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REVISED MK SPECTRAL ATLAS FOR STARS EARLIER THAN THE SUN

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1. INTRODUCTION

Terminology: MK Diagram: The two-dimensional diagram relating MK spectral type and luminosity class.

The present Atlas was prepared to satisfy three requirements: (1) To furnish an improved version of the out-of-print **Atlas of Stellar Spectra** by Morgan, Keenan, and Kellman (University of Chicago Press, 1943) for stars earlier than the Sun; it thus complements the Keenan-McNeil Atlas for the stars of later type. (2) To decrease the classification "noise"; for the sake of determining spectral types and luminosity classes as precisely as possible from plates of relatively low dispersion. (3) By means of (2), to demonstrate how rich the prospects can be for classification in the future, by making use of conceptual improvements developed here, and incorporating them in what we describe as the MK-78 system. These processes, when taken together, will have the result of introducing a finer structure over that part of the MK Diagram occupied by stars earlier than the Sun.

The process described under (3) brings us to a major characteristic of the present Atlas: it is by no means a definitive work. In the early stages of its preparation there was a feeling that it might furnish all that needed to be said about its field for an indefinite period -- or even forever. As the work of preparing the Atlas plates progressed, however, it became clear that the field was being opened up increasingly to new fine structure in the MK Diagram, and to new localized third dimensions. These developments now indicate convincingly that there can be no such thing as a "definitive" spectral atlas - so long as a body of unrecognized, and uninvestigated, specimens exists in the observable region of the universe.

When we label the revised system defined by this Atlas as the MK-78 system, we are taking a step that requires further comment. The earlier MK "domain" has been the spectral region Hβ-Ca II K; here, we extend the spectral range used to the neighborhood of λ 3500 in the cases of certain categories of stars. The Atlas plates show the spectral range used, by the features marked. This increase in spectral range has been possible because of the remarkable quality of the low-dispersion spectrographs designed by a great astronomical instrumentalist, Dr. A. B. Meinel, the first director of the Kitt Peak National Observatory. These spectrographs were installed on several of the smaller reflectors at Kitt Peak and at the Cerro Tololo Inter-American Observatory, and were used by Dr. Abt to obtain all of the spectrograms of lower dispersion illustrated here. Such spectrograms, having dispersions in the range 63 A/mm-125 A/mm, when greatly widened, represent an almost ideal compromise between the factors of differing line-widths due to stellar rotation and the line visibility necessary for accurate spectral classification.

2. THE REALM OF THE SPECIMENS

The basic framework of the MK Diagram has changed little between the 1943 MKK Atlas and the present one; in each case, we have a field defined by a certain number of standard stars - an autonomous, self-consistent field that requires no measures of any kind to establish its validity in use. In the earlier atlas, the procedure was generally followed of defining each box by the means of several stars that had been classified in it. Since these stars are not identical in spectral characteristics, such a procedure introduces a certain amount of noise in the definition of the box. In the present Atlas, we have adopted the procedure of defining each box by a single star; this procedure permits a higher order of discrimination than does the use of multiple standards for each box.

Let us consider the situation where we have obtained classification spectrograms for a number of unclassified specimens. With a single standard for each classification box, we find that we are able to classify more precisely than with multiple standards - both in the two-dimensional MK plane, and in the localized third dimensions discussed below. This is true because the single most important characteristic of the Revised MK Diagram is: **Each box is defined by the patterns and intensities of spectral lines, bands and blends which exist in the spectrum of the standard star. The fundamental standard stars have been observed in a limited spectral range; but this principle holds for any spectral interval observed** - as far as the MK system itself is concerned. It may develop later that a standard is found to show peculiarities in some spectral region, (x), other than the standard one. In such cases, the unsatisfactory standard in spectral region (x) can be classified in terms of other stars classified in the same spectral region which give self-consistent types in that region.

The convention of assumed constant spectral type for standards in all spectral wavelengths is the pivot on which the entire MK-78 system rests. It makes possible the precise localized definition of the MK plane in a manner that approaches the practicable limit in accuracy, and at the same time provides a method for re-classifying fundamental standards that show peculiarities in some wavelengths other than the standard spectral range. So, by this approach, we are able to consider the unobserved realm of specimens as candidates for precise classification by means of the MK boxes, through a simple, visual confrontation between the "unknown" specimen and the fundamental standards nearest to it in appearance - this confrontation to be made by use of spectrograms obtained with the same spectrograph, the same camera, the same photographic emulsion, and the same processing in development. And, in this confrontation, we use the language of lines, bands and blends - **not** the language of stellar atmospheres - this last being a separate process, to be carried out later.

3. THE NATURE OF THE THIRD DIMENSION

Some time ago it appeared that a general third dimension might be applicable to the whole MK Diagram; this would have been a dimension depending on line intensity, such as the weak metallic-line stars in classes F - G. In the case of these weaker-lined stars, such a procedure is possible (but has not yet been carried out satisfactorily); however, it does not seem practicable for O and B stars - and probably not for the A stars. In place of a line-intensity parameter, we find categories of spectra which show various peculiarities and cannot be classified satisfactorily in the ordinary two dimensions. And so it is necessary to develop sharply localized third dimensions for such categories; examples are illustrated in the present Atlas. Some of these localized third dimensions are extremely small when projected on the MK plane (the MK - Hg stars), while others are found over a considerable range in spectral type (Sr II stars).

4. THE SUI GENERIS STANDARDS

The nature of the fundamental standards that define the MK-78 system requires further comment; for this purpose we introduce the concept of the sui generis (literally: of its own kind) object. This can be described by the example of P Cygni (Plate 9). Here we have a complex emission and absorption line spectrum (the stellar radial velocity represented by the emission lines, approximately) and the absorption lines originating in a dense expanding shell. Now the members of the P Cygni class of stellar spectra resemble the prototype in some respects; but it seems unlikely that any member of this class will be found to have identical spectral characteristics with P Cygni itself. In addition, the spectrum of the latter varies with time; so that in this case we have the complication of intrinsic variations in the prototype spectrum. If we wished to go to the possible limit of discrimination in the use of such a standard, we would have to specify the date of the standard spectrograms being used. Here we have an obvious case of unsuitability for use as a standard - so long as we wish to make use of all features for classification; but, in spite of this, we can say that P Cygni is a sui generis object.

The situation is much more favorable in the case of the normal standards illustrated in this Atlas; there can be variations with time in the appearance of Hα in the Ia supergiants of early type, but the other lines in these objects are fairly constant in appearance; in the case of the other fundamental standards of normal stars there is not likely to be difficulty from variable features. And so, when we apply the label sui generis to these stars we are emphasizing the fixed nature of the standards defining the boxes in the MK Diagram.

5. THE DEGREE OF INCOMPLETENESS OF THE MAT ATLAS MORPHOLOGY

There are three areas of incompleteness in the present Atlas: (1) All stars illustrated in the Atlas are of Population I with the exception of HD 22879 (Plate 31), which is of Population II; two other stars, 31 Com (Plate 32) and *v* Peg (Plate 30) are intermediate between Population I and extreme Population II; it can be seen, therefore, that the Atlas deals effectively only with the classification of Population I stars. (2) Many of the boxes of the MK Diagram do not contain defining standard stars, and the local third dimensions are incompletely identified - or not yet even suggested. (3) The problem of illustrating the standard stars in other wavelength regions remains a major task for the future. In addition to these omissions, some of the standard stars adopted can only be observed in one hemisphere. We regret this, and hope to be able to furnish a more nearly complete list of standards at a later time.

In the light of this incompleteness, it should be emphasized that the present Atlas is in effect a report on work in progress; it develops a methodology of power and stability, and gives numerous examples of its use in spectral classification. We can look forward to a time in the future when three necessary steps have been taken. (1) To develop a unitary spectral classification for Population II stars. (2) To populate as many as possible of the boxes of the MK Diagram with a defining star. (3) To carry as far as justified the splitting of boxes (as the A0 V box has been split in Plate 18), for the sake of determining more precise luminosities and distances - and for adding the greatest amount of justified detail to the MK Diagram.

6. SPECTRAL CLASSIFICATION IN GLOBULAR CLUSTERS AND IN GALAXIES

It can be seen from the preceding section that the present Atlas is not adequate to deal with the classification of stellar populations like globular clusters and the Galactic halo population. It is also not suited to precise classification of stars in extragalactic systems which are at differing evolutionary stages from our own Galaxy. In the general case of classification of stars in other galaxies, the most crucial requirement is to retain as much particular information as possible. To guarantee this, we should not take for granted **any** similarities with stars in the solar neighborhood, and should: (1) Create a new, self-consistent classification from the stellar spectra available in each object, using a notation completely different from that of the MK system; (2) when this is finished, we should confront the resulting classifications with the MK classifications as illustrated in the present Atlas; (3) from this confrontation, we should then assess the differences and similarities between the stars in the other galaxy and those in our own. The above procedure can be used only if a considerable number of stars have been observed in the particular galaxy; when only small numbers of spectrograms are available, they must be referred to the MK standards, and their similarities and differences noted.

7. A NOTE ON CLASSIFICATION IN THE SATELLITE ULTRAVIOLET

A classical example of the approach to spectral classification in any new spectral region is furnished by Bidelman's recent paper on spectral classification from Copernicus ultraviolet data (**Highlights of Astronomy, Vol. 4, Part II,** 355-359, 1977). The approach described by Bidelman is a model for a procedure that guarantees preservation of the maximum justified information - and for a careful, descriptive comparison with spectral types from the normal MK spectral region.

8. CONCLUSION

We present herewith a revised structure for the classification of stars earlier than the Sun. The structure has greater precision than that of the MKK Atlas of 1943, partly because of the use of single standard-stars to define each classification box. There are still important problems awaiting attention: (1) The classification of very broad-lined early-type stars is intrinsically less exact than that of the narrower-lined objects; what is needed here is a frame of reference consisting entirely of very broad-lined stars, with this frame fitted to the standard MK-78 boxes by the use of low-dispersion (~ 150 A/mm), fine-grain, high-contrast spectrograms, which would minimize differences in appearance between n and s stars. (2) The MAT Atlas is applicable only to Population I stars; still needed is a general classification that would include Population II stars. (3) The calibration of the MK Diagram for the determination of physical parameters will have to await classification of large numbers of stars on the MK-78 system.

One of us (W.W.M.) wishes to make the following acknowledgments: for the support of a series of grants from the National Science Foundation, which made possible both the preparatory work and the publication of the Atlas: for discussions with Dr.

Lewis M. Hobbs and with Dr. Dimitri Mihalas concerning the new Atlas; to Dr. Martin F. McCarthy, S.J. for a remarkable formulation of the conceptual structure underlying the present Atlas; to Constance Siebert for continuing help.

We wish to acknowledge here the outstanding quality of the printing of the thirty-two Atlas plates carried out by Tru Line Lithographing, Inc. of Sturtevant, Wisconsin. A careful comparison of the printed plates with the original photographic prints establishes the remarkable faithfulness with which the latter have been reproduced. The portfolios were constructed by Troy Plastics Corp. of Burlington, Wisconsin.

NOTES ON ATLAS PLATES

The dispersion of all spectrograms illustrated is ~ 125 A/mm, unless otherwise noted.

Plate 1. **Main Sequence O4-O9**

We may obtain spectral types earlier than O4-O5 by discovering stellar spectra showing a higher level of excitation than the stars of similar luminosity which are MK standards at O4-O5: we may also obtain earlier types by expanding the scale of classification for the O stars by moving the MK standards toward earlier types. The first procedure is clear; the second tends to distort the scale of the MK system.

An important problem for the future is the **spectrographic** identification of the ZAMS for the O7-B2 stars. The brightest members of the Orion Nebula cluster show abnormally broad absorption wings for the Balmer series of H (see **Ann. Rev. Astronomy and Astrophysics, Vol. 11**, Illustration on page 35, 1973). This phenomenon is not shown by the main-sequence stars illustrated in Plate 1. A question to be answered is: Are the luminosities of the stars in Plate 1 higher than those of similar spectral type in the Orion Nebula cluster (the Trapezium cluster)?

Plate 2. **The O5-O6 Supergiants and Two He I 3888 Wolf-Rayet Stars**

The scale of the print of ξ Pup is somewhat more extended in the ultraviolet near N IV 3479-85; the position of this absorption feature actually matches that of the same line in λ Cep.

An interesting point is raised with regard to the strong violet-shifted He I 3888 absorption in the two WN stars: Are these He I 3888 components found in similar strength and velocity in the WC stars?

Plate 3. **Luminosity Effects at O6**

Especial care must be taken in the use of N IV 3479-85 (absorption) as a luminosity criterion at O6. This feature comes to a maximum in main-sequence stars at O4 V (see Plate 1); at this type, it is of similar strength to that in the O6 If standard. It is crucial to the use of this feature that there be no systematic shift in the relative positions of the standard If and class V sequences.

The use of the Botto-Hack criterion for the determination of luminosity classes for the O stars depends sensitively on the dispersion and width of the spectrograms used.

Plate 4. **Main Sequence O9-B3**

The supression of the higher members of the diffuse triplets of He I which lie over the Balmer continuum is probably already present at B2 V. The effect is very pronounced at type B3 V.

Plate 7. **Three O8-B0 Supergiants**
The concluding sentence of the legend should read: ".... we consider the ratio O II : O III to be the fundamental discriminant for spectral type for O9-B0 supergiants."

Plate 11. **Luminosity Effects at B2**

The relationship of the Orion "helium stars" to the ZAMS is an interesting problem. In δ Ori (ft) the He I sharp triplet at λ 4121 is much narrower than the He I diffuse singlets at λ 4009 and 4144. He I 4121 is similar in width in the B2 V standard β Sco (ft) and in δ Ori (ft), but the diffuse singlets and triplets are considerably narrower in the former. Can this be considered as indicating a lower spectroscopic luminosity for δ Ori (ft) than for β Sco (ft)?

Plate 12. **Strong Helium Stars in the Orion Association**

It is possible that the weakening of the higher members of the diffuse triplets in δ Ori (ft), as compared to HR 1890, can be explained in terms of the sudden decrease in intensity of these lines on passing from B2 V to B3 V (see Plate 4). There is some evidence that δ Ori (ft) is very slightly later in spectral type than HR 1890 (~ B2.5 Vh).

Plate 17. **Five B7 III-B9 III Stars**

The discriminating characteristic for these five stars is the presence in each spectrum of very broad lines of He I, coupled with a much narrower stellar Ca II K-line. The hydrogen lines, in each case, indicate a luminosity class of III; that is, the stars are giants, definitely evolved stars, of the order of 1 1/2 magnitudes above the ZAMS at the spectral type at which they have been classified here. L.M. Hobbs has established that the stellar K-lines in the first four stars do not contain any substantial interstellar contribution, by use of an echelle grating spectrograph giving a dispersion of 0.59 A/mm, attached to the 2.7 m reflector of the McDonald Observatory (**P.A.S.P., 90,** 301, 1978).

Each of the first four stars is well-suited to act as a fundamental standard: β Tau as MK-78 standard for B7 III; 20 Tau as standard for a B7 giant which shows abnormally strong Fe II lines, together with the narrow K, broad He I characteristic; α Scl as a spectacular example of the presence of disparate features like strong C II 4267, Fe II, and probably faint Sr II - together with the sharp K, diffuse He I characteristic; μ Lep as one of the classical mercury-manganese stars with the same K, He I appearance.

The principal standard used in the classification of 20 Tau and a Scl was β Tau. In the case of 20 Tau, the comparison with β Tau is close, except for a slight weakening in the He I lines and strengthening in the Fe II lines in the former. The comparison of β Tau with α Scl is also good, except for the well-known enhancement of C II 4267 and strengthening of Fe II in α Scl, and a definite weakening of the Balmer lines in the latter.

The spectrum of μ Lep resembles closely that of a number of the Hg-Mn stars; in particular, we find that the narrow K, diffuse He I structure is present in α And and κ Cnc, both of which are classical members of the mercury-manganese group.

Plate 18. **Luminosity Effects at A0**

The high optical quality of the low-dispersion spectrographs designed by A.B. Meinel makes practicable extremely sensitive discrimination of the extent of the wings of the Balmer lines for stars in the neighborhood of class A0. This has made possible the splitting of MK box A0 V into two: A0 Va and A0 Vb. Stars of the former class turn out to be, in general, main-sequence non-cluster stars (such as the fundamental standard α Lyrae) and main-sequence stars in evolved clusters. Spectral type A0 Vb exhibits markedly broader wings on the H lines, for stars of similar rotational line-broadening; examples are found among clusters having main-sequence turn-offs at B3 and earlier. The star NGC 2516 #29 is located at the extreme edge of the cluster, and does not seem to be a cluster member, since its cluster luminosity would be M_V ~ 0; the spectrum does not resemble that of a white dwarf, since many members of the Balmer series are observed. Its true nature remains to be determined.

It appears feasible at the present time to split spectral types B9 V and B9.5 V into luminosity classes Va and Vb. The star HD 19805 (HL 167 in the α Per cluster) is a good candidate for the standard B9.5 Vb; it is illustrated on Plate 13, as of type B9.5 V.

Plate 20. **Three Ap Stars**

The discovery by Babcock that HR 2534 is a very rapid spectrum variable (pronounced changes in 24 hours) makes it of importance to obtain a series of low dispersion spectrograms for investigating the behavior of the line patterns with the spectral variations. If these line patterns show great changes in appearance, it may be possible to discover other examples of this uniquely interesting star from low-dispersion plates - or even with objective prism cameras.

Plate 22. **17 Lep: An A-Type Shell Star**

The exceedingly strong shell absorptions of Ti II at $\lambda\ \lambda$ 3685 and 3759-61 in 17 Lep are from the lower level a^2F, which is metastable and has an E P of 0.6 volt.

These same absorptions have been observed as shell lines in rapidly rotating A stars by Abt and Moyd (**Ap. J., 182,** 814, 1973).

Plate 23. **Two Diffuse K-Line A-Stars**

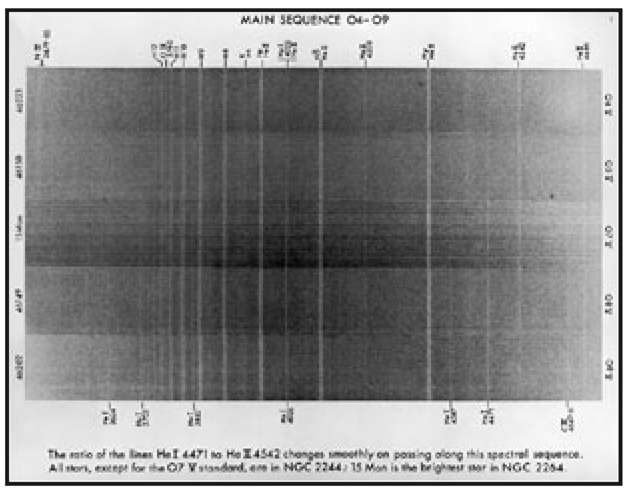
HR. 4369 = HD 98088 is a spectroscopic binary whose orbit was determined by Abt. It is also a magnetic variable (Babcock: **Ap. J. Suppl., 30,** 1958). Abt et al. (**Ap. J., 153,** 177, 1968) have measured the radial velocity of the secondary; the authors state that "... a secondary component of the K-line can be found", but only measured Hα and the D-lines. The authors reject a value of ΔM_V of 0.5 mag. because secondary components would have been observed for many more lines with such a small difference in brightness between the two stars. They adopt a ΔM_V of 1.2 mag. and derive a type of A8.5 V for the secondary.

The width of the wide, shallow K-line in HR 4369 is equal to - or greater than - that in the F0 III standard ξ Leo. If this strong line were identifiable with the spectrum of the secondary star, it seems likely that many secondary components of strong neutral metals would also have been observed. For this reason, we feel that the diffuse K-line in HR 4369 is probably similar in nature to that observed in so many Sr II stars.

Note on the Spectrum of α Scl

The announcement of a Scl as a member of the peculiar manganese group by Morgan (**Ap. J., 73,** 109, 1931) was an error, and is withdrawn herewith.

Plate 1



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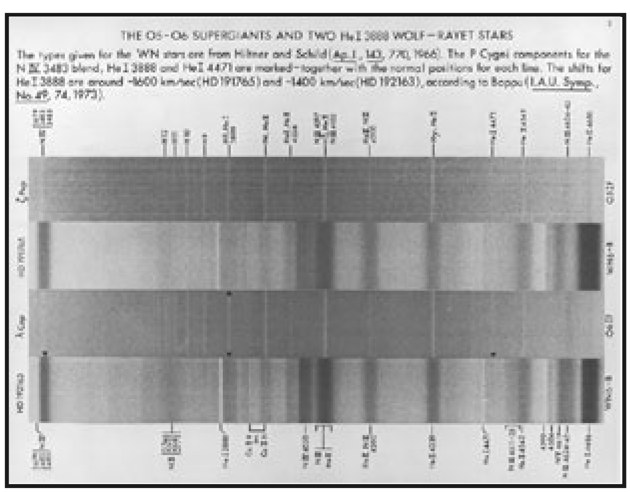

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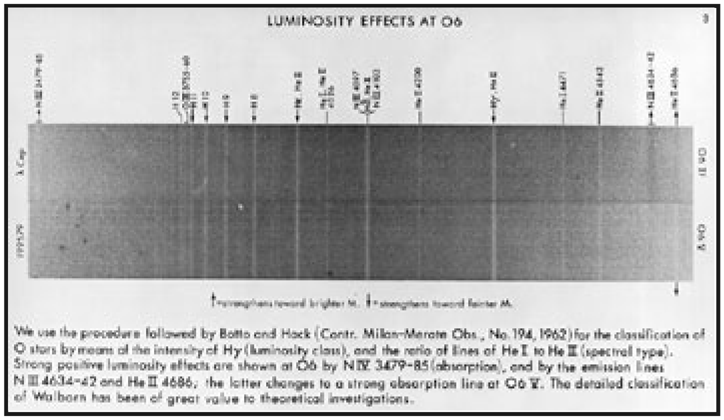

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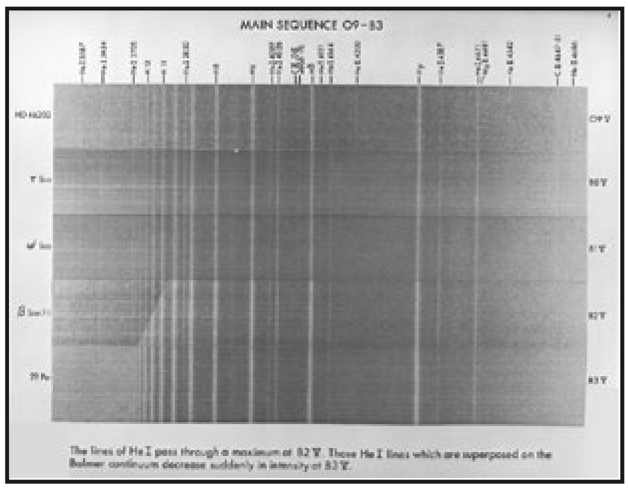

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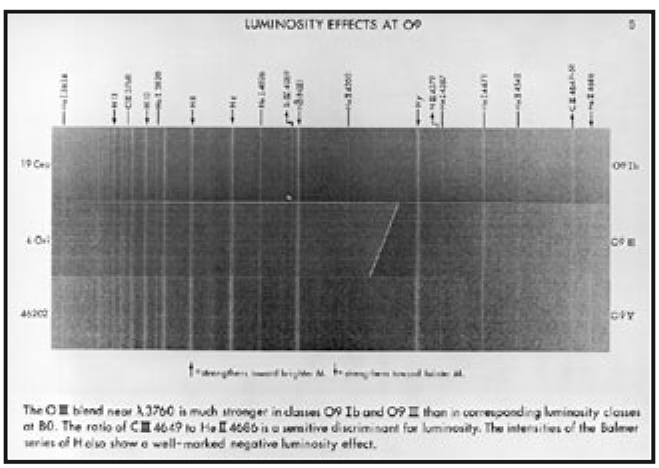

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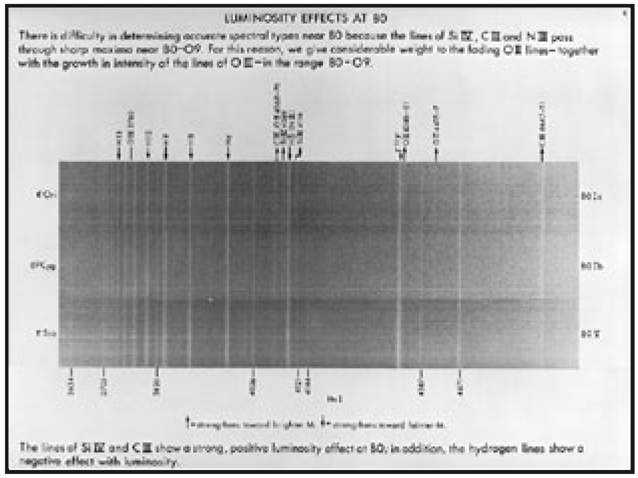

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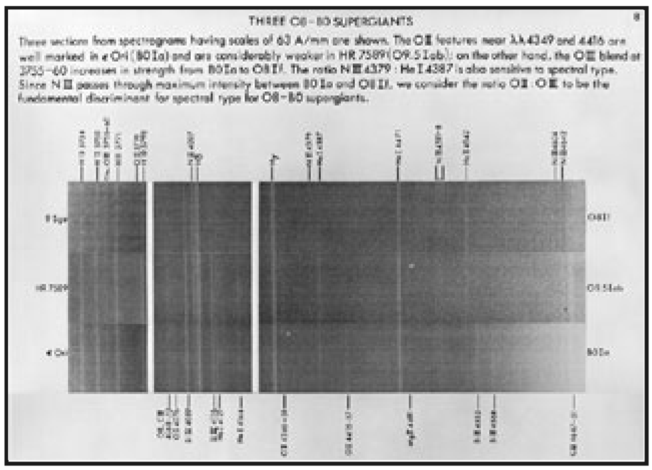

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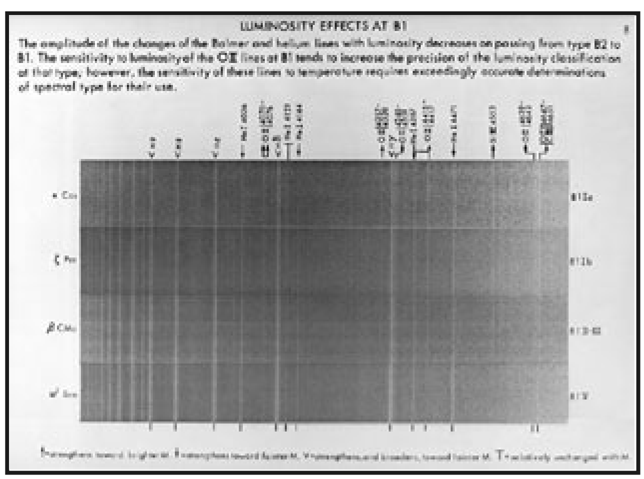

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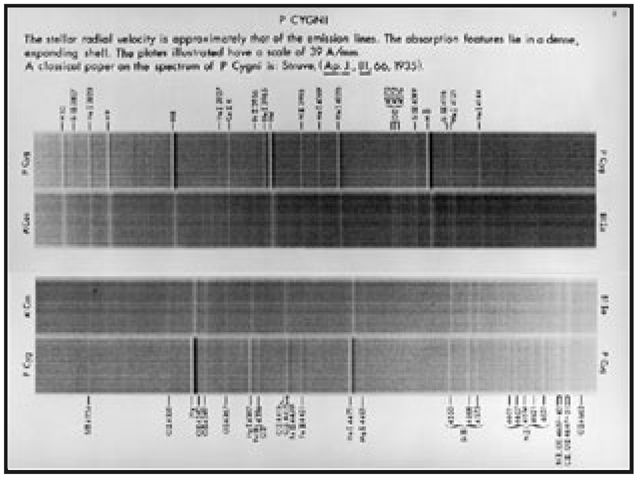

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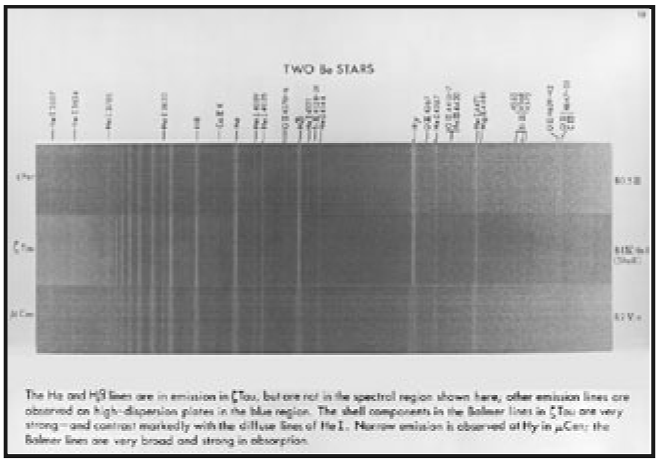

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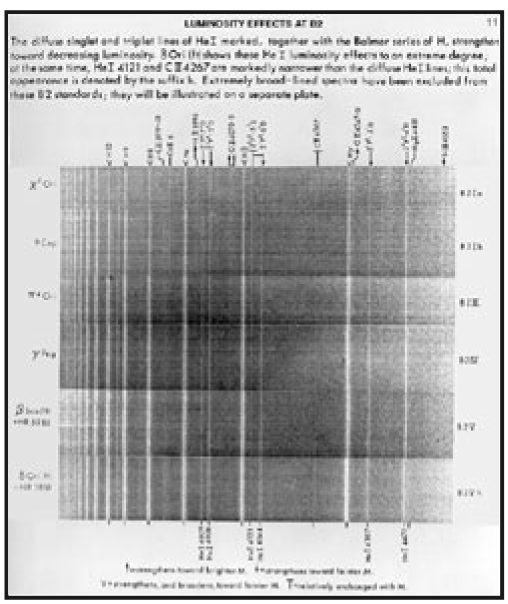

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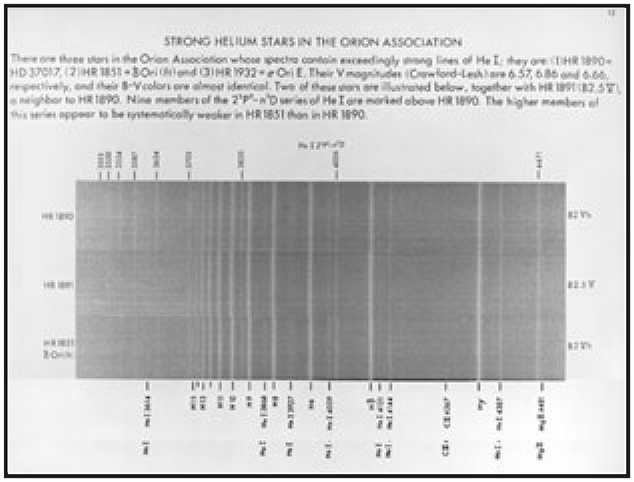

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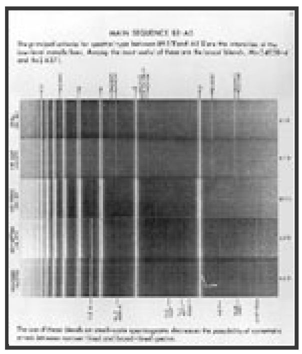

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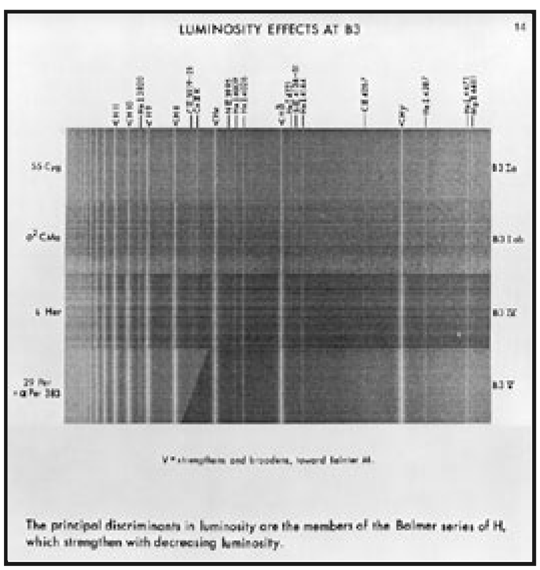

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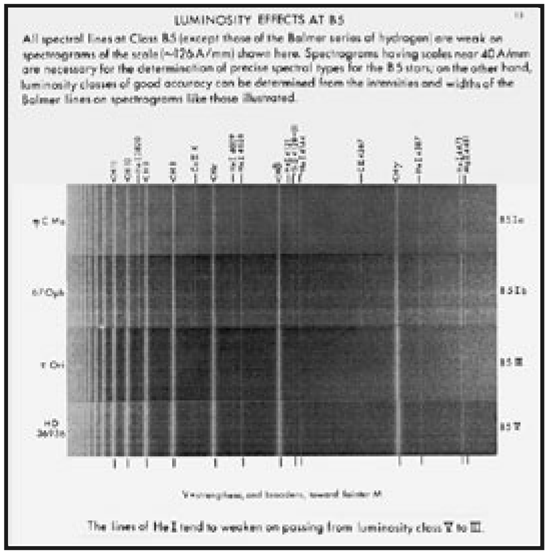

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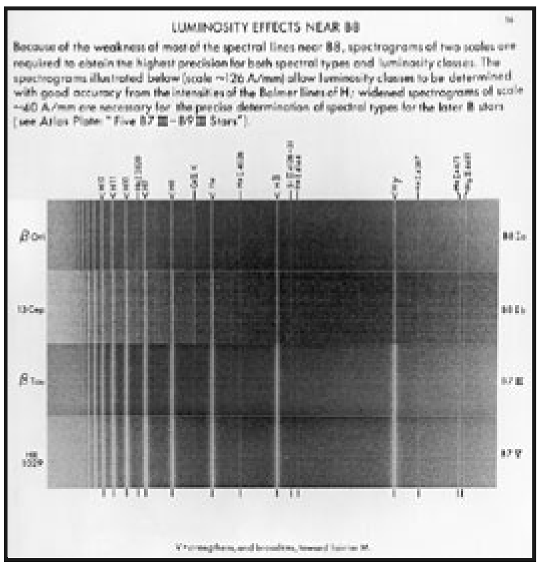

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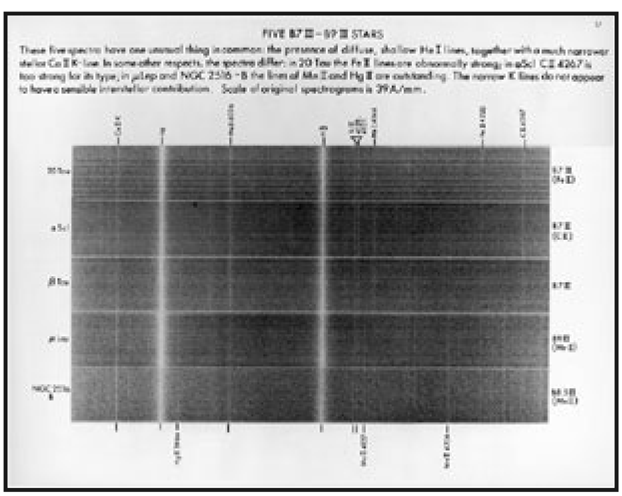

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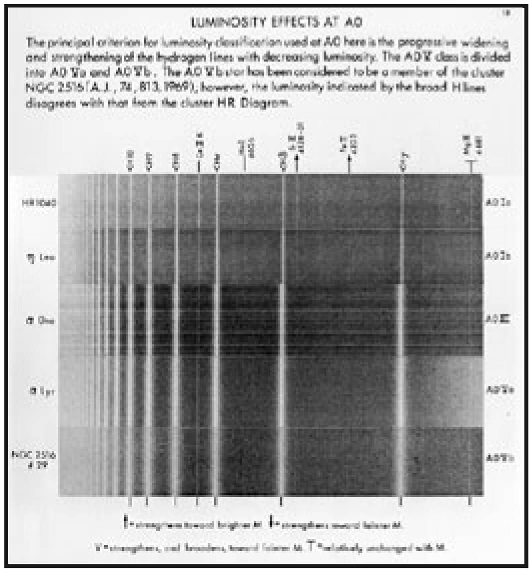

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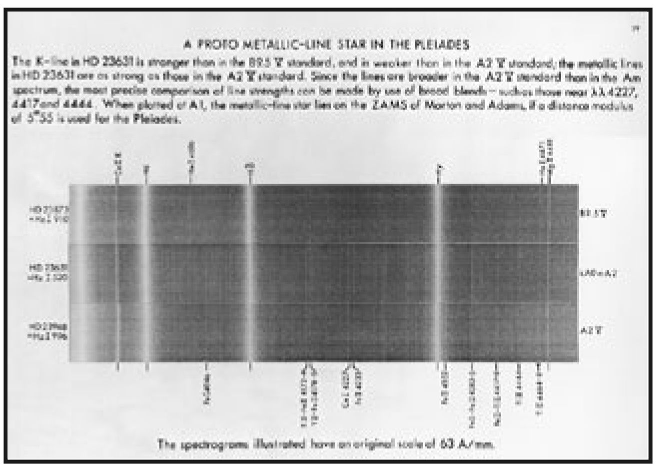

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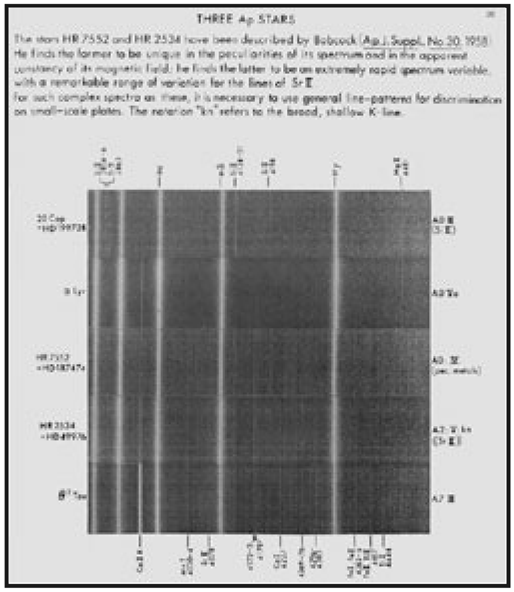

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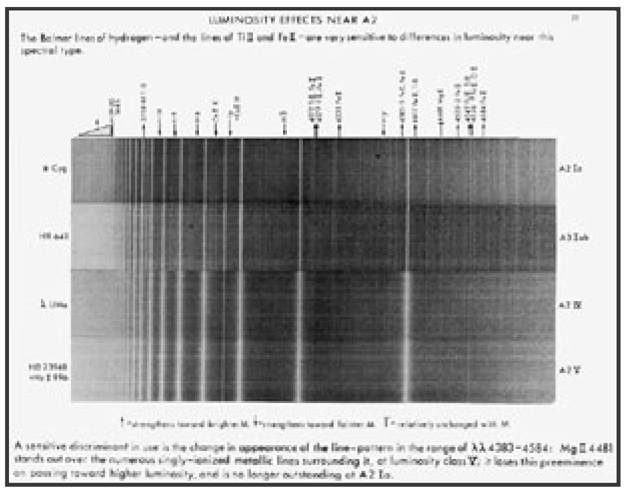

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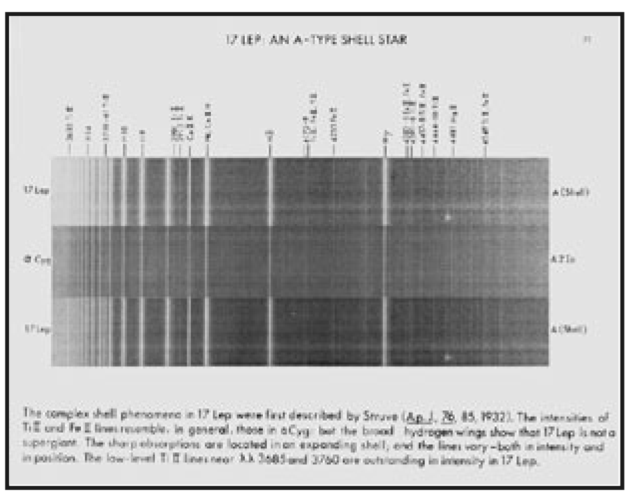

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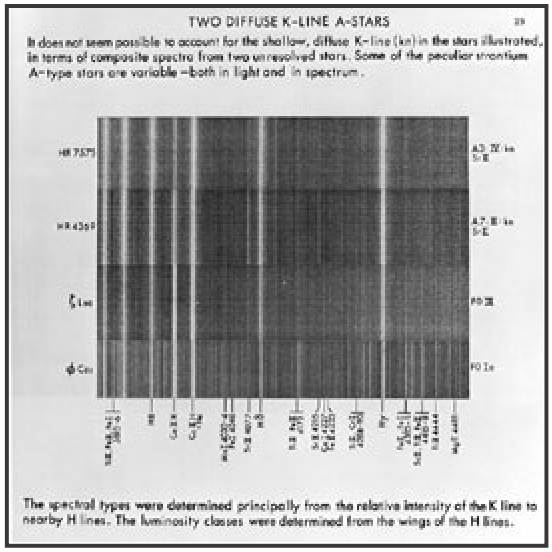

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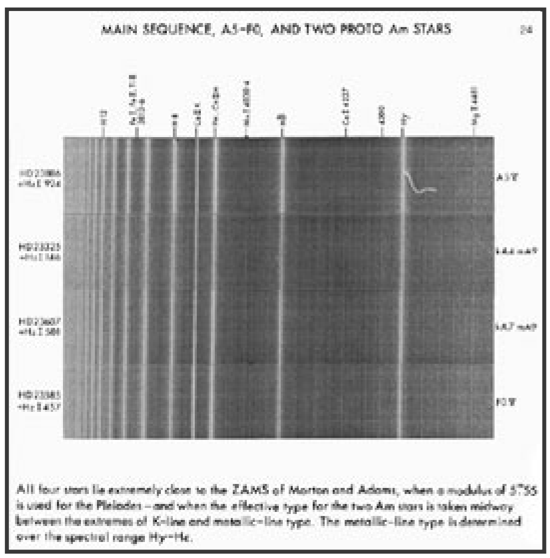

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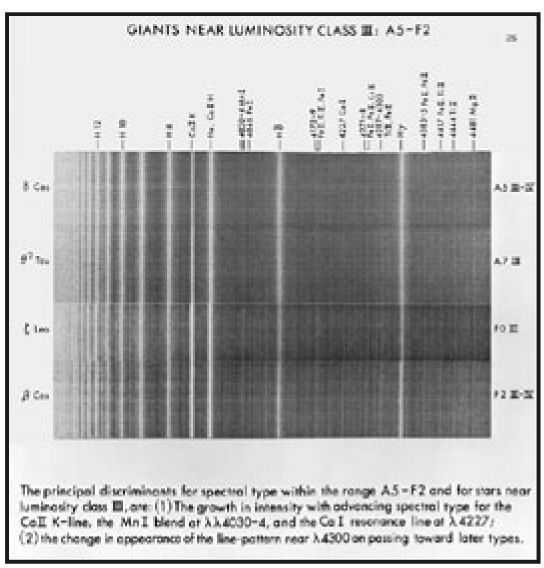

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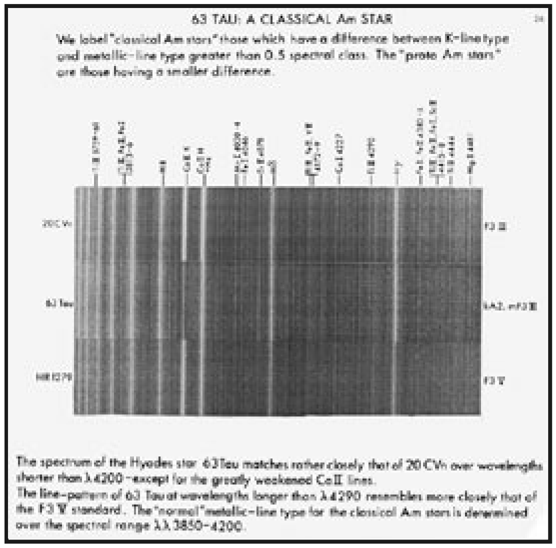

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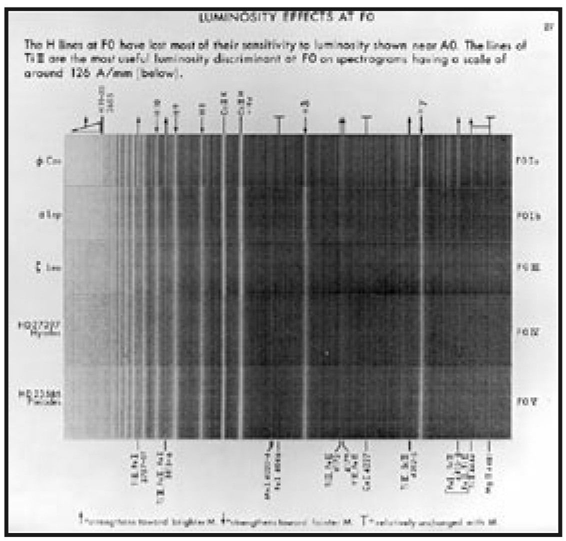


Plate 28

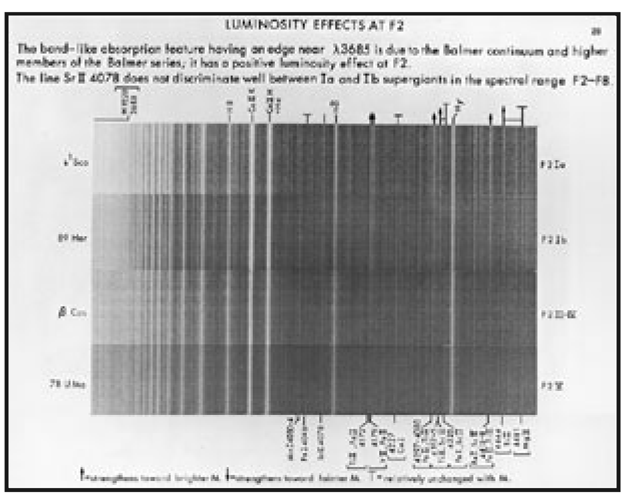


Plate 29

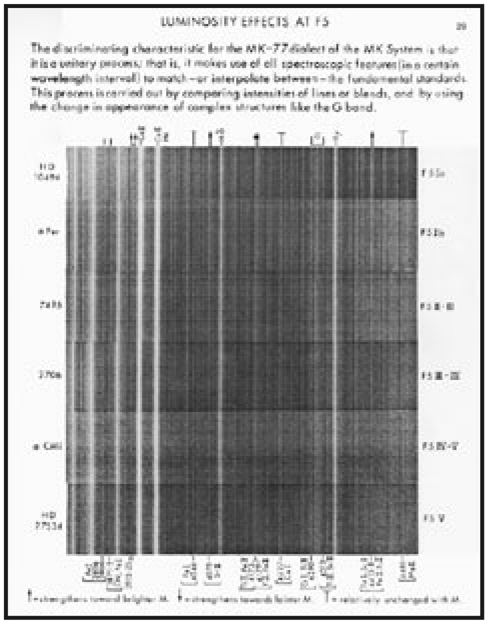


Plate 30

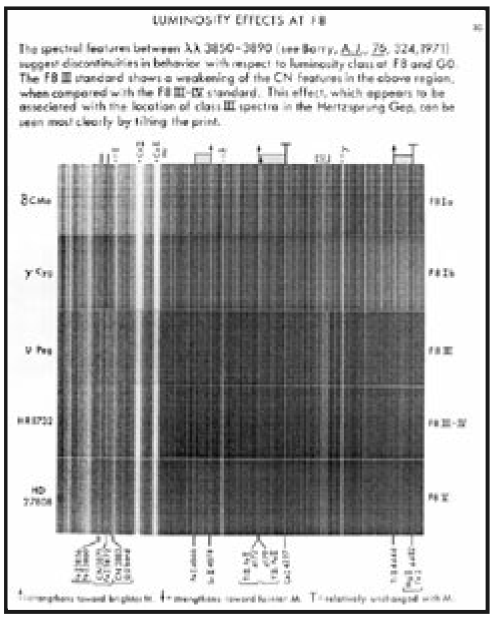


Plate 31

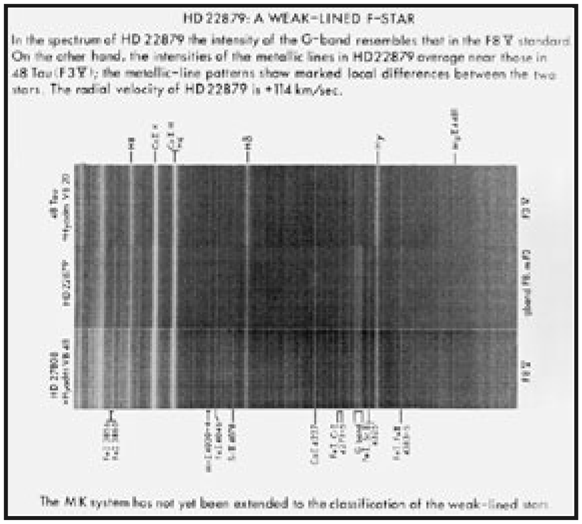
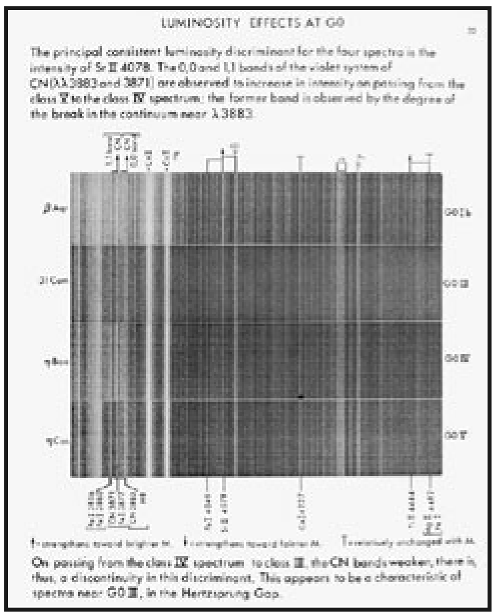

HD 22879: A WEAK-LINED F-STAR
In the spectrum of HD 22879 the intensity of the G-band resembles that in the F8 V standard. On the other hand, the intensities of the metallic lines in HD22879 average near those in 48 Tau (F3 V); the metallic-line patterns show marked local differences between the two stars. The radial velocity of HD 22879 is +114 km/sec.
48 Tau
HD 22879
HD 27808
F3 V
F8 V
The MK system has not yet been extended to the classification of the weak-lined stars

Plate 32


LUMINOSITY EFFECTS AT G0
The principal consistent luminosity discriminant for the four spectra is the intensity of Sr II 4078. The 0,0 and 1,1 bands of the violet system of CN (λλ 3883 and 3871) are observed to increase in intensity on passing from the class V to the class IV spectrum; the former band is observed by the degree of the break in the continuum near λ 3883.
β Aqr
31 Com
η Boo
η Cas
G0 Ib
G0 III
G0 IV
G0 V
On passing from the class IV spectrum to class III, the CN bands weaken; there is, thus, a discontinuity in this discriminant. This appears to be a characteristic of spectra near G0 III, in the Hertzsprung Gap.