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QUANTITATIVE STELLAR SPECTRAL CLASSIFICATION. IV. APPLICATION TO THE OPEN CLUSTER IC 2391

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RESUMEN

En este trabajo realizamos la primera prueba de un método de clasificación espectral estelar (Stock & Stock 1999), aplicándolo a estrellas tempranas. La muestra contiene estrellas miembros del cúmulo abierto IC 2391, para las cuales se dispone de espectros de alta resolución del Projecto UVES del Observatorio Paranal. Mostramos que, en general, las magnitudes absolutas M_V y los colores intrínsecos $(B-V)_0$ pueden ser recuperados dentro de los errores predichos por la calibración original (~ 0.4 para las magnitudes y ~ 0.03 para los colores). Este tipo de precisión nos permite estimar las distancias de estrellas individuales e inferir su membresía, para así obtener una distancia promedio al cúmulo de 156 ± 24 pc, en muy buena concordancia con valores reportados previamente. Finalmente discutimos las ventajas y dificultades de usar este método y cómo puede ser mejorado para su implementación en estudios futuros.

ABSTRACT

In this work we perform the first test of a stellar spectral classification method (Stock & Stock 1999) by applying it to early type stars. The sample of stars are the members of the open cluster IC 2391 that have high-resolution spectra available in the UVES Project of Paranal Observatory. We show that, in general, absolute magnitudes M_V and intrinsic colors $(B-V)_0$ can be recovered within the uncertainties stated in the original calibration (~ 0.4 for the magnitudes and ~ 0.03 for the colors). This accuracy allows us to estimate distances and to infer membership of individual stars to obtain an average distance to the cluster of 156 ± 24 pc, which is in good agreement with previously reported determinations. Finally, we identify and discuss the real strengths and limitations of this method and we suggest how it can be improved for future studies.

Key Words: methods: data analysis — open clusters and associations: individual (IC 2391) — stars: fundamental parameters, classification

1. INTRODUCTION

The absolute magnitude and the intrinsic color are the main quantities to describe stars. The first provides the amount of energy emitted, and combined with the apparent magnitude gives an estimate of the distance to the object. The second is directly related to the temperature of the atmosphere of the star. These properties are expected to imprint themselves on the optical band of the spectrum, especially through the absorption lines of different species. Spectral classification methods are favored to infer these parameters by inspection of those absorption profiles, often by visual inspection, as is the case for the MK system. New *quantitative* classification methods are needed to improve the results and to provide consistency in the process. Many authors have pointed out the need for a fully automated system to classify stellar spectra (see for example the reviews by Bailer-Jones 2002; Allende Prieto 2004; Giridhar, Muneer, & Goswami 2006). Automated systems are more homogeneous (and therefore more appropriate) for the classification of a large number of stars on the basis of a self-consistent system.

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Due to the progress of astronomical instrumentation and the increase of the data acquisition rate, new automated and efficient systems are constantly being developed and improved in order to classify stellar spectra and/or to infer stellar atmospheric parameters from spectral profiles (recent examples include Christlieb, Wisotzki, & Graßhoff 2002; Allende Prieto 2003; Bai, Guo, & Hu 2005; Zhang et al. 2005; Recio-Blanco, Bijaoui, & Laverny 2006; Re Fiorentin et al. 2007). An example of this kind of systems is the method proposed by Stock & Stock (1999, hereafter SS99). This method is based on the determination of a spectral index defined by two external bands placed at each extreme of a central band (Worthey et al. 1994). This index is related to the stellar parameters through second order polynomials. The calibration of this (and any) method is performed by comparing the defined indices with physical parameters of interest, such as the absolute magnitude M_V or the color index $(B-V)_0$. The errors in these parameters will propagate in the resulting calibration, so that in the best case one would expect the results to be as accurate as the data used for calibration. Using the SS99 method it is possible, in theory, to derive absolute magnitudes and intrinsic colors with average uncertainties of ~ 0.3 and ~ 0.02 magnitudes, respectively. This is a reasonably good accuracy taking into account the simplicity of the method, which does not require large computational resources. Another advantage of this method is its relatively low sensitivity to the spectral type. In general, the morphological differences in the spectra of early-type and late-type stars can lead to problems when defining robust indices. The results found in SS99 showed that, on average, the residuals did not vary significantly for stars of different spectral types (in the range A-K). This is due to the fact that there is no need to determine the underlying true continuum. The extension of the method to B-type stars was done by Stock et al. (2002, hereafter SS02). In a subsequent paper, Molina & Stock (2004) applied the same technique to a sample of stars within the spectral types K-M. The effects of variations in the spectral resolution on the sensitivity of the method were analyzed by García et al. (2005). They showed that the method can be applied to low resolution spectra without loss of accuracy and that small variations in the spectral resolution do not affect the determination of the physical parameters for early-type stars. However, their results also established that for late-type stars the method needs to be improved.

To date the proposed method (SS99) has not been used to derive physical parameters for any sample of stars, other than the same stars used for the calibration. In this paper we perform the first test of the method by its application to the stars in an open cluster. Our main goal is to evaluate the method in order to identify its strengths and limitations. The open cluster chosen for this study is IC 2391, since high resolution spectra for ~ 50 possible members are available from the UVES Paranal Observatory Project (Bagnulo et al. 2003). Another reason to choose this cluster is the large amount of studies published in the few last years, which allow us to verify the results obtained using the SS99 method and to compare them with previous work.

This paper is organized in the following way. In § 2 we briefly explain the method used to determine the stellar parameters. In § 3 we describe the sample of stars to which the method is applied. The results obtained are shown in § 4, where a detailed analysis leads us to propose some improvements to the method, which allow us to determine the stellar parameters and to compare them with literature values. Finally, the main conclusions are summarized in § 5.

2. METHOD FOR OBTAINING STELLAR PARAMETERS

It is worthwhile to start by briefly explaining the SS99 method. The first part of the method consists in establishing a series of absorption lines that might provide information on the stellar physical properties. For each line a spectral index (w) is calculated following a procedure similar to the one used by Worthey et al. (1994). For a given line, an inner region (the line itself) and two outer regions (one on each side of the line) are selected based on visual inspection of representative spectra of each spectral type. The complete list of lines and their limits can be found in SS99 and SS02. A linear interpolation between the average fluxes of the outer regions provides a local continuum (or pseudo-continuum). The value of the index w for each absorption line is given by the integration of the inner region:

$$w = \int_{\lambda_1}^{\lambda_2} \frac{F_c - F_\lambda}{F_c}\, d\lambda\,, \qquad (1)$$

where F_c represents the flux in the local continuum and F_λ is the flux in the line between the integration limits.

In the previous papers (SS99, SS02) the authors used first, second and third order polynomials to relate the defined indices to the physical parameters to be recovered. The calibration (i.e., the determination of the coefficients of the polynomials) was made

TABLE 1

STARS IN THE OPEN CLUSTER IC 2391 USED IN THIS WORK ACCORDING TO THEIR CORRESPONDING GROUP (SS99)

Group 1					
Star	Id	Spec. Type	Star	Id	Spec. Type
HD 73287	1	B7V	HD 74275	23	A0V
HD 73503	2	A0V	HD 74516	29	A1V
HD 73681	3	A1V	HD 74535	31	B8s
HD 73952	8	B8Vn	HD 74560	34	B3IV
HD 74146	16	B4IV	HD 74955	41	A1V
HD 74168	17	B9p	HD 74999	42	A1V
HD 74071	13	B5V	HD 75067	45	B8/B9IV/Vn
HD 74196	21	B7Vn	HD 75105	46	B8III/IV
HD 74195	20	B3IV	HD 75184	47	A1V
HD 74169	18	A0IVp	HD 75466	50	B8V
Group 2					
Star	Id	Spec. Type	Star	Id	Spec. Type
HD 73722	4	F5V	HD 74582	36	F3III
HD 73778	5	F0V	HD 74762	40	A5V
HD 74009	10	F3V	HD 75029	43	A2/A3m
HD 74044	11	A3m	HD 75202	49	A3IV
HD 74117	14	F2IV/V	IC 2391-H5	51	F5V
HD 74182	19	A5IV	IC 2391-52	52	F6V
HD 74537	33	A3IV	SHJM 2	73	G2
HD 74561	35	F3V			

by the least squares method. The best results were obtained with second order polynomials with three different lines as independent variables. Thus, if w_1, w_2 and w_3 are the calculated indices of three given lines then the polynomial relating a physical parameter PP (namely the absolute magnitude or the intrinsic color) to these indices is given by

$$PP = a_1 + a_2 w_1 + a_3 w_2 + a_4 w_3 + a_5 w_1^2 + a_6 w_2^2 + a_7 w_3^2 + a_8 w_1 w_2 + a_9 w_1 w_3 + a_{10} w_2 w_3 \,. \quad (2)$$

The information associated to each combination of lines and their coefficients a_i ($i = 1, ..., 10$) can be found in SS99 and SS02.

It is important to remark that the stars used in SS99 were divided into four different groups (numbered from 1 to 4). This separation is based on the profile of certain lines, representative of different ranges of color. The range of spectral types is approximately B9-A2 for stars in Group 1, F0-G5 for Group 2, G0-K0 for Group 3, and K0-M5 for Group 4. Nevertheless, stars belonging to Group 1 were excluded from the calibration in SS99 due to insufficient sample size. The calibration for this group was done independently (using a new sample of stars) and reported in SS02. Therefore, the SS99 polynomials should be used for stars belonging to Groups 2, 3 and 4; while for those stars in Group 1 the polynomials in SS02 are more appropriate.

3. THE SAMPLE OF STARS

The stellar spectra used in this work were obtained from the public database of the UVES Paranal Observatory Project[5] (Bagnulo et al. 2003). These spectra are characterized by a high signal to noise ratio ($S/N \sim 300 - 500$ for the V band), high spectral resolution ($R = \lambda/\Delta\lambda \sim 80000$), and a wide range of wavelengths ($3040 - 10400$ Å). The UVES library contains a total of 48 (presumed) members of the open cluster IC 2391 with available data in the spectral range of interest for this work. According to the SS99 criteria, 20 of these stars were classified into Group 1, 15 into Group 2, and the rest into Groups 3 and 4. The later two groups were excluded from the present analysis because these groups are more sensitive to resolution variations and their analysis

[5] http://www.sc.eso.org/santiago/uvespop.

TABLE 2

ABSOLUTE MAGNITUDES FOR THE STARS IN GROUP 1 OBTAINED WITH EACH COMBINATION DEFINED IN SS02

Id	I	II	III	IV	V	VI	VII	VIII	IX	X	$\overline{M_V}$	σ_M
1	2.52	0.13	0.70	−0.36	−0.17	−0.77	0.64	0.03	0.43	−0.74	0.24	0.95
2	12.17	3.88	4.77	1.94	3.09	0.16	2.65	−0.82	3.61	0.04	3.15	3.66
3	12.66	3.88	4.87	0.95	3.09	0.28	3.19	0.00	6.40	0.37	3.57	3.85
8	6.06	1.08	1.68	0.39	0.62	−0.34	1.37	0.13	1.70	−0.43	1.23	1.86
13	1.70	−0.43	−0.07	−0.86	−0.76	−1.13	0.55	0.16	1.05	−1.09	−0.09	0.96
16	1.60	−0.62	−0.55	−0.98	−0.84	−1.16	0.34	−0.34	0.07	−1.03	−0.35	0.84
17	3.32	0.34	0.71	−0.24	−0.01	−0.51	0.79	0.08	0.74	−0.59	0.46	1.12
18	6.60	1.88	2.64	1.11	1.42	0.08	2.31	0.29	3.77	0.20	2.03	1.99
20	−0.40	−1.74	−1.86	−2.04	−2.00	−1.85	−0.35	−1.07	−0.35	−1.92	−1.36	0.74
21	1.34	−0.48	−0.02	−0.54	−0.74	−1.10	0.15	−0.17	−0.11	−1.08	−0.28	0.71
23	12.41	3.93	4.84	0.98	3.11	0.16	2.61	−0.78	3.71	−0.02	3.10	3.78
29	13.50	4.15	5.12	2.16	3.33	0.16	2.79	−1.00	4.03	−0.02	3.42	4.07
31	1.35	−0.34	−0.12	−0.81	−0.59	−0.71	0.22	−0.09	0.02	−0.79	−0.19	0.65
34	0.29	−1.08	−1.15	−1.44	−1.40	−1.35	0.29	−0.23	0.78	−1.35	−0.66	0.86
42	12.49	3.68	4.51	2.46	2.77	0.17	2.89	0.14	6.37	0.21	3.57	3.73
41	12.26	3.92	4.64	1.94	3.05	0.25	2.93	0.07	6.23	0.37	3.57	3.66
45	2.74	0.32	0.73	0.15	−0.03	−0.63	0.57	0.03	0.47	−0.71	0.36	0.96
46	1.95	−0.15	0.31	−0.66	−0.48	−0.88	0.33	−0.07	0.15	−0.94	−0.04	0.84
47	13.20	4.04	4.98	2.07	3.22	0.30	2.72	−0.91	3.96	−0.02	3.36	3.96
50	4.31	0.91	1.54	0.30	0.53	−0.45	1.12	−0.12	1.10	−0.43	0.88	1.38

would require a new calibration of the method using similar resolution spectra (as it was shown in García et al. 2005). Therefore, our preliminary sample consists of 35 stars which are shown in Table 1. This table contains the star identification, the Id number assigned by Perry & Hill (1969) (in this paper we use this number to identify the stars), the spectral type, and the assigned group according to SS99 criteria.

4. RESULTS AND DISCUSSION

4.1. *Application to the Open Cluster IC 2391*

Following the procedure described in § 2, we have calculated the indices for each one of the 19 lines defined in SS99 (for the stars belonging to Group 2), and for each one of the 12 lines of SS02 (Group 1). Once all these indices were calculated, we determined the physical parameters M_V and $(B-V)_0$ using equation (2) with the coefficients given in SS99 and SS02. The obtained results are shown in Tables 2, 3, 4 and 5. In these tables we include the values of M_V and $(B-V)_0$ resulting for each star when using each of the line combinations (indicated with Roman numbers), defined in SS02 for Group 1 and in SS99 for Group 2. The tables also show, in the last two columns, the averages of all the combinations for each star ($\overline{M_V}$ and $\overline{(B-V)_0}$) and their respective standard deviations (σ_M and σ_0).

In principle, one would expect that for each star the results would not differ significantly for different combinations. This is because these are the best combinations of the method in the sense that they are the combinations with the smallest average residuals r_{av} obtained from the polynomial calibration (SS99, SS02). Nevertheless, we can notice from Tables 2–5 that some combinations of lines differ considerably from others and/or from the corresponding average value. As a consequence, there are relatively large standard deviations for some of the obtained parameters. Remarkable, in particular, is the anomalous behavior of Combination I in Table 2 which corresponds to the combination of lines Hδ, Hγ, and Hβ (SS02). The value obtained for each star using Combination I differs significantly from the values of other combinations. This behavior is observed for all the stars in Table 2, but it is especially evident for stars of spectral type A, for which $M_V > 12$ in all cases. These particular results are extremely anomalous since the typical values for the absolute magnitudes of type A stars lie between 0.3 and 2.4 magnitudes. The values of M_V listed in

TABLE 3

ABSOLUTE MAGNITUDES FOR THE STARS IN GROUP 2 OBTAINED WITH EACH COMBINATION DEFINED IN SS99

Id	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	XIII	$\overline{M_V}$	σ_M
4	2.38	3.21	2.65	3.27	2.77	3.17	3.14	2.70	3.15	3.04	2.63	2.44	3.06	2.89	0.31
5	2.90	3.29	2.87	3.04	2.48	2.99	3.08	2.23	2.95	2.95	2.08	1.80	2.96	2.74	0.45
10	2.79	3.81	3.13	3.39	3.13	2.86	3.13	2.71	3.02	3.06	2.64	2.57	2.98	3.02	0.33
11	1.33	0.93	1.18	0.79	0.43	0.04	−0.29	−0.79	1.69	1.24	1.08	1.22	0.39	0.71	0.72
14	2.82	3.09	2.88	3.07	2.38	2.65	3.14	2.11	2.76	3.01	1.92	1.65	2.97	2.65	0.49
19	3.49	2.19	3.65	2.91	3.11	1.99	2.18	1.83	2.96	3.24	2.65	2.12	2.06	2.64	0.62
33	2.90	2.15	3.36	1.30	1.38	−0.14	−0.24	−0.60	2.66	2.68	1.97	1.91	0.46	1.52	1.30
35	2.98	3.59	3.19	3.56	2.95	3.06	3.44	2.70	3.19	3.37	2.60	2.44	3.33	3.11	0.36
36	1.01	2.06	1.18	1.84	0.78	0.71	1.54	0.73	0.83	0.99	0.42	0.44	1.48	1.08	0.52
40	3.33	0.83	3.75	3.10	2.93	−0.55	−0.80	−0.62	2.96	2.86	2.61	2.12	0.38	1.63	1.80
43	2.30	2.27	2.44	2.01	1.12	1.24	1.47	0.48	2.06	2.36	1.36	1.38	1.60	1.70	0.59
49	3.53	0.33	4.21	2.46	2.78	−0.91	−1.02	−0.64	3.15	3.27	2.88	2.62	0.27	1.76	1.87
51	3.11	4.30	3.61	4.08	3.56	3.39	3.63	3.14	3.56	3.68	3.17	2.94	3.58	3.52	0.38
52	2.91	3.46	3.15	3.60	3.10	3.36	3.61	2.94	3.41	3.61	2.91	2.77	3.53	3.26	0.31
73	3.06	5.00	4.02	4.70	3.57	3.57	3.75	3.06	4.02	4.06	3.38	3.09	3.80	3.78	0.60

TABLE 4

INTRINSIC COLORS FOR THE STARS IN GROUP 1 OBTAINED WITH EACH COMBINATION DEFINED IN SS02

Id	I	II	III	IV	V	VI	VII	VIII	IX	X	$\overline{(B-V)}_0$	σ_0
1	−0.167	−0.141	−0.152	−0.148	−0.149	−0.144	−0.141	−0.143	−0.141	−0.136	−0.146	0.009
2	−0.254	−0.125	−0.194	−0.046	−0.096	−0.087	−0.118	−0.031	−0.187	−0.101	−0.124	0.069
3	−0.268	−0.279	−0.186	−0.054	−0.146	−0.102	−0.136	−0.045	−0.237	−0.131	−0.158	0.083
8	−0.173	−0.139	−0.141	−0.052	−0.118	−0.125	−0.114	−0.039	−0.125	−0.110	−0.114	0.040
13	−0.188	−0.195	−0.176	−0.183	−0.196	−0.193	−0.184	−0.199	−0.183	−0.182	−0.188	0.007
16	−0.203	−0.267	−0.172	−0.203	−0.174	−0.188	−0.167	−0.188	−0.123	−0.159	−0.184	0.037
17	−0.130	−0.129	−0.128	−0.052	−0.118	−0.125	−0.113	−0.039	−0.120	−0.111	−0.107	0.033
18	−0.194	−0.301	−0.156	−0.090	−0.146	−0.133	−0.146	−0.107	−0.209	−0.147	−0.163	0.060
20	−0.208	−0.323	−0.204	−0.223	−0.233	−0.244	−0.227	−0.276	−0.221	−0.215	−0.237	0.036
21	−0.165	−0.141	−0.146	−0.148	−0.144	−0.144	−0.143	−0.143	−0.144	−0.142	−0.146	0.007
23	−0.248	−0.125	−0.181	−0.046	−0.146	−0.102	−0.133	−0.031	−0.235	−0.135	−0.138	0.071
29	−0.277	−0.125	−0.194	−0.046	−0.130	−0.102	−0.141	−0.031	−0.260	−0.144	−0.145	0.081
31	−0.114	−0.129	−0.121	−0.052	−0.118	−0.125	−0.114	−0.039	−0.115	−0.115	−0.104	0.031
34	−0.208	−0.287	−0.199	−0.214	−0.233	−0.244	−0.222	−0.260	−0.211	−0.210	−0.229	0.028
42	−0.235	−0.279	−0.172	0.029	−0.115	−0.102	−0.123	0.108	−0.195	−0.120	−0.120	0.116
41	−0.234	−0.279	−0.167	−0.015	−0.165	−0.123	−0.150	0.026	−0.289	−0.158	−0.155	0.102
45	−0.126	−0.135	−0.125	−0.084	−0.108	−0.125	−0.114	−0.084	−0.117	−0.113	−0.113	0.017
46	−0.140	−0.139	−0.140	−0.091	−0.147	−0.138	−0.138	−0.084	−0.146	−0.139	−0.130	0.023
47	−0.265	−0.125	−0.168	−0.041	−0.132	−0.093	−0.129	−0.031	−0.248	−0.139	−0.137	0.076
50	−0.152	−0.113	−0.147	−0.117	−0.121	−0.120	−0.119	−0.126	−0.125	−0.110	−0.125	0.014

Table 3 are distributed more uniformly among the different combinations, which is reflected in the relatively small standard deviations (σ_M) in comparison with the values in Table 2. However, we must emphasize that the five highest values of σ_M in Table 3 correspond to stars of spectral type A. Regarding the values obtained for the colors (Tables 4 and 5), once again the most dispersed results correspond to type A stars, i.e. these stars always have the largest standard deviations σ_0.

TABLE 5

INTRINSIC COLORS FOR THE STARS IN GROUP 2 OBTAINED WITH EACH COMBINATION DEFINED IN SS99

Id	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	$\overline{(B-V)}_0$	σ_0
4	0.414	0.429	0.437	0.436	0.419	0.421	0.416	0.413	0.392	0.425	0.416	0.419	0.420	0.012
5	0.337	0.362	0.375	0.357	0.357	0.351	0.344	0.345	0.317	0.354	0.359	0.350	0.351	0.014
10	0.332	0.382	0.388	0.351	0.349	0.345	0.352	0.346	0.314	0.359	0.371	0.347	0.353	0.020
11	0.210	0.186	0.248	0.227	0.217	0.206	0.161	0.178	0.028	0.211	0.188	0.199	0.188	0.055
14	0.341	0.389	0.369	0.349	0.359	0.337	0.344	0.338	0.310	0.358	0.365	0.347	0.351	0.020
19	0.258	0.294	0.296	0.286	0.251	0.286	0.266	0.224	0.202	0.256	0.274	0.254	0.262	0.028
33	0.228	0.169	0.238	0.214	0.193	0.200	0.143	0.123	0.022	0.175	0.178	0.219	0.175	0.059
35	0.394	0.431	0.417	0.406	0.407	0.388	0.398	0.386	0.368	0.404	0.405	0.400	0.400	0.016
36	0.362	0.439	0.421	0.371	0.380	0.358	0.361	0.358	0.348	0.381	0.376	0.376	0.378	0.027
40	0.257	0.227	0.254	0.256	0.231	0.230	0.176	0.150	0.051	0.199	0.199	0.245	0.206	0.059
43	0.235	0.232	0.287	0.268	0.265	0.257	0.224	0.219	0.143	0.255	0.245	0.258	0.241	0.037
49	0.242	0.196	0.257	0.227	0.213	0.206	0.156	0.097	0.015	0.165	0.183	0.285	0.187	0.073
51	0.435	0.449	0.475	0.455	0.448	0.431	0.437	0.421	0.413	0.439	0.440	0.440	0.440	0.016
52	0.414	0.444	0.440	0.439	0.429	0.429	0.430	0.428	0.401	0.436	0.424	0.425	0.428	0.012
73	0.531	0.534	0.583	0.567	0.533	0.535	0.544	0.502	0.533	0.530	0.523	0.534	0.537	0.021

From the previous analysis two conclusions can be drawn. First, Combination I for the absolute magnitude in SS02 exhibits an anomalous behavior: the results differ systematically (M_V always showing higher values) and significantly (in comparison with the σ_M values) from the results given by the other combinations. We do not know the reason for this problem, but the systematic nature of this behavior leads us to believe that one or more of the coefficients of the corresponding polynomial could be wrong. To confirm this point it would be necessary to repeat the calibration for this combination of lines, but aside from the inherent difficulties this issue is beyond the scope of this paper. Therefore, we have decided to exclude this combination from the final results.[6] The second conclusion derived from Tables 2-5 is that the application of the method to type A stars would require some kind of special treatment. We will address this point in the following section.

4.2. *Comparison with the parameters derived from the MK-system*

In order to better understand the behavior of the method when applied to the open cluster IC 2391, it is helpful to compare the obtained parameters (Tables 2–5) with the values derived from the spectral types. For this we use the Landolt-Bornstein tables (Schmidt-Kaler 1982). We may assume that the values derived from the MK types are the *expected* values for M_V and $(B-V)_0$, but we have to keep in mind that these values are not necessarily the "correct" ones. In fact, the uncertainties associated with the values derived from the MK types (based on the visual comparison of stellar spectra), are in general larger than the uncertainties associated with the method used in this work. Thus, although the comparison done in this section does not provide information about the accuracy and precision of the method, this analysis helps to understand the behavior of the method and to identify potential problems, as discussed below.

We have first calculated the absolute values of the differences between the values obtained when applying the method (Tables 2, 3, 4 and 5) and the values derived from the MK types. This is done for each star and each line combination (except Combination I in Table 2). Then, for each star, we determined the average value of all these differences. In other words, if $M_V(i,j)$ denotes the magnitude of the i-th star calculated by using the j-th combination and if $M_V^{mk}(i)$ denotes the magnitude derived from its spectral type, then we can define a *deviation parameter* for the magnitude in the form

$$\delta M_i = \frac{1}{N_c}\sum_{j=\mathrm{I}}^{N_c}\left|M_V(i,j) - M_V^{mk}(i)\right| , \qquad (3)$$

N_c being the number of available combinations. The deviation parameter for the color $\delta(B-V)_i$ is calculated in a similar way. These parameters can be zero only if all the combinations yield exactly the same

[6] It is worth mentioning that we have also performed all calculations including the combination I of the Table 2. Although the quality of the results decreases, the main conclusions remain unchanged.

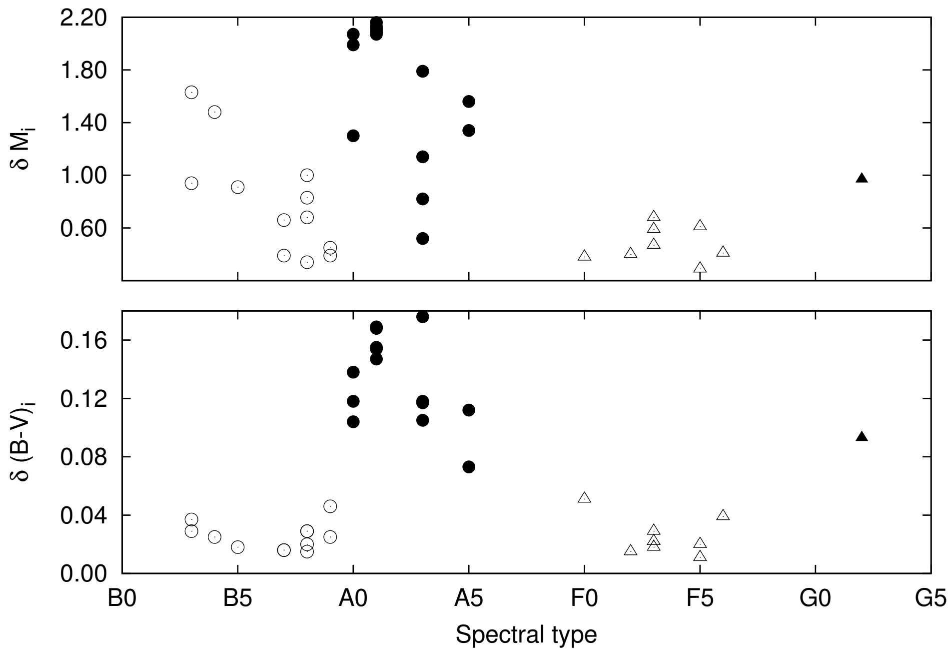

Fig. 1. Deviation parameter (see equation 3) for the absolute magnitude (upper panel) and the intrinsic color (lower panel) for the stars used as a function of the spectral type. Open circles correspond to B stars, solid circles to type A, open triangles to type F, and solid triangles to type G.

result and this result agrees with the one derived from the MK types. Figure 1 shows these deviation parameters for all the stars in the sample as a function of the spectral type. Clearly, most of type A stars (solid circles in Figure 1) exhibit the largest deviations. This behavior can be easily understood by considering the small number of stars belonging to this spectral type used in the original calibration of the method. The sample in SS99 included 487 stars, but only 10 of them were of spectral type A. In fact, Group 1 (that includes early type stars) was excluded from that study because of this reason. In order to extend the calibration to early type stars, an observing program and calibration was carried out later (SS02). However, that work was restricted to spectral types O-B, again excluding the A types. Therefore, it is suitable to apply this calibration to stars belonging to spectral types from O to G, but the total number of A stars used for the final calibration (SS99 and SS02) is rather small and thus the reliability of the results for this spectral type is questionable. In order to solve this problem, it will be necessary to recalibrate the method using a sample of stars that covers a wider and continuous range of spectral types. In this work we have calculated the physical parameters for all the available stars but we have rejected type A stars when estimating the final set of parameters for the open cluster IC 2391.

Now we proceed to calculate a deviation parameter for each combination of lines instead of for each star. To do this, we take the average of all the available stars in a way similar to equation (3). For the magnitude we define

$$\delta M_j = \frac{1}{N_s}\sum_{i=1}^{N_s} M_V(i,j) - M_V^{mk}(i)\,, \qquad (4)$$

where N_s represents the number of available stars (and similarly for the intrinsic color). Note that in this equation we are not taking the absolute value of the difference. We perform the calculations for all the combinations, including the combination I in Table 2, but now we exclude type A stars due to the reasons mentioned previously. The results are shown in Figure 2. The error bars in this figure represent the corresponding standard deviations. These error bars include both the uncertainties of the method itself and the uncertainties of the parameters derived from the MK system. Therefore, these error bars do not indicate the degree of uncertainty associated with a given combination, but they are a meaningful measure of "quality" of a combination relative to others. We see in Figure 2a that, as mentioned before, the worst combination for the magnitude is Combination I. This combination exhibits the largest average difference (∼3 magnitudes), and its standard deviation

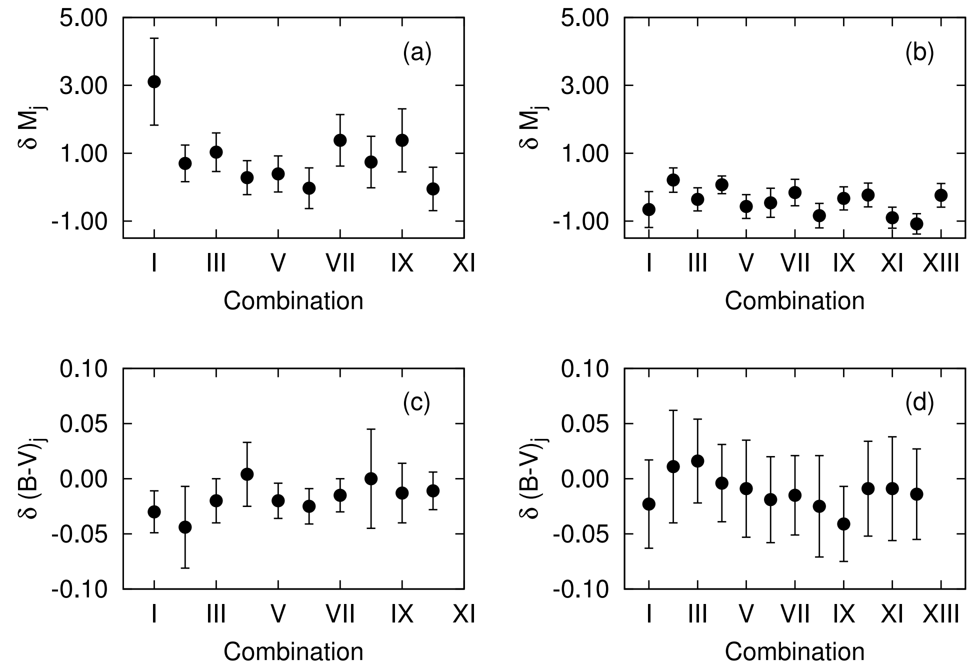

Fig. 2. Deviation parameter (see equation 4) calculated for each combination of lines defined in SS99 and SS02. Panel (a) refers to the absolute magnitudes of Group 1 stars, (b) to the absolute magnitudes of stars in Group 2, (c) to intrinsic colors of Group 1, and (d) to the colors of Group 2. The bars indicate the standard deviations in each case.

is significantly larger than the others. The rest of the combinations, both for M_V and for $(B-V)_0$, show a similar behavior: the average differences are distributed around zero (within the uncertainties), and their standard deviations are nearly the same.

4.3. *A strategy to improve the determination of the stellar parameters*

In Figure 2 we can see that some combinations (apart from Combination I in Figure 2a) exhibit standard deviations larger than those found for the rest. As an example, we can mention Combinations II and VIII in Figure 2c. In principle, one would expect to find less accurate (even biased) results when these combinations are used. These results do not necessarily agree with the SS99 and SS02 results. For example, Combination II in Figure 2c is the "best" one (i.e., that having the smallest average residual r_{av}) according to SS02. In any case, the residual coming from the calibration with a sample of stars is not the same thing as the expected uncertainty when applying a given combination to a star. What combination(s) would we expect to provide the best results? This is not a trivial question. It seems from Figure 2 that most of the combinations behave quite similarly. However, the choice of a particular combination may have undesirable consequences on the final results if this combination works worse for the particular sample of stars considered. This is the case, most likely by chance, of Combination II in Figure 2c.

To solve this problem we propose to average the results obtained with the different combinations. This simple step will diminish any systematic deviation caused by the application of a given combination to a (small) sample of stars such as IC 2391. In order to properly evaluate the suitability of this proposal, we have calculated absolute magnitudes and intrinsic colors for the same sample of stars used in SS99. Afterwards, we have compared the magnitudes and colors used for the calibration with the values obtained from the polynomials (we have used polynomials with three lines as independent variables to be consistent with the results presented here). Figure 3 shows the standard deviations (σ) resulting from the differences between these two values for each combination and for stars belonging to the Groups 2, 3, and 4. The solid horizontal lines in these figures indicate the values obtained when using the average of all the combinations. The values shown are larger than those reported in SS99 because in this case we are using all the stars in the sample and not only the ones used for the calibration of the polynomials. In fact, these are the standard deviations that deter-

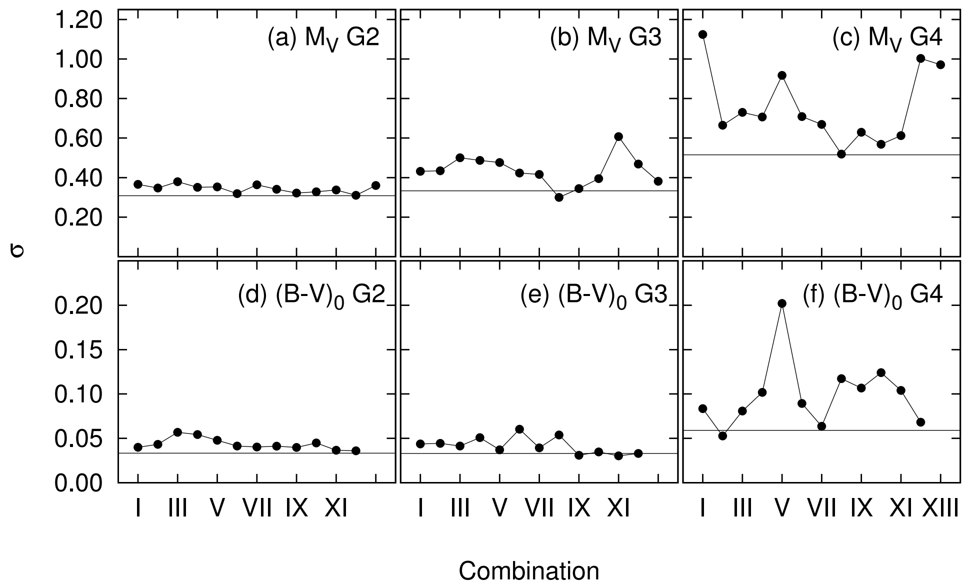

Fig. 3. Standard deviations of the differences between the values assigned to the parameters recovered from the polynomials for the stars used in SS99. Each panel refers to the result of a given parameter (M_V o $(B-V)_0$), and to each of the groups (2, 3 and 4) used in SS99. The horizontal lines indicate the values obtained by using the averages of all the combinations instead of a single one.

mine the uncertainties associated with each polynomial. For the absolute magnitudes the standard deviations are around $\sigma \sim 0.4$ for Groups 2 and 3 but, as expected, are higher (in the range $0.6 \lesssim \sigma \lesssim 1.0$) for Group 4. The same holds for the intrinsic colors, i.e., the method behaves worse for late type stars belonging to Group 4. The important point here is that when the averages of the combinations are used (horizontal lines in Figure 3), the stellar parameters can be recovered with uncertainties of the order of those associated with the best combinations. If we select Combination V to determine the color of a star belonging to Group 4, then we obtain on average, an uncertainty ~ 4 times higher than if we use the average of all the combinations.

Obviously, this effect has a minor impact on early type stars, but this strategy (to use the averages of the results derived from all the available combinations instead of from only one combination) is highly recommended. By choosing a single combination three spectral indices are being used. If at least one of these indices is not well determined because there is a peculiar feature in the spectrum (e.g., a nearby emission line), then the value obtained from the polynomial could be significantly affected. In general, the selection of the polynomial is based on the presence or absence of certain lines in the observed spectrum. What we are suggesting is to select all the available combinations and to average the results because this procedure minimizes the effects of random errors. This is the procedure which we will use to calculate the final values for the stars in our sample, discussed in the next section.

4.4. *Final parameters for the stars in IC 2391*

According to the previous arguments, we have excluded from the analysis both the type A stars and Combination I of Table 2. Next we have determined the absolute magnitudes M_V and the intrinsic colors $(B-V)_0$ for the sample of stars by averaging the values obtained for each combination. These results are listed in Table 6. The columns contain the following information: the identification (Id) of each star according to Perry & Hill (1969), the values obtained for each parameter (M_V and $(B-V)_0$), the values derived from the MK types (indicated with the superscript mk), and the values from different sources in the literature (indicated with the superscript lit). Note that M_V^{mk} and M_V^{lit} can differ significantly. We have calculated the absolute values of the differences between the values from the MK system and from the literature and those calculated in this work. The averages of these differences are 0.59 and 0.35 magnitudes when we compare our results with M_V^{mk} and M_V^{lit}, respectively. Our results are more consistent with the ones reported in the literature indicated in Table 6. The M_V^{mk} values are homogeneous in the

TABLE 6

ABSOLUTE MAGNITUDES AND INTRINSIC COLORS FOR THE STARS IN IC 2391

Id	M_V	M_V^{mk}	M_V^{lit}	$(B-V)_0$	$(B-V)_0^{mk}$	$(B-V)_0^{lit}$
1	−0.01	−0.60	−0.40[d]	−0.146	−0.130	...
8	0.69	−0.25	0.30[a]	−0.114	−0.110	−0.100[a]
13	−0.29	−1.20	−0.60[a]	−0.188	−0.170	−0.150[a]
16	−0.57	−2.05	−0.70[a]	−0.184	−0.185	−0.140[a]
17	0.15	0.20	0.00[a]	−0.107	−0.070	−0.120[a]
20	−1.46	−2.40	−1.80[a]	−0.237	−0.200	−0.180[a]
21	−0.45	−0.60	−0.80[a]	−0.146	−0.130	−0.140[a]
31	−0.36	−0.25	−0.50[a]	−0.104	−0.110	−0.160[a]
34	−0.77	−2.40	−1.20[a]	−0.229	−0.200	−0.170[a]
45	0.10	0.24	−0.30[a]	−0.113	−0.090	−0.100[a]
46	−0.27	−0.95	−0.40[a]	−0.130	−0.110	−0.140[a]
50	0.50	−0.25	0.30[a]	−0.125	−0.110	−0.100[a]
4	2.89	3.50	3.80[a]	0.420	0.440	0.430[a]
5	2.74	2.70	2.70[b]	0.351	0.300	0.360[b]
10	3.02	3.57	3.60[a]	0.353	0.380	0.410[a]
14	2.65	3.00	3.40[a]	0.351	0.350	0.360[a]
35	3.11	3.57	3.33[c]	0.400	0.380	...
36	1.08	1.67	...	0.378	0.377	...
51	3.52	3.50	...	0.440	0.440	...
52	3.26	3.67	...	0.428	0.467	...
73	3.78	4.70	4.25[b]	0.537	0.630	0.570[b]

[a]Perry & Hill (1969).
[b]Eggen (1991).
[c]Patten & Simon (1993).
[d]Buscombe (1965).

sense that they come from only one source (the MK system), and this is the reason why we have used MK to analyze our results. Nevertheless, we have already pointed out that uncertainties associated with M_V^{mk} can be quite large, and this is probably the main reason for the differences in our results. Regarding the colors, the average of the differences between our results and $(B-V)_0^{mk}$ or $(B-V)_0^{lit}$ is 0.023 or 0.029 magnitudes, respectively. Note that the average residual r_{av} for M_V is around 0.30 magnitudes in SS99 and 0.40 magnitudes in SS02, whereas for $(B-V)_0$ it is of the order of 0.02 magnitudes in both works. The average differences obtained are in good agreement with these values.

4.5. *The distance to the open cluster IC 2391*

Using the apparent magnitudes given in the web page of the UVES Paranal Observatory Project and neglecting interstellar absorption, we have estimated the distance modulus and hence the distance for each star in the sample. Table 7 shows the derived distance values ($d_{\rm mod}$), including the errors associated with the method, i.e. the uncertainties propagated from the average residuals of the polynomial calibration. The table also shows, for comparison, the distances and their errors derived from parallaxes given in the Hipparcos catalog ($d_{\rm par}$), which were obtained from the SIMBAD database. The last column shows the percentage difference $(100 \times |d_{\rm mod} - d_{\rm par}|/d_{\rm par})$ for those stars having both distances available. The majority of stars show small differences between $d_{\rm mod}$ and $d_{\rm par}$ ($\lesssim$ 10%), although there are three stars with relatively large differences ($\gtrsim$ 30%).

In order to obtain the best estimation of the distance to the open cluster IC 2391, we have used the following procedure. First, we calculate the distance of each star. Then we compute the average value of the distances and the standard deviation. Stars having distances deviating more than 2.5 times the standard deviation from the average are rejected, and the

TABLE 7

ESTIMATED DISTANCES FOR THE STARS IN IC 2391

Id	$d_{\rm mod}$ (pc)	$d_{\rm par}$ (pc)	Difference (%)
1	261 ± 42	264 ± 35	1.2
8	142 ± 23	155 ± 12	8.3
13	140 ± 22	138 ± 9	1.2
16	142 ± 23	131 ± 8	8.0
17	287 ± 46	296 ± 51	3.0
20	104 ± 17	152 ± 12	31.3
21	158 ± 25	145 ± 10	9.0
31	152 ± 24	148 ± 12	2.6
34	131 ± 21	147 ± 10	10.8
45	738 ± 118	···	···
46	391 ± 63	283 ± 47	38.0
50	143 ± 23	142 ± 10	0.1
4	161 ± 26	···	···
5	160 ± 26	···	···
10	151 ± 24	···	···
14	195 ± 31	···	···
35	175 ± 28	128 ± 15	36.4
36	522 ± 84	···	···
51	164 ± 26	···	···
52	187 ± 30	···	···
73	204 ± 33	···	···

procedure is repeated until no further stars can be rejected. At the end of this procedure, five stars were discarded from the distance estimation: 1, 17, 36, 45, and 46. The value of the distance obtained for the open cluster IC 2391 and its standard deviation is $d = 156 \pm 24$ pc. The three stars having the largest differences from this value are the stars numbered 36, 45, and 46. After reviewing the available literature, we note that several authors have suggested non-membership of these stars to IC 2391 (Perry & Hill 1969; Perry & Bond 1969; Maitzen & Catalano 1986). The distances of Stars 1 and 17 differ by more than 2.5 times the standard deviation from the mean; furthermore, their values are in good agreement with the ones derived from the parallaxes (Table 7). Buscombe (1965) identified Star 1 as a member of IC 2391, whereas Levato et al. (1988) and Dodd (2004) classified it as a non-member. As for Star 17, both Perry & Hill (1969) and Perry & Bond (1969) classified it as a non-member of the cluster. In a recent work, Platais et al. (2007) concluded that none of the five rejected stars are members of IC 2391.

The distance to IC 2391 obtained in this work ($d = 156$ pc) is in very good agreement with the values given by other authors. Barrado y Navascués et al. (2001) estimated a distance of 155 pc, Dodd (2004) derived 147.5 pc, and Platais et al. (2007) obtained 159.2 pc. This good agreement allows us to conclude that, in general, the method used in this work (SS99, SS02) can be applied with confidence to stellar spectra to derive their properties within acceptable uncertainties.

5. CONCLUSIONS

In this work we have applied the method proposed by SS99 and SS02 to a sample of stellar spectra available for the open cluster IC 2391. We have calculated the absolute magnitudes M_V and intrinsic colors $(B-V)_0$ for all the stars studied (Tables 2–5), as well as the distance to the cluster. Both the detailed analysis performed in this work and the comparison of our results with other results from the literature allowed us to evaluate more comprehensively the strengths and limitations (and therefore the potential applicability) of this method.

From our results we can draw the following general conclusions:

- In the method described by SS99 and SS02, the combinations of lines having the smallest average residuals are not necessarily the ones yielding the best results for M_V and $(B-V)_0$. In fact, the average uncertainties may vary significantly among the different combinations, mainly in late type stars. In this work we propose to use the averages of the results derived from all the available combinations instead of from only one combination. We have verified that this procedure reduces considerably the overall uncertainty.

- The method used does not provide reliable results (it generates relatively large uncertainties) when applied to type A stars. The problem seems to lie in the fact that this spectral type was not adequately represented in the original calibration (SS99, SS02). Therefore, a new calibration of the method using a more extensive spectral library becomes necessary.

- From the results obtained for this sample of stars, we conclude that it is possible to derive absolute magnitudes with uncertainties of 0.59 or 0.35 magnitudes, depending on whether the comparison is done with values derived from the spectral type or values reported in the literature, respectively. It is also possible to derive intrinsic colors with average uncertainties of 0.023 or 0.029 magnitudes, depending again on the source used for the comparison. These uncertainties are in agreement with the average residuals associated to M_V and $(B-V)_0$ according to SS99 and SS02.

- Stars numbers 1, 17, 36, 45 and 46 are probably not members of IC 2391. The rest of the stars allowed us to estimate a distance of 156 ± 24 pc for the cluster, which is in good agreement with published values.

Summarizing, this work shows that the method proposed in SS99 and SS02 can be applied in a reliable way to calculate the physical parameters of stellar systems. Both the simplicity of the definition of the indices used and the relatively small uncertainties in magnitude and color values make this method a suitable tool for the analysis of a large number of stellar spectra. Nevertheless, a new calibration is necessary in order to overcome the current limitations of the method, mainly those associated with type A stars.

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