PART III

PHOTOMETRIC CLASSIFICATION

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GENERAL REMARKS ON QUANTITATIVE SPECTRAL CLASSIFICATION

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At the *IAU Symp.* **24** held in Saltsjöbaden in 1964 I had an opportunity to discuss in a general way the procedures for stellar classification on the basis of narrow-band photometry. During the seven years that have elapsed there have been important contributions in this field by a number of astronomers. In this introductory talk I shall discuss, first, questions pertaining to classification systems and the various choices that define them. I also wish to deal, briefly, with problems referring to tests of classification systems and to the calibration of classification indices, as well as with some questions regarding the goals of quantitative spectral classification.

Consider the choice of indices that define a quantitative classification system, i.e. the choice of location and width of the wavelength bands to be measured. The choices have generally been made on the basis of experience previously gained through the development of methods for spectral classification through visual inspection, but they have been guided also by results of numerous tests of particular indices obtained through photometric investigations over several decades. The choice has to be made on the basis of a decision regarding the minimum band width that is practicable with a view to light economy; and it will depend on whether the goal is a classification system applicable for all, or nearly all, types of stars or to stars in a selected region of the Hertzsprung-Russell diagram. Finally the desired accuracy characterized by the degree of homogeneity of the star groups resulting from the classification is relevant.

When the bands that define the indices of a classification have been selected, the next choice pertains to the method of isolation of the bands for intensity measurements to be made, generally, by photoelectric techniques. Interference filters have been widely used for the purpose, mostly in such a way that the band intensities in question are measured consecutively. Use of a spectrograph for the isolation of the bands has obvious advantages, as demonstrated particularly by work in Cambridge, England. When this method has been chosen it is advantageous to avoid the use of an entrance slit that cuts into the stellar image because of the well-known adverse influence on photometric accuracy. This means that the angular dispersion of the spectrograph has to be relatively high.

As an example, let me refer to a grating spectrograph-photometer for photoelectric four-colour photometry in the *uvby* system that has been in use for some years at Kitt Peak National Observatory on a 36-inch reflector. It was designed for the purpose of obtaining simultaneous observations in the four colours. The angular dispersion is sufficient for excellent definition of the 200 Å bands in question without the use of an entrance slit, the proper adjustment of the spectrograph optics being checked every observing night through scanning across the Hδ line of a suitable star (e.g. a bright

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A star) with a narrow slit that is interchangeable with the slot defining the v-band. The focal lengths of collimator and cameras (separate for the four bands) were chosen in such a way that the photomultipliers could be placed side by side in the instrument box.

A more compact spectrograph-photometer of this type has been constructed for use with the Danish 50-cm reflector on La Silla (ESO), Chile. Here the spectrograph serves only the purpose of separating the bands so that the four photomultipliers can again be placed side by side while the wavelength bands are defined through standard *ubvy* filters placed directly in front of the photomultipliers. Thus, to obtain compactness there was some sacrifice with regard to light economy.

Consider next the choice of photometric technique. Photographic photometry has been used successfully in quantitative spectral classification by Bertil Lindblad and his associates, and by Chalonge and his collaborators. However, the advantage of photoelectric photometry in terms of accuracy and time economy are such that this technique has been the preferred one in a number of classification systems developed for observations of one star at a time. For quantitative classification of faint stars in fields the technique of electronic-camera photometry holds great promise, and applications in the nearer future can be expected.

The specification of the sensitivity functions $\varphi(\lambda)$ for the bands that define a quantitative classification system is important. For narrow and intermediate-width bands $\varphi(\lambda)$ depends largely on filter transmission function or exit-slot location, although the transmission curves for the rest of the optics as well as the photomultiplier sensitivity function are of some influence. In actual practice the classification system is often defined through high-precision values of its indices for a sufficiently large number of standard stars, while the relevant sensitivity functions $\varphi(\lambda)$ are only known to some good approximation. Then, when it is desired to duplicate the system with another instrument the sensitivity functions are chosen so that they are close to those defining the original system, in which case accurate reduction to the system defined by the indices for the standard stars can be carried out using simple linear transformations (for an example cf. Crawford and Barnes, 1970).

A principal aim of quantitative spectral classification is subdivision of the stars into sub-groups, homogeneous within specified tolerances. The test for homogeneity may be made through the addition of further indices or, on a broader basis, through high-dispersion measures of several representative stars from each sub-group.

Experience obtained through the last decade has shown that two-dimensional classification is adequate for many purposes for B and A stars, provided that peculiar stars, and for certain applications rapid rotators, can be segregated either through parallel visual inspection of spectra or through the use of a suitable additional index. However, for stars of class F5 and later three-dimensional classification is necessary because the range of variation of the metal-content parameter is much wider. On the other hand the role of the rotation parameter is much reduced here, and peculiar stars are less frequent. In all classification schemes aiming at high accuracy the role of composite spectra must be considered, at least statistically.

In many applications of quantitative spectral classification the aim goes beyond division into homogeneous sub-groups in that it is desired to derive quantities such as effective temperature T_e, absolute visual magnitude M_v, and relative metal content directly from the indices of the classification systems. This means that the indices have to be calibrated.

I cannot here go into details with regard to the calibration of classification indices yielding effective temperature. Let me refer, however, to the progress that has been made possible through the determination of stellar angular diameters using intensity interferometry (cf. Hanbury Brown, 1968) and as a result of the feasibility of intensity measures in the rocket-ultraviolet. It should be mentioned in this connection that the number of stars with directly determined T_e-values of good accuracy is still so limited that accurate calibration taking into account variations of temperature-scale with atmospheric gravity g and relative metal content [Fe/H] can only be carried out using results of model-atmosphere calculations.

With regard to calibration of indices giving the absolute magnitude M_V the procedures are still based on the use of trigonometric-parallax stars as well as cluster- and association-stars. The necessity of including the metal-content parameter in these discussions has become clearer.

With regard to calibration of classification indices in terms of relative metal content there has been considerable progress during the last few years. As an example, let me refer to the calibration of the metal-line index m_1 of photoelectric *uvby* photometry. The previous calibration (cf. Strömgren, 1966; also in this connection Wallerstein, 1962) has been considerably improved through recent investigations by Nissen (1970a, b, 1972). Values of [Fe/H] were determined by Nissen to high accuracy (± 0.06 me) for a number of main-sequence F and G stars through quantitative spectral analysis based on photoelectric measures of intensities in narrow well-defined bands containing only faint lines (the strength of which is not affected by atmospheric microturbulence). It is clear from Nissen's investigation that the metal-line index m_1 when calibrated yields [Fe/H]-values of very good accuracy for the great majority of main-sequence F1–G2 stars, with only a few per cent of the stars possibly deviating due to peculiarities. In particular, there is no doubt that stars of intermediate composition (metaldeficient by a factor of, say, 4 or more relative to the Hyades stars) can be segregated quite reliably with the help of the index m_1.

Calibration in terms of basic atmospheric parameters T_e, g and Z (or [Fe/H]) has proved possible using accurate model atmospheres (cf. Gingerich, 1969; Bell, 1971). In future investigations the inclusion of two parameters characterizing stellar rotation will presumably become more common.

The combination of model-atmosphere calculations and stellar-interior calculations of evolutionary sequences can yield a direct calibration of classification indices in terms of the basic stellar parameters mass age and chemical composition (for an example cf. Strömgren, 1970).

Let me finally refer to the application of quantitative spectral classification to the determination of very accurate colour excesses. Calibration based on nearby unreddened stars makes it possible to determine intrinsic colour indices from classification indices that are insensitive to reddening, and comparison with measured colour indices then gives the colour excess (cf. e.g. Crawford and Perry, 1966; Strömgren, 1972).

Procedures for quantitative spectral classification vary according to the principal goal in their application. Schemes for very accurate classification of brighter stars will differ from those aimed at classification of very faint stars. Certain schemes are tailored for use in galactic research whereas others are meant particularly for investigation of the physics of individual stars.

In this section of the Symposium there will be a number of papers giving results obtained with different systems (systems utilizing the Cambridge indices, developments of the Borgman-Walraven system, the *uvby* $+\mathrm{H}\beta$ system, the Geneva system, the Brorfelde system, the DDO system, the Straižys system, and others) and some of the problems briefly referred to in these introductory remarks will be discussed in detail.

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