THE CALIBRATION OF PHOTOMETRIC DETERMINATIONS OF ABUNDANCE

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ABSTRACT. Photometric abundance determinations using blanketing in the ultraviolet and violet spectral regions as well as the intensity of strong lines and bands is the most important tool in the study of chemical composition of faint and distant stars. However, this method requires the calibration of different photometric quantities in terms of abundance at given temperatures and luminosities. Two principal methods of calibration are in use. One of them uses stars with abundances determined from high dispersion spectra by curve of growth or model atmosphere analysis of the spectral lines. The other one uses synthetic spectra based on model atmospheres which are integrated to imitate the narrow band photometric indices. This paper will summarize the results of the application of both of these methods to calibrate a number of the important photometric systems. Most attention will be given to the late-type stars, which demonstrate the strongest photometric abundance effects.

1. INTRODUCTION

The photometric method of metallicity determination is very attractive since it has the folowing advantages in comparison with spectroscopic methods: (1) much fainter limiting magnitudes, (2) a much faster rate of collecting observational data, (3) the ability to work in clusters and in other crowded fields, (4) the parallel determination of temperatures, gravities or luminosities and interstellar reddenings, and (5) the ability to discover easily objects with peculiar abundances. This gain of information is still more significant since the accuracy of a metallicity determination from photometry and from high dispersion spectroscopy seems to be of about the same order.

However, this does not mean that photometry can everywhere replace spectroscopy. The photometric method gives a number of quantities (color indices, their differences, reddening-free

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parameters, etc.) which are sensitive to abundances. However, these quantities cannot be used without calibration and in this respect high dispersion spectroscopy plays the most important role. In addition, spectroscopy is indispensable for verification of objects with peculiar abundances detected photometrically.

Until recently photometry could not work independently since for the calibration of photometric abundance indicators spectroscopic abundances were necessary. The situation has changed since the appearance of reliable model stellar atmospheres which permit the theoretical calculation of synthetic spectra of stars. These synthetic spectra, convolved with the response functions, give photometric quantities for different temperatures, gravities, and abundances. Now both methods of abundance determination, spectroscopic and photometric, are more and more based on the synthetic spectra. However, the synthetic spectra techniques give reliable results so far only in comparatively narrow spectral regions (tens of Å) for certain temperatures and luminosities. Consequently, this method of calibration is most successful for narrow-band photometry.

The abundance criteria of photometric systems with wide and intermediate band widths are based, as a rule, on the differential blocking effect caused by numerous lines of different elements. Consequently, these systems are able to determine the common effects of hundreds and thousands of lines of different elements. At the same time, narrow-band photometry having half-widths of the order of tens of Å can be used to measure the strengths of strong spectral lines and bands and after corresponding calibration they can give abundances of individual elements. In this respect narrow-band photometry is similar to the equivalent width determination or to the fitting of some absorption feature with its synthetic profile.

In the following sections the abilities of different photometric systems for abundance determinations and their calibration results will be reviewed.

2. WIDE-BAND PHOTOMETRIC SYSTEMS

The (U-B, B-V) diagram is suitable for metallicity determination in two regions. One of them includes metallic-line stars of spectral types A and F and another includes F, G and K subdwarfs and metal deficient giants. With respect to the zero-age main-sequence line the Am stars show ultraviolet deficiencies δ(U-B) of up to 0.15 mag. This deficiency is roughly proportional to metal abundances (Abt 1961; Jaschek and Jaschek 1962). Unfortunately, it is practically impossible to use δ(U-B) as a measure of metallicity due to its strong dependence on luminosity (Eggen and Sandage 1964; Straižys and Kavaliauskaitė 1967) and interstellar reddening. The increase of metallicity, of luminosity and of interstellar reddening shifts the star in the same direction and there is no way to separate them using only photometric UBV data.

The same effects also occur in the region of late-type dwarfs and giants. However, most of the known late-type subdwarfs are relatively close to the Sun, and their interstellar reddening is small. If we neglect the possible small differences in luminosities, the ultraviolet excesses of subdwarfs are a function of metallicity. Fig. 1 shows the position of metal deficient dwarfs of spectral types F, G, and K in the (U-B, B-V) diagram. The ultraviolet excess δ(U-B) for F and G subdwarfs has been calibrated against spectroscopic [Fe/H] by many authors (see Straižys 1982, p.128). One of the latest calibrations is given by Carney (1979). Buser and Kurucz (1978) calibrated the (U-B, B-V) diagram with respect to metallicity by using synthetic colors calculated using model atmospheres by Kurucz (1979). However, the theoretical colors deviate considerably from the observed ones.

The calibration of δ(U-B) in terms of metallicity for K-type dwarfs and subdwarfs is, so far, not possible as there are no reliable spectroscopic values of [Fe/H] with which to calibrate it. At the same time line blanketed model atmospheres or theoretical energy distribution for K-type dwarfs with different metallicities remain unpublished (Eriksson et al. 1979, Bessell and Wickramasinghe 1979, and Thevenin and Foy 1983).

The separation of late subdwarfs can be increased considerably by replacing (B-V) by (R-I) in the two color diagram (Fig. 2). In this diagram the blanketing vectors are almost vertical since the (R-I) color index defines the temperature of G and K stars almost independently of metal abundance. Other indices including red and infrared magnitudes such as (V-R), (V-K), (V-L) and others of the Johnson system, or (R-I) and (G-I) of the Stebbins and Whitford six color system may be also used as temperature criteria.

Smith and Steinlin (1964) were the first who recommended the use of the RGU photographic system for the separation of subdwarfs. The blanketing vectors in the (U-G, G-R) diagram are much steeper than in the (U-B, B-V) diagram and, consequently, the separation of subdwarfs is larger. The diagram was calibrated with respect to metallicity using synthetic colors from model atmospheres by Kurucz (Buser 1979) and spectroscopic [Fe/H] determinations (Trefzger 1981).

Interstellar reddening and the presence of giants reduce the usefulness of the UBV and RGU systems for the detection of subdwarfs and for their metallicity determination.

Metal deficient giants are situated above the solar composition giants both in the (U-B, B-V) and (U-B, R-I) plots, but the ultraviolet excesses, δ(U-B), are much larger in the latter diagram

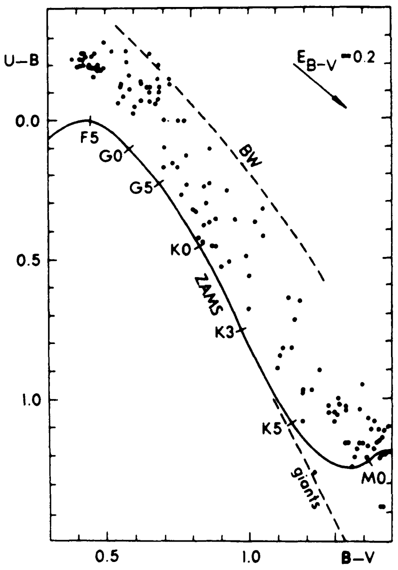

Fig. 1. The (U–B, B–V) diagram for subdwarfs. The smooth line represents the zero-age main sequence; the broken line represents the sequence of solar composition giants; and the line marked BW is a locus of the line-free colors of subdwarf model atmospheres from Bessell and Wickramasinghe (1979). The arrow in the upper right corner denotes the reddening line for E_{B-V} = 0.2 mag.

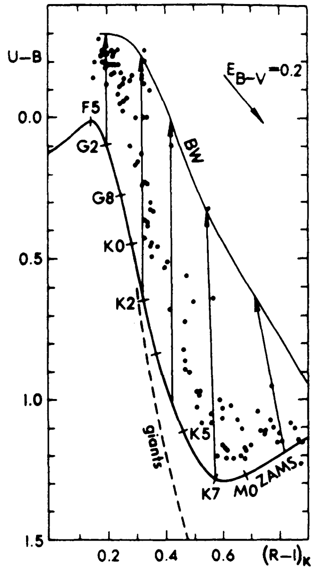

Fig. 2. The (U–B, $[R-I]_K$) diagram for subdwarfs. The designations are the same as in Fig. 1. The arrow lines pointing upwards represent the deblanketing vectors.

(Fig. 3). Extreme metal deficient giants such as HD122563 and HD165195 have δ(U-B) ≈ 0.2 mag. after correction for interstellar reddening in the (U-B, B-V) plot. At the same time these excesses are as large as 0.7 mag. in the (U-B, R-I) diagram. Model atmosphere analysis of the (U-B, B-V) diagram shows a considerable gravity effect (see Böhm-Vitense 1973; Böhm-Vitense and Szkody 1974; Bell and Gustafsson 1978). Probably, a similar effect is taking place in the (U-B, R-I) diagram. At the same time theoretical colors cannot be used to calibrate these diagrams since most models show a considerable ultraviolet excess relative to stars. This is probably caused by "missing opacity", which increases with metal abundance. Despite these difficulties the (U-B), $(R-I)_K$ diagram has been used by Eggen for metallicity estimates for thousands of G and K giants (for references see Straižys 1982 p.173). The (U-B) excess of the giant branch at $(B-V)_o$=1.0 mag. remains one of the principal metallicity criteria for globular clusters (see Sandage and Hartwick 1977). However, the calibration of δ(U-B) using the field and globular cluster giants studied with high dispersion gives contradictory results and leads to the well known vagueness of the metallicity scales (see the discussion in Straižys 1982).

In order to overcome the difficulty with luminosity effects, Canterna (1976), in collaboration with G. Wallerstein, proposed the Washington photometric system consisting of the four wide bandpasses C, M, T_1 and T_2, with mean wavelengths at 3910, 5085, 6330, and 8050 Å and half-widths of the order of 1000 Å. Later on the system was supplemented by the V magnitude of the UBV system. Canterna and Harris (1979) showed that the $(M-T_1, T_1-T_2)$ relation is almost the same for solar chemical composition stars of different luminosity classes with the reddening line nearly parallel to this relation. They supposed that the "green excess" $\delta(M-T_1)$ is a reddening-free, surface gravity free metallicity parameter. It was calibrated in metallicities both with stars known [Fe/H] from high dispersion spectroscopy and by model atmosphere colors using model atmospheres calculated by Böhm-Vitense and Szkody (1974). The main shortcoming of the method seemed to be a very small abundance effect: the "green excess" $\delta(M-T_1)$ did not exceed 0.15 mag. for stars with [Fe/H]≈-2.5. Recently Straižys and Kurilienė (1983) have shown that the luminosity sequences and the reddening lines in the $(M-T_1, T_1-T_2)$ diagram do not coincide exactly and this limits the usefulness of the system in the determination of metallicity.

3. MEDIUM-BAND PHOTOMETRIC SYSTEMS

3.1 The uvbyβ systems

Much work has been done on the metallicity calibration of one of the most widely used photometric systems: the Strömgren uvby system supplemented by the Hβ index. For the determination of the

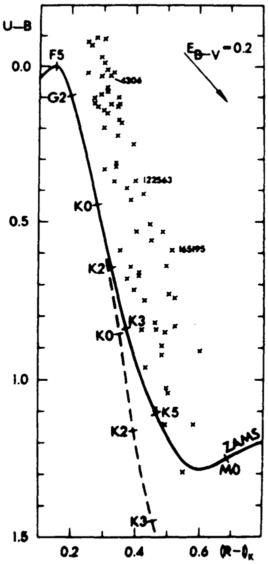

Fig. 3. The (U-B, $[R-I]_K$) diagram for dereddened late-type metal-deficient giants with [Fe/H]<-0.6. The designations are the same as in Fig. 1. The HD numbers of three extreme metal-deficient giants are given. Shown by the courtesy of A. Bartkevičius.

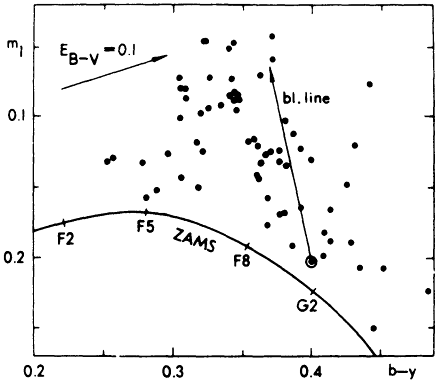

Fig. 4. The (m_1, b-y) diagram for F and early G subdwarfs. The upward arrow represents the blanketing vector for the Sun.

metallicity of Am stars and subdwarfs the (m_1,b-y) or (m_1,β) diagrams are used. Sometimes the color difference m_1 = (v-b) - (b-y) is replaced by the reddening-free parameter $[m_1]=Q_{vby}$=(v-b)-0.82(b-y). In these diagrams A and F-type stars of luminosities V-III form one sequence. Consequently, the deviation δm_1 or $\delta[m_1]$ from the Hyades line is nearly independent of surface gravity and is a measure of metallicity only.

It is known that most of the Am stars usually have larger values of m_1 than the Hyades standard relation at the same effective temperature. The deviation δm_1 is 0.07 mag. in extreme cases. The (m_1,β) diagram was calibrated in terms of iron abundance by Rydgren and Smith (1974), using blocking corrections in different filters determined from high dispersion spectra. The resulting set of isolines of equal metallicity was found to be in reasonable agreement with the iron abundance of 17 normal and Am stars. On the other hand, about 30% of the stars classified as Am spectroscopically are located either near the zero-age main sequence or show negative δm_1 (see Fig. 48 in Straižys (1977). A careful investigation of their photometric and spectral properties is necessary.

Fig. 4 shows the F and early G subdwarfs plotted in the (m_1, b-y) diagram (Straižys 1977). The violet excesses δm_1 are 0.14 mag. for extreme subdwarfs, i.e. half of δ(U-B) in the (U-B, B-V) diagram. The δm_1 excesses have been calibrated by a number of authors. Strömgren (1964), Crawford (1975) and Crawford and Perry (1976) used [Fe/H] values of stars determined from high-dispersion spectra. Nissen (1970, 1981), Gustafsson and Nissen (1972) and Nissen and Gustafsson (1978) used the metallicities determined from a model atmosphere analysis of narrow band photoelectric observations of two groups of metallic lines. It was shown that differential metal abundances can be determined from δm_1, with an accuracy of ±0.10 mag. for F0-G2 dwarfs and mild subdwarfs. However, the calibration extends only down to [Fe/H] = -0.6. Relyea and Kurucz (1978) used Kurucz (1979) model atmosphere fluxes for calibration of δm_1. They concluded that there is an excellent agreement between the theoretical colors and the observations for stars with T_{eff} >8500 K. However, for the stars cooler than A5 the colors are not in good agreement, so the theoretical calibration of photometric metallicity criteria is unreliable.

The (m_1,b-y) diagram can be used also to determine the matallicity of late-type giants (Fig. 5). Bell and Gustafsson (1978) calculated the indices of the Strömgren system for a grid of model atmospheres. Their results were analyzed by Gustafsson and Bell (1979) and Bond (1980) who used them to calibrate the (m_1, b-y) diagram in temperatures and metallicities. Bond also presented an empirical calibration of δm_1 with respect to [Fe/H] using spectroscopic data and photometric data corrected for interstellar reddening. The rms scatter of the [Fe/H] determinations about the resulting relation is ±0.15 dex. He concluded that the calibration seems to reproduce [Fe/H] values within the quoted errors of the spectroscopic determinations. Eggen (1977, 1978, 1983) has used a modified version of the uvby system for metallicity determinations of late-type giants and supergiants. He calibrated reddening-free $\Delta[M_1]$ excesses using spectroscopic [Fe/H] values.

The Strömgren system has been used also to determine the metallicity of RR Lyr stars. The parameter m_1 was shown to be constant with phase during the variation. This means that $\delta[m_1]$ is a better representation of metallicity for this type of star than the ΔS parameter which shows a variation with phase. The δm_1 excesses correlate with other metallicity indicators such as ΔS, $\delta(U-B)$ and spectroscopic [Fe/H] (Epstein and Epstein, 1973; Butler 1975).

3.2 The Geneva system

For metallicity estimates in the Geneva system the photometric parameter $m_2 = (B_1 - B_2) - 0.457\ (B_2 - V_1)$, which measures the violet blanketing, is most useful. This parameter is close to the reddening-free parameter $Q_{B_1B_2V_1}$. Metallic line stars in the (m_2, B_2-V_1) diagram are not well separated from the normal A-stars, except for the coolest ones (Hauck and Curchod 1980). This means that, in addition to line blocking, the photometric parameter m_2 is affected by some other physical characteristics, probably by the projected rotational velocity and binarity. Nicolet and Cramer (1983) suggested for Am stars the second-order photometric parameters l, m, and n which are linear functions of different Q-parameters of the Geneva system. For the interpretation of the (l,m) and (l,n) diagrams, Kurucz models have been used. The authors conclude that the photometric detection of the Am phenomenon must never be considered definite before spectroscopic confirmation. In the case of F and G subdwarfs the situation is much better. The empirical calibration of δm_2 excess against [Fe/H] was given by Hauck (1968, 1973, 1978). Later on North and Hauck (1979) analyzed the (m_2, B_2 - V_1) diagram using Kurucz (1979) model atmosphere fluxes. However, the unsatisfactory agreement of theoretical and empirical indices prevented the use of synthetic colors for calibration purposes. The authors found considerable differences between the theory and observations and suggested that the model atmospheres are not sufficiently blanketed.

In the case of the late-type giants in the Geneva system there is no two-color or (Q, Q) diagram in which abundance effects would be not influenced by luminosity. To overcome this difficulty Grenon (1978, 1981) used a set of second order photometric diagrams exhibiting the effects of gravity and metallicity at given temperature intervals. These second order quantities ε actually are differential color excesses at constant (V_1 - G) index which measures temperature. The

(ε, ε) diagrams were calibrated in terms of M_V and [Fe/H], the latter being taken from spectroscopic determinations in the field and in open clusters. The main shortcoming of the method is the dependence of the ε parameters on interstellar reddening.

Color indices in the Geneva system were calculated for model stellar atmospheres of red giants by Bell and Gustafsson (1978). However, the presence of systematic differences between the theoretical and observed values in the ultraviolet (Gustafsson and Bell 1079) prevents the use of the synthetic spectra for calibration.

3.3 The DDO system

This system was proposed for the classification of G and K stars in terms of temperature, gravity and metallicity. The C_{38-42} index measuring line blocking in the region of λ3800 Å is being used for metallicity determination. The δC_{38-42} excess at C_{45-48} = const. shows a good correlation with spectroscopic [Fe/H] (Osborn, 1973a,b). In this respect the system does not differ much from the other medium band systems. A specific property of the system is the ability to measure the strength of the violet CN band shortward of 4216 Å. The deviation of the C_{41-42} index from the standard sequence in the (C_{41-42}, C_{42-45}) diagram indicates anomalous CN strength and can be identified with composition differences after the elimination of the surface gravity effect. The CN anomaly δ(CN), calibrated by Janes (1975), has been used as a general metallicity parameter for giants of disk population. The linear correlation between δ(CN) and [Fe/H] later was revised by McClure (1979). For metal-poor giants in the field and in globular clusters the violet CN band is weak and is measured with lower accuracy. In the metal-rich clusters it varies considerably from star to star. It seems that in the halo population there is no one-to-one correlation of δ(CN) with [Fe/H]. For stars with different CN strength the δC_{38-42} excess is also not suitable because it is affected by ultraviolet CN bands of different strength. As an alternative for the ranking of globular clusters in metallicities Hesser et al. (1977) have used the (C_{45-48}, C_{42-45}) diagram. The δC_{45-48} excess was calibrated in [Fe/H] by Janes (1979). However, the range of variation of this excess is much smaller than of δC_{38-42} and δ(CN).

Bell and Gustafsson (1978) calculated synthetic spectra and DDO indices for model atmospheres of giants with different metal abundances. The same was done by Bell et al. (1978, 1979), Dickens et al. (1979) and Bell and Dickens (1980) for model atmospheres having various carbon and nitrogen abundances.

All of the photometric abundance criteria in the DDO system can work only when interstellar reddening is absent. When it is present

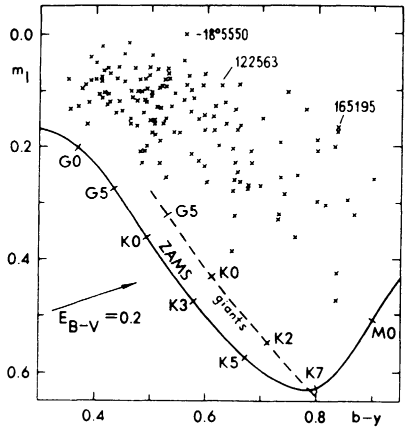

Fig. 5. The (m_l, b−y) diagram for G and K metal-deficient giants with [Fe/H]<−0.6 shown by the courtesy of A. Bartkevičius.

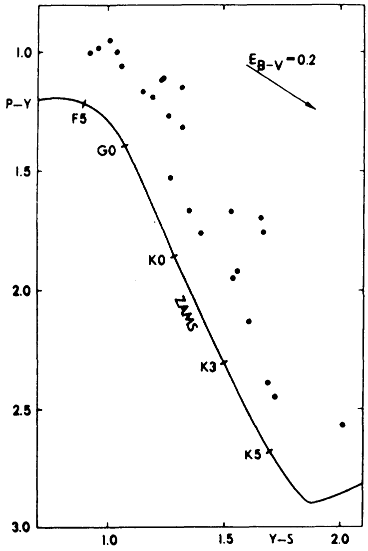

Fig. 6. The (P−Y, Y−S) diagram of the Vilnius photometric system for extreme subdwarfs.

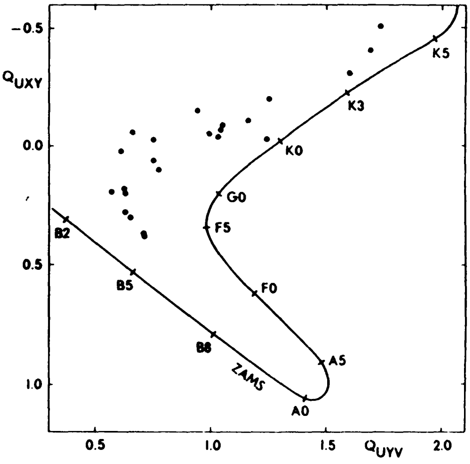

Fig. 7. The reddening-free (Q_{UXY}, Q_{UYV}) diagram of the Vilnius photometric system for extreme subdwarfs.

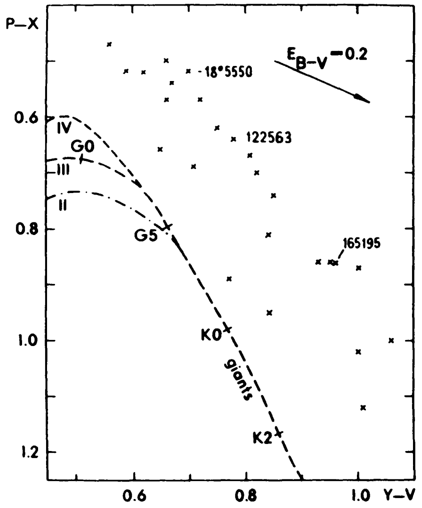

Fig. 8. The (P-X, Y-V) diagram of the Vilnius photometric system for dereddened late-type metal-deficient giants.

the DDO indices must be corrected. The interstellar reddening is usually found using methods based upon the (B-V) indices of stars.

3.4 The Walraven system

Lub and Pel (1977) have recently reviewed the properties of the five-color Walraven VBLUW system. With respect to Am stars the system probably gives no new information in comparison with other systems (Wiertz and van Genderen 1983). In the case of the F and G subdwarfs the most useful two color diagram is the (V-B, B-L) diagram or (L-B, B-V) if we accept the magnitude scale instead of the log I scale used by the Leiden astronomers. In this diagram the gravity effects below F0 are small and δ(B-L) is a metallicity discriminant when interstellar reddening is excluded. Lub and Pel (1977) claim that their photometry is more than twice as sensitive to metallicity differences as is the Strömgren uvby system for F and G stars. In their paper theoretical colors for the Kurucz model atmospheres are used to discuss the possibility of three-dimensional classification in terms of temperature, gravity and metallicity.

The Walraven system has been widely used for the photometric investigation of Cepheids and RR Lyrae type stars. The reddening-free Q_{LBV} parameter was used for the metallicity determination of RR Lyrae stars (Lub 1977, 1979).

3.5 The Arizona system

This 13-color medium-band system was used by Johnson and Mitchell (1968) and Schuster (1976, 1979) for the analysis of F and G subdwarfs. For metallicity determination the (37-45, 45-63) diagram was proposed. The δ(37-45) excess was calibrated by Schuster (1979) using spectroscopic [Fe/H] values.

3.6 The Vilnius system

This system was developed to classify stars in terms of spectral types, luminosities, and metallicities where interstellar reddening is present and where no information from spectral classification is available. The properties of the system have been described in English by Straižys and Sviderskienė (1972) and Straižys (1973, 1975, 1979) and in Russian by Straižys (1977). The metallicity of unreddened or dereddened F and G subdwarfs can be determined in the surface gravity-free (P-Y, Y-S) diagram (Fig. 6) calibrated in [Fe/H] by Bartkevičius and Straižys (1970a) and Bartkevičius and Sperauskas (1983). The ultraviolet excess δ(P-Y) at (Y-S) = const for HD 19445 is 0.36 mag., i.e. larger than δ(B-L) of the Walraven system, δm_1 of the Strömgren system, or δm_2 of the Geneva system. The metallicity and temperature of the reddened F and G subdwarfs can be determined in the reddening-free (Q_{UXY}, Q_{UYV}) diagram (Fig. 7) calibrated by Bartkevičius and Straižys (1970b). The δQ_{UYV} excesses for extreme F and G subdwarfs are ≈ 0.4 mag. The separation of subdwarfs from the remaining stars is single-valued, i.e. no other type of single star appears in the subdwarf region of the Q_{UXY}, Q_{UYV} diagram.

Recently it was shown (Straižys et al. 1984) that the same diagrams can be used for metallicity determination of late G and K subdwarfs. These stars are collected from the lists by Eggen (1969) and Bessell and Wickramasinghe (1979) and are plotted in Figs. 6 and 7. Unfortunately, the calibration of these diagrams in terms of metallicity for G and K subdwarfs has not yet been done due to the absence of reliable spectroscopic abundances and model atmospheres.

The metallicity of unreddened or dereddened G and K subgiants and giants can be determined in the same (P-Y, Y-S) diagram as calibrated by Bartkevičius and Sperauskas (1983) or in the (P-X, Y-V) diagram (Fig. 8) suggested by Bartkevičius and Straižys (1970c) and calibrated by Straižys and Bartkevičius (1982) and Bartkevičius and Sperauskas (1983). These diagrams are surface gravity-free for stars of spectral types G5-K2 and of luminosities IV-III-II. The value of δ(P-X) at (Y-V) = const is 0.33 mag. for the metal-deficient giant BD-18°5550, which has [Fe/H] = -2.8. For the metallicity determination of reddened late-type giants we have no (Q, Q) diagram which would be surface gravity-free. However, Straižys and Bartkevičius (1982) proposed a method based on two diagrams: (P-X, Y-V) and Q_{PYV}, P-X). Both diagrams are surface gravity-free and can be used to determine temperature, metallicity, and color excess. To my knowledge, it is the only method for determining [Fe/H] for reddened late-type giants and subgiants.

All our calibrations in metallicity are based on spectroscopic abundances transformed to a common scale by Bartkevičius (1980, 1984). Our attempts to use the synthetic colors of the Vilnius system calculated using model atmospheres by Bell (1977) showed a certain amount of discrepancy and we avoided using them for calibrations.

Two years ago the joining of the Vilnius and Geneva systems into one seven-color system was suggested (Straižys, Jodinskienė and Hauck 1982; North, Hauck and Straižys 1982). The Vilgen system has mean wavelengths of 350, 374, 402, 468, 516, 550 and 656 nm. This new system has somewhat broader response curves than the original Vilnius system but it maintains all the useful properties of both original systems. In particular, the system allows one to distinguish F and G subdwarfs and G and K metal-deficient giants.

3.7 Narrow-band photometry

In this review only the wide- and medium-band photometric systems currently used for metallicity determinations are considered. Dozens of narrow-band photometric systems measuring the intensities of different atomic lines, their blends and molecular bands are also in use. Even the listing of these systems would take too much space in this paper. On the other hand, narrow-band photometry is not very different from equivalent width measurements by spectroscopic techniques and there is no difference in principle between the two methods. Narrow-band photometry usually determines not the overall metal abundance but only the abundances of individual elements. In this respect it is also closely related to spectroscopic methods. The calibration of measurements of spectral lines and bands is now almost completely based on synthetic spectra calculations. This kind of application of model atmospheres is quite effective since synthetic spectra show the best agreement with observations when comparatively narrow spectral intervals are considered.

4. CONCLUSION

This review shows that astronomers now have a large arsenal of photometric systems and methods for abundance determinations for stars. However, before using them we have to relate their photometric and physical parameters, i.e. to calibrate them. For this we still need model atmospheres giving precise synthetic spectra coinciding with energy distributions of real stars for wide temperature, gravity and abundance ranges.

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DISCUSSION

GUSTAFSSON: It was mentioned that there exists a grid of models for late G and K dwarfs, calculated by Eriksson et al., which is unpublished. This grid is available to anybody interested, but should be used at the user's own risk since we have not yet systematically explored how the predicted fluxes and colors compare with observations.