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THE REVISED Mg_2 INDEX AS A METALLICITY INDICATOR FOR STELLAR SYSTEMS: GIANT ELLIPTICAL GALAXIES AND BULGES

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ABSTRACT

We provide a new calibration of the metallicity dependence of the Mg_2 index in stellar systems. It is based on new isochrones by the Padova group and the latest stellar spectral libraries. Since the Mg_2 line is one of the strongest absorption lines in the optical spectrum, it is often used to determine metallicities of composite stellar systems assuming a certain age. This paper allows one to do this, with an uncertainty of about 0.1 in log Z, for an age range between 8 and 17 Gyr. We estimate that the uncertainties of the current Mg_2 calibrations in the literature amount to another 0.15 in log Z. Using our calibration we find, under conservative assumptions, that the large majority of elliptical galaxies, and also many bulges of spiral galaxies, must have Mg abundances larger than solar; this conclusion depends very little on their star formation history. If [Mg/Fe] = 0, the same can be said for total metallicities. If we assume that [Mg/Fe] = 0.45, only about 38% of the ellipticals must have metallicities (Z) larger than solar.

Subject headings: galaxies: abundances — galaxies: elliptical and lenticular, cD

1. INTRODUCTION

An important problem for population studies in galaxies and in star clusters is the determination of metallicity, or the mass fraction of the elements other than H and He. It has become common practice to use for this purpose the feature made up of the Mg *b* line and the Mg H band around 5200 Å which is termed the Mg_2 index (Burstein et al. 1984). Even though it is fairly certain that ellipticals and other stellar systems have a considerable range in metallicity, and even though it is very difficult to separate age and metallicity, it has been considered useful, for practical purposes, to compute Mg_2 versus metallicity calibrations, based on the assumption that all the stars in a given population are coeval and have uniform metallicity.

The first of these calibrations was published by Mould (1978) and adapted to the Lick System by Gorgas & Efstathiou (1987). In the meantime, several other calibrations have followed (e.g., Peletier 1989; Worthey 1994). The later two authors use fairly similar methods. They choose an initial mass function (IMF), a metallicity, and an age, take a published isochrone, add for all stars long the main sequence, subgiant branch, and giant branch their respective Mg_2 contributions weighted for the IMF and the light of the star, and then make a correction for the latter evolutionary phases. The Mg_2 index is calculated from the theoretical isochrone parameters log T_e, log g, and $M_{\rm bol}$ using a grid of observed stars with a range in metallicity, temperature, and gravity. There are strong recent developments in this field, which give rise to steady improvements in the metallicity-Mg_2 calibration. There now exists a large library of stars with a range in log T_e, log g, and $M_{\rm bol}$ for which Mg_2 is known (Worthey et al. 1994; Gorgas et al. 1993). In addition, new isochrones have become available that use better opacities (Bertelli et al. 1994) and include a better treatment of the later stages of stellar evolution. Unfortunately, there is still no generally accepted treatment for the IMF.

We have included these new developments in a new stellar population synthesis code in order to obtain better solutions for elliptical and spiral galaxies. As a first step, we have reproduced Worthey's 21 absorption line indices for single-age, single-metallicity stellar populations but using the Padova isochrones and their late evolutionary phases. Second, we have calculated integrated absorption line strengths and colors for an evolutionary stellar population synthesis model, similar to the way that, e.g., Arimoto & Yoshii (1986) calculate integrated colors. Third, we have obtained accurate observations for several elliptical and spiral galaxies in the 21 line indices, as well as optical and infrared colors. The models and the results of applying them to our data, will be published in a paper by Vazdekis et al. (1996). Since the Mg_2 index is very important for the study of nearby and distant galaxies as a simple metallicity indicator, we decided to dedicate a separate paper to its calibration as a function of metallicity. We will show here that if the observed Mg_2 index has a value of 0.29 or more, the metallicity of the system will be at least solar, almost independently of its detailed history. The underlying assumptions are little interchange of gas with the neighborhood of the system and a Salpeter IMF. We discuss the implications for nearby elliptical galaxies.

2. THE Mg_2-Z CALIBRATION

In Figure 1 we give our calibration of the Mg_2 index as a function of Z for an age of 13 Gyr. The basis for this cali-

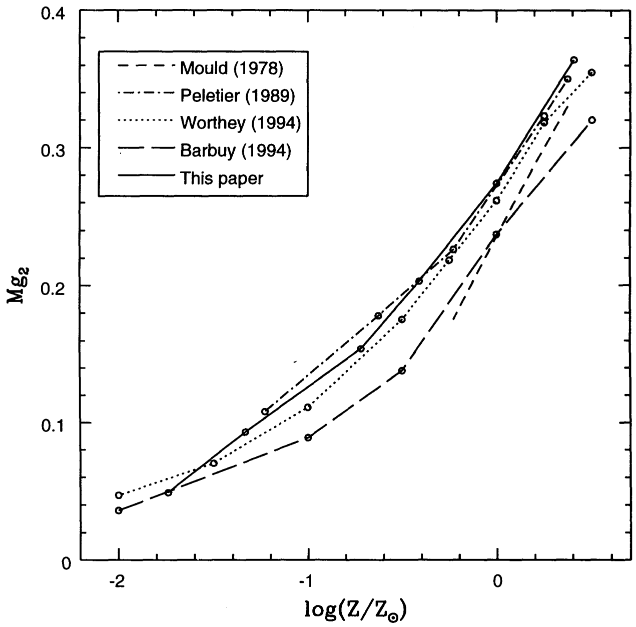

FIG. 1.—Mg_2-Z calibration for an age of 13 Gyr. Compared are Mould (1978), Peletier (1989), Worthey (1994), Barbuy (1994), and this work.

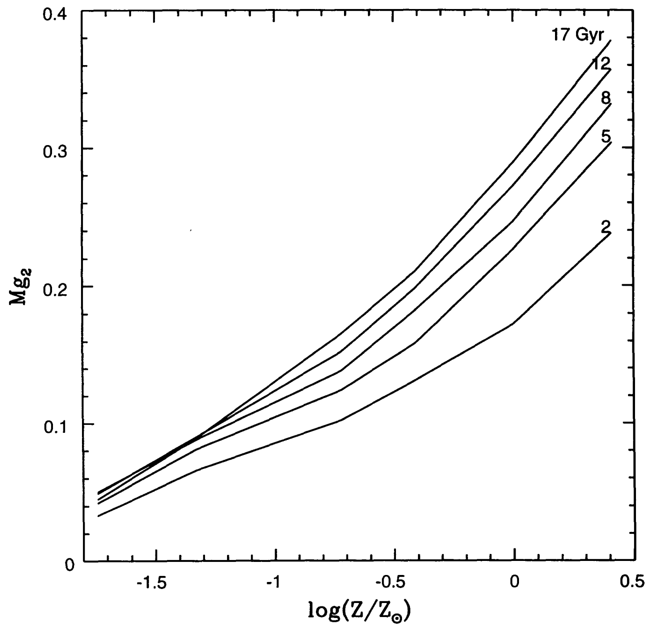

FIG. 2.—Mg_2 vs. Z for five stellar population ages: 2, 5, 8, 12, and 17 Gyr. The lines are from this work. We note that these curves are based on a single-burst hypothesis and assume the metallicity attained in the burst. [Mg/Fe] is assumed to be 0. Their use in the calibration of Mg_2 is explained in the text. Models with a distribution of stellar populations, having different ages, would always yield a higher metallicity for a given maximum age.

bration will be described in detail in a subsequent paper (Vazdekis et al. 1996), but we can describe the main points in a few sentences here. We take the new Padova isochrones, extrapolate them linearly to lower masses, take a Salpeter mass function ($dN/dm \propto m^{-2.35}$) with a lower mass cutoff of 0.08 $M_\odot$, then calculate for each star along the isochrone its Mg_2 index and integrate along the isochrone, weighting according to the IMF. The Mg_2 index for each individual star is calculated using the fitting functions of Worthey et al. (1994).

Also shown in Figure 1 are previous calibrations, by Mould (1978) (as transformed by Gorgas & Efstathiou 1985), Peletier (1989), and Worthey (1994), all for 13 Gyr. The differences between Peletier (1989) and Worthey (1994) are small and consist of different fitting functions, and a different handling of the horizontal branch (HB) and asymptotic giant branch (AGB). Both use the Revised Yale Isochrones (Green, Demargue, & King 1987). Mould (1978) used a semitheoretical method to calculate synthetic spectra and then used the old Yale isochrones (Ciardullo & Demarque 1977) to go from stars to composite stellar systems. Also given is the calibration of Barbuy (1994) based on theoretical model atmospheres and Galactic globular clusters, for [Mg/Fe] = 0 and 15 Gyr. The latter calibration in general gives lower Mg_2 values than we find. Here part of the difference might be that we use observed stars to determine our fitting functions, while she uses a theoretical calibration. Since those stars are generally disk stars close to the Sun, [Mg/Fe] ought to be solar, so we argue that this possibility is not very likely.

The most important difference between the calibration and the most recent ones in the literature is that new isochrones are used that have made use of better opacity tables. Moreover, the AGB evolution has been calculated here explicitly, instead of making an AGB correction. Our results are very close to previous calibrations by Peletier and Worthey.

In Figure 2 we have plotted our new calibration for a range of population ages. The behavior is as expected: for older age, a larger Mg_2 is reached. In Table 1 we show numerically our calibration at 13 Gyr for Mg_2 as a function of Z.

The error in the modeled Mg_2 index is attributable (1) to errors in the isochrones, (2) to the conversion between stellar parameters like temperature, gravity, and metallicity, and Mg_2 for each individual star, (3) to the Helium content Y and IMF that is being used, and (4) to the error in [Mg/Fe] for a given system. For source (2), Gorgas et al. (1993) find an error per star of 0.02 in Mg_2, implying an error of less than 0.02 in the integrated value. We estimate it to be 0.01. The error in Mg_2 resulting from a change in Y was estimated by Weiss, Pelletier, & Matteucci (1995). When changing Y from 0.26 to 0.32, Mg_2 varied by 0.013. This range is more or less the range in which Y is assumed to lie. The variation in Mg_2 attributable to different IMFs is very hard to determine, but probably small, because population synthesis allows only a limited range of IMF slopes for stars which shine in the region of the Mg_2 index, owing to constraints by, e.g., ultraviolet and near-infrared colors. We assume this error to be negligible. Error (1) is probably caused mainly by including too many or too few AGB/HB stars. By comparing various Mg_2-metallicity calibrations, we estimate

TABLE 1

Mg_2 VERSUS Z CALIBRATION FOR VARIOUS AGES

Z	AGE (Gyr) 1	2	5	8	10	13	15	17
0.05	0.169	0.238	0.304	0.332	0.351	0.364	0.371	0.378
0.02	0.125	0.172	0.226	0.246	0.260	0.274	0.282	0.289
0.008	0.087	0.131	0.158	0.182	0.190	0.203	0.207	0.210
0.004	0.076	0.102	0.124	0.138	0.144	0.154	0.159	0.165
0.001	0.048	0.066	0.081	0.088	0.090	0.093	0.091	0.089
0.0004	0.028	0.033	0.042	0.050	0.050	0.049	0.044	0.045

this error to be about 0.01. Finally, the Mg_2-Z conversion of the metals is not solar but, e.g., α-enhanced (e.g., Peletier 1989; Worthey et al. 1992). If external systems have [Mg/Fe] = 0.4 (α_1 in Weiss et al. 1995), the Mg abundance for a given metallicity will go up by a factor of 1.2, and the Fe abundance at the same time will go down. A factor 1.2 corresponds to a change in Mg_2 of 0.03, implying that for a given Z Mg_2 would be greater by 0.03. Observations by Davies et al. (1993) show that there is probably a range in [Mg/Fe] for giant ellipticals. Applying the models of Weiss et al., [Mg/Fe] would lie between 0.3 and 0.6 corresponding to Mg_2 that would be larger for a given Z by between 0.02 and 0.04. Adding the errors, the total uncertainty in Mg_2 is 0.022 mag. For a given Z, Mg_2 would be an extra 0.03 mag higher if the composition of the stellar system is α-enhanced. The value of 0.022 would correspond to about 0.10 in log Z, or about a factor 1.4 in Age.

3. THE METALLICITY OF STELLAR SYSTEMS

In Figure 3 we show Mg_2 now as a function of age for different metallicities. One sees that the graph is increasing monotonically for a given metallicity. Using this family of curves together with the number distribution of observed stars for the extreme cases in which either all star formation occurred in the beginning (primordial bursts) or star formation is taking place on an extended timescale, we can make useful inferences about the metallicity of real systems, taking into account that a system generally will contain stars of more than a single age and metallicity.

For a given observation of Mg_2, the fact that the relation of Mg_2 with age is increasing monotonically shows that the lowest average metallicity that one can obtain from a model is the metallicity that corresponds to the highest age, i.e., 17 Gyr in the present case. In particular, if Mg_2 is found to be 0.29 or higher, the average metallicity has to be solar or higher.

If in the star formation history of a given galaxy all the stars were formed very early (a large primordial burst, one might think here of elliptical galaxies), then we are close to the extreme case, and Mg_2 of 0.29 would correspond to a metallicity close to solar (the exact value depending on the age).

If, as in spiral galaxies the stellar system observed is a mixture of stars with various ages the metallicity must, in general, be greater than solar, and the younger the average population the higher the average metallicity corresponding to a given measured value of Mg_2 will be.

In particular, the value of $Mg_2 = 0.29$ corresponds to solar metallicity only for the case in which the entire stellar population of the model has the extreme age of 17 Gyr. These conditions might be approximated in a real galaxy in which virtually all the stars were formed in an initial burst of star formation, followed by a long period with little star formation and low enrichment after, say, 1 Gyr. However, a general view of the star formation history of elliptical galaxies based on observational criteria indicates a range in metallicities, and theoretical considerations imply that the star formation efficiency of even one most powerful starburst will not be such as to consume 100% of the available gas. Thus, the extreme case chosen above will correspond to a lower limit to the metallicity of a galaxy with measured Mg_2 index.

At the other extreme, we could envisage extended star formation at a slow, constant rate, which would have as a consequence the fact that the majority of the light we receive from the system must have come from stars which were formed within the past 5 Gyr, in which case an Mg_2 index of 0.29 could be produced only if the population observed has a metallicity higher than twice solar.

Clearly the most reasonable case will be intermediate, and this implies that the youngest stars must have metallicities greater than solar to compensate for the older stars with, in general low metallicities, in order to account for the selected measured value of $Mg_2 = 0.29$.

We now apply this to real galaxies, using the sample of Bender, Burstein, & Faber (1993). Figure 4 shows a histogram

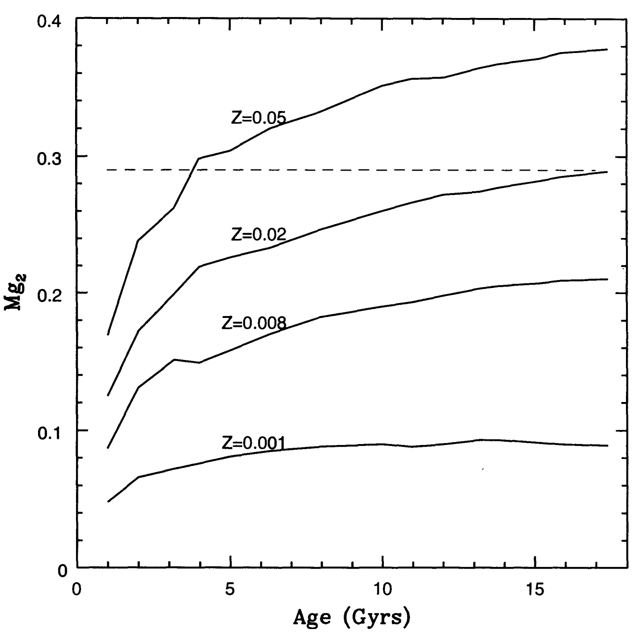

FIG. 3.—Mg_2 vs. age for single-burst models using a Salpeter IMF. We show results using isochrons of four metallicities: $Z = 0.001$, $Z = 0.008$, $Z = 0.02$ (taken as solar), and $Z = 0.05$.

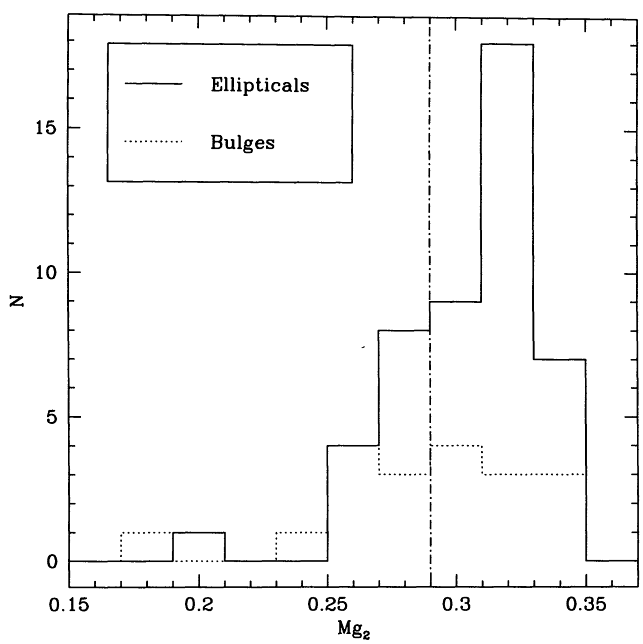

FIG. 4.—Histogram of Mg_2 values for giant ellipticals (*solid lines*) and bulges of bright early-type spirals (*dotted lines*). The data in histogram form are from Bender et al. (1993).

for the giant ellipticals (*solid line*) and the bulges (*dotted line*) of their sample. Note that 72% of the giant ellipticals and 40% of the bulges with measured Mg_2 have a central Mg_2 index of 0.29 or larger. We infer that even if all these systems had single age populations of age 17 Gyr, their metallicities would be solar or greater, and for any reduction in the average age, all would have metallicities higher than solar. For bulges this number is also high, and since many bulges seem to contain younger stellar populations (Balcells & Peletier 1994), a larger fraction will have an average metallicity larger than solar. So, our Galactic bulge, for which Whitford (1978) measured a Mg_2 of 0.25, would, using this calibration, have a metallicity ranging from $\log (Z/Z_{\odot}) = -0.25$ (if the age is 17 Gyr) to just below solar (if the age is 13 Gyr). Of course, since Whitford used very low resolution, his measurement will have to be redone to be of real value.

Assuming that elliptical galaxies are not alpha enhanced, and that the error in the models for Mg_2 is 0.022, as discussed before, the fraction of ellipticals with metallicities larger than solar (at 17 Gyr) varies between 90% and 50%. The numbers will be larger if the stellar systems contain stars younger than 17 Gyr.

If, however, it is believed that they are alpha enhanced, by on the average $[Mg/Fe] = 0.45$, fewer ellipticals will have metallicities (Z-values) larger than solar. The fraction will then vary between 65% and 4%.

One can clearly use the Mg_2 index as a variable parameter for studies of age and metallicity, always in conjunction with complementary indices, as required by the fact that there are a number of physical inputs to any more realistic model. In order to do more than set indicatory limits, as we have done here, one would need to tackle the modeling in a fully evolutionary manner and use multiple line indices, work which we are in the process of performing (Vazdekis et al. 1996). However, this note shows that the Mg_2 index alone is a valuable indicator of metallicity, and that most giant ellipticals and many bulges have metallicities higher than solar.

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