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A CALIBRATION OF Mg_2 VERSUS [Fe/H] AND [Mg/Fe]

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ABSTRACT

We have computed composite synthetic spectra in the wavelength range λλ490–540 nm representing globular clusters in the metallicity range $-2.0 < [Fe/H] < +1.0$. For the metal-rich ($[Fe/H] \gtrsim 0.0$) clusters we adopted stellar populations similar to those of Galactic bulge globular clusters recently studied through color magnitude diagram analyses.

We show that major points in defining the intensity of lines in the spectral region considered are the temperatures of red giants, and their [Mg/Fe] ratios.

The Mg_2 index was measured in the synthetic composite spectra, and plots of Mg_2 versus [Fe/H] are given for the different assumptions. In particular, [Mg/Fe] is included as a parameter for the Mg_2 calibration.

Subject headings: galaxies: abundances — galaxies: stellar content — globular clusters: general — stars: abundances

1. INTRODUCTION

Through the study of metallicities and abundance ratios in galaxies it is possible to trace their chemical evolution, which can give information on the stellar populations present through time. Once the metallicity and abundance ratios are known, it is possible to derive, from the galaxy mean color, its corresponding age.

The Mg_2 index has been of widespread use as a metallicity indicator for composite systems (Faber 1973; Burstein 1979, hereafter B79; Burstein et al. 1984, hereafter BFGK; Worthey, Faber, & González 1992, hereafter WFG92). However, a definitive calibration of Mg_2 versus [Fe/H] and its interpretations still is under debate throughout the literature: in a reference paper, B79 published a calibration $(Mg)_o$ versus [Fe/H] [where $Mg_2 = 1.33\ (Mg)_o + 0.086$] using $(Mg)_o$ measured in integrated spectra of globular clusters of different metallicities, and one "synthetic" metal-rich cluster computed by Mould (1978), from which a relation $[Fe/H] = 3.9Mg_2 - 0.90$ was derived, valid in the range $-0.5 < [Fe/H] < +0.3$ (Terlevich et al. 1981). More recently, a large database of galaxies (Faber et al. 1989; WFG92) and evolutionary synthesis models (Buzzoni, Garibaldi, & Mantegazza 1992; Borges & Freitas Pacheco 1993) were used to establish relations Mg_2 versus [Fe/H].

From a combination of observed stellar spectral features and theoretical HR diagrams to reproduce the spectra of elliptical galaxies, WFG92 conclude that [Mg/Fe] is high in the more massive ellipticals, in contradiction to models of chemical evolution for elliptical galaxies (e.g., Matteucci & Tornambé 1987), but in agreement with one-zone closed-box models for bulges (Matteucci & Brocato 1990).

In order to try to understand better the behavior of the Mg_2 index, as a function of metallicity [Fe/H], we use synthetic composite spectra for single stellar populations representative of globular clusters. In order to reproduce the spectra of metal-rich globular clusters, we use the information contained in BVRI CCD color magnitude diagrams (CMDs) of bulge clusters by Ortolani, Barbuy, & Bica (1990, hereafter OBB90). Synthetic composite spectra of globular clusters were previously built in the literature by Mould (1978) and Tripicco & Bell (1992), using theoretical CMDs. Bica & Alloin (1986), on the other hand, have used integrated observed spectra of globular clusters to study the properties and behavior of spectral features. A somehwat different methodology is employed in the present work: stellar theoretical spectra are used taking into account the observed properties of globular clusters CMDs.

We consider that a first important step in the calibration of Mg_2 versus [Fe/H] for galaxies is the one for globular clusters; when considering early-type galaxies, dilution of lines by the presence of larger fractions of hot stars (P-AGB or younger components) and mix of populations of different metallicities should be considered. Moreover, massive (generally metal-rich) ellipticals might show anomalies due to a different process of formation such as merging (cf. Bender 1992, who also pointed out that, on the other hand, a universal relation between Mg_2 and velocity dispersion seems to exist, which is remarkable since giant ellipticals probably formed by merging, and the faint ellipticals suffered wind-driven mass loss).

In § 2 the basic assumptions in the calculations of synthetic spectra are described. In § 3 the resulting behavior of Mg_2 versus [Fe/H] is shown and discussed. In § 4 the conclusions are summarized.

2. CALCULATIONS

The basic calculations of synthetic spectra in the region of the Mg I triplet lines for individual stars were described in Barbuy (1989), Cayrel et al. (1991), and Barbuy, Erdelyi-Mendes, & Milone (1992a), where it was shown that the wavelength regions of Mg_2 (λλ515.6–519.7 nm) and Mgb (λλ516.2–519.3 nm) are very sensitive to metallicity and practically insensitive to gravity, confirming that these indices appear to be adequate metallicity indicators.

In this work synthetic spectra are computed in the wavelength range λλ490–540 nm for 10 stellar evolutionary stages, for clusters of metallicities in the range $-2.0 < [Fe/H] < +1.0$. Relative to our previous papers, a main difference is the employment of model atmospheres by Kurucz (1992), where metal-rich models are available.

Composite synthetic spectra are then built by adding up the synthetic spectra of individual stars, weighted according to

(1) their visual magnitudes (the Mg I triplet lines at $\lambda_{\mathrm{Mg\,I}} \sim 517$ nm are rather close to the central wavelength of the V band at $\lambda_V = 550$ nm), and (2) relative numbers obtained by a combination of stellar counts directly from the CMDs for giants, and a Salpeter (1955) IMF for the main sequence (for an age of 15 Gyr). The procedures followed are detailed in de Souza et al. (1993).

Magnitudes, temperatures, and gravities of evolutionary stages considered are given in Table 1. Major assumptions for the calculations are the following:

2.1. *Magnitudes*

The magnitudes are derived from the observed CMDs of NGC 6397 ([Fe/H] ≈ −2.0) and 47 Tuc ([Fe/H] ≈ −1.0) by Cannon (1974) and that of NGC 6553, a bulge metal-rich globular cluster (OBB90); for the latter a correction relative to the values given in de Souza et al. (1993) consists of lowering by two magnitudes the turnoff and dwarf stars (see magnitudes of Table 1, based on Fig. 9*a* of OBB90). The resulting spectrum is dominated by the light of giants. We note that the brightest giants for clusters of [Fe/H] ≈ −2.0 and −1.0 are, respectively, 1.5 and 0.8 mag brighter than the ones of [Fe/H] ≈ 0.0.

2.2. *Temperatures*

In Barbuy et al. (1992b) we assumed that the CMDs' color shift to the red as a function of increasing metallicity (see Bica, Barbuy, & Ortolani 1991) is only due to higher opacities, that is, the temperatures should be the same, in clusters of different metallicities, for stars at the same evolutionary stage, where basically the temperatures of 47 Tuc RGB stars were adopted following the infrared (JHK) photometric determinations by Frogel, Persson, & Cohen (1981). The same set of temperatures is considered here, except those of the cooler stars, which had to be revised: the reddest extent of the giant branch of metal-rich globular clusters is a function of metallicity, and more metal-rich RGB tip stars are progressively cooler. *JHK* photometry of NGC 6553 (unpublished) reveals that the RGB tip of NGC 6553 extends one magnitude brighter in *K* than that of 47 Tuc, so that whereas the coolest stars in 47 Tuc show $T_{\rm eff} \approx 3700$ K (Frogel et al. 1981), in NGC 6553 it should reach $T_{\rm eff} \approx 3500$ K. We recall that in CMDs of metal-rich globular clusters where in particular blue colors (*B*, *V*) are plotted in ordinates, the RGB tip happens to be as faint as the horizontal branch (HB). Therefore in such CMDs the brightest stars (here called RGB top) are located where the RGB bends due to the high opacities of the cooler stars (see OBB90, 92, 93). In addition, through fits to TiO bands in the spectra of metal-rich globular clusters, since TiO bands are very sensitive to temperature, it was possible to establish an optimum temperature for the dominating giants at the RGB top (Milone, Barbuy, & Bica 1994). The result is that for the G1 type ([M/H] ≈ 0.0) of globular clusters (Bica 1988), we found effective temperatures $T_{\rm eff} \approx 3750$ K for the RGB top and ≈3500 K for the RGB tip. For [M/H] = +0.5 we adopted $T_{\rm eff} = 3500$ K for the RGB top and tip, given that cooler models are not available. Essentially, the composite spectra for [M/H] = 0.0 and +0.5 should be approximately correct, whereas for [M/H] = +1.0 we maintained $T_{\rm eff} = 3500$ K for the brighter giants, only because of a limitation in the grid of model atmospheres. The Mg_2 value for [M/H] = +1.0 is therefore probably underestimated: it shows a saturation effect, which might disappear if a cooler model had been used.

TABLE 1

STAGES OF EVOLUTION CONSIDERED, VISUAL MAGNITUDES, EFFECTIVE TEMPERATURES, AND GRAVITIES

Stage	M_V	$T_{\rm eff}$	log g
1. Dwarfs 1	4.70	5000	4.4
2. Dwarfs 2	5.20	4500	4.7
3. TO	4.20	5100	4.3
4. Low SGB	1.95	4900	3.8
5. Upper SGB	1.50	4600	2.7
6. HB	0.4, 0.75, 1.03[a]	5100	2.6
7. RGB at HB	0.4, 0.75, 1.03[a]	4500	2.0
8. Ascending RGB	−1.25, −0.55, 0.25[a]	4250, 4000, 3750	1.0
9. Bright tip RGB	−2.15, −1.45, −0.65[a]	4000, 3750, 3500[b]	0.0
10. Descending RGB	..., ..., −0.1[a]	3750, 3500, 3500[b]	0.2

[a] Values adopted respectively for [M/H] = −2.0, −1.0, ≥0.0.

[b] Values adopted respectively for [M/H] = <0.0, 0.0 to +0.3, +0.5 to +1.0

2.3. *Abundance Ratios*

We have adopted [α/Fe] = 0.0 and +0.25. Figure 1 shows the composite synthetic spectrum for [M/H] = 0.0, [Mg/Fe] = 0.0 and +0.25, illustrating the effect of a change in magnesium abundance. The Mg_2 bandpass and the continua are also indicated, where the red continuum point is coincident and the blue continuum is slightly different for the two cases. Note the high opacity which lowers the flux all along the spectrum.

2.4. *Dependence of* Mg_2 *on Stellar Parameters*

A study of the behavior of the absorbed flux at the Mg_2 wavelength region, as a function of stellar parameters $T_{\rm eff}$, log g, and [M/H], was presented in Barbuy et al. (1992a). It is interesting to note that the behavior of Mg_2 for individual stars, as a function of [M/H], resembles the one for composite spectra. The absorbed flux increases with decreasing temperature, similarly to empirical results by Gorgas et al. (1993). Regarding gravity, however, as derived from synthetic spectra, Mg_2 shows only a slight increase with decreasing gravities, whereas Gorgas et al. (1993) found a nonnegligible correlation.

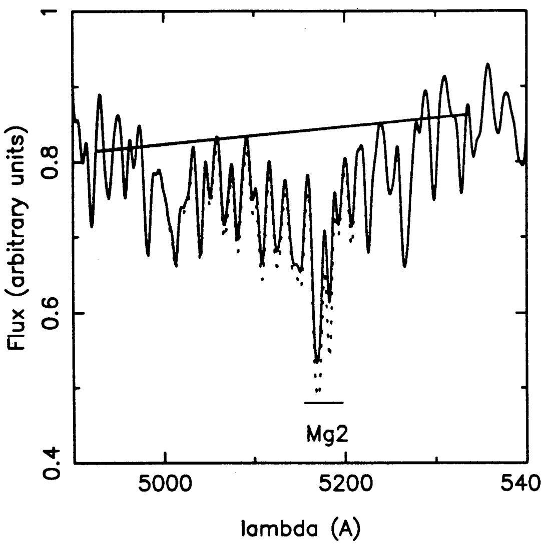

FIG. 1.—Synthetic composite spectrum for [Fe/H] = 0.0, [Mg/Fe] = 0.0 (*solid line*) and +0.25 (*dotted line*) convolved with a FWHM = 6.0 Å Gaussian. The Mg_2 bandpass and the continua adopted are indicated.

TABLE 2

Mg_2 INDICES DERIVED FROM THE PRESENT SYNTHETIC SPECTRA AND THOSE DERIVED FROM THE RELATION ESTABLISHED BY GORGAS ET AL. (1993)

STAGE	INDICES				
	−2.0	−1.0	−0.5	0.0	+0.5
1	0.060	0.145	0.207	0.278	0.355
	0.084	0.205	0.287	0.376	0.469
	0.09	0.19	0.26	0.34	0.42
2	0.156	0.323	0.395	0.463	0.522
	0.217	0.416	0.500	0.575	0.642
	0.18	0.41	0.57	0.76	0.96
3	0.050	0.114	0.175	0.229	0.295
	0.070	0.155	0.243	0.310	0.391
	0.07	0.16	0.22	0.28	0.35
4	0.045	0.106	0.156	0.213	0.28
	0.062	0.151	0.219	0.296	0.382
	0.07	0.16	0.22	0.29	0.36
5	0.034	0.069	0.100	0.141	0.189
	0.058	0.096	0.142	0.200	0.268
	0.07	0.16	0.22	0.28	0.36
6	0.023	0.048	0.069	0.099	0.136
	0.028	0.062	0.092	0.134	0.189
	0.04	0.08	0.10	0.14	0.17
7	0.040	0.085	0.123	0.170	0.221
	0.053	0.124	0.177	0.243	0.311
	0.06	0.14	0.19	0.25	0.32
8	0.039	0.119	0.176	0.418	0.486
	0.065	0.163	0.237	0.505	0.575
	0.07	0.16	0.22	0.30	0.34
9	0.039	0.098	0.166	0.390	0.456
	0.046	0.134	0.222	0.474	0.554
	0.08	0.18	0.26	0.46	0.62
10	0.103	0.245	0.322	0.458	0.496
	0.138	0.308	0.396	0.530	0.580
	0.10	0.23	0.34	0.47	0.62
Composite opulation:					
[Mg/Fe] = 0.0	0.036	0.089	0.138	0.237	0.285
[Mg/Fe] = 0.3	0.047	0.102	0.187	0.302	0.366

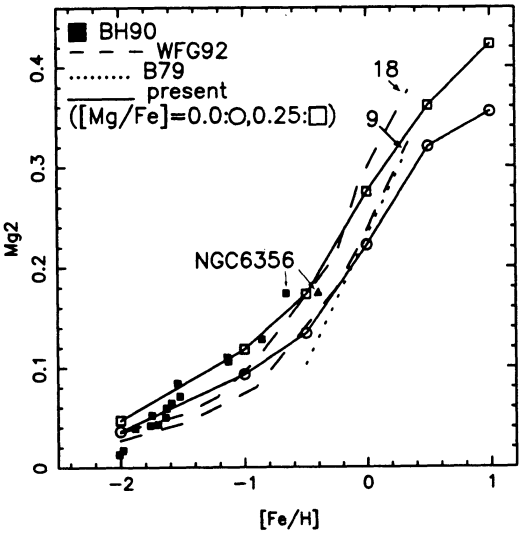

FIG. 2.—Mg_2 vs. [Fe/H]. Present calculations: open circle: [Mg/Fe] = 0.0; open square: [Mg/Fe] = +0.25; *dotted lines*: B79; *dashed lines*: WFG 92 for 9 and 18 Gyr; *filled squares*: BH90, NGC 6356 ([Fe/H] = −0.66 [cf. BH90] and [Fe/H] = −0.4 [cf. Bica et al. 1993]; filled triangle is labeled [see § 3]).

We suggest that the dependence on gravity verified from empirical data may be partly due to a temperature effect, since generally lower gravity stars are progressively cooler, and the two effects are difficult to disentangle. We point out that Gulati, Malagnini, & Morossì (1993) found a factor 2 difference between Mg_2 for stars of $\log g = 1.5$ and 4.5, therefore an intermediate solution between those by Barbuy et al. (1992a) and Gorgas et al. (1993).

For a verification of our Mg_2 values relative to empirical calibrations, in Table 2 are given the Mg_2 indices for the stars used as representative of evolutionary stages (cf. Table 1). The values of Mg_2 corresponding to [Mg/Fe] = 0.0 and +0.25 are given, together with the value derived from the calibration of Gorgas et al.: for the use of their relation (6) of Table 6, we transformed our effective temperatures to $(V-K)$ colors following relations given by Blackwell, Lynas-Gray, & Petford (1991). We find a general good agreement between our values of Mg_2 and those derived by using the Gorgas et al. relation, pointing out that these latter fluctuate between values for the [Mg/Fe] = 0.0 and +0.25.

2.5. *Microturbulence Velocity*

We have adopted a microturbulence velocity of $v_t = 1.0$ km s^{-1} for stars of $\log g \gtrsim 2.0$ and $v_t = 1.8$ km s^{-1} for those of $\log g < 2.0$. It has to be noted that the effect of v_t is nonnegligible.

3. Mg_2 VERSUS [Fe/H]

The Mg_2 index is measured in the composite synthetic spectra, according to its definition given in BFGK: $Mg_2 = -2.5 \log (F_{line}/F_{continuum})$. In Faber et al. (1989) the highest values of Mg_2 are of the order of $Mg_2 \approx 0.345$, with two exceptions consisting of the galaxies DC 23−042 and N1270 with $Mg_2 = 0.369$ and 0.384, respectively. According to Buzzoni et al. (1992), a saturation occurs at $Mg_2 \approx 0.46$ for composite systems; for individual cool and metal-rich stars, values higher than this limit are found here, indicating that the limit of $Mg_2 < 0.46$ might mean in fact a metallicity limit in galaxies, and not a saturation.

In Figure 2 is given the plot of Mg_2 versus [Fe/H] for the composite synthetic spectra of populations representing globular clusters. In the same figure are also plotted the pioneer calibration of B79 and the recent one by WFG92 for 9 and 18 Gyr; data points by Brodie & Huchra (1990, hereafter BH90) are also indicated: these authors defined a metallicity scale for a selection of globular clusters by adopting the metallicity scale of Zinn & West (1984) combined with absorption line indices derived previously by BFGK and Brodie & Huchra (1986).

We note that in the metal-poor side, there is reasonable agreement with WFG92 for [Mg/Fe] = 0.0. The data points by BH90 fit within the interval between [Mg/Fe] = 0.0 and +0.25; we recall that [Mg/Fe] ≈ +0.3 to +0.4 is found in metal-poor field stars. The slight disagreement with BH90 for NGC 6356 is probably due to their underestimation of its metallicity: Bica et al. (1993) deduced [Fe/H] ≈ −0.4 from the morphology of its CMDs, instead of [Fe/H] = −0.66 given in BH90. For the metal-rich side, we show the sensitivity of spectra of bright giants (dominating the integrated spectra) to adopted temperatures and [Mg/Fe] ratio.

The final calibrations for [Mg/Fe] = 0.0 and +0.25 are indicated by solid lines.

The Mg_2 versus [Fe/H] relation for [Mg/Fe] = +0.25 coincides well with the curves by B79 and WFG92 for 9 Gyr; a higher [Mg/Fe] could bring a shift toward the WFG92 18 Gyr one.

4. SUMMARY

We have computed synthetic spectra for representative evolutionary stages of globular clusters of metallicities $-2.0 < [Fe/H] < +1.0$, where magnitudes and star counts are based on observed CMDs.

Composite synthetic spectra corresponding to the stellar populations of globular clusters are built and their Mg_2 indices are measured. The sensitivity of Mg_2 to the temperatures of giant stars and to the [Mg/Fe] ratios adopted is discussed.

The resulting calibrations of Mg_2 versus [Fe/H] for $[Mg/Fe] = 0.0$ and $+0.25$ are presented and compared to results by Worthey et al. (1992).

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