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Mg AND Fe ABSORPTION FEATURES IN ELLIPTICAL GALAXIES[1]

GUY WORTHEY, S. M. FABER, AND J. JESÚS GONZALEZ
UCO/Lick Observatory, Board of Studies in Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064
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ABSTRACT

Fe and Mg indices from two homogenous collections of nuclear elliptical galaxy spectra are compared with model indices. In the average giant elliptical, the [Mg/Fe] ratio exceeds that of the most metal-rich stars in the solar neighborhood by ~0.2–0.3 dex, with a large spread about this mean. This result implies a variable "enrichment effectiveness" of Type II supernovae (SNs) compared with Type Ia SNs in the evolution of ellipticals, caused perhaps by differences in star formation time scales, the initial mass function, or the amount of Fe versus Mg ejected in galactic winds.

Subject headings: galaxies: abundances — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation — galaxies: stellar content

1. INTRODUCTION

An accurate metallicity is needed in order to obtain a reliable age or color estimate for an elliptical galaxy population. For example, changing Z by a factor of 2 changes the adopted age by a factor of 3 at fixed color (Worthey 1991). For several years a program has been ongoing at UCO/Lick Observatory to understand elliptical metallicities better by studying prominent absorption features in optical spectra of ellipticals. This program combines empirical stellar spectral feature strengths (represented by polynomial "fitting functions" derived from stars in the solar neighborhood; Gorgas et al. 1992) with a theoretical HR diagram which is modeled using stellar evolutionary tracks.

We find that models of Fe and Mg spectral features near 5000 Å do not fit ellipticals very well. The most compact (i.e., weak-lined) ellipticals like M32 match well, with $Z \approx$ solar. However, giant ellipticals have strong Mg relative to Fe compared to the models, and this disagreement increases systematically with galaxy size. In fact, it seems possible that the well-known metal enhancement in giant ellipticals is due almost entirely to overabundance of the light elements and that the Fe peak itself is only slightly enhanced. This result is interesting because Mg and Fe are synthesized by two different types of supernovae (Types Ia and II), with different progenitor masses and different evolutionary time scales. Thus, variations in [Mg/Fe] signal (1) differences in the time scale for star formation, (2) a variable initial mass function, or (3) the differential retention of Mg versus Fe in conjunction with galactic winds. That one or more of these varies sytematically with galaxy size is an important new clue to star formation in elliptical galaxies.

We discuss the various interpretations after first describing the observational data and the models. There is an important assumption in our models that the reader should understand thoroughly before progressing to the discussion section.

2. OBSERVATIONS AND MODELS

The first of our two data sets is a survey of nuclear spectra of elliptical galaxies taken at UCO/Lick Observatory with the Image-Dissector Scanner (IDS) on the Shane 3 m telescope. These spectra cover approximately 4000–6200 Å with ~9 Å resolution FWHM. The visible portion of the spectrum was selected because the G- and K-type spectra of stars that dominate this region are amenable to both theoretical and empirical calibration. Further details are given by Burstein et al. (1984) and Faber et al. (1992). The measured line strengths have been corrected for velocity broadening. A galaxy with $\sigma = 200$ km s^{-1} has corrections to Fe5270 $\approx 10\%$, corrections to Fe5335 $\approx 23\%$, and negligible Mg_2 corrections. The sample contains only one galaxy with $\sigma > 250$ km s^{-1} which reduces the extra uncertainty associated with broadening corrections.

These data are supplemented by highly accurate measurements of Hβ, Mg_1, Mg_2, Mg b, Fe5270, and Fe5335 in 28 ellipticals and M31 (Gonzalez 1992). These data are derived from long-slit spectra taken with the CCD cassegrain spectrograph at the Shane 3 m telescope and have a nominal resolution of 3.5 Å FWHM and a wavelength coverage of 4800–5600 Å. The indices were transformed to the IDS system by artificially broadening the spectra and applying small zero-point corrections. Gonzalez's nuclear indices are between 1 and 10 times more accurate than the IDS indices. Nuclear measurements of Fe5270, Fe5335, and Mg_2 are given in Table 1 for both data sets.

Observed galactic line strengths are compared to model indices for single-burst populations calculated as a function of age, Z, Y, and IMF. Indices are calculated utilizing a set of empirical fitting functions (Gorgas et al. 1992) that model the equivalent widths of 11 strong features on the Lick IDS system as a function of stellar temperature ($V-K$), metallicity (taken to be [Fe/H]), and surface gravity. These polynomial functions were derived by fitting to a sample of ~250 field and cluster G and K stars. The fitting functions are coupled to published evolutionary isochrones (VandenBerg & Bell 1985; VandenBerg 1985; VandenBerg & Laskarides 1987; Green, Demarque, & King 1987) and evolutionary tracks (Seidel et al. 1987; Sweigart 1987; Lattanzio 1991). The models utilize a provisional bolometric correction calibration (Green 1988) and the ($T_{\rm eff}$, $V-K$) relation of Ridgeway et al. (1980). Flux curves based on model atmospheres (Bell & Gustafsson 1989) are used to calculate stellar continua. The primordial helium mass fraction Y is taken to be 0.228 (Peimbert & Torres-Peimbert 1976), and solar Y is taken to be 0.274 (Anders & Grevesse 1989). The assumed function $Y = 0.228 + 2.7Z$ reproduces

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solar Y at $Z = 0.0169$. Index strengths are insensitive to the IMF, which is assumed Salpeter.

The models are still schematic with regard to the morphology of the horizontal branch and M giant luminosity functions, but the bulk of the stars that contribute to the Mg and Fe line strengths (G- and K-types) are well handled. Moreover, we are interested mainly in the *ratio* of these features, which is even less dependent on evolutionary details. As a test, we compare model indices to real globular cluster data and to other authors' calibrations in Figure 1. The observed indices have been taken from Burstein et al. (1984), and the adopted values of globular [Fe/H] are summarized in Table 2.

The fits between our calibrations and the clusters are consistent within the errors at all levels of [Fe/H]. However, there appears to be substantial disagreement among the theoretical slopes of Mg_2 versus [Fe/H] near $[Fe/H]_\odot$ as computed by various authors. Buzzoni, Gariboldi, & Mantegazza (1991) have the lowest slope: $dMg_2/d[Fe/H] = 0.14$; Peletier (1989) is next with $dMg_2/d[Fe/H] = 0.22$; we and Mould (1978) are highest with $dMg_2/d[Fe/H] = 0.26$. We understand the large discrepancy with Buzzoni et al.; they have assumed that $\Delta Mg_2 = 0.05\Delta[Fe/H]$ for all stars, whereas the typical red giant that dominates at 5000 Å has a much larger dependence: $\Delta Mg_2 = 0.19\Delta[Fe/H]$ (Faber et al. 1985; Gorgas et al. 1992).

The good agreement with Mould could have been predicted from the similarly good agreement between the fitting functions and individual Mould models found by Gorgas et al. (1992). However, as these authors pointed out, the Lick calibration is purely empirical and therefore must follow the *actual* trend in [Mg/Fe] versus [Fe/H] among the calibrating stars. In contrast, Mould's calibration is theoretical and *assumes* [Mg/Fe] = 0. These two calibrations are equivalent only if [Mg/Fe] is near 0 for the calibrating stars above $[Fe/H]_\odot$. *In this article we make this key assumption.*

Hard data on [Mg/Fe] in Galactic metal-rich stars is sketchy. Gratton & Sneden (1987) analyzed both giants and dwarfs, but their data are too noisy to determine a confident slope near $[Fe/H]_\odot$. Extensive dwarf measurements (François 1986a, b; Nissen, Edvardsson, & Gustafsson 1985) show $[Mg/Fe] \approx 0$ with very flat slope for $[Fe/H] \geq 0$. Finally, the important SMR calibration star μ Leo has [Mg/Fe] "certainly not less than solar" (R. Peterson 1992, private

TABLE 1

Nuclear Feature Strengths in two Galaxy Samples

NGC	Mg_2	Fe5270	Fe5335	NGC	Mg_2	Fe5270	Fe5335
IDS sample (1.″4 × 4″):				5322	0.303	2.97	3.38
221	0.199	3.04	2.81	5631	0.276	3.23	2.34
224	0.334	3.57	3.13	5831	0.304	3.34	3.37
584	0.294	3.32	3.49	7332	0.263	3.53	3.06
596	0.252	3.00	2.74	7454	0.206	2.62	2.24
1023	0.342	3.35	3.22	7457	0.190	2.78	2.26
1052	0.313	2.66	2.82	7626	0.344	2.76	2.70
1172	0.248	2.85	2.49				
2549	0.297	3.48	2.89				
2634	0.298	3.06	2.96	Gonzalez sample (2.″5 × 5″):			
2655	0.216	2.59	2.54	221	0.227	3.02	2.70
2685	0.247	3.19	2.97	224	0.345	3.34	3.19
2781	0.230	2.60	2.83	315	0.323	3.08	3.14
2865	0.209	2.87	2.05	547	0.328	3.18	3.50
3115	0.336	3.73	3.17	584	0.295	3.21	2.96
3377	0.291	2.86	2.71	636	0.285	3.32	3.04
3379	0.341	3.02	2.89	821	0.333	3.29	3.03
3384	0.294	3.26	2.89	1700	0.296	3.31	3.06
3489	0.195	2.66	2.27	2300	0.352	3.27	3.04
3599	0.192	2.93	2.45	3377	0.283	2.91	2.66
3610	0.271	2.94	2.75	3379	0.324	3.22	3.00
3626	0.183	2.41	2.16	4374	0.317	3.18	2.98
4111	0.264	3.03	2.93	4478	0.243	3.04	2.89
4283	0.288	3.27	2.59	4552	0.355	3.22	3.28
4377	0.282	3.26	3.12	4649	0.370	3.31	3.48
4382	0.234	2.90	2.18	4697	0.300	3.31	3.05
4434	0.287	3.18	2.82	5638	0.325	3.17	2.85
4458	0.248	2.22	2.28	5812	0.320	3.25	3.28
4459	0.278	3.34	2.83	5813	0.311	3.08	2.83
4464	0.257	2.61	2.25	5831	0.302	3.37	3.16
4489	0.222	3.01	3.05	5846	0.340	3.18	2.99
4564	0.366	2.86	2.81	6127	0.329	3.07	3.03
4570	0.321	3.55	3.33	6703	0.304	3.23	3.01
4636	0.341	2.94	2.70	7052	0.338	3.18	3.18
4660	0.331	3.04	2.95	7454	0.236	2.72	2.44
4697	0.318	3.23	2.79	7562	0.306	3.25	2.95
4742	0.186	2.53	2.03	7619	0.370	3.36	3.48
4762	0.286	3.29	2.78	7626	0.366	3.15	3.27
5061	0.276	3.02	2.94	7785	0.324	3.14	3.15

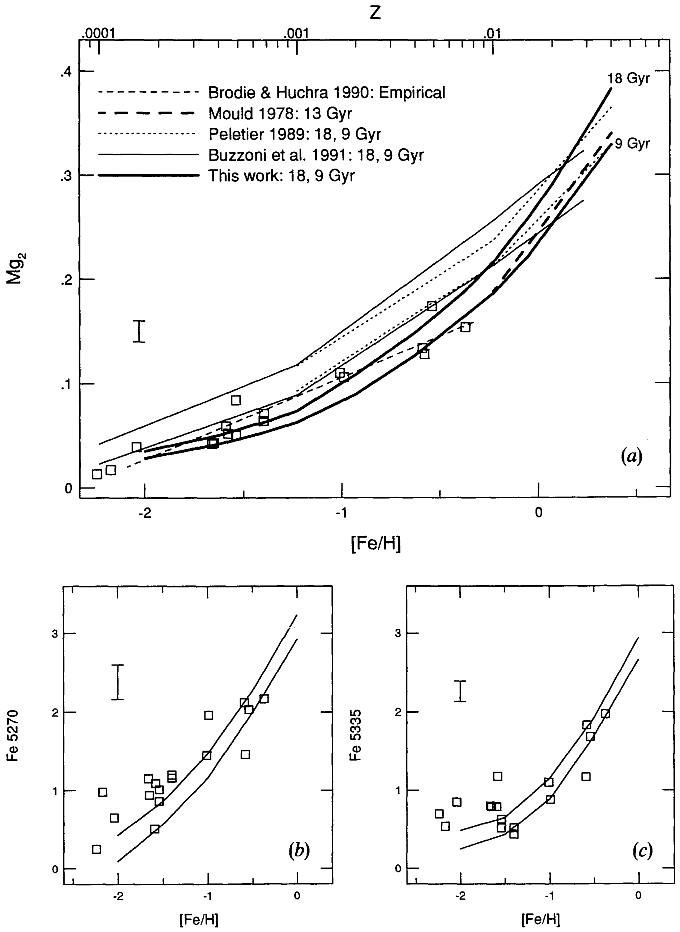

FIG. 1.—(*a*) Observed trend of Mg_2 as a function of [Fe/H] for Galactic globulars compared to various models. Index values are from Burstein et al. (1984) and adopted values of [Fe/H] are listed in Table 2. The Brodie & Huchra (1990) calibration is their empirical fit to Galactic globulars. Mould's calibration is for a 13 Gyr population, all others appear for both 9 (*lower lines*) and 18 (*upper lines*) Gyr populations. The Mould "D-index" was transformed via $Mg_2 = 0.8$ D (see Appendix II in Gorgas et al. 1992). The models of Buzzoni et al. (1991) use mass-loss parameter $\eta = 0.3$. All theoretical calibrations shown assume a Salpeter IMF. Occasional linear interpolation (in log age) was used to obtain 9 and 18 Gyr sequences from the Peletier (1989) and Buzzoni et al. (1991) works. Fe5270 and Fe5335 are shown in (*b*) and (*c*), respectively, for Galactic globulars as a function of [Fe/H]. Models for 9 and 18 Gyr are from this work.

TABLE 2

ADOPTED [Fe/H] VALUES FOR GLOBULAR CLUSTERS

NGC	*M*	[Fe/H]	Reference
5024	53	−2.04	3
5272	3	−1.66	3
5904	5	−1.40	3
6171	...	−0.99	3
6205	13	−1.65	3
6218	12	−1.40	1
6229	...	−1.54	3
6341	92	−2.24	3
6356	...	−0.54	2
6624	...	−0.37	2
6637	69	−0.59	3
6712	...	−1.01	3
6838	71	−0.58	3
6981	72	−1.54	3
7006	...	−1.59	3
7078	15	−2.17	2
7089	2	−1.58	2

Sources for values of [Fe/H]: (1) Sato et al. 1989; (2) Armandroff & Zinn 1988; (3) Zinn & West 1984.

communication). Our provisional conclusion, therefore, is that $[Mg/Fe] \approx 0$ among local metal-rich stars, but this clearly needs to be checked.

3. RESULTS

Figure 2 shows our major result: nuclear values of Fe5270 and Fe5335 are shown versus Mg_2 for the best-observed IDS ellipticals. The scatter is large and real. Residuals from the mean relations are correlated between the two figures. Of main importance is the shallow slope in Fe relative to Mg_2. This shallow slope is a distinct break from the trend among Galactic globulars, in which the Fe features rise steeply with Mg_2 up to nearly the compact-elliptical level (Burstein et al. 1984).

An Fe deficit (or Mg excess) in the strongest-lined galaxies is also indicated by the models of different ages and metallicities shown in Figure 2. The model lines pass close to the compact-elliptical (weak-lined) points, showing nearly solar abundance ratios for these objects. The giant ellipticals, however, show a systematic deficit in Fe relative to Mg_2; their Fe strengths rise only about half as fast as the models predict. A similar result was also noted by Peletier (1989).

The models in Figure 2, especially the overall slope, seem robust. Tests with the models indicate the unimportance of IMF changes, HB morphology, M giant luminosity function, and errors in the log *g* scale. Moreover, since populations add as vectors in Figure 2, the Fe discrepancy cannot be cured by invoking spreads in age or metallicity.

The models are intended to represent $[Mg/Fe] = 0$ and would need to be corrected if in fact [Mg/Fe] is falling versus *Z* among the local calibrating stars. The effect of the maximum decrease consistent with Gratton & Sneden (1987) was estimated using theoretical spectra kindly generated for us by C. M. Dalle Ore using the models of R. Kurucz. The correction in Figure 2 would increase Mg_2 by 0.025 mag at $[Fe/H] = +0.25$, while Fe would remain nearly constant. This makes the model slope somewhat shallower, but even a correction of 3 times this amount still leaves the model slope steeper than the observed relation. If the calibrating stars have $[Mg/Fe] \approx 0$, as indicated by François (1986a, b), no correction is needed.

That $[Mg/Fe] > 0$ in giant ellipticals therefore seems probable, but the only ironclad conclusion (carefully stated) is that [Mg/Fe] must exceed substantially that of the most metal-rich stars in the solar neighborhood. Measuring [Mg/Fe] accurately is impossible, as we lack stellar evolutionary tracks with varying abundance ratios. However, judging from the models at hand, the observed rise in [Fe/H] appears to be roughly half that of [Mg/H]. Regardless of whether an old or young age is chosen, the abundance of Mg then comes out 0.2–0.3 dex higher than Fe for the average strongest-lined galaxy. A further corollary is that Fe by itself does not vary a great deal.

Gonzalez's gradient measures in Figure 3 confirm and extend these conclusions. The main result is that the Fe trends *within* galaxies are steeper than the relation linking the nuclei. The same difference is seen in Fe5335 and was also detected by Efstathiou & Gorgas (1985) and by Peletier (1989). Within a

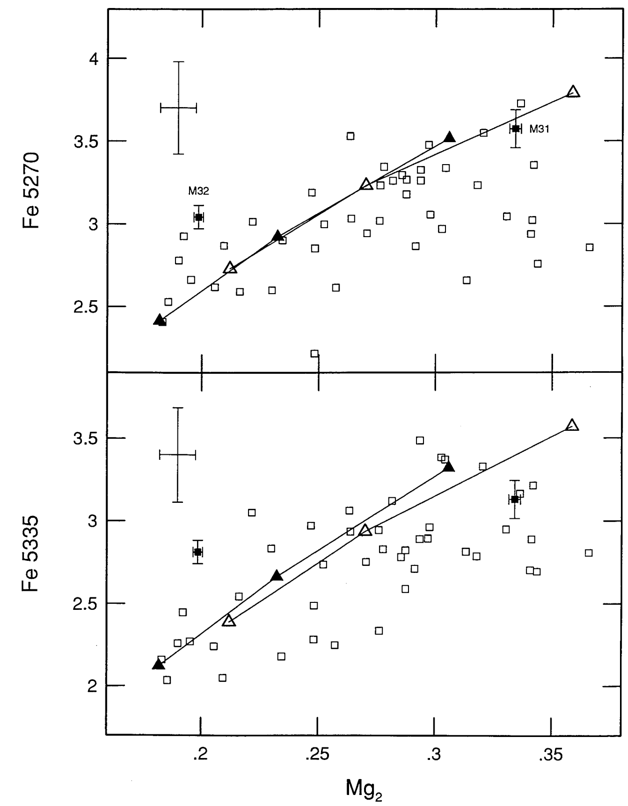

FIG. 2.—Fe line strengths, corrected for velocity broadening, of the best-observed IDS elliptical nuclei vs. Mg_2, from Table 1. Scatter is real and residuals from the mean relations are correlated between (*a*) and (*b*). The smaller errors of M32 and M31 are shown, along with an approximate maximum 1 σ error bar. Model predictions for ages 9 (*solid*) and 18 Gyr (*open*) are superposed. Symbols appear at [Fe/H] = −0.25, 0.0, and +0.25. No combination of age and metallicity can account for the shallow slope of the observations.

galaxy, Fe and Mg follow the model slope (i.e., [Mg/Fe] ≈ constant), but the *global average* [Mg/Fe] is clearly varying from galaxy to galaxy. The collective Fe-Mg relationship for all old populations is thus two-dimensional, with each galaxy following its own enrichment line. The precise location of the nucleus along this line depends on the maximum degree of nuclear enrichment achieved (and on the spatial resolution of the observations).

4. CONSTRAINTS ON ELLIPTICAL FORMATION

Since Fe and Mg are made by two different types of supernovae (Type Ia vs. Type II) a change in their ratio could signal a difference in the ratio of Fe peak to Type II light elements generally. Now, the Fe-peak elements control the temperature of the giant branch and thus the light contribution of the coolest M giants (Renzini 1977). Fe should therefore correlate closely with TiO strength and infrared spectral features. The rather small variations seen in these quantities are consistent with their being controlled by Fe.

In contrast, Type II element variations would have a big impact on the spectrum. Oxygen opacity largely controls the turnoff temperature (Renzini 1977), and therefore also blue-visual colors and Balmer line strengths. Large variations are also expected (and are seen) in individual light-element features such as Mg *b*, MgH, and Na D (Faber 1973; Bica & Alloin 1986). Further checks are needed, but it appears plausible that the major driver of spectral variations in elliptical galaxies is in fact light, not Fe-peak, elements.

Three scenarios for varying [Mg/Fe] in elliptical galaxies can be considered. In the discussion that follows, we assume that Type Ia SNs are primarily responsible for the production of Fe and that Type II SNs produce lighter elements, including Mg, along with some Fe. For completeness, however, we note that massive ($\sim 35\ M_\odot$) Type II SNs produce a factor of 10 or more Mg and other light elements relative to Fe than do less massive ($\sim 15\ M_\odot$) SNs (Woosley 1986) so that, in principle, Type II SNs can produce variable [Mg/Fe] all by themselves, and Type Ia SNs can be excised from scenarios that follow.

1. *Different star formation time scales.*—This scenario exploits the fact that Type II SNs come from massive stars with lifetimes shorter than 10^8 yr, while Type Ia SNs result from binary mass transfer, which sets in more slowly and lasts for Gyr. There results a well-known time delay between the production of the light elements and the bulk of the Fe peak, with the consequence that the first generations of stars have enhanced [Mg/Fe]. The higher [Mg/Fe] of giant ellipticals would be explained if they made stars *more rapidly*.

In fact, the dynamical time scales of giant ellipticals are about 3 times *longer* than those of compact ellipticals (e.g., Blumenthal et al. 1984). Also, in a hierarchical clustering scheme, giant ellipticals would plausibly form later because they are larger objects. Thus, standard wisdom would seem to predict longer time scales for star formation in giant ellipticals, not shorter. But before ruling this scenario out completely, we note counterbalancing evidence that comes from our Hβ measurements of elliptical spectra. These data, which we will discuss at length in a future paper, are actually consistent with more rapid, that is, earlier, star formation in giant ellipticals. Thus the question of time scales remains open.

2. *A variable IMF.*—The second mechanism posits a differ-

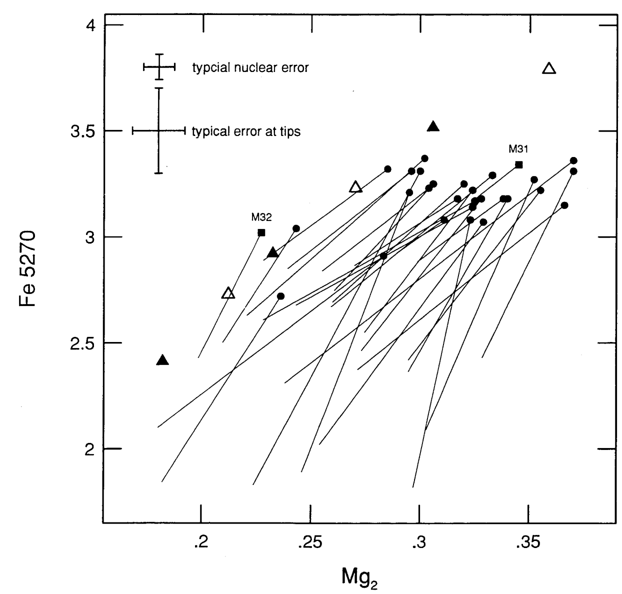

FIG. 3.—Fe5270–Mg_2 gradient data from the Gonzalez long-slit CCD data. Values for the central 5″ of each galaxy are shown as solid dots. Averages of the furthest radii (typically 15″–20″) are shown as the tips of the attached lines. Model points are redrawn from Fig. 2*a*. Note that the *internal* slopes are similar to the model predictions, but the slope of the nuclei is much more shallow.

ence in the IMF, with giant ellipticals having more very massive stars, more Type II SNs, and more light-element production. No conclusive evidence exists at this time to prefer this view over any other; however, it fits rather neatly with the concept of bimodal star formation developed to explain star formation in our own Galaxy. In this picture, low-mass star formation is quiescent and regulated by internal cloud parameters like magnetic field and temperature. High-mass star formation, on the other hand, is triggered by external conditions such as passage through a spiral arm.

A comparable external variable in ellipticals could be the ambient effective gas pressure due to cloud-cloud collisions. Since this scales roughly as the dispersion $\sigma^2_{\rm cloud}$, the effective ambient pressure in merging galaxies would be about 100 times higher than in spiral arms. Even among ellipticals, there is a difference of a factor of ~ 10 between compacts and giants. If higher $\sigma_{\rm cloud}$ favored more massive stars, the higher abundance of light elements in giant galaxies would be naturally explained.

The variable IMF theory also helps to explain the observed tight correlation between Mg_2 and σ. Throughout this paper we have spoken loosely of "giant" versus "compact" elliptical galaxies, tacitly implying that abundance scales best with galaxy mass. In fact, Mg_2 scales more closely with *velocity dispersion* than it does with luminosity or any other parameter (Bender 1992). High σ would translate directly to high Mg_2 through the strength of the upper IMF.

3. *Selective loss mechanisms.*—The usual mechanism for gas loss is the SN-driven galactic wind. In standard models (Arimoto & Yoshii 1987; Matteucci & Tornambè 1987), winds are effective at later times in giant ellipticals owing to their deeper potential wells. Giant ellipticals are therefore predicted to have *lower* [Mg/Fe] owing to the time-scale argument above. This is in direct contradiction to the observations.

It might be possible to save the wind picture by introducing a selective loss mechanism that retains Mg with greater efficiency than Fe. For instance, mergers may trigger exceptionally powerful starbursts in giant ellipticals that could drive out all previously accumulated Fe-rich gas. The next generations of stars would then be preferentially Mg-rich. This or some other coupling between wind properties and galaxy structure should be considered.

5. SUMMARY

We have presented observations of feature strengths in old stellar populations and compared them with models. This comparison shows that the average giant elliptical has more light elements in general than the most metal-rich stars in the solar neighborhood and probably has [Mg/Fe] $\approx$ 0.2–0.3 dex. Three possible evolution scenarios were discussed, all based on the assumption that Mg and Fe are produced by different types of supernovae. These scenarios invoke variable star formation time scales, variable IMFs, and selective mass loss of Fe compared to Mg. No clear choice among them exists at the present time, but the quantity [Mg/Fe] clearly provides an important new tool for studying star formation in old stellar populations.

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REFERENCES

Anders, E., & Grevesse, N. 1989, Geochim. Cosmochim. Acta, 53, 197
Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Armandroff, T. E., & Zinn, R. 1988, AJ, 96, 92
Bell, R. A., & Gustafsson, B. 1989, MNRAS, 236, 653
Bender, R. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy (Dordrecht: Kluwer), 267
Bica, E., & Alloin, D. 1986, A&A, 162, 21
Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Nature, 311, 517
Brodie, J. P., & Huchra, J. P. 1990, ApJ, 362, 503
Burstein, D., Faber, S. M., Gaskell, C. M., & Krumm, N. 1984, ApJ, 287, 586
Buzzoni, A., Gariboldi, G., & Mantegazza, L. 1991, AJ, submitted
Efstathiou, G., & Gorgas, J. 1985, MNRAS, 215, 37P
Faber, S. M. 1973, ApJ, 179, 731
Faber, S. M., Friel, E. D., Burstein, D., & Gaskell, C. M. 1985, ApJS, 57, 711
Faber, S. M., Worthey, G., Dalle Ore, C. M., Keane, M., Gonzalez, J. J., Tran, H. D., & Burstein, D. 1992, in preparation
François, P. 1986a, A&A, 160, 264
———. 1986b, A&A, 165, 183
Gonzalez, J. J. 1992, Ph.D. thesis, Univ. of California, Santa Cruz
Gorgas, J., Faber, S. M., Burstein, D., Gonzalez, J. J., Courteau, S., & Prosser, C. 1992, ApJS, submitted
Gratton, R. G., & Sneden, C. 1987, A&A, 178, 179
Green, E. M. 1988, in Calibration of Stellar Ages, ed. A. G. Davis Philip (Schenectady, NY: L. Davis), 81
Green, E. M., Demarque, P., & King, C. R. 1987, The Revised Yale Isochrones and Luminosity Functions (New Haven: Yale Univ. Observatory)
Lattanzio, J. C. 1991, ApJS, 76, 215
Matteucci, F., & Tornambè, A. 1987, A&A, 185, 51
Mould, J. 1978, ApJ, 220, 434
Nissen, P. E., Edvardsson, B., & Gustafsson, B. 1985, in Production and Distribution of CNO Elements, ed. I. J. Danziger, F. Matteucci, & K. Kjär (Garching: ESO), 131
Peimbert, M., & Torres-Peimbert, S. 1976, ApJ, 203, 581
Peletier, R. 1989, Ph.D. thesis, Rijksuniversiteit Groningen
Renzini, A. 1977, in Advanced Stages in Stellar Evolution, Saas-Fee Lectures 1977, ed. P. Bouvier & A. Maeder (Geneva: Geneva Observatory), 166
Ridgeway, S. T., Joyce, R. R., White, N. M., & Wing, R. F. 1980, ApJ, 235, 126
Sato, T., Richer, H. B., & Fahlman, G. G. 1989, AJ, 98, 1335
Seidel, E., Demarque, P., & Weinberg, D. 1987, ApJS, 63, 917
Sweigart, A. V. 1987, ApJS, 65, 95
VandenBerg, D. A. 1985, ApJS, 58, 711
VandenBerg, D. A., & Bell, R. A. 1985, ApJS, 58, 561
VandenBerg, D. A., & Laskarides, P. G. 1987, ApJS, 64, 103
Woosley, S. E. 1986, in Nucleosynthesis and Chemical Evolution, ed. B. Hauk & A. Maeder (Geneva: Geneva Observatory), 1
Worthey, G. 1991, BAAS, 23, 1457
Zinn, R., & West, M. 1984, ApJS, 55, 45