16 23.3 −26 13	1.08:	† M1.5 Iab	
30 g Her	6146	148783	16 25.4 +42 06	5.0 var	† M6$^-$ III	
29 Her	6159	149161	16 27.9 +11 42	4.84	† K7 III	
ζ Her	6212	150680	16 37.5 +31 47	2.80	† G1 IV	
κ Oph	6299	153210	16 52.9 + 9 32	3.20	† K2 III	
	6337	154143	16 58.5 +14 14	4.98	† M3$^-$ III	Formerly 32 Oph
α^1 Her	6406	156014	17 10.1 +14 30	3.1–3.9	† M5 Ib-II	
π Her	6418	156283	17 11.6 +36 55	3.16	† K3 IIab	
σ Oph	6498	157999	17 21.5 + 4 14	4.34	† K2 II	
β Dra	6536	159181	17 28.2 +52 23	2.80	† G2 Ib-IIa	
BM Sco		160371	17 34.4 −32 10	6.2 var	K2.5 Ib	
β Oph	6603	161096	17 38.5 + 4 37	2.77	† K2 III	
	6617	161664	17 41.7 −22 27	6.2:	† G3 Iab-Ib	
μ Her	6623	161797	17 42.5 +27 47	3.41	G5 IV	
ξ Dra	6688	163588	17 51.8 +56 53	3.74	† K2 III	
θ Her	6695	163770	17 52.8 +37 16	3.84	† K1 IIa CN +2	
ν Oph	6698	163917	17 53.5 − 9 46	3.34	† K0$^-$ IIIa CN −1	
ξ Her	6703	163993	17 53.9 +29 16	3.70	G8 III	
γ Dra	6705	164058	17 54.3 +51 30	2.23	† K5 III	
71 Oph	6770	165760	18 02.5 + 8 43	4.64	G8 III	
AX Sgr		165782	18 02.6 −18 34	7.4 var	G8 Ia	
104 Her	6815	167006	18 08.1 +31 23	4.97	† M3 III	
	6842	167818	18 11.8 −27 05	4.65	K3 II	

Table 2—(*Continued*)

Name	BS = HR	HD	1900	V	Type	Remarks
106 Her	6868	168720	$18^h16\overset{m}{.}1$ $+21^\circ55'$	4.96	† M1 IIIb	
η Ser	6869	168723	18 16.1 − 2 54	3.26	† K0 III-IV	
κ Lyr	6872	168775	18 16.4 +36 01	4.32	K2 III CN 1	
		168815	18 16.6 −15 08	7.3:	$K5^+$ II	
109 Her	6895	169414	18 19.4 +21 43	3.84	† K2.5 IIIab	
XY Lyr	7009	172380	18 34.8 +39 35	5.8–6.8	M4-M5 II	
β Sct	7063	173764	18 41.9 − 4 51	4.22	G4 II CN 1	
δ^2 Lyr	7139	175588	18 51.0 +36 46	4.30	† M4 II	
	7164	176123	18 53.6 −18 42	6.3	G3 II	
δ Dra	7310	180711	19 12.5 +67 29	3.07	† G9 III	
θ Lyr	7314	180809	19 12.9 +37 57	4.35	† $K0^+$ II	
κ Cyg	7328	181276	19 14.8 +53 11	3.77	† G9 III	
		181475	19 15.5 − 4 41	7.4	M0 II	
6 α Vul	7405	183439	19 24.6 +24 28	4.45	M1 IIIb	High vel.?
V 450 Aql		184313	19 28.8 + 5 15	6.3–6.9	M5-M5.5 III	
μ Aql	7429	184406	19 29.2 + 7 10	4.44	K3 IIIb	
σ Dra	7462	185144	19 32.6 +69 29	4.69	K0 V	
	7475	185622A	19 34.9 +16 21	6.40	† K4 Ib	
α Sge	7479	185758	19 35.6 +17 47	4.37	G1 II	
β Sge	7488	185958	19 36.5 +17 15	4.37	† G9 IIIa CN 2	
V 973 Cyg	7523	186776	19 41.4 +40 28	6.4 var	M3 IIIa L-1:	High vel.
γ Aql	7525	186791	19 41.5 +10 22	2.72	† K3 II	
ε Dra	7582	188119	19 48.5 +70 01	3.82	† G7 IIIb CN-1	
β Aql	7602	188512	19 50.4 + 6 09	3.71	† G8 IV	
η Cyg	7615	188947	19 52.6 +34 49	3.89	† K0 III	
γ Sge	7635	189319	19 54.3 +19 13	3.48	K5-M0 III	
		190788	20 01.5 +25 19	8.2:	$M3^-$ Ib	Balmer lines str.
22 Vul	7741	192713	20 11.2 +23 12	5.67	† G3p Ib-II	Shallow H & K.
	7759	193092	20 13.3 +40 03	5.23	K3.5 IIab-IIb	
39 Cyg	7806	194317	20 19.9 +31 52	4.43	K3 III	
RW Cyg			20 25.2 +39 39	7.6–8.8	† M3-4 Ia-Iab	
EU Del	7886	196610	20 33.4 +17 55	6.3 var	M6 III L-1	High vel.
ε Cyg	7949	197989	20 42.2 +33 36	2.46	† $K0^-$ III	
3 Aqr	7951	198026	20 42.5 − 5 24	4.42	† M3 III	
AZ Cyg			20 54.5 +46 04	8.1–9.4	† M2-4 Iab	
ξ Cyg	8079	200905	21 01.3 +43 22	3.71	† K4.5 Ib-II	
61 Cyg A	8085	201091	21 02.4 +38 15	5.23	† K5 V	
61 Cyg B	8086	201092	21 02.4 +38 15	6.02	† K7 V	
63 Cyg	8089	201251	21 03.1 +47 15	4.54	† K4 Ib-IIa	
ζ Cyg	8115	202109	21 08.7 +29 49	3.19	G8 II CN 1	Note 3
		202380	21 10.3 +59 42	7.0:	† $M2^-$ Ib	
1 Peg	8173	203504	21 17.5 +19 23	4.08	K1 III	
2 Peg	8225	204724	21 25.4 +23 12	4.54	† M1 III	
β Aqr	8232	204867	21 26.3 − 6 01	2.58	† G0 Ib	
ρ Cyg	8252	205435	21 30.2 +45 09	4.02	G8 III CN-1, Hydr. str.	
75 Cyg	8284	206330	21 36.3 +42 49	5.10	† M1 IIIab	
ε Peg	8308	206778	21 39.3 + 9 25	2.40	† K2 Ib	Note 4
9 Peg	8313	206859	21 39.8 +16 53	4.32	† G5 Ib	
μ Cep	8316	206936	21 40.4 +58 19	4.0:	† M2 Ia	
KZP 5468		207076	21 41.4 − 2 40	7.2:var	M7 III:	
12 Peg	8321	207089	21 41.5 +22 29	5.29	K0 Ib	Hyd. lines str.
α Aqr	8414	209750	22 00.6 − 0 48	2.93	† G2 Ib	
ζ Cep	8465	210745	22 07.4 +57 42	3.36	† K1.5 Ib	
RW Cep		212466	22 19.4 +55 28	6.8–7.5	K0 0-Ia	
KZP 102195	8621	214665	22 34.7 +56 17	5.5:	M4 III	
μ Peg	8684	216131	22 45.2 +24 04	3.48	G8 III^+	
ι Cep	8694	216228	22 46.1 +65 40	3.52	$K0^-$ III	

Table 2—(*Continued*)

Name	BS = HR	HD	1900	V	Type	Remarks
λ Aqr	8698	216386	$22^h47^m.4$ − 8°07′	3.76	M2.5 IIIa L-1	
	8726	216946	22 52.0 +49 12	5.0:	M0$^-$ Ib	
	8752	217476	22 55.9 +56 24	5.1:	G5 var 0	See Text
β Peg	8775	217906	22 58.9 +27 32	2.4:	M2.5 II-III	Sl. var.
55 Peg	8795	218329	23 02.0 + 8 52	4.51	† M1 IIIab	
ϕ Aqr	8834	219215	23 09.2 − 6 35	4.22	M1.5 III	
8 And	8860	219734	23 13.1 +48 28	4.86	† M2 III	
γ Cep	8974	222404	23 35.2 +77 04	3.22	K1 IV	
	9010	223173	23 42.1 +56 54	5.51	K3$^-$ II	
ψ Peg	9064	224427	23 52.7 +24 35	4.66	† M3 III	
30 Psc	9089	224935	23 56.8 − 6 34	4.41	M3 III	

Note 1. RX Boo. Usually gM8, but sometimes as early as M7.5. Weak Balmer emission at times.

Note 2. ϵ Oph. In Roman's 1952 list the star is classified as G8 III wk 1, and the line intensities of Thackeray (1949) also indicate weak metallic lines. There appears to be a real discrepancy with our plates of 1954, 1956, and 1972, which all show lines of at least normal strength for a type of K0$^-$.

Note 3. ζ Cyg. Called Ba-star by Chromey et al (1969), but since Ba II 4554 is not definitely stronger on our plates than in other stars of the same luminosity, we do not list it among the semibarium stars. Wilson's K-line width gives an anomalously low luminosity (IAU 1973).

Note 4. ϵ Peg. Classified as a Ba-star by Warren (1970). The excess abundance of heavy elements estimated by Williams (1971b) was not confirmed by van Paradijs & de Ruiter (1972). On our spectrograms, Ba II 4554 is not definitely enhanced in comparison with its strength in similar supergiants. The reported sudden changes (Wood 1972) in the star's brightness may be expected to be reflected in spectral changes.

normal standards has made possible increased precision in the classification of the latter. For example, the giants of classes G8–M3 can often be subdivided into luminosity subclasses IIIa, IIIab, and IIIb, when several good plates of each star are available, while the stars that could not be assigned to one of these finer subdivisions are classified merely as III, II, etc.

In arriving at the tighter network of type stars in Table 1 we have necessarily made changes in a few of the older standards, but these have been minimal for most luminosity classes because there has seemed to be no reason to alter the original framework. Since the Sun is a fundamental zero point for the scale of effective temperatures, it is retained as a spectral zero point at G2 V. With type M0 defined in principle as that of a spectrum in which the stronger TiO band can just be detected at the dispersions of most objective prism surveys ($\approx$250 Å/mm in the blue), the λ4954 band is clearly visible in the K5 star at the standard scale of 80 Å/mm, and just perceptible at K4. Among the types that differ from those given in Johnson & Morgan (1953) or Keenan (1963) are β Dra, G0 Ib-IIa; κ Cyg, G9 III; η Per A, K2.5 Ib-IIa; ξ Cyg, K4.5 Ib-IIa; and 119 Tau, M2 Iab-Ib.

The earlier lack of enough of the more luminous supergiants to give good sequences of types has been partially overcome by drawing upon the extensive surveys made with objective prisms and either blue- or infrared-sensitive plates. Among the more extensive of the discovery lists are those of Bidelman (1957), Blanco & Nassau (1957), Albers (1972), and unpublished lists from the Michigan Schmidt plates made available by Dr. MacConnell. The most comprehensive catalogue bringing together the published types of supergiants, based on slit and slitless spectrograms, is that of Humphreys (1970b).

In the new and tighter network of supergiants the highest luminosity class, 0, is defined (Keenan 1971) by the four reddest of the brightest stars in the Large Magellanic Cloud. These are the stars originally called "super supergiants" by Feast & Thackeray (1956). The types given for these HDE stars in Table 1 and in the enlargement (Figure 3) are based on slit spectrograms taken at the Cerro Tololo Inter-American Observatory. The revised temperature types do not differ greatly from those assigned originally by Feast, Thackeray & Wesselink (1960), though the scale has been expanded to give G7 0 for HDE 268757 in order to make it more consistent with the rapid change in color index along the sequence. It should be noted that HDE 269953 and HDE 269723, which differ by three subdivisions here, were given the same type, G0, by Feast et al. It is likely that most of this difference represents a real change with time, for the brightest supergiants are notoriously variable in both temperature and luminosity. Two extreme examples are ρ Cas [from F8 Ia to G+M I at the unusual 1945–6 minimum (Beardsley 1961)], and BS 8752 [slow changes between G0 0 and G5 0 in the last twenty years (Keenan 1971)]. The best that we can do is to determine the most frequent spectral type for the more inconstant red stars, and this has been done here with the exception of BS 8752, for which the type refers to spectrograms of January, 1970.

The precision of spectral types has been estimated by C. and M. Jaschek (1972) as $\sigma = \pm 0.6$ subdivisions, based on all the types collected in the 1964 La Plata *Catalogue of Stellar Spectra Classified in the Morgan-Keenan System.* These types are normally on the same system, but come from such a heterogeneous group of observers and instruments that their accuracy and precision both should be appreciably less than those of a homogeneous set. Until there are enough of the revised types to permit a similar analysis, at least some feeling for the degree of confidence that can be placed in the spectroscopic discrimination of stars can be gained by inspection of the luminosity sequence near type G0 shown in Figure 4. Among the more useful criteria of luminosity of this type are the ratios 4172/Hδ, 4178/Hδ, Fe 4376/Fe 4385, 4404/Fe 4383.

These and other features in the blue region provide the most sensitive indicators of luminosity, but the extreme redness of the cool supergiants [for which $[B-V]_0$ is approximately 1.8 (Lee 1970)] makes it difficult and inefficient to observe them at short wavelengths. Consequently, several observers have attempted to classify at longer wavelengths. In the red region, good indicators of temperature type are present, but the weakness and scarcity of lines from ionized elements have hindered the estimation of luminosity except for types G0 and earlier, where the well-known sensitivity of OI 7774 to pressure is very valuable (Osmer 1972). Attempts to find atomic features that would be useful at low dispersion have not been very successful (Gahm 1970). At dispersions of the order of 10 Å/mm or better, however, it is possible to measure the width of the core of the absorption line Hα, and Kraft, Preston & Wolff (1964) showed that this width becomes greater with increasing luminosity in the way that the emission width of Ca II K

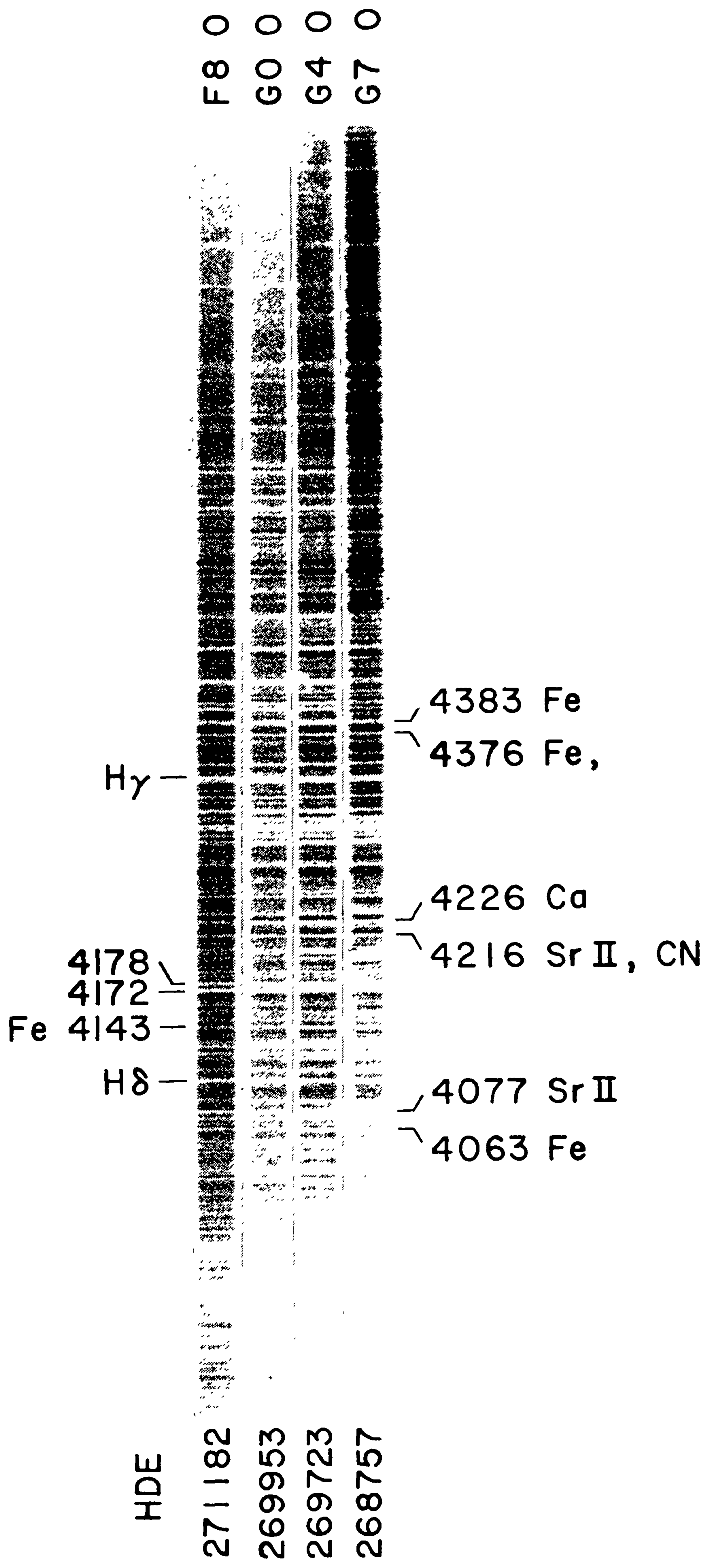

Figure 3 Sequence of types for the four latest super supergiants of the Large Magellanic Cloud. These define luminosity class O. Plates obtained at Cerro Tololo Inter-American Observatory.

1973ARA&A..11...29M

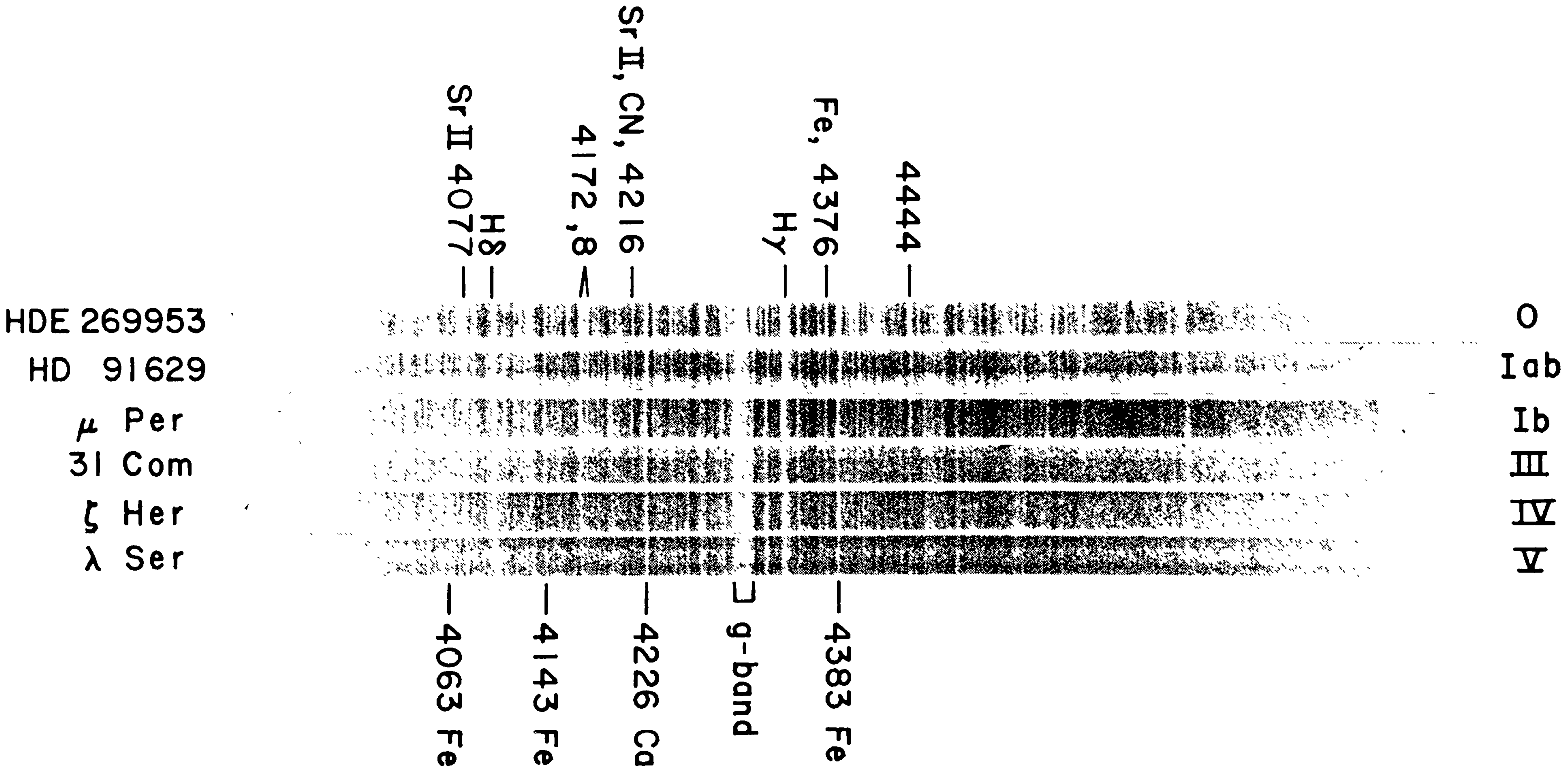

Figure 4 Luminosity sequence near type G0. Plates obtained at Cerro Tololo Inter-American Observatory and Kitt Peak National Observatory.

increases (Wilson–Bappu effect). For G- and K-type stars they found that the absolute magnitude in the ultraviolet correlates fairly well with the width of Hα, but that in M-type stars the development of wings in the giants prevents their being distinguished from supergiants by this method.

More recently, the red region has been studied again on coudé spectrograms at 16 Å/mm by Gahm & Hultquist (1972). After measuring the emission edges of Hα in giants they concluded that: "It is evident that among luminous late-type stars, the Hα lines cannot serve as a luminosity discriminant, due to interfering variable Hα emission." They obtained spectral types and luminosity classes for some of the supergiants in the range K0 to M5, using line intensities as criteria. Those lines most sensitive to luminosity were Ba II 5853, 6141, and 6496, Sc II 4584, La II 6390, Fe II 6516, and Sc II 6604.

Greater use has been made of the near infrared region between λλ7000 and 8700 Å. Most recent work has been carried out at moderate dispersions ($\approx$150 to 200 Å/mm) following the lead of Sharpless (1956), who carried out temperature classification on the basis of the TiO and VO bands and assigned luminosities largely on the strength of the infrared CN bands, with some help from the lines of neutral K, Ti, and Fe. In general, the infrared features do not permit quite such precise classification as can be carried out on blue-sensitive plates, though Humphreys (1970a) was able to obtain reasonably consistent results in both spectral regions for late-type supergiants.

The calibration of spectral types and luminosity classes in terms of effective temperatures and absolute magnitudes is beyond the scope of this article, but a discussion of recent work, with recognition of the many unsolved problems, will be found in Symposium No. 54 of the International Astronomical Union (1973).

2. *Stars Differing in Composition*

It is now generally accepted that differences in the ratio of hydrogen to all the elements heavier than helium are responsible for most of the differences between the spectra of the more extreme Population I and Population II stars. Throughout type F, and as late as G8, the Population II halo stars are characterized by relatively weak lines of most of the common metals. In contrast, there are some stars in which these lines are stronger than in our "normal" stars, and abundance analyses sometimes give excesses in the ratio of metals/hydrogen for these stars. Roman (1952) applied the designations "wk lines" and "str lines," respectively, in classifying the spectra of these two groups.

In spectra later than G5 a more consistent indicator of metal abundance is the amount of absorption by the cyanogen molecule. Usually the $\Delta v = 1$ sequence of CN, with its 0,1 head at 4216 Å, is observed, but the stronger $\Delta v = 0$ sequence with its longward head at 3883 Å can be used if spectrograms exposed in the near ultraviolet are available. When the CN absorption is strong, additional heads in both bands are observable; and Roman (1952), following Nassau and Morgan, employed the designation "λ4150 stars" to characterize those in which the dip in the spectrum due to the convergence of the 3–4, 4–5, 5–6, etc heads near that wavelength is conspicuous. For stars with apparently weak CN bands she used the designation "wk CN."

In order to subdivide these rather broad groups of stars, Keenan (1963) followed the spectral type and luminosity class with the symbol CN and a number running from 3 for stars with cyanogen bands much stronger than normal to -3 for stars with CN so weak that the bands were scarcely perceptible. When a star had the normal CN strength for its temperature and luminosity, no symbol was used. This scale and notation were used for the strong CN stars by Schmitt (1971) also.

Most observers who have made photometric measurements of the CN bands and metallic lines, either by photometry with filters or by spectrophotometry, have not usually given symbols to be added to the spectral types, but have presented their results in tables. The recent practice has been to give the parameter [M/H] (Spinrad & Taylor 1969) or [Fe/H] (Helfer 1969, Williams 1971a,b). The quantity tabulated under either of these headings is the derived logarithmic difference between the metal/hydrogen ratio in the given star and in the Sun, which is normally taken as the standard of reference. In the case of measurements of CN bands, the data tabulated are usually the CN absorption in the given star and the difference between this quantity and the mean absorption for a standard star of the same temperature and luminosity (Griffin & Redman 1960, Janes & McClure 1971, Yoss & Lutz 1971).

There is not always a one-to-one correspondence between the strengths of metallic lines and of CN bands, and as the number of variables increases we are faced with the fundamental question: Is it worthwhile to complicate the spectral types by adding symbols for these several composition parameters? We believe that it is often worth doing so, for two reasons:

1. Tabulated abundances involve some assumptions about atmospheric structures, and are not direct records of what can be observed. Even when clearly defined measures of specific features are given in a table, these data cannot be compared with some other observer's measures made in a different spectral region without going through a process of reductions which may not be straightforward.
2. Spectral types provide a short summary of the character of a star, and often are much more convenient than reference to a table which the reader or observer may not have available.

In assigning classification symbols we recognize the responsibility to keep them as simple as possible. To represent the strength of the common metallic lines we suggest the symbols L$-$2, L$-$1, L+1, L+2, etc. These will normally be used only for spectra in which CN is not strong enough to allow CN anomalies to be reliably observed at low dispersions (as in early G-type stars). For stars in which there is a discrepancy between the metallic lines and CN bands, both the CN and L symbols can be employed.

Another type of composition difference is displayed by the *barium* stars, in which the lines of heavy elements of the third and fourth periods are enhanced relative to those of the lighter elements Fe, Ti, Ca, etc. In the blue region these stars are normally recognized by the strengthening of Ba II 4554, and the symbols

Ba 1, Ba 2, etc, introduced by Warner (1965), serve to define the strength of the heavy elements in their spectra. We have added only the symbol Ba O for stars in which the Ba II enhancement is barely noticeable at about 80 Å/mm. These stars, several of which were first included among the barium stars by Williams (1971a), might be termed "semi-barium stars," for abundance analyses by various authors have not been in agreement as to how much, if at all, the heavy elements are overabundant in their atmospheres. Since the lines of an ionized element, such as Ba II, tend to strengthen as the luminosity increases, it is difficult to distinguish that pressure effect from a real abundance effect in bright giants and supergiants. The only semibarium star included in Table 2 is o Vir, G8 III Ba O.

Conversely, in any Ba star, both the lines of Sr II and the bands of CN are also enhanced much as they would be in a star of considerably higher luminosity. This makes classification difficult, for the only criteria remaining valid for the assignment of luminosity classes are those, such as the ratio Fe 4376/Fe 4383, which involve mainly the comparison of intersystem lines from the lowest level of iron with normal permitted lines. We do not feel that the problems of classification of such stars have been completely solved, and suspect similar difficulties in most photometric classification systems.

Even in the strong-CN and weak-CN stars, where Sr II seems to behave normally, luminosity estimates have often been influenced by the appearance of the cyanogen bands.

Since further work needs to be done on all of these groups of stars, only a few of the best-known members have been included in Table 2 in order to provide illustrations of the way in which the notation is expanded to take account of the composition effects.

The two groups of banded spectra of different composition, the carbon and the S-type stars, have been omitted from this review for lack of space.

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