Astron. Astrophys. 325, 693–699 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Quantitative spectral classification based on photoelectric spectrum scanner measurements of F-K stars*

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Received 22 December 1995 / Accepted 4 December 1996

Abstract. New criteria of quantitative spectral classification have been introduced and the method of stepwise linear regression to these criteria for quantitative spectral classification of F-K stars has been applied to the Bochum photoelectric spectra.

Key words: stars: fundamental parameters, classification

1. Introduction

In Paper I (Schmidt-Kaler and Malyuto, 1996) we began to study the classification of stars by means of photoelectric scanner spectra obtained at Astronomisches Institut at Bochum (resolution 10Å). Two criteria (the ratios of intensities in selected intervals including the hydrogen line $H\gamma$, G-band and some ajacent strong metallic lines) were shown to be indicators of spectral and luminosity classes. In the present paper we extend the measurements to other spectral intervals, produce additional criteria and outline a scheme of quantitative spectral classification of F-K stars which may be applicable to galactic studies.

2. Definition of spectral criteria

Our study is based on spectra obtained with the photoelectric spectrum scanner designed at Astronomisches Institut at Bochum (used with a resolution of about 10Å, the wavelength range about 3500-8500Å). The scanner has been attached to the 61cm Cassegrain telescope of the University of Bochum, which is located at the European Southern Observatory at la Silla, Chile. An available sample of 54 F-G-K MK standard stars are used in our analysis (some peculiar or binary stars according to Hoffleit, 1982, have been excluded). Table 1 contains the list of our stars together with the most reliable published data. The main source of MK types is the catalogue of Garcia (1989) where the MK data were compiled in accordance with the recommendations by the authors of the MK system (Morgan and Keenan). Other MK sources are (in order of preference) the following: a) recent refined MK classification by Keenan and McNeil (1989), Gray and Garrison (1989) and Gray (1989); b) MK types selected in the Simbad database, operated at Strasbourg Centre de Donnees Stellaires. All photometric data were taken from the Simbad database. The source of [Fe/H] is the catalogue of Cayrel de Strobel et al. (1992) with an extension compiled by Malyuto (1994). As in Paper I, each measurement in our analysis refers to an area confined by the border wavelengths for an interval, the spectral energy distribution and the zero level. To choose the intervals for measurements and to define criteria for our analysis, the following sources were consulted:

1) Many strong lines and bands measured by means of narrow-band photoelectric photometry and used by different authors as temperature and gravity criteria (the references were taken from the lists by Straizys, 1992).

2) Classification criteria chosen from an analysis of those objective prism spectra (Seitter, 1975, Bartaya, 1979, Jimsheleishvili, Malyuto, 1981) whose resolutions (3-10Å) are similar or somewhat higher than in the case of our data.

3) Intervals chosen by visual inspection of our own spectral scans of MK standard stars revealing a clear dependence on spectral or luminosity class.

4) The intervals chosen by a similar inspection as in the previous paragraph, but of spectra (resolution about 6Å) obtained with a CCD camera (Corral et al., 1994).

We chose the intervals for measurements in a such way that the sensitivity to spectral and/or luminosity effects were different for two adjacent or near-by intervals. The ratios of measurements in such intervals may then serve as classification criteria (indices) with minimum contamination by interstellar extinction. The differences in the mean wavelengths for each ratio do not exceed 90Å, 1 and the appropriate reddening effects in the ratios reach 2% only in a few extreme cases. Table 2 contains the border wavelengths for the intervals with indications of the principal measured features. We used the Catalogue of Solar

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* Table 4 is available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http:/cdsweb.u-strasbg.fr/Abstract.html

Table 1. The list of the MK standard stars used in the analysis

HD	V	$B-V$	MK	[Fe/H]
2151	2.80	0.62	G2IV	–0.23
9270	3.61	0.98	G7IIIa	
10700	3.50	0.72	G8V	–0.60
12311	2.90	0.24	F0III-IV	
15798	4.75	0.45	F5V	0.00
20630	4.83	0.68	G5V	0.04
20794	4.27	0.71	G8V	–0.54
20807	4.54	0.60	G1V	0.10
22484	4.28	0.58	F9IV-V	
26690	5.29	0.36	F3V	
26965	4.41	0.82	K0.5V	–0.34
27256	3.35	0.91	G8II-III	
30652	3.19	0.45	F6V	0.11
32887	3.19	1.46	K4III	
36079	2.84	0.82	G5II	
36673	2.58	0.21	F0Ib	–0.12
38393	3.60	0.47	F7V	–0.14
40136	3.70	0.34	F1V	–0.20
45348	-0.72	0.15	A9II	–0.03
50877	3.87	1.74	K2Iab	0.20
54605	1.80	0.72	F8Ia	0.01
61421	0.34	0.40	F5IV-V	0.01
63700	3.35	1.25	G6Iab-Ib	0.24
67594	4.34	0.97	G2Ib	
69267	3.52	1.48	K4III	0.21
74006	3.97	0.94	G7Ib-II	
75691	4.01	1.27	K2.5III	
76294	3.11	1.00	G9IIIa	–0.12
78647	2.21	1.66	K4.5Ib	0.23
79940	4.62	0.45	F5III	
81797	1.98	1.44	K3IIIa	–0.19
84441	2.98	0.80	G1II	–0.11
89388	3.40	1.54	K2.5II	0.54
90772	4.66	0.51	A9Ia	
90853	3.82	0.31	F0Ib	
91942	4.45	1.62	K3.5II	
100261	5.13	1.08	G3O-Ia	
101947	5.06	0.77	G0O-Ia	
102365	4.89	0.68	G3V	–0.53
102870	3.61	0.55	F9V	0.06
105707	3.00	1.33	K2.5IIIa	
109379	2.65	0.89	G5IIb	
113226	2.83	0.94	G8IIIab	–0.04
115617	4.74	0.71	G6.5V	–0.02
117176	5.00	0.69	G4V	–0.11
121370	2.68	0.58	G0IV	0.17
123139	2.06	1.02	K0IIIb	0.03
124897	-0.04	1.23	K1.5III	–0.38
128620	-0.01	0.71	G2V	0.11
141004	4.43	0.60	G0V	–0.04
145544	3.80	1.16	G2Ib-IIa	0.10
147675	3.89	0.91	G9III	–0.05
156026	6.34	1.16	K5V	–0.34
161797	3.41	0.76	G5IV	0.32

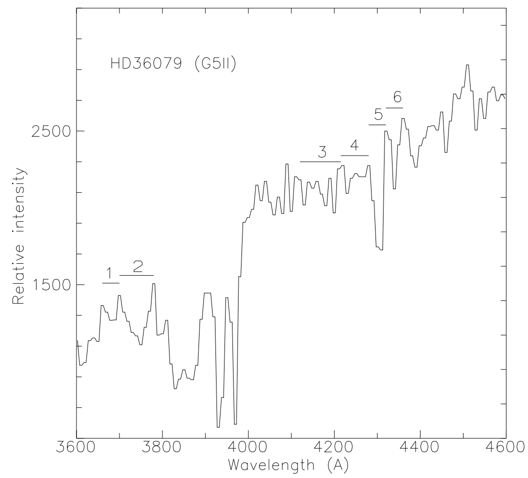

Fig. 1a. The spectrum of HD36079 (G5 II) obtained with the Bochum photoelectric scanner for the wavelength region 3600 - 4600Å. The intervals selected for measurements were marked with the horizontal bars.

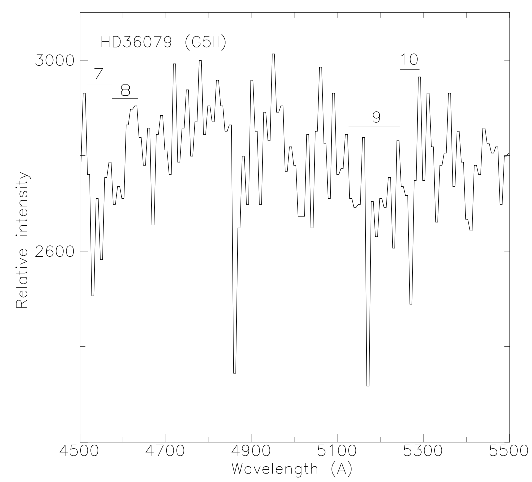

Fig. 1b. The same as in Fig. 1a but for the wavelength region 4500 - 5500Å.

Spectrum (Moore et al., 1966) to identify the features. An example is presented in Figs. 1a-1b. Each interval includes at least four channels of 10Å each. Table 3 contains the list of classification indices. Two of them (No. 2 and 4) are the same as the quantities M/T and G/H in Paper I, respectively.

The internal accuracy of the indices was estimated from repeated measurements (two stars have been measured four times, four stars have three times and three stars two times). The averaged rms errors of one measurement for each index (expressed in percent) are given in Table 3. The accuracies of these errors have been estimated, too. We see that these estimates seem to be real and show good internal consistency (about 1 per cent on the average). Table 4 contains the averaged values of the classification indices used in our analysis.

To analyse our measurements as a function of MK classification, the discrete values of MK spectral and luminosity

Table 2. The border wavelengths for the intervals in Å

Interval No.	Left side	Right side	$\Delta\lambda$	Prominent features (λ in Å)
1	3660	3700	40	3680, FeI; 3685, TiII; 3687, FeI
2	3700	3780	80	3720, 3735, 3749, FeI; 3750, 3771, HI
3	4120	4215	95	4132, FeI; 4176-200, FeI,CN; 4215, CN
4	4215	4280	65	4227, CaI; 4253, CrI, FeI; 4272, FeI
5	4280	4320	40	4290, CrI; 4299, CH, FeI; 4308, CH, FeI
6	4320	4360	40	4340, HI
7	4515	4575	60	4528, FeI; 4549, FeII, TiII
8	4575	4635	60	4582, CaI, FeI; 4602-3, CrI, FeI
9	5125	5245	120	5134-52, FeI; 5172, MgI; 5210, CrI; 5227-33, FeI
10	5245	5290	45	5270, FeI, CaI

Table 3. The classification indices (the ratios of measurements in the intervals)

Indice No.	Interval No. (from Table 2)	Wavelengths for intervals in Å	Difference of mean wavelengths	Criterion rmserror in per cent
1	1/2	(3660-3700)/(3700-3780)	60	3.4±1.2%
2	3/4	(4120-4215)/(4215-4280)	80	1.8±0.6
3	4/6	(4215-4280)/(4320-4360)	92	1.0±0.4
4	5/6	(4280-4320)/(4320-4360)	40	2.0±0.7
5	7/8	(4515-4575)/(4575-4635)	90	0.7±0.2
6	9/10	(5125-5245)/(5245-5290)	83	0.7±0.3

classes were transformed into numerical codes which vary continuously. The numerical spectral codes for spectral classes were the same introduced earlier by West (1970): F0 = 4.0, G0 = 5.0, K0 = 6.0. For MK luminosity classes we used the following luminosity codes : V = 7.0, IV = 6.0, III = 5.0, II = 4.0, Ib = 3.0, Iab = 2.0, Ia = 1.0, IaO = 0.5. To check how these codes are connected with the continious main physical parameters, we plotted effective temperatures against spectral codes for MK luminosity classes V, III and I (Fig. 2), and absolute magnitudes against luminosity codes for MK spectral classes F0, G0 and K0 (Fig. 3) from the MK calibration by Schmidt-Kaler (1982). These figures show that the dependences are different but they are rather smoth. It means that, if necessary, one may relate codes with these main physical parameters. However we prefer to use here the MK types which are directly determined physical parameters. The diagram "Spectral codes against luminosity codes" for our standard stars is presented in Fig. 4. We see that the stars are rather uniformly distributed along the spectral and luminosity classes.

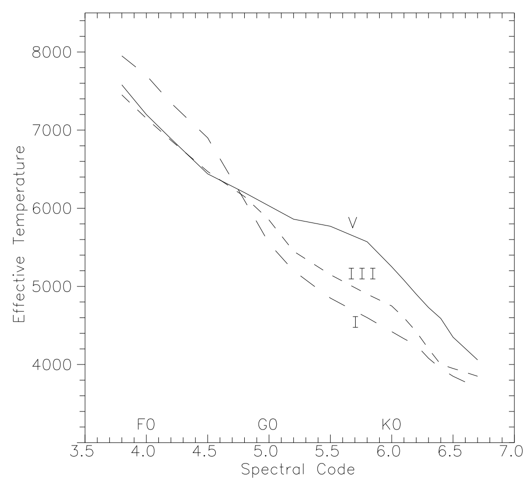

Fig. 2. The diagram "Effective temperatures against spectral codes" by Schmidt-Kaler (1982). The solid line corresponds to luminosity class V, the short-dashed line to luminosity class III, the long-dashed line to luminosity class I

Our standards are classified in the literature as normal stars in the MK system (see Table 1); therefore we may suggest that these stars have nearly normal metallicities. In fact the [Fe/H] values are known from the literature for the majority of them (see the same Table) and indeed a few stars only have moderate metal deficiency ([Fe/H] between -0.3 and -0.6). We found no metallicity effects in our diagrams. Therefore with good reason the metallicity parameter may be ignored in the present analysis.

The results of measurements were presented in the form of diagrams "indices against spectral codes". Two examples may be found in Paper I. Some indices are sensitive mainly to spectral

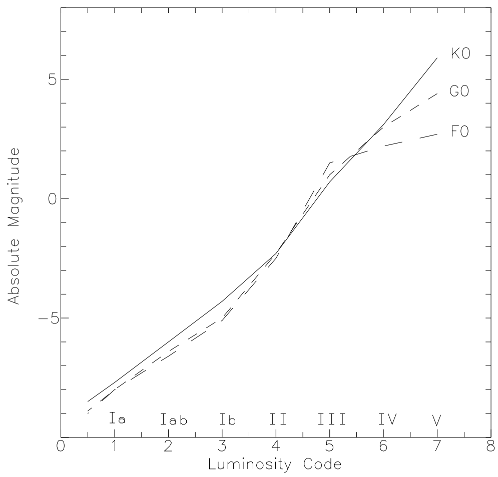

Fig. 3. The diagram "Absolute magnitudes against spectral codes" by Schmidt-Kaler (1982). The solid line corresponds to spectral class K0, the short-dashed line to spectral class G0, the long-dashed line to spectral calss F0

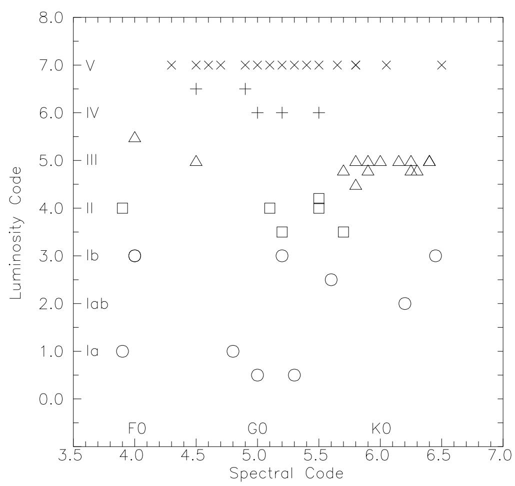

Fig. 4. The diagram "Luminosity codes against spectral codes" for the standard stars. Both MK types and codes are given. The following designations are used: crosses - luminosity class V, plus signs - IV-V, IV, triangles - III, II-III, squares - II, I-II, circles - I, Ia-O

class, whereas other ones are responsive also to luminosity class. It seems reasonable to combine the indices which behave similarly respect to spectral and luminosity classes. Judging from the diagrams "indices against spectral codes", the indices 3. 4 and 6 (see Table 3) were averaged (each of them is sensitive to spectral class but only slightly dependent on luminosity class), the quantity

$$I_S = 2.5\log(ind_3 + ind_4 + ind_6)/3)$$

is treated as the spectral class index. In Fig. 5 the index I_S was plotted against spectral classes (codes). We see that this index is connected very tightly with spectral class except for supergiants which deviate slightly and are more scattered.

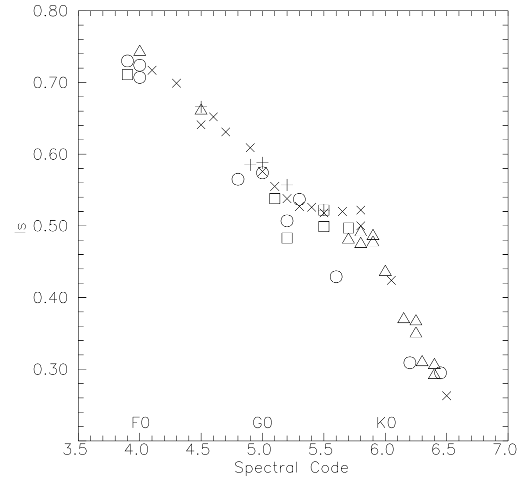

Fig. 5. The diagram "I_S against spectral codes" for the standard stars. The designations are the same as in Fig. 4

We found unreasonable to combine the indices sensitive to luminosity class because of their different behaviour in the diagrams "indices against spectral codes" and we treated them individually. For three indices (No. 1, 2 and 5 in Table 3, which are most sensitive to luminosity effects) the quantities

$$I_1 = 2.5\log ind_1, I_2 = 2.5\log ind_2, I_3 = 2.5\log ind_5$$

were calculated and are considered here as luminosity class indices.

Our experience with classification indices (Malyuto, Oestreicher, Schmidt-Kaler, 1996) has shown that two-index diagrams (one index against the other) are well suited for classification purposes, if a luminosity sensitive index is plotted against a temperature sensitive one (the luminosity effects are more pronounced and the data scatter are smaller than in case of diagrams "indices against MK spectral codes"). In two-index diagrams both measurements are performed almost simultaneously and therefore possible spectral variations only slightly influence these diagrams. One uncertain physical parameter (MK spectral class) is not involved in diagrams if we are interested only in determination of luminosity classes.

In Figs. 6, 7 and 8 the two-index diagrams are given where luminosity sensitive indices I_1, I_2 and I_3, respectively, were plotted against the spectral type indice I_S. We see that the two-index diagram in Fig. 6 are useful only in separating supergiants from other stars. The luminosity effects are more pronounced in Figs. 7 and 8 and the corresponding diagrams may be used in determining luminosities if $I_S < 0.6$ (for G-K spectral classes if we judge from Fig. 5).

3. Definition of the linear regression model

A mathematical apparatus has been developed by Malyuto and Shvelidze (1989) to elaborate the scheme of automated quantitative spectral classification with the use of classification criteria

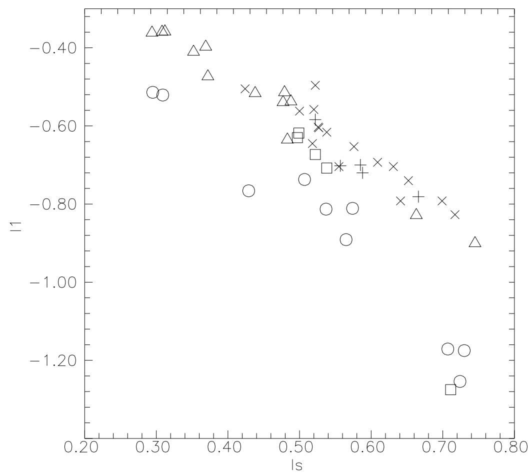

Fig. 6. The diagram "I_1 against I_S" for the standard stars. The symbols are the same as in Fig. 4

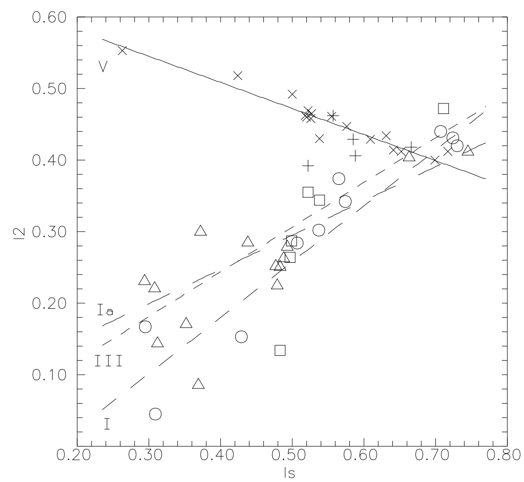

Fig. 7. The diagram "I_2 against I_S" for the standard stars. The symbols are the same as in Fig. 4. The different lines describe curves of constant luminosity class (V, III, I and Ia), see the next section

based on Abastumani objective prism spectra. This approach contains the statistical method of stepwise linear regression enabling us to define the analytical dependences between classification criteria and the main physical parameters. The method has been successfully applied to the Strömgren photometric data (Malyuto, 1994) for F-stars and to spectrophotometric data obtained with the RUBIKON device for M-stars (Malyuto, Oestreicher, Schmidt-Kaler, 1996).

Multiple linear regressions for analytical representation of various dependences are widely used in astronomy (see, e.g., Heck 1983) as well as in other natural sciences. We used the regression model:

$$Y = b_o + \sum_{k=1}^{q} b_i x_i,$$

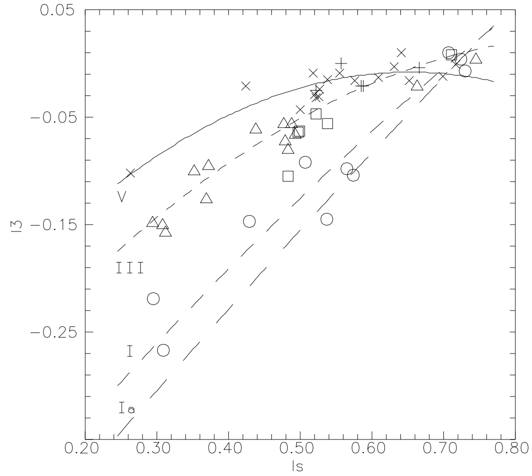

Fig. 8. The diagram "I_3 against I_S" for the standard stars. The designations are the same as in Fig. 7

where Y are the dependent variable (in this context - luminosity class sensitive classification index, I_2 or I_3, described in the previous section), x_i are independent variables (spectral class sensitive classification index I_S and luminosity codes L and/or functions of these parameters), b_0, b_i are regression coefficients. q is the number of independent variables.

A statistical method of stepwise linear regression is meant for introducing a redundant set of independent variables and applying a stepwise procedure for choosing the best subsets of independent variables. Some statistical packages containing algorithms of stepwise linear regression have been elaborated and applied by investigators to various statistical tasks (see, e.g., Afifi, Azen, 1979). In astronomy, one may refer to Heck and Merch (1980) where the well-known package BMDP has been used to select a subset of the most significant variables in their linear model used in predicting spectral classifications from photometric observations. Another sample of appling stepwise linear regression technique may be found in the paper of Schuster and Nissen (1989) where the package MINITAB has been applied to Strömgren photometric data.

In defining our linear regression model we use the software package CTATEC-5 (Tiits et al., 1986), based on Jennrich's (1977) scheme of calculating partial correlation coefficients. Some details, as well as an example, may be found in Malyuto (1994). Our initial redundant set of the independent variables was rather arbitrary and was inspired by the visual appearance of Figs. 7 and 8. We tried the full polynomial with powers up to the third order together with their products (I_S, ${I_S}^2$, ${I_S}^3$, L, L^2, L^3, $I_S L$, ${I_S}^2 L$, $I_S L^2$, the total number of the terms was nine) and we found the approach to be quite satisfactory.

The method of stepwise linear regression has been applied to each of the diagrams in Figs. 7 and 8 from Sect. 2. As a result we have obtained the following analytical model (Fig. 7):

$$I_2 = 0.359 - \underset{0.911}{0.361 L} + \underset{0.908}{0.0576 L^2} + \underset{0.891}{0.567 I_S L} - \underset{0.876}{0.088 I_S L^2},$$

with the multiple correlation coefficient R=0.949. The respective partial correlation coefficients for each term are given in the second row.

The analytical model for the data in Fig. 8 is

$$I_3 = 0.595{+}0.819I_S{+}0.053L{-}0.00015L^3{-}0.090LI_S^2,$$
$$\qquad 0.960 \qquad 0.916 \qquad 0.525 \qquad\qquad 0.888$$

the multiple correlation coefficient is R=0.985. All terms are significant on the 95% significance level.

We see from Fig. 7, that the index I_2 is good for luminosity classification of stars of luminosity classes V and IV and their segregation from stars of higher luminosities (with $I_S < 0.6$). But the model lines are mixed among giants and supergiants and reliable luminosity classification is impossible in that region of the diagram. On the contrary, in Fig. 8 the scatter is somewhat larger for dwarfs. The model lines are well segregated among giants and supergiants and the index I_3 is good for luminosity classification in the respective region of the diagram (again with $I_S < 0.6$). Combination of the indices I_2 and I_3 seems to be effective in luminosity classification of all luminosity classes.

The model lines in Figs. 7 and 8 were used for graphical inversion of the model (in other words to calculate luminosity codes from the measured indices for our standard stars). The rms differences (published minus calculated luminosity codes) were

0.81 of luminosity codes (41 stars, $I_S < 0.6$).

from the diagram in Fig. 8 (the luminosity sensitive indice I_3 were used). As expected, the scatter is larger for stars of luminosity classes IV and V (see the data comparison in Fig. 9).

From the diagram in Fig. 7 the luminosity codes were calculated with the use of the luminosity indice I_2 (only for stars with $I_2 > 0.38$, where stars of luminosity class IV and V are located). If we combine these data with the data from Fig. 8 for the remaining stars, the respective rms difference is only

0.41 of luminosity codes (41 stars, $I_S < 0.6$).

In Fig. 9 the calculated luminosity codes were plotted against published ones, different designations were used for the codes determinations from Fig. 8 (crosses) and from Fig. 7 (circles). We conclude that the combination of the diagrams in Fig. 7 and 8 provides a refined luminosity classification for G-K stars of all luminosity classes.

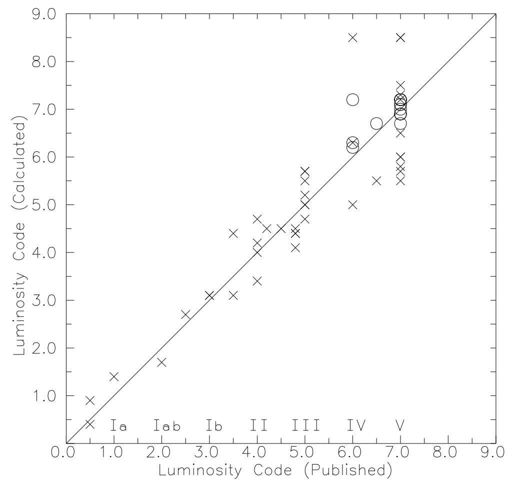

Fig. 9. Comparison of the published luminosity codes with the codes calculated from the index I_3 (crosses) for all stars and with the codes calculated from the index I_2 (circles) for the stars with $I_2 > 0.38$ (luminosity classes IV and V). Only the stars with $I_S < 0.6$ are considered

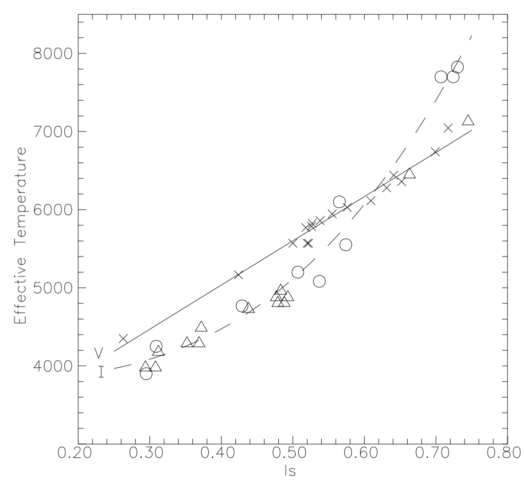

Fig. 10. The diagram "Effective temperatures against I_S" for the standard stars of luminosity classes I (circles), III (triangles) and V (crosses). The solid line corresponds to luminosity class V, the long-dashed line - luminosity class I

4. Analysis of MK spectral classes

MK spectral classes were not discussed in the previous section and should be treated separately. We have seen from Fig. 5 of Sect. 2 (where the spectral type index I_S was plotted against spectral classes), that this index is connected very tightly with spectral classes (except for supergiants). But the relationship for dwarfs is non-linear. This relationship reminds us of the solid line in Fig. 2 of Sect. 2 (the MK calibration "effective temperatures against spectral classes" for dwarfs). Therefore we may guess that the dependence "effective temperatures against I_S" for dwarfs should be very simple (almost linear). Fig. 10 confirms our expectations. Appling the method of stepwise linear regression (see the previous section) to these data we found the following very simple analytical dependences (demonstrated in Fig. 10):

$$T_{eff} = 2771 + 5660 I_S$$

for 17 stars of luminosity class V (R= 0.988) and

$$T_{eff} = 3802 + 10497 {I_S}^3$$

for 10 stars of luminosity class I (R = 0.988), the rms differences (published minus calculated values) being equal to about 100 K and 240 K, respectively.

We may guess from Fig. 10 that giants (triangles) should follow to same relationship as supergiants (circles) if $I_S < 0.6$, but the same relationship as dwarfs (crosses) if $I_S > 0.6$. Subgiants (luminosity cass IV) and bright giants (luminosity class

II) are absent in this Fig. because there are no calibration lines for these classes in MK calibration data by Schmidt-Kaler (1982). Any interpolation with available calibrations seems to be very uncertain (up to 600 K) and a new calibration for the intermediate luminosity classes is very desirable (as well as improved calibrations for other luminosity classes).

Since the calibration of MK spectral types against effective temperatures and absolute magnitudes set up by Schmidt-Kaler (1982), many new data became available (or will be available in the nearest future). As to MK spectral classes, the most important new source is the catalogue of MK spectral types for 963 standard stars compiled by Garcia (1989). The more recent Perkins catalogue of revised MK types for the 1054 G, K, M standard stars by Keenan and McNeil (1989) should be added. New refined MK classifications have been published for about 200 earlier type (A and F) stars by Garrison (1989) and Gray and Garrison (1989), authors who work very closely to the Morgan and Keenan's system.

To calibrate MK types against abslolute magnitudes the Hipparcos catalogue of very accurate trigonometric parallaxes is undoubtedly an invaluable source. For distant supergiants with uncertain trigonometric parallaxes, information about their membership in clusters may be useful in estimating absolute magnitudes, and this information may be derived from another invaluable source - the Simbad database operated at Strasbourg, France, which containes references for a huge amount of stars.

Our spectral indices may be used in future MK calibration to smooth and interpolate the MK data. Application of indices from non-photographic spectral wavelength ranges may help to recognize binaries and peculiar stars. Future MK calibration will help in improving spectral classification techniques and will be used in many other fields of astronomy.

5. Conclusions

New criteria of quantitative spectral classification have been introduced and the method of stepwise linear regression to these criteria for quantitative spectral classification of stars has been applied by means of the Bochum photoelectric spectra. The desirablity of a new MK calibration has been motivated. We hope to continue the analysis with the use of the additional Bochum data. Our technique may equally well be applied to other similar sets of spectral data (atlases of MK standards, stellar spectral libraries, etc.)

Acknowledgements. This work was done during a stay of one of us (V.M.) at Bochum, which was kindly financed by Kernforschungszentrum Karlsruhe / Internationales Büro Bonn, whose help is gratefully acknowledged. V.M. acknowledges also support in the form of a grant from Estonian Science Foundation. We are grateful to the referee for valuable suggestions and remarks which radically improved the paper. This research has made use of the Simbad database, operated at CDS, Strasbourg, France.

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