ON THE PRACTICAL APPLICATION OF THE MK AND RELATED SPECTRAL-CLASSIFICATION SYSTEMS TO SPECTROGRAMS OF VARIOUS RESOLUTIONS

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ABSTRACT

For MK classification of program field stars the "normal" observer is confronted with a number of practical problems, rendering classification on the true MK system very difficult. These problems concern completeness of standard-star grid, spectrogram resolution, comparison of originals-reproductions, spectrogram density levels, spectrogram widening and emulsion. A new atlas of slit spectrograms at 74 Å mm^{-1} is presented, giving good coverage especially for high-luminosity stars. MK classification from spectral intensity tracings is discussed. Advantages include easy distribution and sharing of standards, relaxation of resolution requirements and wide acceptable density range. Apparent shortcomings of the method seem easy to overcome. An atlas of spectral intensity tracings is presented. Some problems regarding objective-prism classification are discussed for higher as well as lower resolution. Quantitative classification methods are commented. Work in progress is presented on systems for two-dimensional classification of low-resolution objective-prism spectrograms of stars with spectral types earlier than G0.

1. INTRODUCTION

Small doubt can remain today concerning the fundamental importance of the MK system for spectral classification. Regarding the visual inspection of spectrograms practically all work done presently is either presented directly in MK terminology or is made available in systems calibrated in terms of "classification boxes" in the MK frame of reference. Classification systems based on photometric measurements may and should of course be calibrated more or less directly in

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terms of luminosity and intrinsic color through use of trigonometric parallaxes, double stars, clusters, etc. However, in practice a correlation with the MK system is nearly always made, either as a matter of necessity or in order to improve the value and usefulness of the results deduced. In any case, such a correlation is a most essential requirement for a sound interpretation of photometric data, as ever so accurate photometric measurements may in practice never be able to resolve the finer features distinguishable through proper use of MK-classification spectrograms.

2. PROBLEMS AFFECTING MK CLASSIFICATION OF FIELD STARS

The classification in the MK system of program field stars is met with a multitude of often rather subtle problems. Many of these have been touched upon during the present colloquium and many more exist. As we have also heard these days, impressive efforts have been and are currently being taken in order to resolve such problems by means of various refinements in the framework of the MK system. However, only a few, very experienced astronomers can, as a matter of fact, be said to classify on the true MK system, and, even more important, only some very few departments have access to the instruments and the spectrogram files necessary to transform the observational data into the true MK system.

Let me mention briefly some of the most current and annoying obstacles preventing a "normal" observer from arriving at optimum or near-optimum results of his or her spectral classification intended to be on the MK system. Unfortunately, these difficulties, although of major importance to most classification data, are only occasionally touched upon.

Firstly, there is the problem of adequate sets of standards. Ideally, the classification of program stars should be made through comparisons with spectrograms of fundamental standard stars, obtained with the same equipment and under the same observing conditions as those of the program stars. This is in practice a hard requirement even for observing programs concerned with limited domains in the MK system, not to speak about work in clusters, associations, etc., where one is met with stars, the spectral types of which are spread over a considerable range in temperature as well as in luminosity. Not only does the typical observer then normally work at an unfavorable latitude and in an inadequate hour-angle interval. Added to this, he or she is as a rule simply time-limited from obtaining even a basic grid of standard-star spectrograms. Certainly, this is a situation far from ideal but we all know that it is a rather frequent state of affairs.

Secondly, our observer has to face the problem of an observing-system dispersion or resolution deviating more or less markedly from that of available sets of standard-star spectrograms. In the absence of spectrograms of MK standards taken with the observing equipment, reference has to be made to existing sets of such spectrograms. For a long time the only set available was the MKK atlas (Morgan *et al.* 1943) and the list of standard stars given by Johnson and Morgan (1953), the work being based on spectrograms with a prismatic dispersion of 125 Å mm^{-1} at $H\gamma$. Most modern spectrographs in use give spectrograms far from this. First of all, the dispersion of light is normally achieved through a grating. Further, the growing interest in stellar radial velocities has strongly tended to push the dispersions chosen up to values well beyond 100 Å mm^{-1}, or with resolutions notably better than 2 Å. A typical compromise between radial-velocity feasabilities and exposure-time economy results in a dispersion around 80 Å mm^{-1}. This gives spectrograms which are, unfortunately, widely different from those defining the genuine MK system. The resulting difference in resolution may well cause considerable systematic classification effects in the absence of proper standards, as was also mentioned by Garrison (1978). Some time ago the situation was partly alleviated through the publication of the atlas of grating stellar spectra by Abt et al. (1968) and later through the appearance of the *Atlas of Spectra of the Cooler Stars* by Keenan and McNeil (1976). However, the classification grid presented by the Abt *et al.* atlas is considerably less fine than that given by the MKK atlas. Further, also in this case the dispersion was rather low, 128 Å mm^{-1}. For stars with spectral types G and later one is considerably better off having access to the Keenan-McNeil atlas, based on grating spectrograms with dispersions of 75-85 Å mm^{-1}. Recently, Landi *et al.* (1977) have made an important contribution to stellar classification through the publication of an atlas of grating stellar spectra at a dispersion of 42 Å mm^{-1}. Again however, resolution troubles are present. Especially for stars of intermediate and late spectral types the difference in resolution between the Landi *et al.* (1977) atlas on one side and the MKK and Abt *et al.* (1968) atlases on the other side is large enough to make classification criteria rather incompatible. The completion and publication of the Morgan, Abt and Tapscott atlas (Abt 1978) will in the near future ensure a very essential advancement in the status of MK standard-star data. As the dispersion of the spectrograms utilized for this atlas is 125 Å mm^{-1}, our observer, with spectrograms of typically 80 Å mm^{-1}, is still in trouble.

As a third obstacle for the intended MK classification there is the fact that even if we disregard the resolution differences between the observing systems and the true MK system, in a comparison with this system, use has to be made of standard-spectrogram reproductions.

In principle one could then reproduce the program spectrograms to gain in compatibility. In practice however, the resulting possible (probable!) loss of information content is prohibitive. Thus, our observer ends up comparing his or her own originals to standard-star spectrogram reproductions. This is far from ideal.

As a fourth obstacle, the insufficient compatibility between spectrograms of program and standard stars is in practice very often considerably increased by the fact that regrettable fractions of the sets of program spectrograms show densities deviating notably from those of the standard-star spectrograms. Not only will an unfortunate lack of exposure meters for existing spectrographs continue to give rise to such spectrograms, but also all kinds of malfunctions and inadequate weather conditions will contribute, as will the desire of many radial-velocity observers to make their spectrograms rather strong.

The fifth classification obstacle I want to take up is one which has always been and will always continue to be a major quality limitation for most classification work done. I am thinking of spectrogram widening. The standard-star spectrograms for definition of the MK system were all widened to more than 1 mm. For instance, Morgan and Keenan (1973) widen to 1.3 mm. How many of the normal field workers can in practice afford such a luxury? Even for brighter program stars such widening normally implies exposure times of catastrophic length. For most field stars it is completely out of the question. Let me mention, as an example, that with a 1.5-m telescope and a dispersion around 75 Å mm^{-1}, a good spectrogram with a widening of 1.3 mm on IIa-O emulsion of a 10th magnitude A star would require an observing time of nearly two hours. And that observing time refers to a very bright field star. It must be realized that in most cases the widening to be adopted unfortunately does not reach the level of pure quality considerations. It remains a simple question of spectrogram or non-spectrogram. As for the choice of dispersion, a compromise between quality needs and light economy normally forces our observer to a rather uncomfortable acceptance of widenings which are in fact much too modest. In practice he or she normally ends up with widenings somewhere in between 0.50 and 0.25 mm, with the smaller ones being mandatory for a regrettably large fraction of the apparently faintest (and often most interesting) stars. With such sets of program-star spectrograms there is actually small immediate need of high-widening standard-star spectrograms. It should be added that the above-emphasized needs for radial-velocity determinations are normally greatly satisfied even by the modest values of the spectrogram widening mentioned (Abt and Smith 1969; Ardeberg and Maurice 1977a, 1977b). Most certainly, I feel no difficulty whatsoever agreeing with Walborn (1978) in his pointing out the extremely strong need existing for a more generous allotment policy regarding the use of large telescopes for spectral-classification programs. However, until general allotment policies have changed to this effect, we clearly must take advantage of the observing time available.

As a sixth major obstacle towards good field-star MK classification one should mention the diversity of emulsions in current use. The choice of emulsion is of course a parameter normally much more free than those defined by the other obstacles mentioned. For some types of instrument it may, however, create problems well comparable to those introduced by non-standard dispersion.

Let me finally end the list of our observer's agonies referring to the fact that for stars of the highest luminosity the lists of standard stars are considerably less complete than they ought to be. Obviously, nobody can really be blamed for that, but the difficulty is anyhow serious. Partly, the situation is saved by the lists given by Bidelman (1951, 1954).

3. SPECTRAL ATLAS AT 74 Å mm^{-1}

In the course of several years we, at the European Southern Observatory, have collected spectrograms of MK standard and reference stars taken for the purpose of various programs with emphasis on stars of higher luminosities. The spectrograms were taken with the Marseille spectrograph (Baranne et al. 1969) at the Cassegrain focus of the 1.52-m telescope (Fehrenbach 1968), and the observing conditions were kept as constant as possible throughout the observing period concerned. Kodak IIa-O emulsion on film was used and all films were developed in D19. The grating dispersion is 74 Å mm^{-1} and the projected slit width was 18μ on the film corresponding to a resolution of approximately 1.3 Å. The spectral interval covered extends roughly from 3300 Å to 5000 Å. The spectrograms were widened to between 0.4 and 0.5 mm.

We have decided to try to make our results concerning MK standard and reference stars available to interested observers. Such work is now in progress through a collaboration between Eric Maurice from Marseille, Harri Lindgren from Lund, and myself.

The dispersion of our spectrogram falls in between those of existing classification atlases and close to that of most modern Cassegrain spectrographs in use. Further, our sets of standard and reference stars are rich in high-luminosity objects, which seems helpful to many projects. Finally, the fact that all spectrograms have complete intensity calibrations provides the possibility for a more flexible use of the data than normally made. I will come back to this latter point.

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As primary classification standards we adopted (naturally) those given by Morgan and Keenan (1973) as dagger types and those listed as MK standards by Johnson and Morgan (1953) and not revised by Morgan and Keenan (1973). As additional classification standards we adopted those given as non-dagger types by Morgan and Keenan (1973), those given by Keenan and McNeil (1976), and some few stars from Morgan et al (1943) and one star from Abt et al. (1968), not taken up by Johnson and Morgan (1953) or by Morgan and Keenan (1973).

Further, as primary reference stars for MK classification we adopted those in the lists recommended by Morgan and Keenan (1973), i.e. those published by Hiltner et al. (1969) and by Lesh (1968). This also holds for the lists given by Morgan et al. (1955) and by Garrison et al. (1977).

Finally, we adopted as additional reference stars some high-luminosity objects given by Bidelman (1951, 1954).

Our O-star sequence contains several stars classified and even established as standard stars by Walborn (1972, 1973). However, we do not claim to be able to reproduce his luminosity classifications and therefore we do not adopt his classification system. I guess that our widening may be somewhat insufficient for Walborn's delicate criteria.

The rather limited number of stars of higher absolute luminosities in the lists of standard stars for the MK system is a serious problem for work on galactic stars and even more so for the investigations of extragalactic systems. Therefore, we have decided to use as a special list of reference stars a sequence of high-luminosity objects belonging to the Large Magellanic Cloud and observed with the same equipment and under the same conditions as the standard stars. The list is given by Ardeberg et al. (1972). We do not claim the classification quality of the list to be compatible to that of the lists of standard and reference stars just mentioned. We are, however, extremely pleased to note that later revision by Morgan and Keenan (1973) of four of the stars belonging to this list shows a very good agreement.

Additionally, we have observed a sequence of Wolf-Rayet stars taken from the list of Smith (1968).

The present status of our files of spectrograms of MK standard and reference stars plus those of stars in the Large Magellanic Cloud and of Wolf-Rayet stars is displayed in Table I. We hope to be able to fill in the gaps (especially for low-luminosity stars) rather soon.

TABLE I

Present status of our files of spectrograms at 74 Å/mm of MK standard and reference stars plus those from a sequence of stars in the Large Magellanic Cloud. For the "normal" MK boxes asterisks denote those represented by at least one spectrogram of satisfactory quality. For the Wolf-Rayet stars corresponding types are given. See text for further information.

	O4	O5	O6	O7	O8	O9	O9.5	B0	B0.5	B1	B2	B3	B5	B8	B9	A0	A1	A2	A5	A7	F0	F2	F5	F8	G0	G2	G5	G8	K0	K2	K5	M2	M5	M6
LMC			*			*	*	*		*	*	*	*	* *	*	*	*	*	* *		* *			* *	*	*								
IaO										*														*	*		*	*						
Ia							*	*	*		* *	* *	*	* *	*	*	*	*	*		*	*	*	*		* *	*					*		
Iab												*								*		* *		*							*	*		
Ib						*	*			*		*	*		*	*		*	*	*	*	*	*		*	*	* *	*		* *		*		
II						*	*	*			*	*		*	*				*			*	*	* *		*	*			*	*			
III						*		*	*	*			*	*																			*	*
IV								*				* *			*									*										
V	*	*	*	*	*	*	*	*	*	*		* *	* *			*	*																	

Wolf-Rayet WC 5 WC 6 WC 7 WC 9 WN 6 WN 7 WN 8

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Finally I should mention, that as a final classification atlas we intend to publish not only reproductions on paper but also direct copies of our spectrograms on film or plates. This way we hope to improve the direct compatibility between standard and program spectrograms and also to enlarge the useful density interval.

4. MK CLASSIFICATION FROM SPECTRAL INTENSITY TRACINGS

Traditionally, spectral classification in the MK system has been made through direct visual inspection of spectrograms. As an alternative, use has sometimes been made of quantitative studies of line intensities and also of continua in spectrograms. In this connection photoelectric narrow-band photometry and scanning will not be discussed. Objective-prism techniques will be dealt with separately below.

Some of the problems connected with MK classification from visual plate inspection have been discussed above. Quantitative classification methods have sometimes gained considerable success. The most well-known example is the Barbier-Chalonge-Divan system of stellar classification (Barbier et al. 1935; Chalonge and Divan 1952, 1953, 1973) covering the complete "normal" luminosity range for spectral types earlier than G0 by means of spectrophotometric evaluation of the strength and position of the Balmer discontinuity. The system is rather accurately calibrated in terms of MK boxes. A two-dimensional classification system close to the Barbier-Chalonge-Divan one, but exploiting also measures of line intensities, has been developed by Hack (1953). From measurements of line intensities and profiles in spectrograms Sinnerstad (1961a,b) constructed a scheme for two-dimensional classification of early-type stars.

Quantitative classification methods have certainly many advantages. However, there are also a number of problems involved in the adoption of such methods for purposes of current spectral (MK) classification. First of all, quantitative classification methods are in practice normally rather laborious and time consuming even with the use of modern computer techniques. Secondly, they often require special observing instrumentation. One may mention the (rather elegant) special spectrograph needed for observing in the Barbier-Chalonge-Divan system and the Hack system. The problems arising when other systems are used are often prohibitive for general use of the methods. Thirdly, even if there is no strong dependence on observing equipment, there is very often a pronounced dependence on resolution, making transformations of classification criteria ambiguous. Finally, and perhaps most important, quantitative classification methods depend on certain selected criteria and not on the complete spectrum in the way MK classification actually should be done.

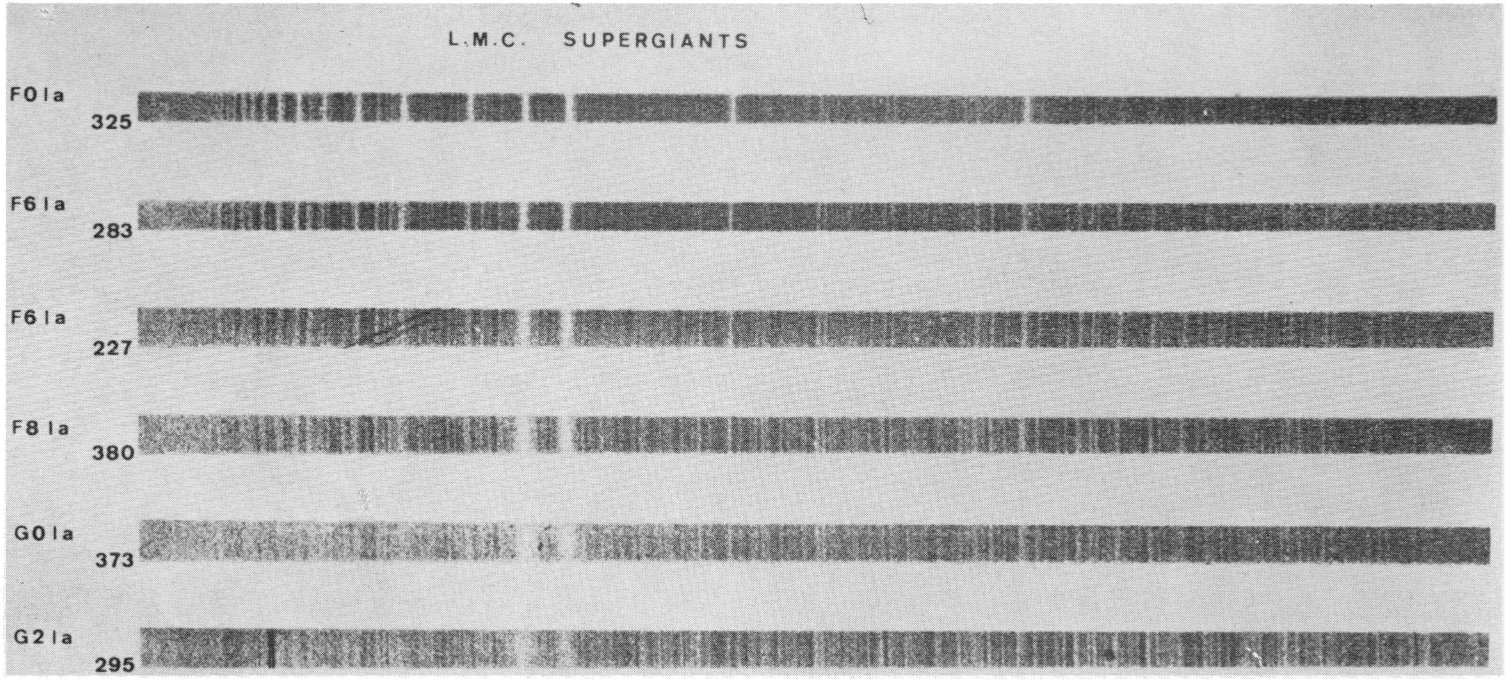
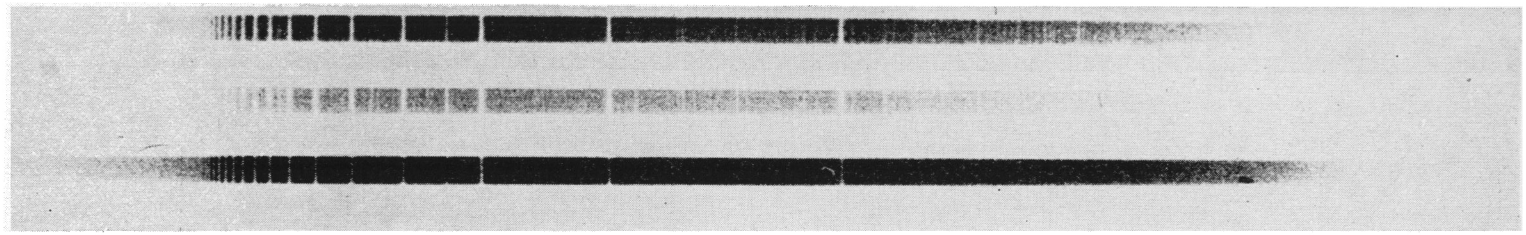


Fig. 1. Limited sequence of cool stars of high luminosity belonging to the Large Magellanic Cloud. Original dispersion is 74 Å/mm.



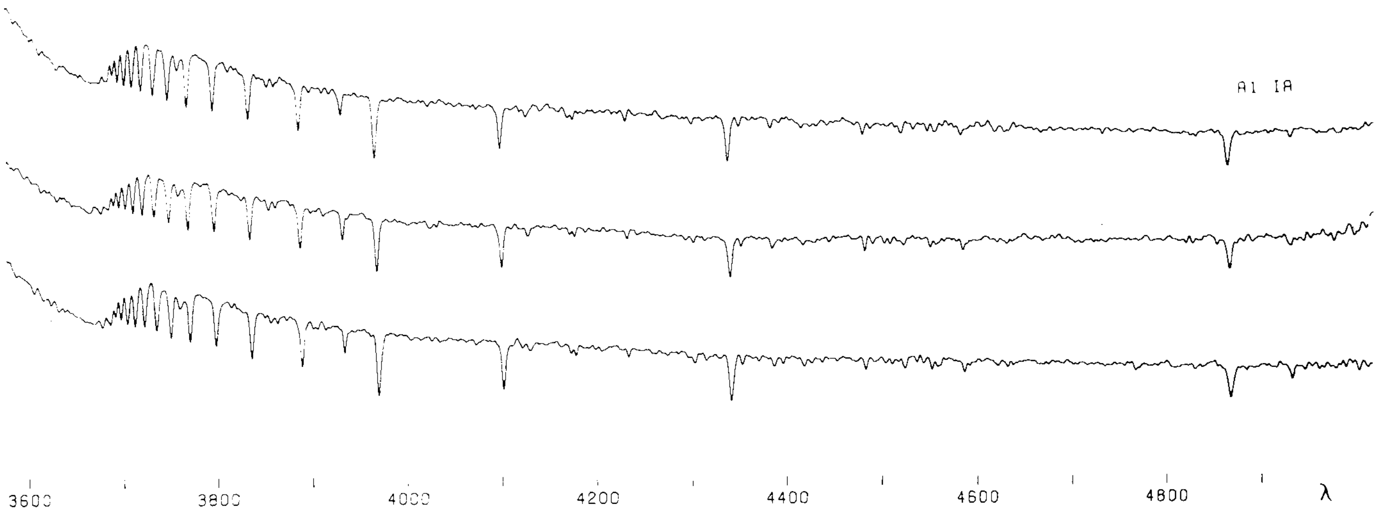


Fig. 2. Example of the difference in the acceptable density range for visual spectrogram inspection and tracing classification. Three spectrograms of the same star (spectral type A1 Ia but a different density levels) are shown, followed by the corresponding tracings. The original dispersion is 74Å/mm and the value of the gaussian filter is 16 μ m.

Tracings of slit spectrograms have often been used for illustration purposes but hardly ever for large-scale (MK) spectral classification based on visual inspection. Oddly enough, the situation is similar for objective-prism spectroscopy, where the coupling between tracing and quantitative methods is very strong. This is a somewhat remarkable situation and I want to mention some of the advantages of spectral classification based on visual inspection of tracings of slit spectrograms.

A very strong advantage of tracing classification is the ease with which standard-star material may be reproduced and distributed. All observers making use of a certain spectrograph and the same kind of emulsion may easily share a single set of standard-star spectrograms and/or interchange tracings of such spectrograms. This is in sharp contrast to the corresponding situation when direct inspection of spectrograms is made. The resulting gain in observing efficiency and standard-data completeness is obvious.

Another advantage of tracing classification, which is maybe even more important than that of standard-data reproductivity, is the very notable relaxation of resolution requirements. Once we have, for a suitable set of standard stars, digitized spectral-tracing intensity data of a certain resolution, we may easily proceed to comparisons of these data with any program-star tracing data of reasonably comparable resolution through an intermediary instrument-profile convolution process. This means much more generous restrictions concerning the choice of instrumentation as well as receiver and emulsion, although I am not fully as optimistic as Vardya (1978), suggesting comparisons of plates with dispersion 50 Å mm^{-1} to plates with 5000 Å mm^{-1}. Again, there is a sharp contrast to direct spectrogram inspection.

A third important advantage of classification from tracings is that with this method the acceptable density range for the original spectrograms is considerably wider than when the spectrograms have to be inspected directly. Still there are of course definite limits, especially to the low-density side, but the gain is very clear. As a particular advantage, one may point to the fact that excellent classification use can be made also of the large numbers of spectrograms made primarily for radial-velocity measurements and therefore sometimes exposed to densities notably higher than ideal for direct visual spectrogram inspection.

Even regarding spectrogram widening, tracing classification offers advantages over direct inspection of spectrograms, although these advantages are admittedly less obvious than those already mentioned. Especially for spectrograms with widenings approaching (or

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surpassing) the lower limit of acceptability, tracings often prove extremely useful.

Finally, I think it fair to conclude that in most cases visual inspection from tracings may give less rise to ambiguities and personal equations in clasification than direct spectrogram inspection. For instance, we all know the problems concerning the luminosity classification of B8-A2 stars.

One may of course ask why direct visual spectrogram inspection has maintained such a dominating position in MK classification, even when practiced under unfavorable conditions. Part of the answer is certainly that the people defining the MK system worked and still work that way and do it pefectly well. However, this does by no means imply that other people do even nearly as well.

Another, probably very important, reason for the strong position of visual spectrogram classification is the "direct" type of approach of the method. Once the spectrograms have been taken and developed, no further data treatment has to be made before final classification. This advantage is, however, mainly illusory. Actually, "avoiding" the conversion of densities into intensities means presuming that the calibration relations are always the same, linear and independent on wavelength. Certainly, those are effects more or less automatically taken into account by the most experienced classifiers, but most people have considerable difficulties doing it in a proper manner.

Further, an apparently important advantage of direct visual spectrogram inspection has been its ability of noise filtering, i.e. the ability to distinguish between weak spectral features and irrelevant plate noise. This noise consists of two kinds, either emulsion flaws or just grain noise. Emulsion flaws are normally easily detected on tracings, because of the peculiar line shapes they produce. Moreover, a quick supplementary look at the spectrogram (for instance when it is traced) easily reveals such features. Emulsion grain noise may well be taken care of through numerical noise filtering, using Gaussians. That this has very often been neglected in tracing work is astonishing.

In summary, I feel it safe to conclude that spectral classification from tracing inspection can provide considerable advantages in many situations and for a large number of observers. These advantages include also the essential over-all picture plus the fact that it can relieve the "normal" classifier from lots of problems.

The approach of tracing classification has doubtlessly much in common with that of the pictorial presentation of digital data for classification purposes developed by Kinman and Mahaffey (1978). However, the tracing approach is undoubtedly much less complex, especially for "normal" institutes.

5. ATLAS OF SPECTRAL TRACINGS

Based on the spectral atlas at 74 Å mm^{-1} described above we have started work on an atlas of spectral tracings intended for a wide interval of resolutions around that given by our observing system, i.e. approximately 1.3 Å.

The intensity calibrations made for all our stellar spectrograms cover the same wavelength region as those. The range in intensity corresponds to 3.8 magnitudes and it is divided in 13 steps (Maurice 1975). Both calibration and stellar spectrograms are recorded in density with the PDS measuring machine of the Lund Observatory. In all cases a slit width of 4μm is used and digitization is made with a step length of 2μm.

From the calibration spectrograms we derive a linear relation between emulsion noise and density, Using this relation, the original density, i.e. $D = \log T^{-1}$ where T denotes measured fractional film (plate) transmission, is transformed into a quasi density, $D' = k_1 \cdot \log(a + b \cdot D) + k_2$. Here a and b are the constants derived for the above mentioned linear relation, and k_1 and k_2 are constants chosen to transform the scale of D' into that of D. In order to remove irrelevant emulsion noise for the stellar spectrograms, gaussian filtering is made in D'. We can in this case for the filter choose a constant value for the standard deviation, σ. From empirical testing σ = 16μm has been found suitable. After filtering, the data are retransformed into D.

From the calibration spectrograms calibration curves are constructed with intervals of approximately 15 Å. For this procedure Baker density, i.e. $\Delta = \log(T^{-1} - 1)$, is used. The relations between (Baker) density and intensity (on a logarithmic scale) are approximated with spline functions (Reinsch 1967)

For the conversion from density to intensity for the stellar-spectrogram data, interpolation is always made between four calibration curves, except at the extremes of the wavelength interval dealt with. Final tracing of the stellar spectrograms is made in intensity on a logarithmic scale versus wavelength. In comparisons it should be remembered that depending on the original spectrogram transmission data, the resulting noise in log I is always considerably larger for the extremes of the wavelength interval reproduced than for its more central parts.

So far, we have made no attempt at rectifying resulting stellar continua, which are now entirely dependent on the wavelength dependence of the spectrum of the calibration source. For the final tracin tracing atlas such rectification will be made.

Except for a spectral-tracing atlas representing the original resolution, we intend to make the data available on magnetic tape. This will allow convenient use with data of different resolutions after appropriate instrument-profile convolutions. It is further planned to preparing tracing atlases with some different standard resolutions for quick comparisons.

Finally, it is added that the present material is now taken into account for quantitative analyses of spectral-type and luminosity-class criteria. It is intended to compare and possibly combine this with cross-correlation methods for spectral classification. Such work is under way. Quantitative methods are regarded as an important supplement to visual classifications, although the latter should always be entitled to the preference due to its inclusion of the over-all picture of the spectrum.

6. OBJECTIVE-PRISM SPECTROGRAMS

Given adequate instrumentation and excellent seeing conditions, the objective-prism technique may give spectrograms of very high quality. With sufficient spectral resolution objective-prism plates may well be used for visual classification on the MK system. Such classification has since long been performed with plates from the Fehrenbach-type radial velocity astrographs (see for instance Fehrenbach 1966), the method being restricted only concerning luminosity classification of stars of spectral types O and B. More recently, impressive amounts of MK classifications of excellent quality have been made from plates taken with the Michigan Curtis Schmidt telescope at Cerro Tololo in Chile (Houk et al. 1974; Houk and Cowley 1975; Houk 1978).

Whereas the large radial-velocity astrographs and the Schmidt telescope mentioned give dispersions of 110 Å mm^{-1} (at 4210 Å) and 108 Å mm^{-1}, respectively, Morgan et al. (1943) give 140 Å mm^{-1} (at Hγ) as a lower limit for objective-prism classification on the MK

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system, provided seeing quality is excellent (and the emulsion gives a plate resolution of 15-20μm). Because of these limitations it has to be accepted that most classification work based on visual inspection of objective-prism plates is bound to be on systems with a classification resolving power considerably lower than that of the MK system.

Even if data of quality comparable to that of the MK system can be obtained only from objective-prism plates of higher resolution, the, by far, largest amounts of spectral information will no doubt continue to result from work on objective prism plates of low resolution. If we still want to obtain good over-all two-dimensional classifications we have to turn to quantitative classification methods.

7. QUANTITATIVE METHODS

If quantitative methods are applied to objective-prism spectrograms, classification quality may be raised considerably. This has been demonstrated by Lindblad and Steinquist (1934). Since then, large amounts of classification data have been derived from measurements of line depths and color equivalents in objective-prism spectrograms, mainly of low resolution. Typically, this type of procedure has resulted in classifications, which have been partly one-dimensional, partly two-dimensional, depending on spectral type. For later spectral types also abundance determinations have been made following similar procedures (Samson 1969).

For objective-prism plates of "MK resolution", application of quantitative methods to studies of selected criteria may result in data of impressive quality, as has been demonstrated by McCarthy et al. (1966), by Yoss (1973) and by Schmidt-Kaler et al. (1976). For somewhat lower resolution multi-criterion studies were made by West (1970).

Following our work on MK classification of slit spectrograms we have initiated comparisons between classifications from 74 Å mm^{-1} slit spectrograms and spectrograms obtained at La Silla, Chile, with the Fehrenbach radial-velocity astrograph (110 Å mm^{-1} at 4210 Å). Whereas plates taken with the latter telescope under good seeing conditions display spectrograms of MK quality, it is evident that even only slightly unfavorable seeing quality deteriorates the spectrogram quality considerably. In the latter case, however, quantitative analysis is extremely helpful, especially for stars of earlier spectral types. Also cross-correlation methods seem quite valuable. In this context it is interesting to note the impressive results obtained for radial-velocity measurements based on cross correlation by Fehrenbach and Burnage (1978).

It is a somewhat curious fact, that for a very long time most quantitative classification methods have largely relied upon the same criteria as methods based purely on visual spectrogram inspection, i.e. line-intensity ratios and comparison of band features. The normal result has been a classification which is in practice only one-dimensional for spectral types earlier than about G0. This is extremely unfortunate, as the early-type stars are of highest importance for a wide range of astronomical work, expecially as they include large numbers of high-luminosity objects.

In a collaboration betwen Bo Virdefors from Lund and myself, work has been directed for some time towards testing of various classification criteria applicable to stars with spectral types earlier than about G0. Our primary aims have been to obtain reliable two-dimensional data, measurable in low-resolution spectrograms, and to avoid criteria causing the limiting magnitudes to be unfavorably bright.

Unfortunately, we have found these considerations to be in conflict with each other. The most efficient tool for two-dimensional classification of low-resolution objective-prism spectrograms of stars with spectral types earlier than G0 seems to be the Hack (1953) version of the Barbier-Chalonge-Divan method (Chalonge and Divan 1952). This seems to be especially true for a somewhat modified approach.

The most essential modification introduced by Hack is the replacement of λ_1, providing a measure of the position of the Balmer discontinuity, for a Balmer-line strength. In low-resolution spectrograms such a line strength is normally much more reliably measured than λ_1, even if λ_1 is intrinsically the best choice.

A major reason for the impossibility of determining λ_1 reliably for larger numbers of fainter stars, is that the necessity for measurements down to at least 3400 Å in practice makes the limiting magnitudes prohibitively bright. In fact, this is a difficulty affecting not only measurements of the position of the Balmer discontinuity but also those of its strength, D. However, in the latter case for most practical applications sufficient accuracy may be obtained from measurement of only a single point shortward of the Balmer limit, i.e. just beyond 3650 Å. Taking into account the nearness of this point to the wavelength (3704 Å) used for measurement of the Balmer-discontinuity strength, the exclusion of measurements further towards the ultraviolet is in practice not extremely serious, regarding the general uncertainty anyhow unavoidable in work with objective-prism spectrograms. The comparatively small range of λ_1 makes it considerably more vulnerable to variations in the ultraviolet gradient than D.

Thus, we have for main criteria chosen a quantity D', measuring the strength of the Balmer (pseudo) discontinuity and a Balmer-line strength, $H\gamma\delta$, being the average of those of $H\gamma$ and $H\delta$. Moreover, in order to be able to separate stars falling on either side of the Balmer-discontinuity maximum, we further measure the strength of the K line. Finally, also the G band is measured when possible. This is advantageous from two points of view. Firstly, it considerably improves the spectral-type consistency for F stars. Secondly, comparison of the relations between $H\gamma\delta$ and D' on the one side, and between G (G-line strength) and D' on the other side, is a useful indicator of metallicity. Together with the strength of the K line this provides a rough third dimension. Reference is made to Table II.

We are, in fact, using a sample of criteria similar to that mentioned by Schmidt-Kaler (1978). At least for the time being, we have, however, adopted a semi-automatic approach. This means that we normally center the spectrograms on the photometric slit and that every star is checked for possible over-lapping on the objective-prism plates as well as on a B chart. We consider this a notable gain in reliability. On the other side, our semi-automatic mode certainly, at least in principle, means a heavy time loss compared to a fully automatic treatment of the plates. Taking into account the current state of art of automatic spectral classification we presently gain lots of time, being able to derive final classification data.

In some galactic fields we have speeded up very much simply by using measurement data at hand. These are taken from objective-prism spectrophotometry by Rydström (1978, 1978) in a large Milky Way region in Perseus. Whereas the conventional Uppsala classification system used measurements only in the range 3780 - 4400 Å (Ljunggren and Oja 1961), Rydström (1976, 1978) considerably increased the wavelength interval to 3455 - 6200 Å.

For OB stars Rydström measured a Balmer-discontinuity strength, called D_2. This parameter was, however, measured only to group the OB stars into five spectral sub-classes. We have used the measurement data given by Rydström and derived D_2 values for all stars measured with spectral types earlier than G0. These together with data on Balmer-line, K-line and G-band strengths were used for two-dimensional classification. The presence among the Rydström stars of many stars with good MK classifications and/or data on the Barbier-Chalonge-Divan system makes it rather easy to check the accuracy of our classification data. Preliminary comparison data indicate standard deviation values for $(B-V)_0$ and M_V, which for average data from four spectrograms correspond to approximately one sub-class in spectral type and two sub-classes in luminosity class. This may be compared to the corresponding data given by Schmidt-Kaler et al. (1976) and by Schmidt-Kaler (1978). Albeit the considerably lower resolution

TABLE II

MAIN PARAMETERS FOR SPECTRAL CLASSIFICATION AT LOW RESOLUTION OF STARS WITH SPECTRAL TYPES EARLIER THAN G0.

Spectral Type	O4	O5	O6	O7	O8	O9	O9.5	B0	B0.5	B4	B2	B3	B5	B8	B9	A0	A1	A2	A5	A7	F0	F2	F5	F8	G0
Parameter																									
D'	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Hγδ	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
K														—	—	—	—	—	—	—	—	—	—	—	—
G																						—	—	—	—

D' is a measure of the strength of the Balmer discontinuity, Hγδ the average strength of the lines Hγ and Hδ, and K and G are the strengths of the K line and the G band, respectively.

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of the spectrograms used by the Bochum group, their resulting accuracy seems better than ours. Still, however, we regard our standard-deviation data as quite satisfactory.

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DISCUSSION

Andersen: I should like to confess my membership in Dr. Walborn's club of rock-bound reactionaries. I am convinced that much time is spent trying to evaluate inferior material. This time could be spent much more profitably getting better basic material. I also believe that observers accept too readily the limitations of existing instrumentation. A wonderful little spectrograph like Dr. Garrison's can be built at the price of one or two observing trips to Chile, and for a program of any appreciable size the instrument is certainly justified. Secondly, if oscilloscope measuring engines, like the Grant machine, are used for the radial velocity measurement, then there is no need for exposing radial-velocity spectrograms more densely than classification spectra.

Ardeberg: In my opinion, this boils down to a very general problem in observing astronomy; the confrontation of observational facilities wished for and those actually at hand. There are certainly no difficulties drawing up pictures of wonderfully equipped observatories. However, as long as these are not realized in practice, we have to use what is available. It is perfectly true that use of profile over-lapping for radial-velocity determinations very much does away with the need for strong spectrograms. But there are still very many departments without access to measuring engines providing such facilities.

Walborn: I think most of the obstacles to proper spectral classification you list can be overcome in principle. If that is really impossible in practice, then I suggest that MK types should not be given. A critical evaluation of the inferior observational material should be made, and the results described in terms of the range of MK types within which a given spectrum could lie, or with some other notation.

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At CTIO with the 60-inch telescope, B = 10 is obtained at 78 Å mm^{-1} with widening 1.2 mm on N_2-baked IIa-O plates in 30 min. Spectral classification studies are also being carried out with the 4-meter telescope.

Ardeberg: As a matter of fact one should always, whatever the circumstances, evaluate one's material and describe the results in terms of classification accuracy. Otherwise it is virtually impossible for anybody else to use the data with reasonable confidence. My exposure-time example did not refer to N_2-baked emulsion. Actually we have had quite some bad experience regarding fogging when N_2 baking has been used. I guess that your experience of the method is more favorable than mine. If your exposure time refers to plates with clean background I am impressed.

Fehrenbach: Our aim should not be to classify for the sake of classification itself. We should classify in order to be able to carry out galactic and extra-galactic studies, such as those of galactic structure and rotation, of galactic evolution, and of the LMC rotation and stellar distribution.

Ardeberg: I fully agree with this statement. On the other hand I am sure that we also strongly agree, that in spectral classifications we should try to obtain the highest quality possible.

Wing: I think we should make a distinction between the system on which results are expressed and the accuracy with which they are expressed. Sometimes it is not practical to achieve the same accuracy that is inherent in the set of MK standard stars, perhaps because of smaller widening, but the classifications can still be on the MK system if they are based on MK criteria and compared with MK standards. It is the responsibility of the observer to evaluate his accuracy, normally by observing standard stars, and to state what it is.

Ardeberg: This comment is very much in line with my own outlook. I feel that the responsibility you mentioned ought to be rather strongly felt in all conditions.

Welin: Are you going to include in your atlas spectra of different metallicities, thus enabling classification also of e.g. very low-metallicity stars?

Ardeberg: As a matter of fact, standard spectrograms of stars with non-normal metallicities have been requested also by other colleagues. For the time being such stars are not included in our grids, but we will keep the request in mind and see what we can do about it.

Keenan: You have brought out several interesting and worthwhile points. I agree that it is just as satisfactory to classify on tracings — if your instrument gives tracings directly. If you start with a photograph there are two disadvantages to making tracings:

1. Much time is lost in making tracings.

2. Defects, such as pinholes or scratches, can be seen and allowed for in direct examination, but on tracings they may distort lines without the observer being aware of it.

Ardeberg: I am rather pleased with your positive general comment concerning tracing classification. As I mentioned briefly before, the effects of possible defects, such as you mentioned, can be fully avoided at the expense of a rapid check of the spectrogram before tracing classification is made. I am sure that you can agree to this. So we are left with the time lost in deriving the tracings. I admit this is a draw-back of the method.

Lesh: Along the line of Dr. Wing's comment, one can put the matter even more graphically. Doing MK classification on radial velocity plates is analogous to measuring radial velocities on classification plates. It is possible, but the error will be very large, and it should be thoroughly investigated. In the case of classification this means observing a grid of standards with the same equipment as the unknowns, and carefully considering how many subgroups can be distinguished.

Ardeberg: While I agree with your statement, I just want to emphasize that these considerations refer only to the cases when the radial-velocity observer has found it advantageous to make his spectrograms relatively dense. As mentioned recently, this is not necessary if proper measuring devices are available.

Walborn: If "low accuracy" MK classification is to be done with inferior observational material, the users of compilations must be exceedingly critical. Otherwise discrepancies with other kinds of data may be predominantly observational, and the possibility of detecting physically significant correlations or divergences will be lost.

Ardeberg: Yes, I think that extraordinary care should be taken, if densely exposed radial-velocity spectrograms are used for purposes of MK classification. As Dr. Lesh mentioned, the errors will be very large. Such errors can certainly often mask systematic errors, as was touched upon by Dr. Garrison the other day.

Lynga: Let me give the view of an observer, who gets five nights on a telescope like ESO's and who has no chance to take standards as well as his program stars. There is then a problem of dissemination of standard star appearance and this may well be the best done with tracings.

Ardeberg: This is exactly the predominating situation of the "normal" observer. It is my hope that a wider adoption of tracing classification will prove helpful.

Gratton: I wish to go back to Professor Fehrenbach's remark with which I most heartily agree. Although I fully understand the importance of spectral classification, we should never forget that it is only a tool to understand stellar and galactic structure and evolution. So, in my opinion "accuracy" as an attribute of a classification depends essentially on how well it reflects the fundamental physical parameters of a star: temperature, gravity, chemical composition etc. We heard this morning Böhm-Vitense's magnificent lecture on this subject. I believe that this is the right way to approach the problem of stellar classification.

I only wish (speaking as an observer) that our theoreticians would be more explicit. To speak about 2, 5, or 7 parameters is all right, but we would like to have from our colleagues a hint of where to look to find out the values of these parameters. We can then make an effort towards their experimental observation, that is towards a real correct classification.

Ardeberg: Personally, I feel that the MK system provides by far the best recipe for the time being concerning statistical determination of such parameters. Theoreticians should in this way be decently equipped with observational parameters, again statistically speaking.

Garrison: One way around the problem of taking a grid of standards when the astronomer has only a few nights on a large telescope is to use a small telescope (6-10 inches) to feed the large telescope spectrograph. I intend to do this for the CFH telescope.

Of course, another possibility is to consider more modest programs. It is better to do a small program well than a large one poorly, in my opinion.

Ardeberg: A small-telescope arrangement as mentioned would no doubt be a considerable help.

Keenan: Another way of avoiding the problem of taking standard stars with large telescopes is to have a small telescope and spectrograph giving the same scale.

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Ardeberg: I think that the suggestions made by Drs. Garrison and Keenan are extremely important. However, in practice such comparatively non-glamorous projects are normally not fully and sufficiently appreciated by observatory designers. I really hope that the Garrison small-telescope arrangement will not be an isolated practical approach to the problem.

Abt: In response to a comment by Dr. Andersen, I might point out that Kitt Peak and Cerro Tololo have essentially identical spectrographs with a variety of dispersions on their 1-m telescopes, the 1.5-m and 2.1-m telescopes, the coudé spectrographs, etc., so that similar spectra can be obtained in both hemispheres.