

GRADIENTS OF ABSORPTION-LINE STRENGTHS IN ELLIPTICAL GALAXIES

CHIAKI KOBAYASHI

Department of Astronomy, School of Science, University of Tokyo 7-3-1, Hongo, Bunkyo-ku, Tokyo 113-0033, Japan; chiaki@astron.s.u-tokyo.ac.jp

AND

NOBUO ARIMOTO

Institute of Astronomy, School of Science, University of Tokyo 2-21-1, Osawa, Mitaka, Tokyo 181-8588, Japan; arimoto@mtk.ioa.s.u-tokyo.ac.jp

Received 1998 May 27; accepted 1999 July 19

ABSTRACT

We have restudied line-strength gradients of 80 elliptical galaxies. Typical metallicity gradients of elliptical galaxies are $\Delta[\text{Fe}/\text{H}]/\Delta \log r \simeq -0.3$, which is flatter than the gradients predicted by monolithic collapse simulations. The metallicity gradients do not correlate with any physical properties of galaxies, including central and mean metallicities, central velocity dispersions σ_0 , absolute B magnitudes M_B , absolute effective radii R_e , and dynamical masses of galaxies. By using the metallicity gradients, we have calculated mean stellar metallicities for individual ellipticals. Typical mean stellar metallicities are $\langle[\text{Fe}/\text{H}]\rangle \simeq -0.3$ and range from $\langle[\text{Fe}/\text{H}]\rangle \simeq -0.8$ to $+0.3$, which is contrary to what Gonzalez & Gorgas claimed; the mean metallicities of ellipticals are not universal. The mean metallicities correlate well with σ_0 and dynamical masses, though relations for M_B and R_e include significant scatters. We find fundamental planes defined by surface brightnesses SB_e , $\langle[\text{Fe}/\text{H}]\rangle$, and R_e (or M_B), the scatters of which are much smaller than those of the $\langle[\text{Fe}/\text{H}]\rangle$ - R_e (or $\langle[\text{Fe}/\text{H}]\rangle$ - M_B) relations. The $\langle[\text{Fe}/\text{H}]\rangle$ - $\log \sigma_0$ relation is nearly parallel to the $[\text{Fe}/\text{H}]_0$ - $\log \sigma_0$ relation but systematically lower by 0.3 dex; thus the mean metallicities are about one-half of the central values. The metallicity-mass relation or, equivalently, the color-magnitude relation of ellipticals holds not only for the central parts of galaxies but also for entire galaxies. Assuming that Mg_2 and Fe_1 give $[\text{Mg}/\text{H}]$ and $[\text{Fe}/\text{H}]$, respectively, we find $\langle[\text{Mg}/\text{Fe}]\rangle \simeq +0.2$ in most of elliptical galaxies. $\langle[\text{Mg}/\text{Fe}]\rangle$ shows no correlation with galaxy mass tracers such as σ_0 , in contrast to what was claimed for the central $[\text{Mg}/\text{Fe}]$. This can be most naturally explained if the star formation had stopped in elliptical galaxies before the bulk of Type Ia supernovae began to occur. Elliptical galaxies can have significantly different metallicity gradients and $\langle[\text{Fe}/\text{H}]\rangle$, even if they have the same galaxy mass. This may result from galaxy mergers, but no evidence is found from presently available data to support the same origin for metallicity gradients, the scatters around the metallicity-mass relation, and dynamical disturbances. This may suggest that the scatters have their origin at the formation epoch of galaxies.

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

1. INTRODUCTION

How elliptical galaxies formed is one of key questions of modern astronomy. Two competing scenarios have so far been proposed: elliptical galaxies should form monolithically by gravitational collapse of gas cloud with considerable energy dissipation (e.g., Larson 1974b; Arimoto & Yoshii 1987), or alternatively ellipticals should form via mergers of relatively small galaxies (e.g., Toomre & Toomre 1972; Kauffmann & White 1993; Cole et al. 1994). Elliptical galaxies show apparently little evidence for on-going star formation—the bulk of their stars are old (e.g., Kodama & Arimoto 1997; Stanford, Eisenhardt, & Dickinson 1997; Kodama et al. 1998a)—yet some ellipticals show strong signs of recent dynamical disturbances (Schweizer et al. 1990; Schweizer & Seitzer 1992). Observational evidence is confusing and controversial.

The merger hypothesis assumes that gaseous disklike galaxies formed first by assembling subgalactic clumps, then two grown-up disk galaxies of similar mass collided into a single giant elliptical galaxy (e.g., Kauffmann & White 1993; Kauffmann & Charlot 1998). Alternatively, an elliptical galaxy could form if many small galaxies accreted onto a massive disk galaxy (e.g., Cole et al. 1994; Baugh et al. 1998). Observationally, the dynamical disturbances such as shells/ripples, transient dust lanes, and multiple and/or

counterrotating cores (e.g., Kormendy & Djorgovski 1989) all seem to support the scenario that elliptical galaxies formed via hierarchical clustering of smaller galaxies (Schweizer & Seitzer 1992), which is a picture predicted by cold dark matter (CDM) cosmology. The merger hypothesis may easily explain the morphology-density relation of galaxies in clusters (Dressler 1980; Dressler et al. 1997), a significant number of interacting galaxies at high redshifts (Driver, Windhorst, & Griffiths 1995), Butcher-Oemler effects (Butcher & Oemler 1978, 1984), and E+A galaxies (Dressler & Gunn 1983, 1992). However, collisions and mergers of galaxies should be less frequent at the cluster center because of the large velocity dispersions of galaxies there (Ostriker 1980). A recent *Hubble Space Telescope* (*HST*) observation reveals conspicuous spiral arms dominated by A-type stars in the E+A galaxies (Franx et al. 1996), which suggests that the Butcher-Oemler galaxies are not ellipticals but spiral galaxies falling onto a cluster potential for the first time witnessed at the instant of being transformed into S0 galaxies. Elliptical galaxies are surrounded by huge numbers of globular clusters (GCs). The number of globular clusters relative to galaxy luminosity (specific frequency) is almost twice that in spiral galaxies (Harris 1991). If ellipticals formed via mergers of spiral galaxies, at least similar amount of GCs should be born during

the merger events (van den Bergh 1982, 1990). True, young GCs are discovered in merging galaxies (Whitmore & Schweizer 1995), but these GCs are far less numerous than would be required to explain the high specific frequencies of ellipticals. On the other hand, GCs in elliptical galaxies have bimodal $[\text{Fe}/\text{H}]$ distributions (Forbes, Brodie, & Grillmair 1997), which has been considered to support the merging hypothesis.

The dissipative collapse hypothesis assumes that the bulk of stars in an elliptical formed during an initial burst of star formation, which was induced by the collisions of fragmented clouds in protogalaxies and terminated by a supernova-driven galactic wind that expelled the leftover interstellar gas from the galaxies (e.g., Larson 1974b; Arimoto & Yoshii 1987). The galactic wind is supposed to play an essential role in enriching heavy elements in hot intracluster gas (Ciotti et al. 1991). Elliptical galaxies after the wind should evolve passively (Kodama et al. 1998a). The shells and ripples would appear when ellipticals captured nearby dwarf galaxies. These dynamical disturbances would be detectable for a couple of gigayears, but the capture itself would not introduce any significant change in the stellar constituents of galaxies, since the mass involved in the secondary formation of stars is at most 10%, as the study of $\text{H}\beta$ absorption and broadband colors of elliptical galaxies shows (Kodama & Arimoto 1998). The galactic wind predicts tight correlations among global properties of galaxies, including a color-magnitude relation (Bower, Lucey, & Ellis 1992) and a fundamental plane (Djorgovski & Davis 1987; Dressler et al. 1987). Recent observations of clusters at high redshifts confirm that these relationships hold even at $z \sim 1$ (Dickinson 1996; Schade, Barrientos, & Lopez-Cruz 1997; Kelson et al. 1997; Stanford et al. 1998). A progressive change of the color-magnitude relation as a function of look-back time clearly indicates that the bulk of stars in ellipticals formed at redshifts $z_f \gtrsim 2.5\text{--}4$ (Kodama et al. 1998a).

In this paper, we study gradients of absorption-line strengths of elliptical galaxies. In the last two decades, the line-strength gradients of ellipticals were extensively studied by Faber (1977, hereafter F77), Efstathiou & Gorgas (1985, hereafter EG), Couture & Hardy (1988, hereafter CH), Peletier (1989, hereafter PEL), Gorgas, Efstathiou, & Aragón-Salamanca (1990, hereafter GEA), Boroson & Thompson (1991, hereafter BT), Davidge (1991a, 1991b, 1992, hereafter D91a, D91b, D92), Bender & Surma (1992, hereafter BS), Carollo, Danziger, & Buson (1993, hereafter CDB), Davies, Sadler, & Peletier (1993, hereafter DSP), Gonzalez (1993, hereafter GON), Hes & Peletier (1993, hereafter HP), Saglia et al. (1993, hereafter SAG), Carollo & Danziger (1994a, 1994b, hereafter CDa, CDb), Sansom, Peace, & Dodd (1994, hereafter SPD), Cardiel, Gorgas, & Aragón-Salamanca (1995, hereafter CGA), and Fisher, Franx, & Illingworth (1995a, hereafter FFI). Major lines so far studied are Mg_2 , Mg_b , Fe_1 5270 Å, Fe_2 5335 Å, $\text{H}\beta$, and $\text{H}\gamma$ lines. The first four metallic lines are degenerate in age and metallicity, while the two hydrogen lines are sensitive to stellar age (Burstein et al. 1984; Faber et al. 1985; Gonzalez 1993; Worthey 1994). Recently, Vazdekis & Arimoto (1999) have broken up the age-metallicity degeneracy of $\text{H}\gamma$ by including neighboring metallic lines in such a way that the resulting $\text{H}\gamma$ depends only on age. The approach is thus very promising, but no attempt has yet been conducted to estimate ages of giant ellipticals. We therefore should keep

in mind that some giant elliptical galaxies in the field might be significantly younger than cluster ellipticals (Franceschini et al. 1998; Kodama, Bower, & Bell 1998b) and that the radial gradients of metallic lines may be caused by not only radial variation of stellar metallicity but also equivalent variation of mean stellar age. This paper discusses the gradients of the four metallic lines and $\text{H}\beta$, but mainly the Mg_2 and Mg_b gradients because Fe_1 and Fe_2 are easily influenced by a possible gradient of stellar velocity dispersion whose spatial distribution in a galaxy is still difficult to measure precisely.

Previous studies showed that $(\text{Mg}_2)_0$ correlate with the velocity dispersion σ_0 at the galaxy center (Davies et al. 1987; Burstein et al. 1988; Bender, Burstein, & Faber 1993). A similar relation holds for $(\text{Mg}_2)_0$ and total absolute magnitudes M_B (Faber 1973; Burstein 1979; Terlevich et al. 1981; Dressler 1984). If, and it is admittedly a big “if,” one can assume that elliptical galaxies are old, one can convert Mg_2 into the metallicity Z either empirically (Burstein et al. 1984; Faber et al. 1985) or theoretically with the help of population-synthesis models (Mould 1978; Peletier 1989; Buzzoni, Gariboldi, & Mantegazza 1992; Barbuy 1994; Worthey 1994; Casuso et al. 1996; Bressan, Chiosi, & Tantalo 1996; Kodama & Arimoto 1997). For example, if the Worthey (1994) calibration is adopted, one finds that the typical metallicity gradient of elliptical galaxies is $\Delta \log Z / \Delta \log r \simeq -0.3$. The radial gradient of metallic line strength can be naturally explained by the dissipative collapse picture. However, the measured gradients are less steep than those predicted by numerical simulations of the collapse model. For example, Larson’s hydrodynamical simulations gave $\Delta \log Z / \Delta \log r \sim -0.35$ (Larson 1974a) and -1.0 (Larson 1975), and Carlberg’s N -body simulations gave $\Delta \log Z / \Delta \log r \sim -0.5$ (Carlberg 1984). This discrepancy could be interpreted if mergers flatten an original gradient; indeed numerical simulations showed that the gradient in a disk galaxy should be halved after three successive mergers of galaxies with similar sizes (White 1980). However, both simulations of the dissipative collapse and successive mergers leave room for the improvement because some essential physical processes, such as star formation, thermal feedback from supernovae, and metal enrichment, were not taken into account.

Elliptical galaxies with larger values of $(\text{Mg}_2)_0$ tend to show steeper Mg_2 gradients (Gorgas et al. 1990; Carollo et al. 1993; Gonzalez & Gorgas 1996). Since a brighter elliptical usually has a larger $(\text{Mg}_2)_0$ (Davies & Sadler 1987), Gonzalez & Gorgas (1996) suggested that a larger $(\text{Mg}_2)_0$ is cancelled by a steeper gradient and that elliptical galaxies should have very similar mean stellar metallicities, regardless of their luminosities and masses. If this is true, the color-magnitude relation is nothing but a local relation that holds only for the central part of a galaxy and may not reflect the formation process of ellipticals. One should use global metallicities instead of local ones in studying the origin of ellipticals. Therefore, it is particularly important to estimate mean stellar metallicities of ellipticals accurately and study relations with other global features of galaxies.

No tight correlations between the Mg_2 gradient and other properties of galaxies are yet confirmed. The Mg_2 gradient and the central velocity dispersion σ_0 may correlate (Davidge 1992) but with a significant scatter (Gorgas et al. 1990), and cD galaxies deviate from that relation considerably (Carollo et al. 1993). However, Davies et al. (1993)

did not find any significant correlation between the Mg_2 gradient and σ_0 . Nevertheless, the local colors and the line strengths correlate tightly (Davies et al. 1993; Carollo & Danziger 1994a), and both show strong correlations to the local escape velocity (Franx & Illingworth 1990; Davies et al. 1993; Carollo & Danziger 1994a). Elliptical galaxies that deviate considerably from the ridge line of the Mg_2 -absolute magnitude relation tend to have larger values of Σ , the degree of dynamical disturbances (Schweizer et al. 1990), but the Mg_2 gradient is not correlated to Σ nor to the isophotal shape a_4/a (Davidge 1992).

If elliptical galaxies formed monolithically from a massive gas cloud, the Mg_2 gradient should correlate with global properties of galaxies. Carlberg (1984) showed that more massive galaxies have steeper metallicity gradients. An apparent lack of such correlations may suggest that the Mg_2 gradient was built up via a series of successive mergers of gas-rich galaxies. The situation surrounding Mg_2 gradient studies is complicated and confusing. This we believe is due to a lack of suitable sample of the Mg_2 gradient. The total exposure time required to measure the Mg_2 gradient is much longer than for broadband color gradients. Therefore, a single group of authors can observe only a limited number of galaxies. What is worse, the quality of the data is not uniform. We have studied 187 line-strength gradients of 133 early-type galaxies. After carefully examining the quality of the data, we have chosen data for 80 elliptical galaxies. Section 2 describes how the data are selected and analyzed. Section 3 gives a definition of the mean stellar metallicities of ellipticals. Section 4 gives our main results, and our discussions and conclusions are given in §§ 5 and 6, respectively.

2. LINE STRENGTH GRADIENTS

2.1. Line Strength Gradients

We have studied 187 gradients of Mg_2 , Mg_b , Fe_1 5270 Å, Fe_2 5335 Å, and $H\beta$ lines for 133 early-type galaxies. Data are taken from 20 data sources: F77, EG, CH, PEL, GEA, BT, D91a, D91b, BS, D92, CDB, DSP, GON, HP, SAG, CDa, CDb, SPD, CGA, and FFI. To demonstrate a global view of line-strength gradients, we summarize Mg_2 and Mg_b gradients of these galaxies in the Appendix. Unfortunately, accurate and precise line-strength gradient data are difficult to obtain, requiring long integrations on bright objects with large telescopes to obtain high enough signal-to-noise ratios (S/Ns) (e.g., DSP; GON); thus the quality of these data is not uniform, and we are obliged to abandon many of them because of poor quality as described below (we are indebted to the anonymous referee for reminding us of the differing quality of the gradient data and were helped considerably by the referee's recommendation that we make brief descriptions for the data sources, but we are entirely responsible for any critical remarks we make): F77: data quality is poor, there are no error bars in figures, but errors are quite large, the sky subtraction is poor, and perhaps no velocity dispersion correction has been made [trustworthiness = (index strengths, gradients) = (fair, poor)]; CH: data quality is poor outside nucleus, the gradients are uncertain, and the sky subtraction is poor [trustworthiness = (poor, poor)]; PEL: the calibration is suspicious, and the error bars may be underestimated [trustworthiness = (good, good)]; GEA, EG: data quality is poor outside nucleus, errors are large, the sky subtraction

is poor, and velocity dispersion correction may not have been done [trustworthiness = (fair, poor)]; BT: the quality of spectra is poor outside nucleus, the sky subtraction is poor, and the error bars are not given, but the velocity dispersion correction is reasonable [trustworthiness = (fair, good)]; D91a, D91b, D92: the calibrations are suspicious, data quality is reasonable for two of three galaxies, and sky subtraction is poor, but it is not clear whether or not velocity dispersion correction has been done [trustworthiness = (poor, fair?)]; BS: the calibration is good, but the sky subtraction is suspicious, it is not clear whether or not velocity dispersion corrections have been made [trustworthiness = (fair, fair)]; CDB: except for Mg_2 , the calibration is uncertain, and there is significant contamination of emissions in galaxy spectra [trustworthiness = (good, excellent)]; DSP: the calibration is done carefully, but the sky subtraction is suspicious but better than most [trustworthiness = (excellent, excellent)]; GON: the calibration is excellent except for Mg_1 and Mg_2 , which are affected by chromatic focus variations, and for $H\beta$ the velocity dispersion correction is suspicious [trustworthiness = (excellent, excellent)]; HP: the calibration is suspicious [trustworthiness = (good, good)]; SAG: zero points of indices are off, and the velocity dispersion correction is suspicious [trustworthiness = (poor, good)]; CDa, CDb: the calibrations are uncertain for Fe_1 and Fe_2 , and the sky subtraction is suspicious [trustworthiness = (good, excellent)]; SPD: the data are uncalibrated, the sky subtraction is poor, and the velocity dispersion correction is probably wrong [trustworthiness = (poor, poor)]; CGA: the calibration is off by 0.014 mag, and no velocity dispersion correction has been done [trustworthiness = (poor, poor)]; FFI: the calibration is uncertain, the sky subtraction and velocity dispersion correction are good, but the emission is suggested to be contaminated by [O III] [trustworthiness = (good, excellent)].

Of these 20 data sources, we have adopted five (BS, CDB, DSP, CDa, and CDb) that provide excellent Mg_2 gradient data for 46 ellipticals and two (GON and FFI) that give high-quality Mg_b gradient data for an additional 34 elliptical galaxies. These authors almost universally used CCDs as detectors instead of photon counters because of unreliability of the wavelength and flux calibrations of photon counters (e.g., Peletier 1989; Trager et al. 1998).

We apply a linear regression analysis for the line-strength gradients by accounting for observational errors:

$$\text{Index}(r) = (\text{Index})_e + \frac{\Delta \text{Index}}{\Delta \log r} \log \frac{r}{r_e} \equiv A - B \log \frac{r}{r_e}, \quad (1)$$

where r is the projected radius and the subscript e indicates values defined at an effective radius r_e . When the line-strength gradients are measured at different position angles, we use the effective radius r_e^* corrected for an eccentricity, as was done by DSP. Effective radii and eccentricities are taken from the original references, if available, and are supplementally taken from Davies et al. (1983), Djorgovski & Davis (1987), and Davies et al. (1987).

In general, linear regression lines give good approximations, but observed index values are systematically smaller at the innermost central parts and at the outer regions beyond r_e . At galaxy centers with $\log r/r_e \lesssim -1.5$, the gradients are smeared out because of poor seeing condi-

tions, and in the outer regions errors arising from the sky subtraction give poor fits. Therefore, we exclude these regions from our fitting. BS, DSP, CDB, CDa, and CDb all used the Lick indices (Burstein et al. 1984; Faber et al. 1985), while FFI and GON used the Gonzalez (1993) indices. However, differences are too small to affect the present analysis. CDB, DSP, CDa, CDb, and FFI converted spectral resolution of their measurements to Lick scales, but the differences are negligible for Mg_2 and Mg_b , which are our main concern.

Table 1 gives the resulting fitting parameters of the line-strength gradients for 80 elliptical galaxies. Columns (1)–(7) give the name of galaxy, the reference, the index name, the intercept at r_e and its error, and the gradient and its error, respectively. Mg_b is most suitable for a study of line-strength gradients, but the number of galaxies is not large enough to derive the statistics. The number of galaxies with Mg_2 gradient data is largest in our sample. Fe_1 shows similar gradients to Mg_2 , but Fe_2 shows a larger scatter, since it is very vulnerable to spectral resolution and the gradient of velocity dispersions. Therefore, we use Fe_1 instead of $\langle Fe \rangle = (Fe\ I + Fe\ II)/2$, which was used in previous studies. $H\beta$ is an age-sensitive index (Worthey 1994) and shows flat or positive gradients (DSP; GON; FFI). A negative gradient of $H\beta$ emission may explain this (DSP), but it may instead be due to a decreasing stellar age toward the galaxy center (GON; FFI). If the $H\beta$ gradients reflect the age gradient within a galaxy, our old-age assumption for ellipticals is not correct anymore. The metallic line-strength gradients (Mg_2 , Mg_b , Fe_1 , and Fe_2) are all degenerate in age and metallicity, and a simple use of a stellar population synthesis model in converting the line-strength gradients to metallicity gradients would not be justified. We have solved the age-metallicity degeneracy by analyzing the absorption-line gradients together with the $H\beta$ gradients (§ 2).

2.2. Metallicity Gradients

Since it is not certain whether all elliptical galaxies are equally old, we convert the line-strength gradients to the metallicity gradients in two alternative ways: (assumption A) we assume that all ellipticals are 17 Gyr old and convert the indices to the metallicity, or (assumption B) we assume that ellipticals are of different ages and that the line-strength gradients reflect both the metallicity and age gradients. We have solved the age-metallicity degeneracy of the gradients by studying the Mg_2 and $H\beta$ gradients simultaneously, but the number of galaxies for which $H\beta$ data are available is small, and $H\beta$ may be affected by emission contamination. Therefore, we first calculate mean stellar metallicities of individual ellipticals under assumption A and derive correlations between the mean stellar metallicity and other physical properties of galaxies. We then examine whether scatters of these correlations become smaller if we take into account a possible age effect under assumption B.

2.2.1. Index-Metallicity Relations

Under assumption A, the index-metallicity relations can be derived from spectral synthesis models. Comparing the relations given by seven different population synthesis models (Mould 1978; Peletier 1989; Buzzoni et al. 1992; Barbay 1994; Worthey 1994; Casuso et al. 1996; Bressan et al. 1996), we find that, except for those of Mould (1978) and Barbay (1994), these models give very similar relations

unless the metallicity is too low ($[Fe/H] > -1$). These relations are approximately given by the following form:

$$[Fe/H] = p(\text{Index}) - q. \quad (2)$$

Hereafter, we shall use the index-metallicity relations derived from the Worthey (1994) SSP models for 17 Gyr old galaxies:

$$[Fe/H] = 5.85Mg_2 - 1.65,$$

$$[Fe/H] = 0.45Mg_b - 1.87,$$

$$[Fe/H] = 0.67Fe_1 - 2.16,$$

$$[Fe/H] = 0.59Fe_2 - 1.77.$$

Quite often Mg_2 gives an $[Fe/H]$ value ~ 0.2 dex higher than that derived from Fe_1 . It may be due to our use of Worthey's model, which assumes $[\alpha/Fe] = 0$ for α elements such as oxygen, magnesium, silicon, etc. We will discuss this in § 4.5. If we use Worthey's SSP models for 12 Gyr old galaxies, we obtain systematically higher metallicities, but none of our main conclusions needs to be modified.

If the metallic line-strength gradients are indeed reflecting the metallicity gradients, the observational data suggest that the gradients can be approximated in the following form:

$$[Fe/H] = \log \frac{Z_e}{Z_\odot} - c \log \frac{r}{r_e}, \quad (3)$$

where $Z_\odot = 0.02$ is the solar metallicity and Z_e gives the stellar metallicity derived at $r = r_e$. The coefficient c gives the slope of metallicity gradient. On the other hand, from equations (1) and (2) we get the following equation:

$$[Fe/H] = (Ap - q) - Bp \log \frac{r}{r_e}, \quad (4)$$

which gives the parameters Z_e and c in equation (3) for individual galaxies.

Figure 1 shows histograms of the line-strength gradients of the four indices, $-\Delta Mg_2/\Delta \log r$, $-\Delta Mg_b/\Delta \log r$, $-\Delta Fe_1/\Delta \log r$, and $-\Delta Fe_2/\Delta \log r$. Note that there is no sign of bimodality in the frequency distributions of the Mg_2 , Mg_b , Fe_1 , and Fe_2 gradients. This implies that, whatever the origin is, the gradients were formed by a single physical process. The average values are $\Delta[Fe/H]/\Delta \log r = -0.30 \pm 0.12$ (Mg_2), -0.34 ± 0.16 (Mg_b), -0.28 ± 0.16 (Fe_1), and -0.25 ± 0.13 (Fe_2). All indices suggest that the metallicity gradients are in the range $-0.6 \leq \Delta[Fe/H]/\Delta \log r \leq -0.1$. The typical metallicity gradient is about $\Delta[Fe/H]/\Delta \log r \sim -0.3$, which is slightly steeper than the original estimate because we have excluded the central regions where the gradients are significantly altered by poor seeing. The gradients thus derived are considerably flatter than the theoretical value -0.5 predicted by Carlberg (1984).

Figure 2 shows the frequency distribution of Mg_2 at galaxy center, $(Mg_2)_0$, for 572 elliptical galaxies (*dashed line*) given by Davies et al. (1987), and 80 ellipticals (*solid line*) studied in this article. We note that there is no systematic difference between the two samples; thus we believe that we are dealing with a fairly good sample of elliptical galaxies in the local universe. Figure 3 gives frequency distributions of the four indices measured at the effective radius (i.e.,

TABLE 1
LINE-STRENGTH GRADIENTS OF ELLIPTICAL GALAXIES

Galaxy (1)	Reference (2)	Index (3)	(Index) _e (4)	Error (5)	Δ Index	
					$\Delta \log r$ (6)	Error (7)
NGC 315	DSP	Mg ₂	0.277	0.002	-0.038	0.003
		Fe ₁	3.136	0.085	0.142	0.144
		H β	1.456	0.049	0.131	0.095
NGC 547	GON	Mg _b	4.294	0.109	-0.654	0.099
		Fe ₁	2.316	0.127	-0.574	0.117
		Fe ₂	2.493	0.173	-0.167	0.160
		H β	1.363	0.122	0.052	0.111
NGC 584	GON	Mg _b	3.932	0.049	-0.317	0.045
		Fe ₁	2.332	0.053	-0.563	0.049
		Fe ₂	2.226	0.059	-0.441	0.054
		H β	2.037	0.045	0.144	0.042
NGC 636	GON	Mg _b	3.585	0.067	-0.546	0.069
		Fe ₁	2.698	0.072	-0.411	0.074
		Fe ₂	2.267	0.085	-0.483	0.087
		H β	1.846	0.081	-0.005	0.083
NGC 720	GON	Mg _b	4.673	0.257	-0.388	0.230
		Fe ₁	2.553	0.268	-0.318	0.242
		Fe ₂	3.082	0.315	0.213	0.284
		H β	2.478	0.241	0.669	0.218
NGC 741	DSP	Mg ₂	0.246	0.002	-0.064	0.003
		Fe ₁	2.228	0.159	-0.762	0.173
		H β	1.698	0.078	0.355	0.098
NGC 821	GON	Mg _b	3.492	0.094	-0.861	0.085
		Fe ₁	2.481	0.101	-0.510	0.091
		Fe ₂	2.566	0.113	-0.165	0.103
		H β	2.101	0.086	0.366	0.078
NGC 1052	CDB	Mg ₂	0.245	0.004	-0.073	0.004
		Fe ₁	2.565	0.194	-0.438	0.230
NGC 1209	CDB	Mg ₂	0.237	0.003	-0.058	0.003
		Fe ₁	2.920	0.261	-0.426	0.254
NGC 1298	CDB	Mg ₂	0.188	0.016	-0.031	0.012
NGC 1453	GON	Mg _b	3.687	0.090	-1.044	0.081
		Fe ₁	2.667	0.107	-0.261	0.097
		Fe ₂	2.655	0.144	-0.267	0.132
		H β	1.363	0.101	0.323	0.091
NGC 1600	DSP	Mg ₂	0.266	0.004	-0.078	0.006
		Fe ₁	2.411	0.078	-0.551	0.127
		H β	1.832	0.115	0.328	0.140
NGC 1700	GON	Mg _b	3.457	0.079	-0.620	0.083
		Fe ₁	2.526	0.085	-0.566	0.090
		Fe ₂	2.456	0.099	-0.340	0.105
		H β	2.090	0.067	0.121	0.071
NGC 2434	CDa	Mg ₂	0.171	0.001	-0.061	0.001
		Fe ₁	2.294	0.061	-0.376	0.059
		Fe ₂	2.101	0.059	-0.306	0.057
NGC 2663	CDb	Mg ₂	0.259	0.001	-0.059	0.001
		Fe ₁	2.729	0.049	-0.388	0.044
		Fe ₂	1.827	0.051	-0.771	0.046
NGC 2778	GON	Mg _b	4.137	0.124	-0.491	0.121
		Fe ₁	2.751	0.140	-0.203	0.137
		Fe ₂	2.000	0.159	-0.591	0.158
		H β	0.863	0.143	-0.387	0.151
NGC 2832	FFI	Mg _b	4.285	0.125	-0.475	0.098
		H β	1.429	0.105	0.018	0.081
NGC 2974	CDB	Mg ₂	0.223	0.005	-0.054	0.004
NGC 3078	CDB	Mg ₂	0.245	0.003	-0.056	0.003
		Fe ₁	2.779	0.261	-0.494	0.189
NGC 3136B	CDB	Mg ₂	0.192	0.008	-0.051	0.004
NGC 3226	CDB	Mg ₂	0.202	0.005	-0.059	0.004
NGC 3250	CDB	Mg ₂	0.265	0.005	-0.044	0.005
		Fe ₁	2.768	0.398	-0.691	0.467
NGC 3260	CDB	Mg ₂	0.204	0.012	-0.065	0.011
NGC 3377	GON	Mg _b	2.409	0.073	-1.432	0.105
		Fe ₁	1.982	0.074	-0.713	0.106

TABLE 1—Continued

Galaxy (1)	Reference (2)	Index (3)	(Index) _e (4)	Error (5)	Δ Index			
					$\Delta \log r$ (6)	Error (7)		
NGC 3379.....	DSP	Fe ₂	1.398	0.080	-0.900	0.116		
		H β	1.883	0.065	0.207	0.093		
		Mg ₂	0.245	0.001	-0.055	0.001		
		Fe ₁	2.272	0.025	-0.452	0.032		
		Fe ₂	2.483	0.074	-0.417	0.100		
NGC 3557.....	CDB	H β	1.636	0.025	0.077	0.025		
		Mg ₂	0.251	0.004	-0.044	0.004		
		Fe ₁	3.344	0.445	-0.163	0.398		
		NGC 3608.....	GON	Mg _b	3.301	0.085	-1.037	0.073
		Fe ₁		3.305	0.094	0.207	0.081	
Fe ₂	2.424	0.114		-0.262	0.100			
H β	1.686	0.111		0.076	0.101			
NGC 3818.....	GON	Mg _b		2.900	0.159	-1.709	0.156	
Fe ₁		2.055	0.167	-0.899	0.165			
Fe ₂		1.817	0.184	-0.887	0.181			
H β		1.513	0.143	0.025	0.140			
NGC 4073.....		FFI	Mg _b	4.619	0.163	-0.135	0.121	
H β	1.095		0.147	-0.291	0.110			
NGC 4261.....	DSP	Mg ₂	0.276	0.002	-0.058	0.003		
		Fe ₁	2.603	0.054	-0.497	0.070		
		Fe ₂	2.640	0.076	-0.601	0.085		
		H β	1.538	0.019	0.212	0.030		
		NGC 4278.....	DSP	Mg ₂	0.244	0.001	-0.060	0.002
Fe ₁	2.628	0.016		0.053	0.043			
Fe ₂	2.294	0.014		-0.388	0.031			
H β	1.372	0.029		1.289	0.049			
NGC 4365.....	BS	Mg ₂		0.239	0.003	-0.060	0.003	
NGC 4374.....		DSP	Mg ₂	0.260	0.001	-0.055	0.001	
Fe ₁	2.717		0.048	-0.150	0.061			
Fe ₂	2.350		0.075	-0.410	0.095			
H β	1.697		0.042	0.326	0.052			
NGC 4406.....	BS		Mg ₂	0.237	0.008	-0.046	0.006	
NGC 4472.....		DSP	Mg ₂	0.292	0.002	-0.033	0.001	
Fe ₁	2.803		0.043	-0.388	0.040			
Fe ₂	2.754		0.054	-0.594	0.053			
H β	1.347		0.028	-0.061	0.026			
NGC 4478.....	GON		Mg _b	3.972	0.055	-0.326	0.069	
Fe ₁		2.355	0.061	-0.605	0.077			
Fe ₂		2.244	0.072	-0.490	0.090			
H β		1.685	0.072	-0.148	0.093			
NGC 4486.....		DSP	Mg ₂	0.289	0.001	-0.056	0.001	
Fe ₁	2.587		0.034	-0.398	0.038			
Fe ₂	2.763		0.075	-0.306	0.076			
H β	1.377		0.043	0.535	0.050			
NGC 4489.....	GON		Mg _b	2.328	0.123	-0.695	0.105	
Fe ₁		2.415	0.124	-0.414	0.106			
Fe ₂		1.711	0.131	-0.575	0.112			
H β		2.269	0.109	-0.036	0.094			
NGC 4494.....		BS	Mg ₂	0.157	0.006	-0.082	0.004	
NGC 4552.....	GON		Mg _b	4.248	0.048	-0.756	0.056	
Fe ₁		2.522	0.053	-0.445	0.062			
Fe ₂		2.391	0.060	-0.465	0.072			
H β		1.646	0.040	0.318	0.046			
NGC 4636.....		DSP	Mg ₂	0.234	0.001	-0.078	0.002	
Fe ₁	2.367		0.057	-0.549	0.070			
Fe ₂	2.727		0.090	-0.294	0.104			
H β	1.995		0.082	0.676	0.096			
NGC 4649.....	GON		Mg _b	4.636	0.051	-0.584	0.042	
Fe ₁		2.341	0.056	-0.523	0.046			
Fe ₂		2.337	0.073	-0.539	0.062			
H β		1.255	0.042	-0.056	0.034			
NGC 4696.....		CDB	Mg ₂	0.277	0.007	-0.024	0.004	
NGC 4697.....	GON		Mg _b	2.896	0.072	-0.979	0.055	
Fe ₁		2.000	0.079	-0.747	0.060			
Fe ₂		1.688	0.089	-0.746	0.068			
H β		1.732	0.064	0.070	0.050			

TABLE 1—Continued

Galaxy (1)	Reference (2)	Index (3)	(Index) _e (4)	Error (5)	Δ Index	
					$\Delta \log r$ (6)	Error (7)
NGC 4839.....	DSP	Mg ₂	0.247	0.004	-0.058	0.006
		H β	1.252	0.118	-0.098	0.175
NGC 4874.....	FFI	Mg _b	3.902	0.284	-0.725	0.224
		H β	1.383	0.260	-0.027	0.201
NGC 5011.....	CDB	Mg ₂	0.234	0.007	-0.048	0.005
NGC 5018.....	CDB	Mg ₂	0.211	0.001	-0.031	0.001
		Fe ₁	2.702	0.028	-0.332	0.029
		Fe ₂	2.470	0.029	-0.463	0.031
NGC 5044.....	CDB	Mg ₂	0.309	0.005	-0.010	0.005
NGC 5077.....	CDB	Mg ₂	0.244	0.007	-0.057	0.007
		Fe ₁	2.750	0.384	-0.362	0.376
NGC 5090.....	CDB	Mg ₂	0.288	0.006	-0.032	0.006
		Fe ₁	2.692	0.504	-0.373	0.448
NGC 5322.....	BS	Mg ₂	0.221	0.005	-0.037	0.005
NGC 5638.....	GON	Mg _b	3.286	0.079	-1.152	0.085
		Fe ₁	2.521	0.083	-0.384	0.091
		Fe ₂	2.162	0.092	-0.429	0.101
		H β	1.694	0.082	0.037	0.089
NGC 5796.....	CDB	Mg ₂	0.287	0.004	-0.038	0.004
		Fe ₁	2.795	0.308	-0.491	0.255
NGC 5812.....	GON	Mg _b	4.091	0.076	-0.622	0.074
		Fe ₁	2.604	0.081	-0.446	0.080
		Fe ₂	2.460	0.090	-0.498	0.089
		H β	1.679	0.068	-0.036	0.067
NGC 5813.....	GON	Mg _b	3.637	0.105	-0.847	0.085
		Fe ₁	2.844	0.118	-0.059	0.097
		Fe ₂	2.320	0.151	-0.146	0.124
		H β	0.945	0.129	-0.188	0.104
NGC 5831.....	GON	Mg _b	3.203	0.067	-0.973	0.077
		Fe ₁	2.516	0.072	-0.497	0.083
		Fe ₂	2.106	0.080	-0.657	0.093
		H β	1.988	0.070	0.106	0.079
NGC 5846.....	CDB	Mg ₂	0.317	0.003	-0.007	0.002
		Fe ₁	2.683	0.161	-0.360	0.127
NGC 5903.....	CDB	Mg ₂	0.230	0.009	-0.041	0.006
NGC 6127.....	GON	Mg _b	4.113	0.109	-0.728	0.105
		Fe ₁	2.304	0.121	-0.503	0.118
		Fe ₂	2.482	0.140	-0.200	0.138
		H β	1.522	0.096	0.030	0.092
NGC 6166.....	FFI	Mg _b	3.029	0.210	-1.236	0.182
		H β	2.388	0.172	1.293	0.141
NGC 6702.....	GON	Mg _b	3.530	0.101	-0.236	0.085
		Fe ₁	2.649	0.117	-0.306	0.099
		Fe ₂	2.627	0.147	-0.258	0.123
		H β	2.155	0.119	0.001	0.100
NGC 6868.....	CDB	Mg ₂	0.269	0.005	-0.039	0.004
		Fe ₁	2.604	0.229	-0.621	0.211
NGC 7052.....	GON	Mg _b	4.137	0.127	-0.734	0.122
		Fe ₁	2.543	0.139	-0.278	0.134
		Fe ₂	2.555	0.163	-0.178	0.160
		H β	2.316	0.118	0.962	0.113
NGC 7097.....	CDB	Mg ₂	0.203	0.003	-0.090	0.004
		Fe ₁	1.972	0.232	-0.990	0.250
NGC 7192.....	CDa	Mg ₂	0.197	0.001	-0.059	0.001
		Fe ₁	2.256	0.040	-0.481	0.039
		Fe ₂	1.786	0.042	-0.647	0.041
NGC 7200.....	CDB	Mg ₂	0.213	0.004	-0.112	0.006
NGC 7454.....	GON	Mg _b	2.533	0.095	-0.610	0.090
		Fe ₁	2.076	0.096	-0.462	0.092
		Fe ₂	1.973	0.104	-0.266	0.099
		H β	1.962	0.085	-0.100	0.081
NGC 7562.....	GON	Mg _b	4.151	0.059	-0.331	0.054
		Fe ₁	2.944	0.063	-0.082	0.059
		Fe ₂	2.	0.072	-0.391	0.067
NGC 7619.....	GON	H β	1.590	0.057	-0.029	0.052
		Mg _b	4.040	0.066	-0.846	0.059

TABLE 1—Continued

Galaxy (1)	Reference (2)	Index (3)	$(\text{Index})_e$ (4)	Error (5)	ΔIndex	
					$\Delta \log r$ (6)	Error (7)
NGC 7626	DSP	Fe ₁	2.245	0.077	-0.650	0.069
		Fe ₂	2.541	0.109	-0.433	0.099
		H β	1.549	0.073	0.119	0.063
		Mg ₂	0.259	0.001	-0.069	0.001
		Fe ₁	3.118	0.039	0.005	0.040
		Fe ₂	2.674	0.050	-0.448	0.062
NGC 7720	FFI	H β	1.256	0.032	-0.050	0.028
		Mg _b	3.272	0.294	-1.186	0.225
		H β	2.616	0.261	0.947	0.199
NGC 7768	FFI	Mg _b	3.630	0.187	-0.620	0.133
		H β	1.319	0.197	-0.030	0.140
NGC 7785	GON	Mg _b	3.785	0.070	-0.679	0.063
		Fe ₁	2.625	0.082	-0.247	0.075
		Fe ₂	2.648	0.105	-0.219	0.096
		H β	1.568	0.084	0.048	0.076
IC 1459	CDB	Mg ₂	0.260	0.003	-0.065	0.003
		Fe ₁	2.885	0.195	-0.431	0.200
IC 3370	CDB	Mg ₂	0.239	0.004	-0.018	0.003
IC 4889	CDB	Mg ₂	0.227	0.005	-0.027	0.005
IC 4943	CDB	Mg ₂	0.219	0.004	-0.037	0.003
Abell 496	FFI	Fe ₁	2.359	0.217	-0.598	0.198
		Mg _b	2.936	0.750	-1.291	0.516
ESO 323-16	CDB	Mg ₂	0.218	0.005	-0.042	0.004

NOTES.—Cols. (4) and (5): Intercept at the effective radius and error. Cols. (6) and (7): Gradient and error.

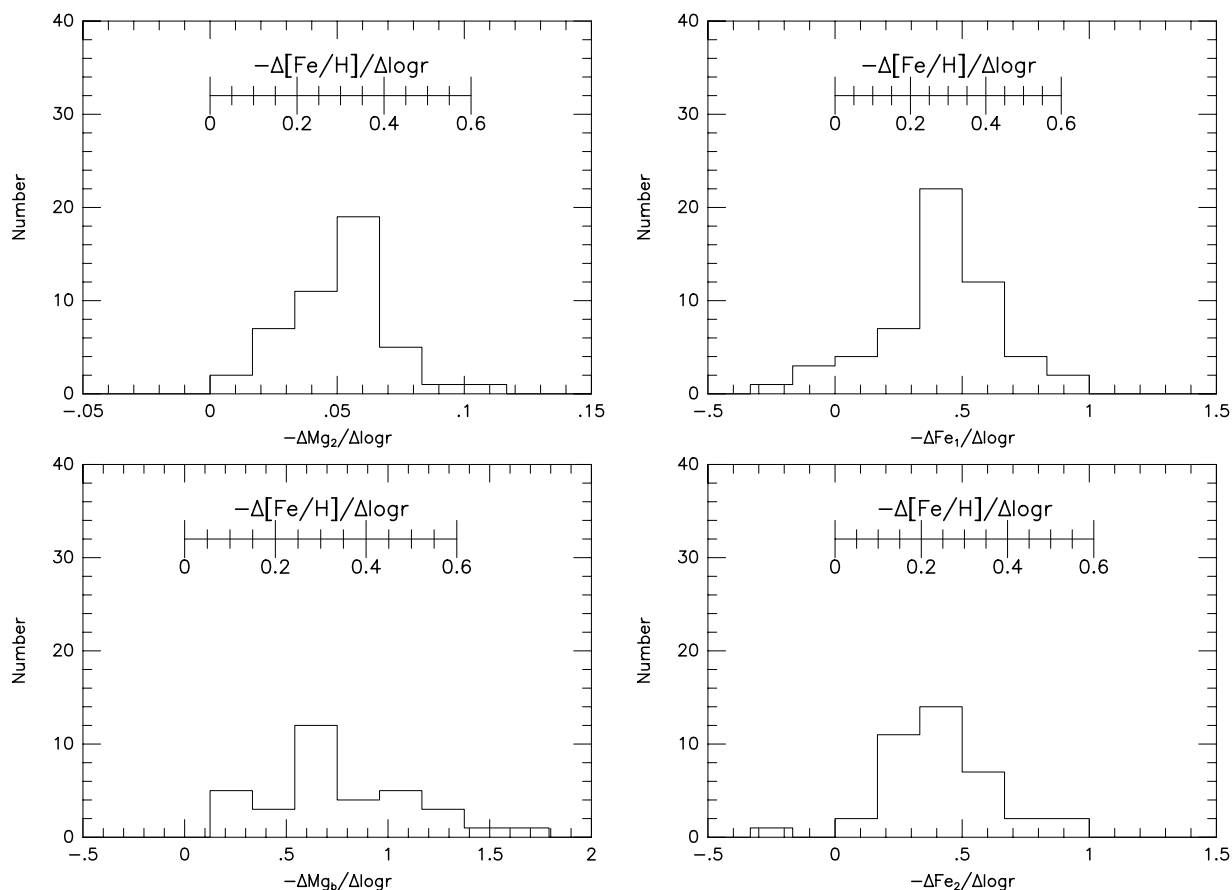


FIG. 1.—Frequency distributions of the line-strength gradients. Clockwise from the upper-left to the lower-left, the panels show Mg₂, Fe₁, Fe₂, and Mg_b. The metallicity scales are taken from the index-metallicity relations of the Worthey (1994) population synthesis models, provided that galaxies are 17 Gyr old.

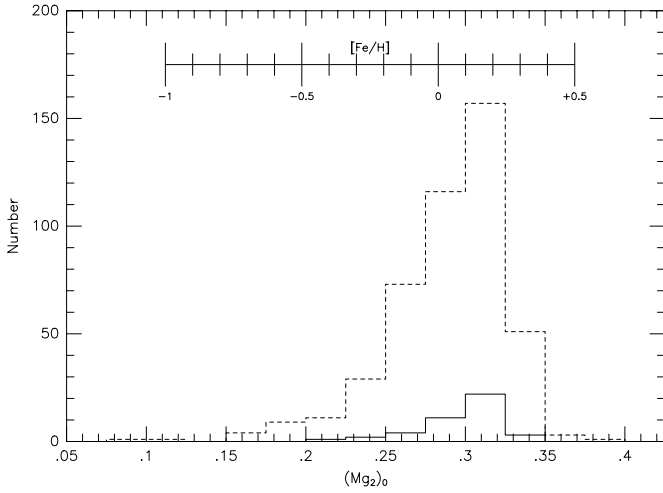


FIG. 2.—Frequency distribution of Mg_2 at a galaxy center for 572 ellipticals (*dashed line*) taken from Davies et al. (1987) and 46 ellipticals from our sample (*solid line*). The metallicity scale is the same as in Fig. 1.

the intercept at $r = r_e$). As we will see later (§ 3), the metallicities evaluated at $r = r_e$ give good measures for the mean stellar metallicities. The average values are $\langle [Fe/H] \rangle = -0.18 \pm 0.19$ (Mg_2), -0.15 ± 0.24 (Mg_b), -0.37 ± 0.17 (Fe_1), and -0.36 ± 0.18 (Fe_2). Contrary to the claim of Gonzalez & Gorgas (1996), the mean metallicities of ellipticals are not universal but range from

$\langle [Fe/H] \rangle \simeq -0.8$ to $+0.3$. The typical mean stellar metallicity of elliptical galaxies is about one-half solar, $\langle [Fe/H] \rangle \simeq -0.3$, which is considerably smaller than the stellar metallicity $[Fe/H]_0 \simeq +0.2$ measured at the galaxy center. From a similar study of the Mg_2 gradients but with a much smaller sample of ellipticals, Arimoto et al. (1997) found that the mean metallicity of typical elliptical galaxies with $\sigma_0 \geq 250$ km s $^{-1}$ is $\langle [Fe/H] \rangle \simeq -0.06 \pm 0.13$. Our sample includes 19 ellipticals with $\sigma_0 \geq 250$ km s $^{-1}$, from which we obtain $\langle [Fe/H] \rangle \simeq -0.04 \pm 0.11$. Thus, a claim made by Arimoto et al. (1997) remains unexplained; i.e., the iron abundance of the interstellar mediums of luminous elliptical galaxies, as derived from *ASCA* X-ray observations of the iron L complex, is at variance with the abundance expected from the stellar populations as derived from current population synthesis methods of optical spectrum.

2.2.2. Index-Metallicity-Age Matrices

Under assumption B, we find that the relations among two indices (one is $H\beta$ and the other is either Mg_2 or Mg_b), age, and metallicity can be approximated with the following matrix forms:

$$\begin{pmatrix} \text{Index}_1 \\ \text{Index}_2 \end{pmatrix} = \begin{pmatrix} s_1 & s_2 \\ s_3 & s_4 \end{pmatrix} \begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} + \begin{pmatrix} q_1 \\ q_2 \end{pmatrix}, \quad (5)$$

$$\begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} = \begin{pmatrix} p_1 & p_2 \\ p_3 & p_4 \end{pmatrix} \begin{pmatrix} \text{Index}_1 - q_1 \\ \text{Index}_2 - q_2 \end{pmatrix}, \quad (6)$$

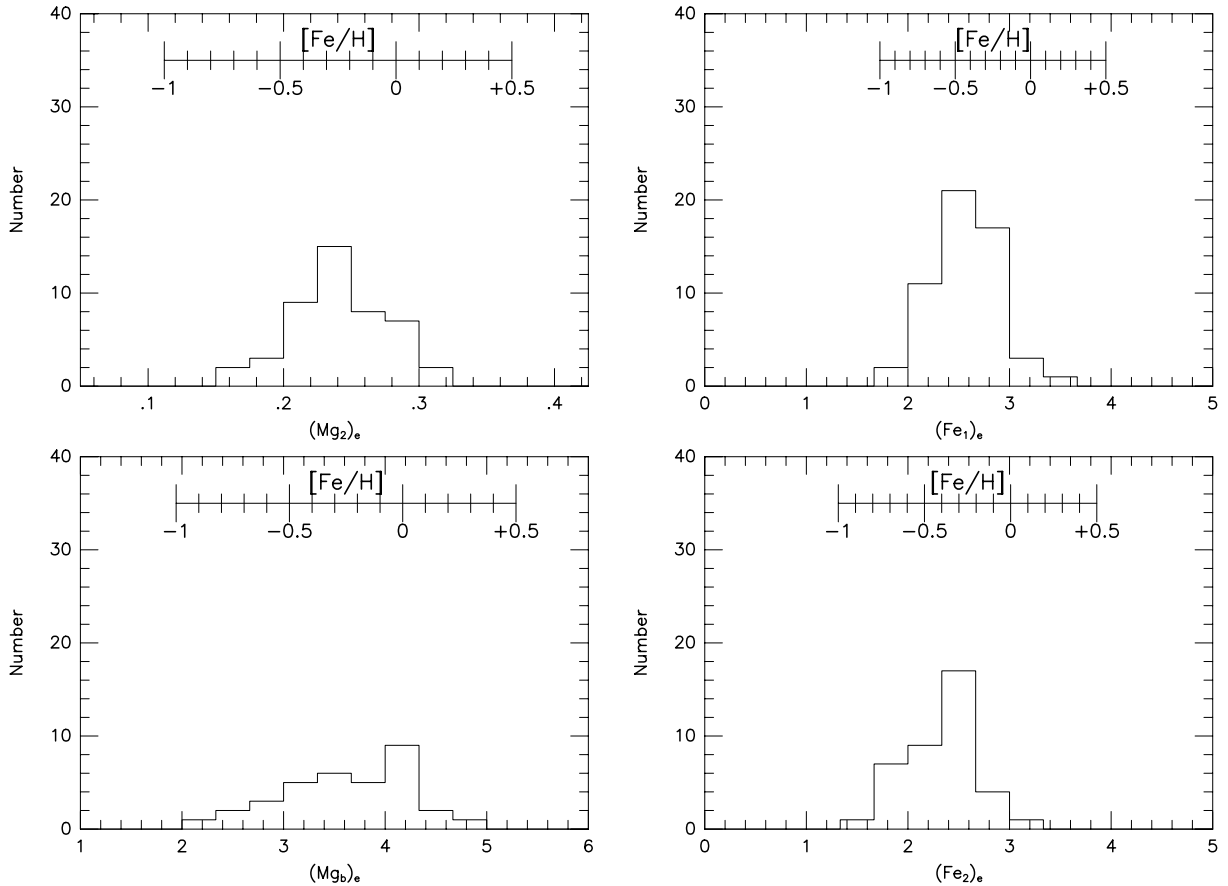


FIG. 3.—Same as Fig. 1, but for the intercepts at the effective radius

where t_9 is an age in units of Gyr. If we adopt the Worthey (1994) models, we obtain

$$\begin{aligned} \begin{pmatrix} H\beta \\ Mg_2 \end{pmatrix} &= \begin{pmatrix} -0.0425 & -0.607 \\ 0.00414 & 0.182 \end{pmatrix} \begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} + \begin{pmatrix} 2.12 \\ 0.211 \end{pmatrix}, \\ \begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} &= \begin{pmatrix} -34.9 & -116. \\ 0.792 & 8.12 \end{pmatrix} \begin{pmatrix} H\beta - 2.12 \\ Mg_2 - 0.211 \end{pmatrix}, \\ \begin{pmatrix} H\beta \\ Mg_b \end{pmatrix} &= \begin{pmatrix} -0.0425 & -0.607 \\ 0.0583 & 2.28 \end{pmatrix} \begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} + \begin{pmatrix} 2.12 \\ 3.18 \end{pmatrix}, \\ \begin{pmatrix} t_9 \\ [Fe/H] \end{pmatrix} &= \begin{pmatrix} -37.1 & -9.89 \\ 0.950 & 0.692 \end{pmatrix} \begin{pmatrix} H\beta - 2.12 \\ Mg_b - 3.18 \end{pmatrix}, \end{aligned}$$

which are valid for $8 \lesssim t_9 \lesssim 17$ and $-0.5 \lesssim [Fe/H] \lesssim 0.5$ (see Fig. 4). With these equations, we can easily derive both metallicity gradient and age gradient simultaneously from the two line-strength gradients. From equations (1) and (6), we obtain the following formal relations that give the age and metallicity gradients for individual galaxies:

$$t_9 = p_1(A_1 - q_1) + p_2(A_2 - q_2) - (p_1 B_1 + p_2 B_2) \log \frac{r}{r_e} \quad (7)$$

and

$$\begin{aligned} [Fe/H] &= p_3(A_1 - q_1) + p_4(A_2 - q_2) \\ &\quad - (p_3 B_1 + p_4 B_2) \log \frac{r}{r_e}, \end{aligned} \quad (8)$$

where A_1, B_1 are for Index₁ and A_2, B_2 are for Index₂.

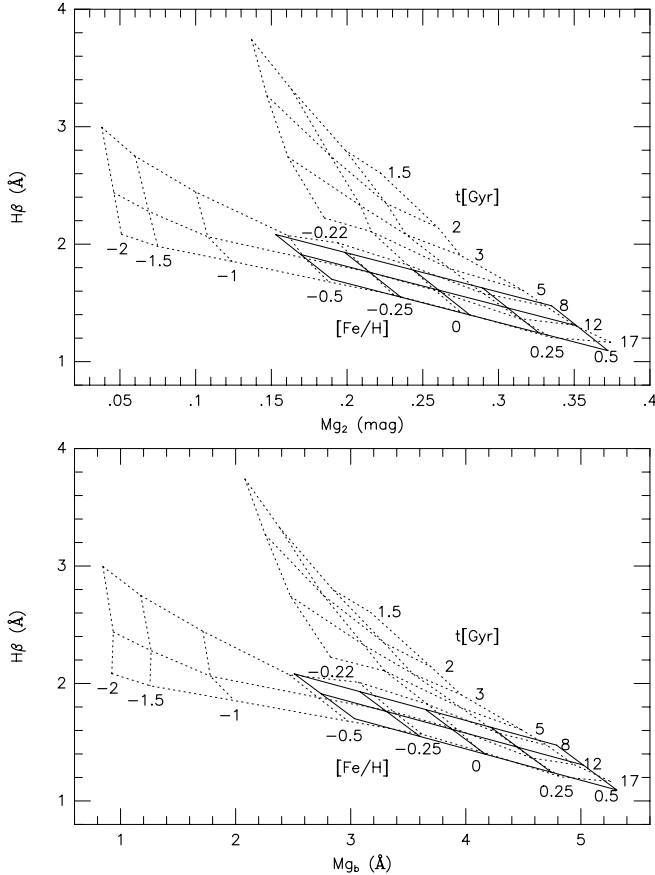


FIG. 4.— $H\beta$ vs. (upper panel) Mg_2 and (lower panel) Mg_b relations as functions of age and metallicity. Dotted lines give simple the stellar population models of Worthey (1994), and solid lines show the approximated relations adopted in this paper.

In applying these relations to individual ellipticals, however, we find that resulting ages for several galaxies are not realistic (much larger than 17 Gyr). This may probably due to the poor quality of $H\beta$ gradient data. We therefore further assume that the age gradients are small and could be ignored. We take into account only the possibility that the whole stellar population of a galaxy is systematically young, that is, we estimate the typical age of a galaxy with the intercept of $H\beta$ at the effective radius. Assuming no age gradients (i.e., $s_2 \sim 0, B_1 \sim 0$), we have derived the metallicity gradients by using the following equations for Mg_2 and Mg_b :

$$t_9 = (A_1 - q_1)/s_1 \quad (9)$$

and

$$[Fe/H] = \frac{(A_2 - q_2 - s_3 t_9)}{s_4} - \frac{B_2}{s_4 \log r/r_e}. \quad (10)$$

3. MEAN STELLAR METALLICITY

It is well known that surface brightness profiles of elliptical galaxies are not fitted well with the so-called de Vaucouleurs' law (Caon, Capacciolo, & D'Onofrio 1993; Graham & Colless 1997; Binggeli & Jerjen 1998). We, therefore, use Sersic's law, which is a generalized de Vaucouleurs' law, by replacing the power index $1/4$ with $1/n$. The parameter n correlates with the luminosity of a galaxy; a bright elliptical has an $n = 4$ profile, while a dwarf elliptical has an exponential $n = 1$ profile (Binggeli & Jerjen 1998). In this section, we derive the mean stellar metallicity of an elliptical galaxy by using the observed line-strength gradients and the theoretical index-metallicity relations.

We assume that an elliptical galaxy is spherically symmetric and the surface brightness profile is given by Sersic's law:

$$I(r) = I_e \exp \left[-b \left\{ \left(\frac{r}{r_e} \right)^{1/n} - 1 \right\} \right], \quad (11)$$

$$I_e = \frac{1}{2n\pi e^b b^{-2n} \Gamma(2n)} \frac{L_*}{r_e^2}, \quad (12)$$

where r is the projected radius and r_e is de Vaucouleurs' effective radius, b is a function of n determined from the definition of the effective radius, and $b(n)$ is approximately given by the following equation:

$$b(n) = -0.326463 + 1.99927n. \quad (13)$$

The luminosity within the radius r is given by

$$L(r) = \int_0^r 2\pi r I(r) dr = 2n\pi e^b b^{-2n} r_e^2 I_e \Gamma \left[2n, 0, b \left(\frac{r}{r_e} \right)^{1/n} \right], \quad (14)$$

where Γ is the general Gamma function. The total luminosity is given by

$$L(\infty) = 2n\pi e^b b^{-2n} \Gamma(2n) r_e^2 I_e = L_*. \quad (15)$$

If we assume that the projected metallicity distribution is given by an exponential form, as the observed Mg_2 gradients suggest, then

$$\bar{Z}(r) = Z_e \left(\frac{r}{r_e} \right)^{-c}, \quad (16)$$

TABLE 2
METALLICITY GRADIENTS AND MEAN METALLICITIES OF ELLIPTICAL GALAXIES

GALAXY (1)	REFERENCE (2)	Mg ₂		Mg _b		Fe ₁		Fe ₂		Mg ₂	Mg _b	Fe ₁	Fe ₂
		Z _e (3)	c (4)	Z _e (5)	c (6)	Z _e (7)	c (8)	Z _e (9)	c (10)	<[Fe/H]> (11)	<[Fe/H]> (12)	<[Fe/H]> (13)	<[Fe/H]> (14)
NGC 315	DSP	0.0185	-0.225	...	...	0.0179	0.096	...	...	0.00	...	-0.05	...
NGC 547	GON	...	...	0.0227	-0.293	0.0050	-0.387	0.0099	-0.098	...	0.11	-0.51	-0.30
NGC 584	GON	...	...	0.0156	-0.142	0.0051	-0.380	0.0069	-0.260	...	-0.09	-0.50	-0.42
NGC 636	GON	...	...	0.0109	-0.245	0.0091	-0.277	0.0073	-0.285	...	-0.23	-0.30	-0.39
NGC 720	GON	...	...	0.0335	-0.174	0.0072	-0.214	0.0220	0.126	...	0.25	-0.41	0.04
NGC 741	DSP	0.0121	-0.372	...	...	0.0044	-0.514	...	...	-0.14	...	-0.51	...
NGC 821	GON	...	...	0.0099	-0.386	0.0065	-0.344	0.0109	-0.097	...	-0.22	-0.42	-0.25
NGC 1052	CDB	0.0119	-0.428	...	...	0.0074	-0.295	...	...	-0.12	...	-0.38	...
NGC 1209	CDB	0.0108	-0.341	...	...	0.0128	-0.287	...	...	-0.20	...	-0.14	...
NGC 1298	CDB	0.0056	-0.183	...	...	...	...	...	...	-0.53	...	...	...
NGC 1453	GON	...	...	0.0121	-0.468	0.0086	-0.176	0.0123	-0.157	...	-0.09	-0.34	-0.19
NGC 1600	DSP	0.0159	-0.457	...	...	0.0058	-0.372	...	...	0.02	...	-0.45	...
NGC 1700	GON	...	...	0.0096	-0.278	0.0069	-0.382	0.0094	-0.200	...	-0.27	-0.37	-0.30
NGC 2434	CDa	0.0044	-0.356	...	...	0.0048	-0.253	0.0058	-0.180	-0.58	...	-0.57	-0.51
NGC 2663	Cdb	0.0145	-0.344	...	...	0.0095	-0.262	0.0040	-0.454	-0.07	...	-0.28	-0.58
NGC 2778	GON	...	...	0.0193	-0.220	0.0099	-0.137	0.0051	-0.349	...	0.02	-0.29	-0.52
NGC 2832	FFI	...	...	0.0224	-0.213	...	...	...	...	...	0.08	...	...
NGC 2974	CDB	0.0090	-0.315	...	...	...	...	...	...	-0.29	...	...	...
NGC 3078	CDB	0.0119	-0.327	...	...	0.0103	-0.333	...	...	-0.16	...	-0.22	...
NGC 3136B	CDB	0.0059	-0.297	...	...	...	...	...	...	-0.48	...	...	...
NGC 3226	CDB	0.0067	-0.342	...	...	...	...	...	...	-0.40	...	...	...
NGC 3250	CDB	0.0157	-0.259	...	...	0.0101	-0.466	...	...	-0.06	...	-0.17	...
NGC 3260	CDB	0.0069	-0.380	...	...	...	...	...	...	-0.38	...	...	...
NGC 3377	GON	...	...	0.0032	-0.642	0.0030	-0.481	0.0022	-0.530	...	-0.55	-0.69	-0.79
NGC 3379	DSP	0.0120	-0.324	...	...	0.0047	-0.305	0.0098	-0.246	-0.16	...	-0.57	-0.27
NGC 3557	CDB	0.0130	-0.257	...	...	0.0247	-0.110	...	...	-0.14	...	0.10	...
NGC 3608	GON	...	...	0.0081	-0.465	0.0233	0.140	0.0090	-0.155	...	-0.26	0.07	-0.33
NGC 3818	GON	...	...	0.0054	-0.766	0.0033	-0.606	0.0040	-0.523	...	-0.22	-0.56	-0.54
NGC 4073	FFI	...	...	0.0317	-0.061	...	...	...	...	...	0.20	...	...
NGC 4261	DSP	0.0182	-0.338	...	...	0.0078	-0.335	0.0121	-0.354	0.03	...	-0.34	-0.14
NGC 4278	DSP	0.0119	-0.350	...	...	0.0081	0.036	0.0076	-0.229	-0.15	...	-0.39	-0.39
NGC 4365	BS	0.0111	-0.348	...	...	...	...	...	...	-0.18	...	...	...
NGC 4374	DSP	0.0148	-0.323	...	...	0.0093	-0.101	0.0082	-0.242	-0.07	...	-0.32	-0.35
NGC 4406	BS	0.0107	-0.271	...	...	...	...	...	...	-0.23	...	...	...
NGC 4472	DSP	0.0227	-0.190	...	...	0.0107	-0.262	0.0141	-0.350	0.08	...	-0.23	-0.08
NGC 4478	GON	...	...	0.0163	-0.146	0.0053	-0.408	0.0071	-0.289	...	-0.07	-0.48	-0.40
NGC 4486	DSP	0.0216	-0.326	...	...	0.0076	-0.269	0.0143	-0.180	0.10	...	-0.37	-0.12
NGC 4489	GON	...	...	0.0030	-0.312	0.0058	-0.279	0.0034	-0.339	...	-0.77	-0.49	-0.70
NGC 4494	BS	0.0037	-0.478	...	...	...	...	...	...	-0.60	...	...	...
NGC 4552	GON	...	...	0.0216	-0.339	0.0069	-0.300	0.0086	-0.274	...	0.10	-0.41	-0.32
NGC 4636	DSP	0.0103	-0.458	...	...	0.0054	-0.371	0.0136	-0.173	-0.16	...	-0.48	-0.15
NGC 4649	GON	...	...	0.0323	-0.262	0.0052	-0.353	0.0080	-0.318	...	0.25	-0.51	-0.34
NGC 4696	CDB	0.0184	-0.140	...	...	...	...	...	...	-0.02	...	...	...
NGC 4697	GON	...	...	0.0054	-0.439	0.0031	-0.503	0.0033	-0.440	...	-0.46	-0.67	-0.67
NGC 4839	DSP	0.0123	-0.336	...	...	...	...	...	...	-0.14	...	...	...
NGC 4874	FFI	...	...	0.0151	-0.325	...	...	...	...	...	-0.06	...	...
NGC 5011	CDB	0.0104	-0.283	...	...	...	...	...	...	-0.23	...	...	...
NGC 5018	Cdb	0.0076	-0.179	...	...	0.0091	-0.224	0.0096	-0.273	-0.40	...	-0.31	-0.27
NGC 5044	CDB	0.0283	-0.059	...	...	...	...	...	...	0.15	...	...	...
NGC 5077	CDB	0.0119	-0.331	...	...	0.0098	-0.244	...	...	-0.16	...	-0.27	...
NGC 5090	CDB	0.0214	-0.186	...	...	0.0090	-0.252	...	...	0.05	...	-0.31	...
NGC 5322	BS	0.0087	-0.219	...	...	...	...	...	...	-0.33	...	...	...
NGC 5638	GON	...	...	0.0080	-0.517	0.0069	-0.259	0.0063	-0.253	...	-0.24	-0.42	-0.46
NGC 5796	CDB	0.0210	-0.225	...	...	0.0105	-0.331	...	...	0.05	...	-0.21	...
NGC 5812	GON	...	...	0.0184	-0.279	0.0078	-0.301	0.0095	-0.294	...	0.01	-0.35	-0.27
NGC 5813	GON	...	...	0.0115	-0.380	0.0114	-0.040	0.0078	-0.086	...	-0.15	-0.24	-0.40
NGC 5831	GON	...	...	0.0073	-0.436	0.0068	-0.335	0.0059	-0.387	...	-0.32	-0.40	-0.44
NGC 5846	CDB	0.0316	-0.041	...	...	0.0089	-0.243	...	...	0.20	...	-0.32	...
NGC 5903	CDB	0.0098	-0.237	...	...	...	...	...	...	-0.27	...	...	...
NGC 6127	GON	...	...	0.0188	-0.327	0.0049	-0.339	0.0098	-0.118	...	0.04	-0.54	-0.30
NGC 6166	FFI	...	...	0.0061	-0.554	...	...	...	...	...	-0.33	...	...
NGC 6702	GON	...	...	0.0103	-0.106	0.0084	-0.206	0.0119	-0.152	...	-0.28	-0.35	-0.21
NGC 6868	CDB	0.0166	-0.228	...	...	0.0078	-0.419	...	...	-0.05	...	-0.30	...

TABLE 2—Continued

GALAXY (1)	REFERENCE (2)	Mg ₂		Mg _b		Fe ₁		Fe ₂		Mg ₂ ⟨[Fe/H]⟩ (11)	Mg _b ⟨[Fe/H]⟩ (12)	Fe ₁ ⟨[Fe/H]⟩ (13)	Fe ₂ ⟨[Fe/H]⟩ (14)
		Z _e (3)	c (4)	Z _e (5)	c (6)	Z _e (7)	c (8)	Z _e (9)	c (10)				
NGC 7052	GON	...	...	0.0193	-0.329	0.0071	-0.187	0.0108	-0.105	...	0.05	-0.42	-0.26
NGC 7097	CDB	0.0068	-0.526	...	...	0.0029	-0.668	...	...	-0.31	...	-0.57	...
NGC 7192	CDa	0.0063	-0.348	...	...	0.0046	-0.325	0.0038	-0.382	-0.43	...	-0.58	-0.64
NGC 7200	CDB	0.0078	-0.652	...	...	...	...	...	...	-0.16	...	...	...
NGC 7454	GON	...	...	0.0037	-0.273	0.0035	-0.312	0.0049	-0.157	...	-0.69	-0.70	-0.59
NGC 7562	GON	...	...	0.0196	-0.148	0.0133	-0.056	0.0066	-0.231	...	0.01	-0.17	-0.45
NGC 7619	GON	...	...	0.0174	-0.379	0.0045	-0.438	0.0106	-0.255	...	0.03	-0.54	-0.24
NGC 7626	DSP	0.0145	-0.405	...	...	0.0174	0.004	0.0127	-0.264	-0.04	...	-0.06	-0.15
NGC 7720	FFI	...	...	0.0079	-0.532	...	...	...	...	...	-0.24	...	...
NGC 7768	FFI	...	...	0.0114	-0.278	...	...	...	...	...	-0.20	...	...
NGC 7785	GON	...	...	0.0134	-0.305	0.0081	-0.166	0.0122	-0.129	...	-0.12	-0.37	-0.20
IC 1459	CDB	0.0148	-0.382	...	...	0.0121	-0.290	...	...	-0.04	...	-0.17	...
IC 3370	CDB	0.0110	-0.103	...	...	...	...	...	...	-0.25	...	...	...
IC 4889	CDB	0.0094	-0.157	...	...	...	...	...	...	-0.31	...	...	...
IC 4943	CDB	0.0085	-0.215	...	...	0.0054	-0.403	...	...	-0.34	...	-0.48	...
Abell 496	FFI	...	...	0.0056	-0.579	...	...	...	...	...	-0.36	...	...
ESO 323-16	CDB	0.0084	-0.246	...	...	...	...	...	...	-0.34	...	...	...

NOTES.—Cols. (4), (6), (8), (10): Intercepts at the effective radius for Mg₂, Fe₁, Fe₂, and Mg_b.

and the metallicity gradient is then given as

$$[\text{Fe}/\text{H}] = \log \bar{Z}(r) = \log \frac{Z_e}{Z_\odot} - c \log \frac{r}{r_e},$$

which is the same as equation (3). The parameters c and Z_e are determined from the parameters A and B in equation (1), and the index-metallicity relations are given by equation (8), or equations (4) and (10).

By analogy to the surface brightness of stars, the surface brightness profile of metals can be defined as

$$I_Z(r) = \bar{Z}(r)I(r). \quad (17)$$

Then the luminosity of metals within radius r is given by

$$L_Z(r) = \int_0^r 2\pi r I_Z(r) dr = b^{cn} \frac{\Gamma[2n - cn, 0, b(r/r_e)^{1/n}]}{\Gamma[2n, 0, b(r/r_e)^{1/n}]} Z_e L_*. \quad (18)$$

The total luminosity of metals is

$$L_Z(\infty) = b^{cn} \frac{\Gamma(2n - cn)}{\Gamma(2n)} Z_e L_* \simeq Z_e L_*, \quad (19)$$

where we note that the constant $b^{cn}\Gamma(2n - cn)/\Gamma(2n)$ is nearly equal to unity, as shown below.

If we assume that the mass-to-light ratio M/L is constant within a galaxy, the total mass of metals contained in stars can be given as

$$M_Z(\infty) = b^{cn} \frac{\Gamma(2n - cn)}{\Gamma(2n)} Z_e M_* \simeq Z_e M_*, \quad (20)$$

where M_* is the total mass of stars in a galaxy. Finally the mean stellar metallicity can be given by

$$\langle Z \rangle \equiv \frac{M_Z(\infty)}{M_*} = b^{cn} \frac{\Gamma(2n - cn)}{\Gamma(2n)} Z_e \simeq Z_e. \quad (21)$$

Although equation (21) gives an excellent measure for the mean stellar metallicity of an elliptical galaxy, we hereafter

use an explicit definition to calculate $\langle[\text{Fe}/\text{H}]\rangle$ in such a way that we can take into account observed scatters of the metallicity gradients:

$$\langle[\text{Fe}/\text{H}]\rangle = \log \left[b^{cn} \frac{\Gamma(2n - cn)}{\Gamma(2n)} \frac{Z_e}{Z_\odot} \right]. \quad (22)$$

In Table 2, we give the metallicity gradient parameters for 80 elliptical galaxies derived under assumption A (hereafter, unless otherwise mentioned, all metallicities are calculated under assumption A). Columns (1) and (2) give the name of galaxy and the reference. Columns (3) and (4), (5) and (6), (7) and (8), and (9) and (10) give the metallicity Z_e measured at the effective radius and the gradient c derived from Mg₂, Mg_b, Fe₁, and Fe₂ gradients, respectively. Columns (11)–(15) give the mean metallicities derived from the Mg₂, Mg_b, Fe₁, and Fe₂ gradients, respectively.

A typical elliptical galaxy has $n = 4$ and $c \sim 0.3$ (Fig. 1), to which the constant $b^{cn}\Gamma(2n - cn)/\Gamma(2n)$ in equation (21) becomes $\simeq 1.1$; thus the mean metallicity of galaxy is very close to the metallicity measured at the effective radius. Arimoto et al. (1997) already showed that this is the case for smaller sample of galaxies if de Vaucouleurs' surface brightness profile is assumed. In this study, we have generalized it to Sersic's surface brightness profile and have found that, as long as the slope c is smaller than 0.4, as is the case for most ellipticals, the mean metallicity is approximately given by Z_e , which is smaller than the true mean by at most ~ 0.15 dex. Z_e values estimated by the Mg₂-, Mg_b-, Fe₁-, and Fe₂-gradients are given in Table 2.

The top section of Table 3 gives the mean metallicities for 12 ellipticals derived from the Mg₂ gradients under assumption B. $H\beta$ corrections are explicitly taken into account. Columns (1) and (2) give the name of galaxy and the reference. Columns (3), (5), and (8) give the mean metallicities calculated from different equations as are indicated on the top line of the table; i.e., column (3) gives $\langle[\text{Fe}/\text{H}]\rangle$ without any age gradient corrections, column (5) gives $\langle[\text{Fe}/\text{H}]\rangle$ with constant age corrections, and column (8) gives $\langle[\text{Fe}/\text{H}]\rangle$ with age gradient corrections, respectively. Column (4) gives a typical age $(t_0)_e$ estimated from the inter-

TABLE 3
MEAN METALLICITIES CORRECTED WITH $H\beta$

GALAXY (1)	REFERENCE (2)	EQUATIONS (22), (2), (4) $\langle[Fe/H]\rangle$ (3)	EQUATIONS (22), (5), (10)		EQUATIONS (22), (6), (8)		
			$(t_9)_e$ (4)	$\langle[Fe/H]\rangle$ (5)	$(t_9)_e$ (6)	Δt_9 (7)	$\langle[Fe/H]\rangle$ (8)
Mg ₂ Gradient							
NGC 315	DSP	0.00	15.6	0.02	15.4	-0.1	0.03
NGC 741	DSP	-0.14	9.9	0.01	10.6	-5.0	-0.03
NGC 1600	DSP	0.02	6.7	0.21	3.6	-2.3	0.27
NGC 3379	DSP	-0.16	11.4	-0.04	12.8	3.7	-0.05
NGC 4261	DSP	0.03	13.7	0.08	12.7	-0.7	0.10
NGC 4278	DSP	-0.15	17.6	-0.18	22.2	-38.0	-0.15
NGC 4374	DSP	-0.07	9.9	0.08	8.9	-4.9	0.08
NGC 4472	DSP	0.08	18.2	0.04	17.4	5.9	0.08
NGC 4486	DSP	0.10	17.5	0.06	16.8	-12.2	0.04
NGC 4636	DSP	-0.16	2.9	0.12	1.6	-14.5	0.09
NGC 4839	DSP	-0.14	20.4	-0.24	26.1	10.1	-0.29
NGC 7626	DSP	-0.04	20.3	-0.15	24.5	9.8	-0.16
NGC 547	GON	0.11	17.8	0.06	17.1	4.5	0.11
Mg _b Gradient							
NGC 584	GON	-0.09	1.9	0.28	-4.4	-2.2	0.44
NGC 636	GON	-0.23	6.4	0.03	6.2	5.6	0.07
NGC 720	GON	0.25	-8.5	0.88	-28.1	-21.0	1.45
NGC 821	GON	-0.22	0.4	0.17	-2.4	-5.1	0.22
NGC 1453	GON	-0.09	17.8	-0.16	23.1	-1.7	-0.31
NGC 1700	GON	-0.27	0.7	0.13	-1.7	1.6	0.19
NGC 2778	GON	0.02	29.6	-0.32	37.2	19.2	-0.35
NGC 2832	FFI	0.08	16.2	0.08	14.7	4.0	0.14
NGC 3377	GON	-0.55	5.5	-0.34	16.4	6.5	-0.53
NGC 3608	GON	-0.26	10.2	-0.14	14.9	7.4	-0.18
NGC 3818	GON	-0.22	14.3	-0.29	25.3	16.0	-0.29
NGC 4073	FFI	0.20	24.1	0.01	23.8	12.1	0.07
NGC 4478	GON	-0.07	10.2	0.09	8.3	8.7	0.18
NGC 4489	GON	-0.77	-3.5	-0.26	2.9	8.2	-0.36
NGC 4552	GON	0.10	11.1	0.22	7.0	-4.3	0.30
NGC 4649	GON	0.25	20.3	0.14	17.7	7.9	0.26
NGC 4697	GON	-0.46	9.1	-0.30	17.2	7.1	-0.43
NGC 4874	FFI	-0.06	17.3	-0.09	20.2	8.2	-0.10
NGC 5638	GON	-0.24	10.0	-0.12	14.7	10.0	-0.12
NGC 5812	GON	0.01	10.4	0.16	7.3	7.5	0.29
NGC 5813	GON	-0.15	27.6	-0.46	39.1	15.4	-0.59
NGC 5831	GON	-0.32	3.1	-0.01	4.7	5.7	0.01
NGC 6127	GON	0.04	14.0	0.08	12.9	6.1	0.16
NGC 6166	FFI	-0.33	-6.4	0.20	-8.5	-35.8	0.23
NGC 6702	GON	-0.28	-0.8	0.18	-4.8	2.3	0.28
NGC 7052	GON	0.05	-4.7	0.57	-16.8	-28.4	0.95
NGC 7454	GON	-0.69	3.7	-0.36	12.2	9.7	-0.50
NGC 7562	GON	0.01	12.5	0.11	10.1	4.3	0.19
NGC 7619	GON	0.03	13.4	0.08	12.7	4.0	0.13
NGC 7720	FFI	-0.24	-11.7	0.43	-19.4	-23.4	0.54
NGC 7768	FFI	-0.20	18.8	-0.26	25.2	7.2	-0.38
NGC 7785	GON	-0.12	13.0	-0.04	14.5	4.9	-0.04

NOTES.—Cols. (3), (5), and (8): Mean metallicities calculated with eqs. (4), (10), and (8), respectively. Cols. (4) and (6): Age at the effective radius. Col. (7): Age gradient.

cept of $H\beta$ at the effective radius by using equation (9). Columns (6) and (7) are parameters of the age gradients, the intercept $(t_9)_e = p_1(A_1 - q_1) + p_2(A_2 - q_2)$ at the effective radius and the gradient $\Delta t_9 = -(p_1 B_1 + p_2 B_2)$, both calculated with equation (7). For individual galaxies, $\langle[Fe/H]\rangle$ values given in columns (5) and (8) are nearly identical; thus the age gradient correction is not crucial for deriving $\langle[Fe/H]\rangle$. For NGC 4278, NGC 4486, NGC 5636, NGC 4839, and NGC 7626 we obtain unexpectedly large

values of Δt_9 . This is probably because the $H\beta$ gradients are contaminated by emission components. We note that $\langle[Fe/H]\rangle$ values given in column (3) are not much different from those given in columns (5) and (8). Therefore, we conclude that the age corrections for $\langle[Fe/H]\rangle$ are not important. The bottom section of Table 3 is the same as the top, except that it is for 31 ellipticals with the Mg_b gradients. Except for 16 galaxies to which both equations (10) and (8) give unreasonable ages and age gradients, the resulting

$\langle[\text{Fe}/\text{H}]\rangle$ values given in columns (3), (5), and (8) are nearly the same.

4. GLOBAL SCALING RELATIONS

Gonzalez & Gorgas (1996) claimed that elliptical galaxies with larger $(\text{Mg}_2)_0$ tend to have steeper Mg_2 gradients. They therefore suggested that the mass-metallicity relation of elliptical galaxies holds only for the central metallicity and claimed that the mean metallicity of elliptical galaxies should be universal. Since the mass-metallicity relation, or equivalently the color-magnitude relation, of elliptical galaxies has been a fundamental relation for which any theory of galaxy formation should account (e.g., Arimoto & Yoshii 1987; Kodama & Arimoto 1997; Kauffmann & Charlot 1998), it is important to verify whether mean stellar metallicities of ellipticals correlate tightly with other global properties, including luminosities, or if the mean metallicities are just universal for all ellipticals, regardless of their masses.

Table 4 gives the physical properties of 80 elliptical galaxies. Columns (1)–(3) give the name of galaxy, the reference, and the morphology type taken from RC3, respectively. Columns (4)–(8) give the central Mg_2 index (mag) and the central velocity dispersion (km s^{-1}), both taken from Davies et al. (1987), and the absolute effective radius (kpc), the absolute magnitude in the B band (mag), and $\kappa_1 = (\log \sigma_0^2 + \log R_e)/\sqrt{2}$, which was introduced by Bender, Burstein & Faber (1992) as a galaxy mass tracer, respectively. The effective radius and the absolute magnitude are calculated from Burstein et al. (1987) with the distance modulus estimated from the D_n - σ relation of elliptical galaxies by C. Ikuta & N. Arimoto (1999, private communications).

In the following arguments, we use, if necessary, the ratio $(v/\sigma)^*$ of the rotational velocity to the velocity dispersion; the parameter a_4 , which shows the distortion of the isophotal contour (Bender et al. 1993); the parameter Σ , which shows the kinematical peculiarity (Schweizer & Seitzer 1992); and the gas mass M_{gas} , which is estimated from the *ASCA* X-ray observations (Matsushita 1997).

In the following sections, we demonstrate the global scaling relations for elliptical galaxies. Table 5 gives the

result of our attempts to search for the relations. Column (3) gives the number of galaxies used, and column (4) gives the correlation coefficient. The scaling laws are given in column (5) if the correlation coefficients are appreciably significant.

4.1. Gradients versus Mean Metallicity

In Figures 5a and 5b, we plot the Mg_2 gradients against $[\text{Fe}/\text{H}]_0$ and $\langle[\text{Fe}/\text{H}]\rangle$, respectively. Contrary to the claim of Gonzalez & Gorgas (1996), Figures 5a and 5b show no evidence for any correlation. A study of Mg_b gradients, although not shown here, reaches the same conclusion.

4.2. Gradients versus Mass

Figures 6a–6d show the Mg_2 gradient against galaxy mass tracers; the central velocity dispersion σ_0 , the absolute B magnitude M_B , the absolute effective radius R_e , and $\kappa_1 = (\log \sigma_0^2 + \log R_e)/\sqrt{2}$. Contrary to a prediction of numerical simulation (Carlberg 1984), Figure 6 shows no evidence for any correlation.

4.3. Metallicity-Mass Relation

The color-magnitude relation of elliptical galaxies is usually interpreted as meaning that luminous galaxies have higher mean stellar metallicities (Arimoto & Yoshii 1987; Kodama & Arimoto 1997). Figures 7a and 7c show how $\log \sigma_0$ correlates with $[\text{Fe}/\text{H}]_0$ and $\langle[\text{Fe}/\text{H}]\rangle$, respectively. Both are derived from Mg_2 . The $\langle[\text{Fe}/\text{H}]\rangle$ - $\log \sigma_0$ relation is well defined and has nearly the same slope as the $[\text{Fe}/\text{H}]_0$ - $\log \sigma_0$ relation but is systematically 0.3 dex lower; i.e., the mean stellar metallicity is about one-half of the central metallicity. We note that the age correction achieved by using $\text{H}\beta$ changes this relation little. Figure 7b shows an equivalent relation derived from Mg_b . Although the slope is similar to that defined by Mg_2 , the scatters are quite large. Figures 7d–7f are the same as Figure 7c but for the other mass tracers, M_B , R_e , and κ_1 , respectively. We can also find a similar metallicity-mass relation for κ_1 with a little larger scatter, and in the cases of M_B and R_e scatters become much larger. This is because the relation with M_B and R_e is a face-on view of the fundamental plane, which we discuss in § 4.4. Therefore, we conclude that the metallicity-mass

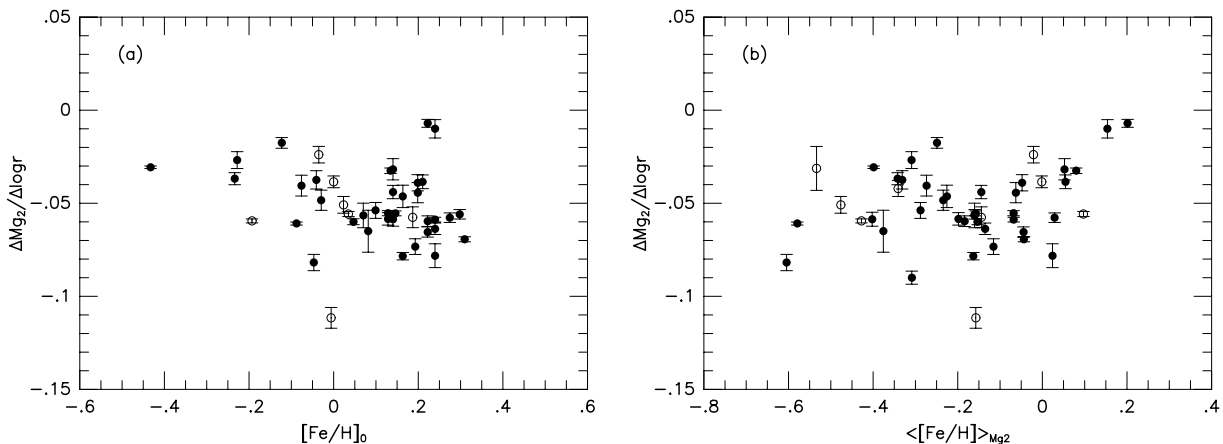


FIG. 5.— Mg_2 gradient vs. the metallicity. Open and filled circles show cD and elliptical galaxies, respectively, for (a) the central metallicity and (b) the mean stellar metallicity calculated with eq. (22).

TABLE 4
PHYSICAL PROPERTIES OF ELLIPTICAL GALAXIES

Galaxy (1)	Reference (2)	Type (3)	$(M_{g_2})_0$ (mag) (4)	$\log \sigma_0$ (km s^{-1}) (5)	$\log R_c$ (kpc) (6)	M_B (mag) (7)	κ_1 (8)
NGC 315	DSP	cD	0.283	2.582	1.36	-22.99	4.61
NGC 547	GON	E	0.319	2.233	...	...	...
NGC 584	GON	E	0.283	2.336	0.46	-20.41	3.63
NGC 636	GON	E	0.273	2.193	0.29	-19.31	3.31
NGC 720	GON	E	0.330	2.393	0.70	-20.92	3.88
NGC 741	DSP	E	0.324	2.447	1.29	-22.38	4.37
NGC 821	GON	E	0.304	2.299	0.87	-21.08	3.87
NGC 1052	CDB	E	0.316	2.314	...	...	...
NGC 1209	CDB	E	0.305	2.322	0.44	-20.22	3.59
NGC 1298	CDB	cD	...	...	...	...	...
NGC 1453	GON	E	0.327	2.462	0.98	-21.98	4.17
NGC 1600	DSP	E	0.324	2.507	1.10	-21.92	4.33
NGC 1700	GON	E	0.278	2.367	0.47	-20.99	3.68
NGC 2434	CDa	E	0.268	2.312	0.99	-22.04	3.97
NGC 2663	CDb	E	0.324	2.449	1.59	-24.41	4.58
NGC 2778	GON	E	0.313	2.220	0.58	-20.07	3.55
NGC 2832	FFI	cD	0.340	2.558	...	-22.20	...
NGC 2974	CDB	E	0.300	2.346	0.73	-20.94	3.83
NGC 3078	CDB	E	0.334	2.377	0.65	-21.01	3.82
NGC 3136B	CDB	cD	0.287	2.220	1.51	-23.51	4.21
NGC 3226	CDB	E	0.307	2.307	0.92	-20.59	3.91
NGC 3250	CDB	E	0.317	2.422	1.01	-22.44	4.14
NGC 3260	CDB	E	0.297	2.281	0.84	-20.72	3.82
NGC 3377	GON	E	0.270	2.117	0.28	-19.19	3.19
NGC 3379	DSP	E	0.308	2.303	0.29	-19.86	3.46
NGC 3557	CDB	E	0.307	2.465	0.93	-22.22	4.15
NGC 3608	GON	E	0.312	2.310	0.64	-20.34	3.72
NGC 3818	GON	E	0.315	2.314	0.67	-20.75	3.75
NGC 4073	FFI	cD	0.321	2.442	1.35	-22.39	4.41
NGC 4261	DSP	E	0.330	2.468	0.82	-21.43	4.07
NGC 4278	DSP	E	0.291	2.425	0.52	-20.55	3.79
NGC 4365	BS	E	0.321	2.394	0.67	-20.51	3.86
NGC 4374	DSP	E	0.305	2.458	0.70	-21.28	3.97
NGC 4406	BS	E	0.311	2.398	0.92	-21.51	4.04
NGC 4472	DSP	E	0.306	2.458	0.93	-21.83	4.14
NGC 4478	GON	E	0.253	2.173	0.10	-19.19	3.14
NGC 4486	DSP	cD	0.289	2.558	0.97	-21.81	4.30
NGC 4489	GON	E	0.198	1.690	...	...	...
NGC 4494	BS	E	0.275	2.093	0.31	-19.17	3.18
NGC 4552	GON	E	0.324	2.417	0.45	-20.60	3.74
NGC 4636	DSP	E	0.311	2.281	0.93	-21.01	3.89
NGC 4649	GON	E	0.338	2.533	0.80	-21.45	4.15
NGC 4696	CDB	cD	0.277	2.348	1.79	-23.93	4.59
NGC 4697	GON	E	0.297	2.217	0.58	-20.08	3.55
NGC 4839	DSP	cD	0.315	2.413	1.13	-21.73	4.21
NGC 4874	FFI	cD	0.328	2.389	...	...	...
NGC 5011	CDB	E	0.278	2.360	0.85	-21.89	3.94
NGC 5018	CDb	E	0.209	2.348	0.75	-21.95	3.85
NGC 5044	CDB	E	0.324	2.369	1.21	-21.88	4.21
NGC 5077	CDB	E	0.295	2.439	0.69	-20.86	3.94
NGC 5090	CDB	E	0.307	2.435	1.10	-22.42	4.22
NGC 5322	BS	E	0.276	2.350	0.56	-20.54	3.72
NGC 5638	GON	E	0.317	2.201	0.48	-19.67	3.45
NGC 5796	CDB	E	0.319	2.398	0.72	-21.66	3.90
NGC 5812	GON	E	0.324	2.310	0.61	-20.86	3.70
NGC 5813	GON	E	0.308	2.377	0.91	-21.29	4.00
NGC 5831	GON	E	0.289	2.220	0.64	-20.37	3.60
NGC 5846	CDB	E	0.321	2.444	1.13	-21.99	4.26
NGC 5903	CDB	E	0.270	2.371	0.91	-21.65	4.00
NGC 6127	GON	E	...	...	...	...	...
NGC 6166	FFI	cD	0.340	2.513	1.62	-23.14	4.70
NGC 6702	GON	E	0.272	2.260	0.94	-21.14	3.86
NGC 6868	CDB	E	0.317	2.456	0.80	-21.24	4.04
NGC 7052	GON	E	...	...	...	...	...
NGC 7097	CDB	E	...	...	...	...	...

TABLE 4—Continued

Galaxy (1)	Reference (2)	Type (3)	(Mg ₂) ₀ (mag) (4)	log σ ₀ (km s ⁻¹) (5)	log R _e (kpc) (6)	M _B (mag) (7)	κ ₁ (8)
NGC 7192	CDa	cD	0.250	2.267	0.70	-20.39	3.70
NGC 7200	CDB	cD	0.282	2.290	0.60	-20.01	3.67
NGC 7454	GON	E	0.206	2.049	0.48	-19.49	3.24
NGC 7562	GON	E	0.291	2.386	0.81	-21.43	3.95
NGC 7619	GON	E	0.336	2.528	0.92	-21.63	4.22
NGC 7626	DSP	E	0.336	2.369	0.99	-21.64	4.05
NGC 7720	FFI	cD	0.339	2.484	1.20	-22.33	4.36
NGC 7768	FFI	E	0.322	2.384	1.11	-21.78	4.16
NGC 7785	GON	E	0.296	2.464	0.94	-21.83	4.15
IC 1459	CDB	E	0.321	2.489	0.73	-21.42	4.04
IC 3370	CDB	E	0.262	2.316	0.84	-21.29	3.87
IC 4889	CDB	E	0.244	2.246	0.60	-20.90	3.60
IC 4943	CDB	E	0.243	2.223	0.47	-19.30	3.48
Abell 496	FFI	E	...	...	...	...	...
ESO 323-16	CDB	cD	...	...	...	...	...

NOTES.—Col. (4): Central Mg₂ index. Col. (5): Central velocity dispersion. Col. (6): Effective radius in kpc. Col. (7): Absolute magnitude in B band. Col. (8): Mass tracer κ₁ = (log σ₀² + log R_e)/√2.

relation of ellipticals holds not only for the galaxy center but also for the whole stellar population within a galaxy. When we use the mean metallicity with the correction of age estimated by Hβ in Table 3, the scatters in the metallicity-mass relations do not become smaller.

4.4. Metallicity–Mass–Surface Brightness Plane Fundamental

The fundamental plane (FP) is a correlation of elliptical galaxies with 2 + *n* parameters (e.g., Djorgovski & Davis 1987; Dressler et al. 1987) and is a clue to understanding the formation and evolution of elliptical galaxies. One possible interpretation of the FP, defined by central velocity dispersions σ₀, absolute effective radii R_e, and surface brightnesses within an effective radius SB_e, attributes it to a correlation of the mass-to-light ratio *M*/*L* to the total luminosity, or equivalently, to the total galaxy mass (e.g., Faber et al. 1987). The FP is observed up to *z* ~ 0.5 by recent *HST*

observations (Kelson et al. 1997), which can be understood as an evidence for passive evolution of cluster elliptical galaxies since *z* < 0.5. The FP can be defined for colors or (Mg₂)₀ instead of σ₀ (de Carvalho & Djorgovski 1989). As we have seen above, <[Fe/H]> correlates well to σ₀. Therefore, we study whether <[Fe/H]> defines new FPs with other global scaling properties. Table 6 gives the FPs of our sample; the first four are already well-known FPs and the last two are the new FPs found in this study. Figures 7*d* and 7*e* (<[Fe/H]> against M_B and R_e, respectively) include significant scatters, which is because these figures are the face-on view of the FPs (<[Fe/H]>, SB_e, and M_B or R_e). Even if we include a parameter SB_e in the <[Fe/H]>-log σ₀ relation (Fig. 7*c*), we cannot reduce the scatter, which means that Figure 7*c* provides the exact edge-on view of the FP.

Figure 8 shows a new fundamental plane defined by <[Fe/H]>, R_e, and SB_e. We interpret it as the correlation of the metal mass-to-light ratio M_z/*L* with the total lumi-

TABLE 5
GLOBAL SCALING RELATIONS

<i>x</i>	<i>y</i>	<i>N</i>	<i>r</i>	Regression Line
[Fe/H] ₀	ΔMg ₂ /Δ log <i>r</i>	43	-0.21	...
<[Fe/H]>	ΔMg ₂ /Δ log <i>r</i>	46	0.22	...
log σ ₀	ΔMg ₂ /Δ log <i>r</i>	43	0.17	...
log R _e	ΔMg ₂ /Δ log <i>r</i>	42	0.26	...
κ ₁	ΔMg ₂ /Δ log <i>r</i>	42	0.27	...
M _B	ΔMg ₂ /Δ log <i>r</i>	42	0.33	...
log σ ₀	[Fe/H] ₀	43	0.45	<i>y</i> = 0.76 <i>x</i> - 1.73
log σ ₀	<[Fe/H]>	43	0.74	<i>y</i> = 1.46 <i>x</i> - 3.62
log R _e	[Fe/H] ₀	42	0.22	...
log R _e	<[Fe/H]>	42	0.33	...
κ ₁	[Fe/H] ₀	42	0.37	<i>y</i> = 0.20 <i>x</i> - 0.71
κ ₁	<[Fe/H]>	42	0.59	<i>y</i> = 0.37 <i>x</i> - 1.62
M _B	[Fe/H] ₀	42	0.19	...
M _B	<[Fe/H]>	42	0.37	...
log σ ₀	<[Mg/Fe]>	27	0.22	...
log R _e	<[Mg/Fe]>	26	0.15	...
κ ₁	<[Mg/Fe]>	26	0.00	...
M _B	<[Mg/Fe]>	26	0.21	...

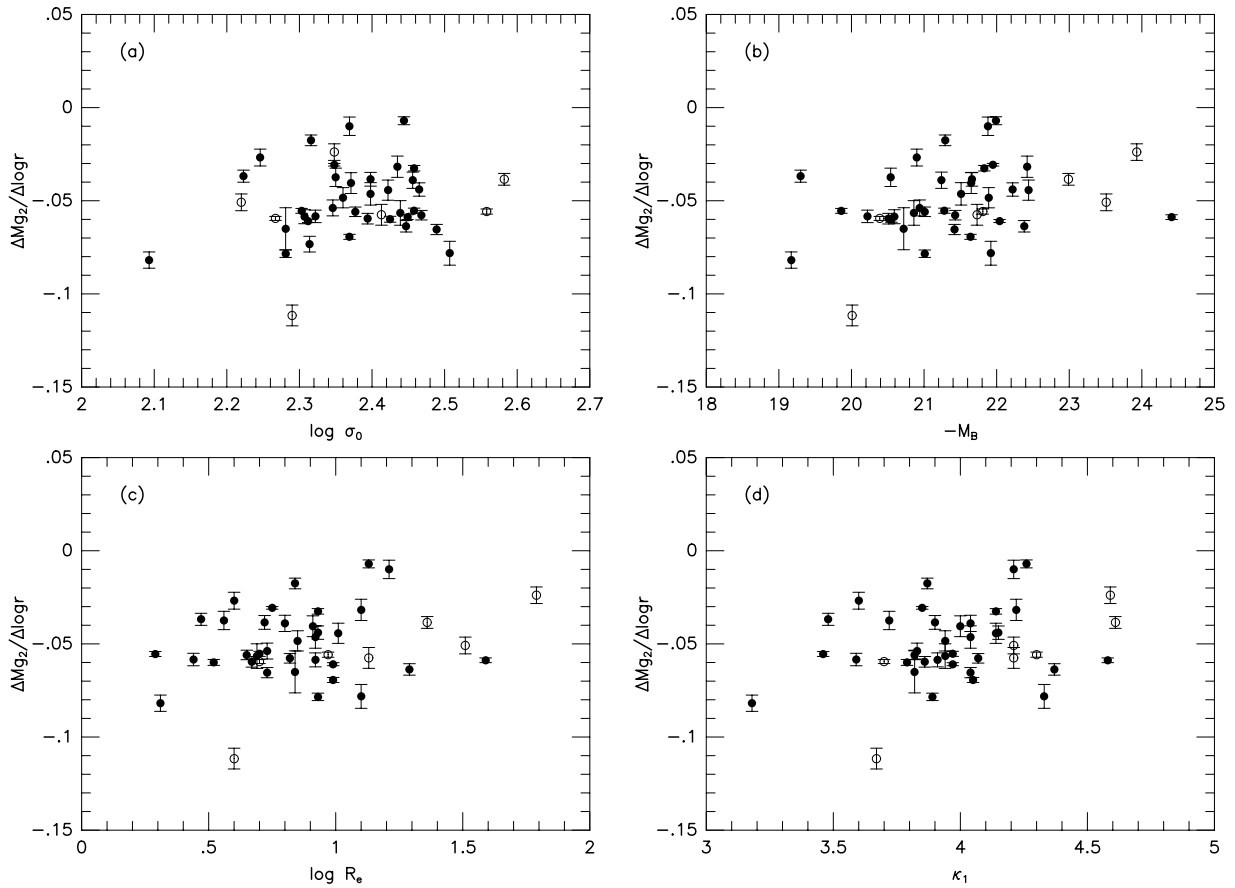


FIG. 6.— Mg_2 gradient vs. the mass tracers: (a) the central velocity dispersion σ_0 , (b) the absolute B magnitude M_B , (c) the absolute effective radius R_e , and (d) the dynamical mass $\kappa_1 = (\log \sigma_0^2 + \log R_e)/\sqrt{2}$. Symbols are the same as in Fig. 5.

nosity. The σ_0 - SB_e - R_e FP is given by

$$\sigma_0 \propto R_e^{0.64} \langle \Sigma \rangle_e^{0.68} . \quad (23)$$

The $\langle [Fe/H] \rangle$ - SB_e - R_e FP is

$$\langle Z \rangle \propto R_e^{1.26} \langle \Sigma \rangle_e^{1.38} . \quad (24)$$

With the definition of the surface brightness $\langle \Sigma \rangle_e \equiv 2L/\pi R_e^2$ ($SB_e \equiv -2.5 \log \langle \Sigma \rangle_e$), the virial theorem $GM/R_e \propto \sigma_0^2$, and the definition of metallicity $M_Z/M \equiv \langle Z \rangle$, we get

$$M/L \propto R_e^{-0.42} L^{0.35} \quad (25)$$

and

$$M_Z/L \propto R_e^{-1.91} L^{1.73} , \quad (26)$$

where L , M and M_Z are the luminosity, the mass, and the mass of the metals of the galaxy, respectively.

4.5. Magnesium Enrichment?

It has been quite often claimed that magnesium and perhaps other α -elements are overabundant in central regions of elliptical galaxies (Worthey, Faber, & Gonzalez 1992; Davies et al. 1993; Gonzalez 1993; Fisher et al. 1995a). In particular, Fisher et al. (1995a) demonstrated that ellipticals with larger σ_0 tend to have larger $[Mg/Fe]_0$ (cf. Trager et al. 1998). We have studied whether this is also true for the mean abundances of these elements.

Figure 9 compares $\langle [Fe/H] \rangle$ given by Mg_2 and Fe_1 , respectively. As is clearly seen, $\langle [Fe/H] \rangle_{Mg_2}$ are higher than $\langle [Fe/H] \rangle_{Fe_1}$ by ~ 0.2 dex. If Mg_2 and Fe_1 reflect the abundances of magnesium and iron, respectively, Figure 9 implies that magnesium is enhanced by ~ 0.2 dex with respect to iron in everywhere within a galaxy. We have checked if there is any systematic difference in the gradients of Mg_2 and Fe_1 but fail to find any clear correlation. We do not find any relation between $\langle [Mg/Fe] \rangle$ and dynamical or

TABLE 6
FUNDAMENTAL PLANES

x	y	z	N	Regression Line
$\log \sigma_0$	$\log R_e$	SB_e	42	$x - 0.64y + 0.27z = 7.70$
$\log \sigma_0$	M_B	SB_e	42	$x - 0.09y + 0.12z = 3.17$
$(Mg_2)_0$	$\log R_e$	SB_e	42	$x - 0.26y + 0.13z = 2.80$
$(Mg_2)_0$	M_B	SB_e	42	$x - 0.04y + 0.09z = 1.41$
$\langle [Fe/H] \rangle$	$\log R_e$	SB_e	42	$x - 1.26y + 0.55z = 10.56$
$\langle [Fe/H] \rangle$	M_B	SB_e	42	$x - 0.16y + 0.28z = 2.41$

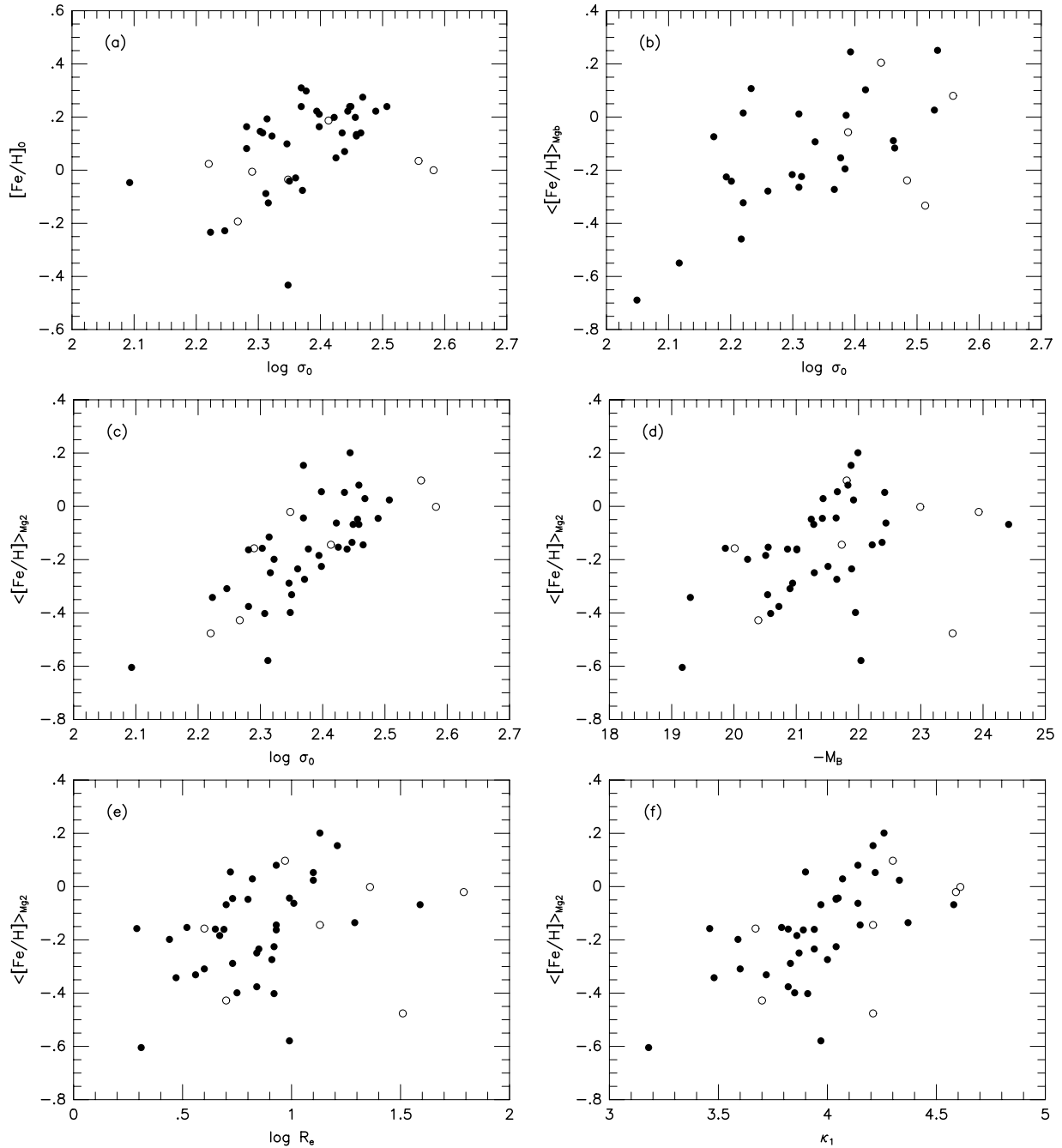


FIG. 7.—Metallicity vs. the mass tracers: (a–c) σ_0 , (d) M_B , (e) R_e , and (f) κ_1 . (a) Central metallicity derived from the central Mg_2 index. (b) Mean stellar metallicity derived from the Mg_b gradient. (c–f) Mean stellar metallicity derived from the Mg_2 gradient. Symbols are the same as in Fig. 5.

luminous masses, as shown in Table 6. We also note that in Figure 9 there is no trend of increasing $\langle [Mg/Fe] \rangle$ toward higher $\langle [Fe/H] \rangle_{Mg_2}$, or, in other words, $\langle [Mg/Fe] \rangle \simeq +0.2$ in most elliptical galaxies independent of their mass, in contrast to what was claimed for $[Mg/Fe]_0$. This can be seen much clearly in Figures 10a–10d, in which we plot $\langle [Mg/Fe] \rangle$ against $\log \sigma_0$, M_B , R_e , and κ_1 , respectively. Obviously, these figures do not show any correlation at all.

However, a word of caution is necessary. The magnesium enhancement might not be real. Although Fe_1 is less fragile to the velocity dispersion gradient than Fe_2 , the observational errors of Fe_1 are much larger than those of Mg_2 . It

is not yet fully understood whether Mg_2 gives $[Mg/H]$ and Fe_1 traces $[Fe/H]$. Indeed, Mg_2 depends strongly on carbon, iron, and several other species (Tripicco & Bell 1995). An increase of metallicity increases the opacity and changes the structure of stellar atmosphere, as a result of which the indices will be strengthened; thus Mg_2 should also be sensitive to $[Fe/H]$. Therefore, one should keep in mind that the ratio of Mg_2 to Fe_1 may not directly give the $[Mg/Fe]$ ratio.

The point we wish to make here is as follows. Previously, it was claimed that more massive ellipticals tend to have higher $[Mg/Fe]$ ratios (e.g., Fisher et al. 1995a). This claim based on the assumption that Mg_2 and Fe_1 give $[Mg/H]$

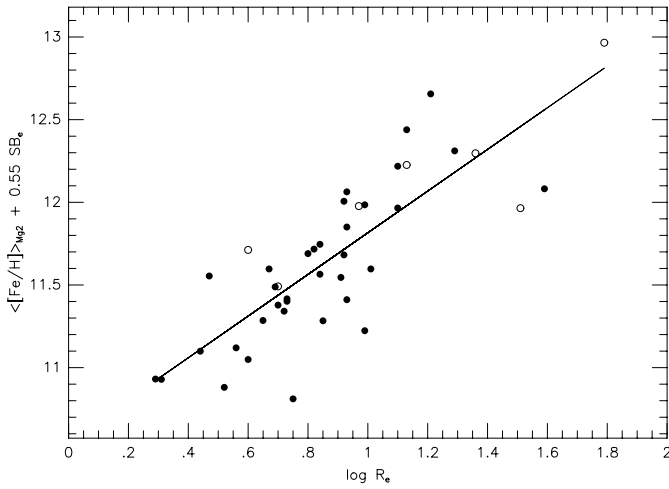


FIG. 8.—Fundamental plane for the absolute radius, the surface brightness, and the mean metallicity. The symbols are the same as in Fig. 5.

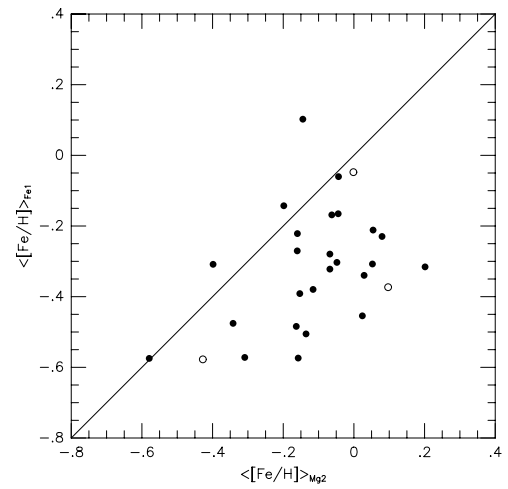


FIG. 9.—Comparison of the mean metallicities derived from Mg_2 and Fe_1 . The symbols are the same as in Fig. 5.

and $[Fe/H]$, respectively, and used only central values of Mg_2 and Fe_1 for their analyses. Under the same assumption, but if $\langle [Mg/H] \rangle$ and $\langle [Fe/H] \rangle$ are used instead, there exists no clear correlation between $\langle [Mg/Fe] \rangle$ and the galaxy mass (Figs. 10a–10d). If the assumption we made turns out to be wrong, our conclusion should be wrong, but the Fisher et al. (1995a) argument should also lose its standing point.

Magnesium is mainly produced by Type II supernovae (SNe II), while the bulk of iron is produced by Type Ia

supernovae (SNe Ia), and SNe II and SNe Ia have different lifetimes; 10^{6-8} yr and a few Gyr, respectively (cf. Kobayashi et al. 1998). Thus, the $[Mg/Fe]$ ratio provides crucial constraints on the timescale of chemical enrichment in elliptical galaxies. Based on the previous findings for the ratio of Mg_2 and Fe_1 at the galaxy center, it has been suggested that the magnesium enhancement in elliptical galaxies can be explained (e.g., Worthey et al. 1992; Matteucci 1994) if (1) the duration of star formation is shorter than a few gigayears before SNe Ia start to explode; (2) the slope of the

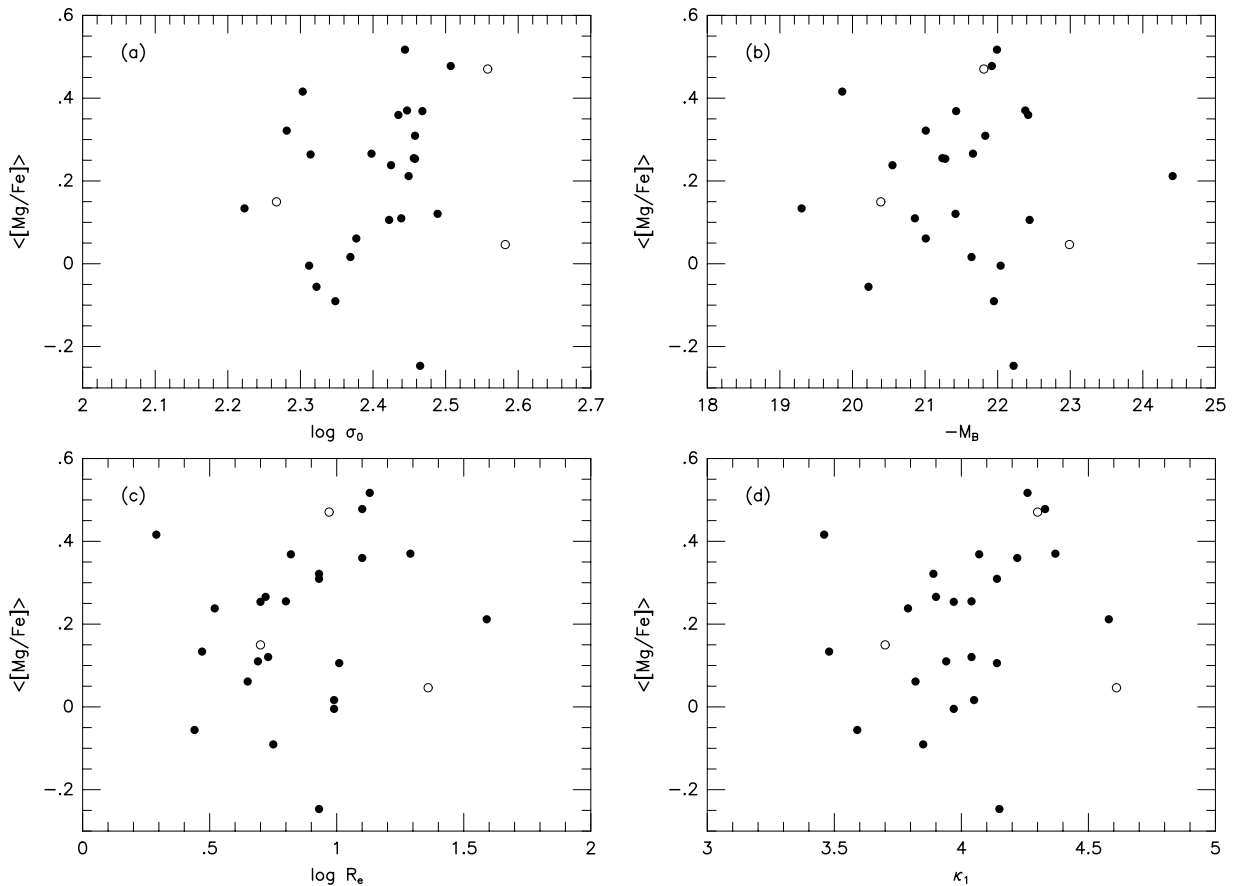


FIG. 10.—Mean $[Mg/Fe]$ ratio vs. the mass tracers (a) σ_0 , (b) M_B , (c) R_e , and (d) κ_1 . Symbols are the same as in Fig. 5.

initial mass function (IMF) is flatter than the slope of the Salpeter IMF to produce more SNe II; (3) the metal-enriched wind induced selective mass loss and ejected the iron-enriched gas before it was consumed to form the next generation of stars (Vader 1986, 1987); (4) the binary frequency is smaller and produces fewer SNe Ia in ellipticals (Arimoto et al. 1997); (5) SNe Ia explode less frequently in metal-rich environments, contrary to theoretical expectations (Kobayashi et al. 1998); or (6) the yields of SNe II significantly depend on the metallicity (Maeder 1992). In the present study, we find that $\langle [\text{Mg}/\text{Fe}] \rangle \simeq +0.2$ regardless of the galaxy mass. This can be most naturally explained if star formation had stopped in elliptical galaxies before the bulk of SNe Ia began to explode, as was already predicted by the galactic wind model by Arimoto & Yoshii (1987). A recent detailed study of metallicity effects on SNe Ia by Kobayashi et al. (1998) suggests that the duration of star formation in elliptical galaxies should be ~ 1 Gyr.

5. DISCUSSIONS

5.1. Dispersion

Global metallicities of elliptical galaxies correlate with central velocity dispersions but only with rather large dispersions (Fig. 7c). This comes from the fact that the metallicity gradient of elliptical galaxies is not uniquely determined by the galaxy mass. Figure 11 shows three sequences of galaxies with various gradients. All galaxies are normal ellipticals showing no significant peculiarity. The left column shows a sequence of $(\text{Mg}_2)_e = \text{const}$, so that these galaxies have the same intercepts at the effective radius and yet show different gradients. This means that elliptical galaxies can have the same mean metallicities even if the metallicities at the galaxy center are considerably different. The middle column shows a sequence of $(\text{Mg}_2)_0 = \text{const}$, thus these galaxies have the same central Mg_2 but different gradients. This implies that even if the galaxy mass is the same, elliptical galaxies can have significantly different mean stellar metallicities. The right column shows a sequence of $\Delta \text{Mg}_2 / \Delta \log r = \text{const}$, indicating that ellipticals can have the same Mg_2 gradient while global metallicities are different.

5.2. Errors

Nonnegligible scatters observed in the $\langle [\text{Fe}/\text{H}] \rangle - \log \sigma_0$ relation (Fig. 7c) might arise from observational errors involved in the line-strength measurements and the velocity dispersions. To see if one can attribute the dispersion entirely to the observational errors, we evaluate the individual errors.

The effective radius r_e is sometimes difficult to determine, and in the worst case r_e differs by almost $10''$ from author to author (Fisher, Illingworth, & Franx 1995b). However, with $\Delta \text{Mg}_2 / \Delta \log r \simeq -0.051$, the change brought into mean metallicities is $\Delta [\text{Fe}/\text{H}] \sim 0.05$ and thus is negligibly small.

It is not always the case that the same spectral resolutions are adopted. The offset resulting from differing resolution is as large as $\Delta \text{Mg}_2 \sim 0.03$ and $\Delta \text{Fe}_1 \sim 0.5$. The resulting errors in $\langle [\text{Fe}/\text{H}] \rangle$ are $\Delta [\text{Fe}/\text{H}]_{\text{Mg}_2} \sim 0.2$ and $\Delta [\text{Fe}/\text{H}]_{\text{Fe}_1} \sim 0.3$, which could partly but not entirely account for the dispersions.

Velocity dispersions in ellipticals usually decrease from the galaxy center to the outer area. The correction factors are 1.02 for Mg_2 , 1.23 for Fe_1 , and 1.5 for Fe_2 at a velocity

dispersion $\sigma = 300 \text{ km s}^{-1}$; the corrections are negligible for the Mg_2 gradient but significant for the Fe_1 and Fe_2 gradients (Davies et al. 1993).

Some elliptical galaxies are known to have surface brightness profiles that deviate significantly from de Vaucouleurs' law (Caon et al. 1993; Binggeli & Jerjen 1998; Graham & Colless 1997). Therefore, we use Sersic's law for the surface brightness profile and study how the resulting mean metallicity depends on the n parameter. We find that the effect of changing n is negligibly small.

Many ellipticals tend to have shallower gradients at the galaxy center. Although it is likely that this is caused by poor seeing, one may argue that it introduces errors in the resulting metallicity. However, the stellar mass involved within $\log r/r_e = -1.5$ is only $\sim 2\%$, and therefore the errors due to this effect should be small.

The mass-to-light ratio M/L differs from galaxy to galaxy (Faber & Jackson 1976; Michard 1980; Schechter 1980). This would affect the absolute magnitudes M_B , but not the velocity dispersions.

None of the observational errors can fully account for the large scatter in the $\langle [\text{Fe}/\text{H}] \rangle - \log \sigma_0$ relation. Therefore, we conclude that the scatters in metallicity-mass relations are at least partly real.

5.3. Mergers?

To examine whether this dispersion of the metallicity gradient and the scatter of metallicity-mass relations come from galaxy mergers, we check whether the metallicity gradients and the residuals from the ridge line of $\langle [\text{Fe}/\text{H}] \rangle - \log \sigma_0$ relation correlate with dynamical disturbances, such as the ratio of rotational velocity to velocity dispersion $(v/\sigma)^*$, the isophotal contour deviation a_4 , the dynamical peculiarity Σ , and the mass of hot X-ray gas M_{gas} . We fail to find any definite evidence suggesting that the dispersion of metallicity gradient, the scatter of metallicity-mass relations, and the dynamical disturbances come from the same origin.

5.4. Age Effects?

The major results and conclusions of this article entirely depend on our assumption that line-strength gradients should be read as the metallicity gradients. The gradients of Mg_2 , Mg_b , Fe_1 , and Fe_2 may also arise from a gradient of age that decreases from the galaxy center to the outer halo. Indeed, in many cases $\text{H}\beta$ shows a positive gradient and thus is consistent with the age gradient scenario. To estimate possible influences of the age gradient on our $\langle [\text{Fe}/\text{H}] \rangle$, we have assumed that the Mg_2 and $\text{H}\beta$ gradients are caused by both metallicity and age and have derived the age and metallicity gradients simultaneously (Table 3). Except for the cases in which we obtain unexpectedly large ages and/or age gradients, the resulting $\langle [\text{Fe}/\text{H}] \rangle$ are not much different from what we obtain with no age gradients, and the scatter of the metallicity-mass relation is nearly the same even if age gradients are considered. However, $\text{H}\beta$ is not a good age indicator, and until it becomes possible to analyze the gradients of a new $\text{H}\gamma$ index defined by Vazdekis & Arimoto (1999), one cannot conclusively exclude the possibility of age gradients.

Nevertheless, we wish to claim that the line-strength gradients are due to the metallicity gradient. Quite recently, Tamura et al. (1999) measured gradients of $HST V_{606} - I_{814}$ colors of seven elliptical-like galaxies in the Hubble Deep

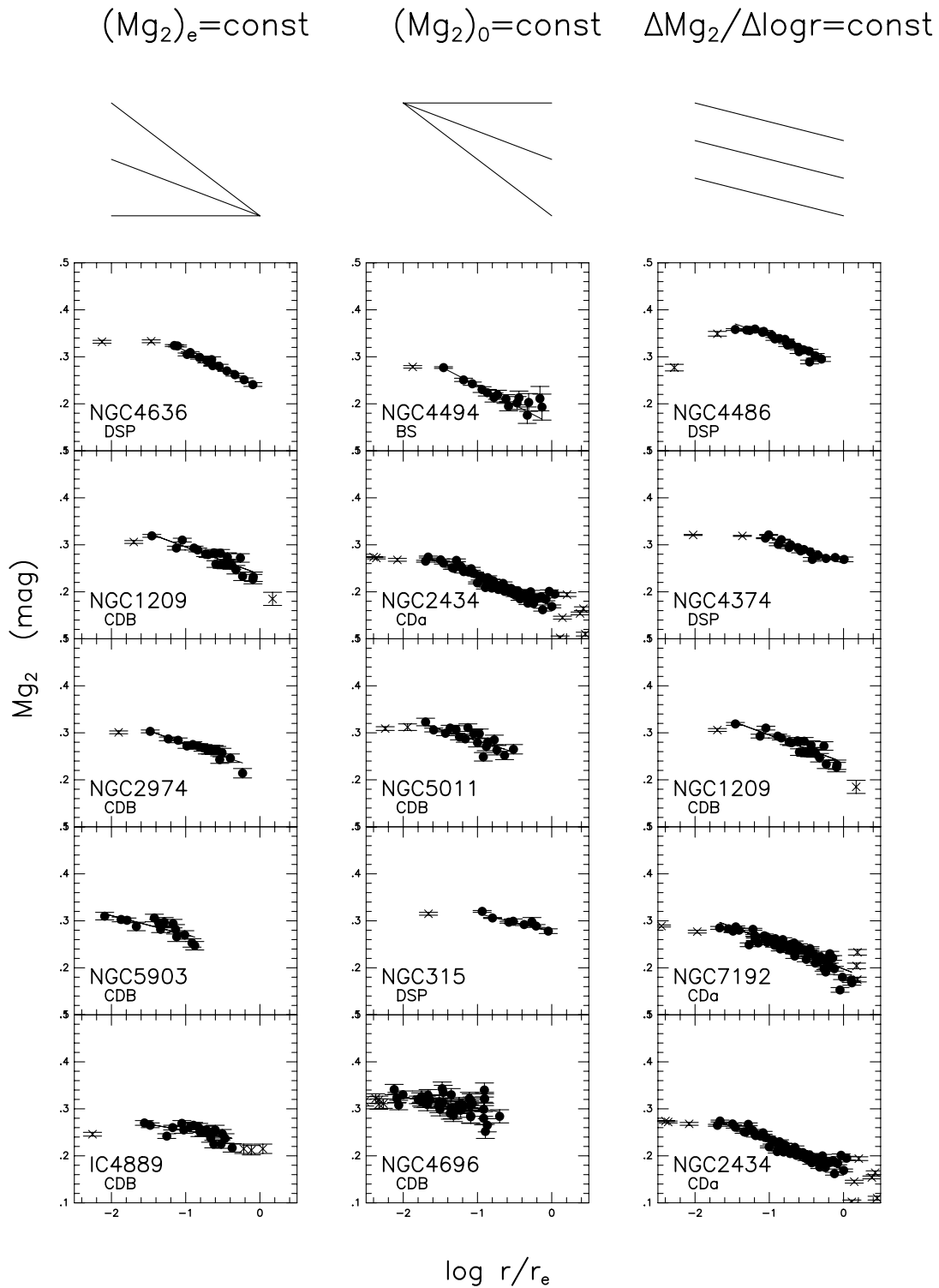
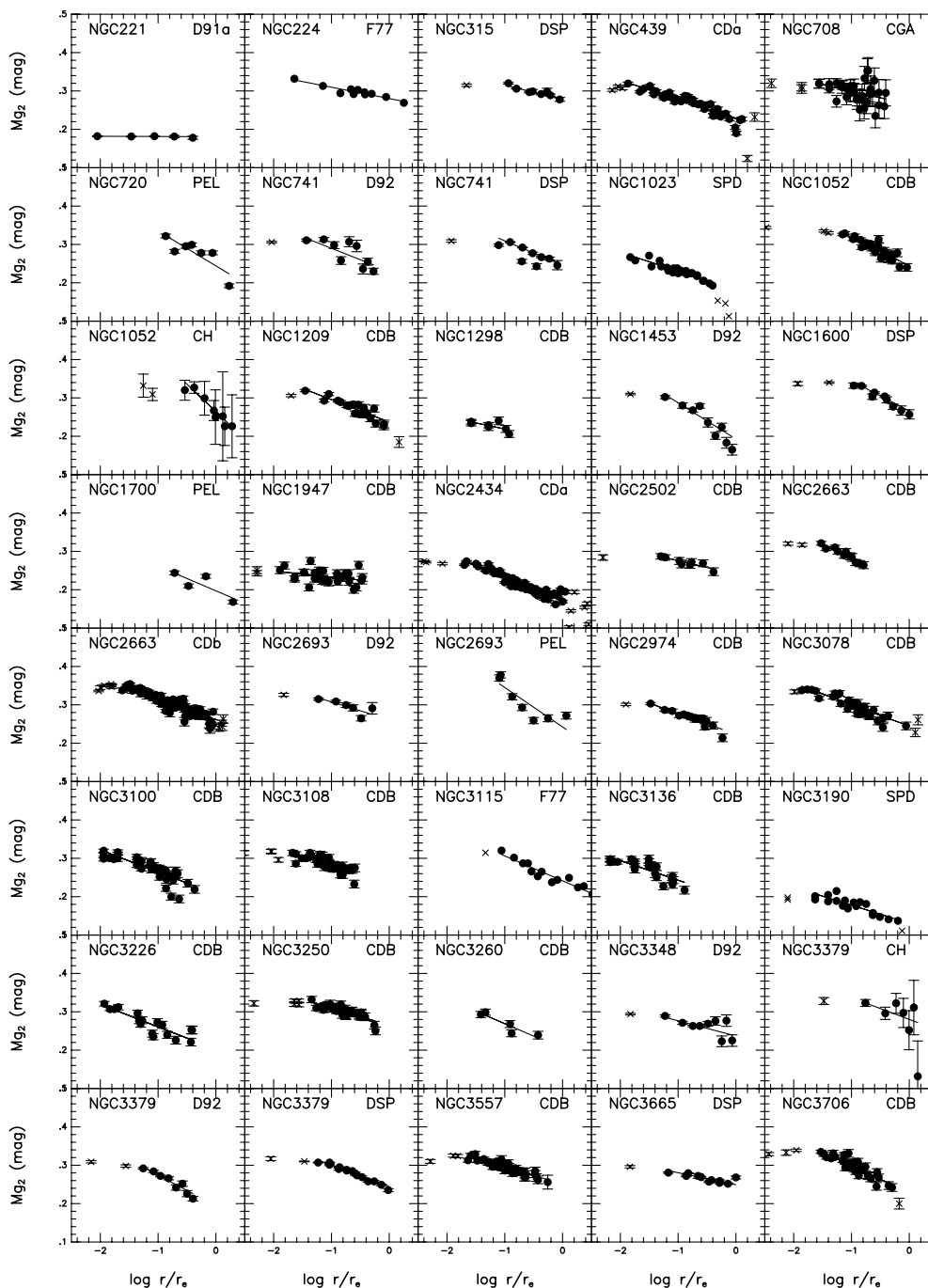


FIG. 11.— Mg_2 gradients of elliptical galaxies. The left, middle, and right columns give the sequences of $(Mg_2)_e = \text{const}$, $\log \sigma_0 = \text{const}$, and $\Delta Mg_2 / \Delta \log r = \text{const}$, respectively.

Field (HDF), 2–456.0 ($z = 0.089$), 2–121.0 ($z = 0.475$), 3–790.0 ($z = 0.562$), 3–321.0 ($z = 0.677$), 4–744.0 ($z = 0.764$), 4–493.0 ($z = 0.847$), and 4–752.0 ($z = 1.013$). These galaxies are red and their luminosity profiles follow de Vaucouleurs' law; thus it is very likely that they are genuine ellipticals. The $V_{606} - I_{814}$ gradients of these galaxies do not show significant differences, and this means that the color gradients of ellipticals have evolved passively

since $z \approx 1$. Tamura et al. (1999) build two evolutionary sequences of ellipticals by assuming that (1) the color gradients are entirely due to the metallicity gradient (a metallicity sequence) and (2) the color gradients arise from the age gradient (an age sequence). The color gradients of the metallicity sequence evolve passively and do not change significantly from the present to $z \approx 1$. On the other hand, the color gradients of the age sequence become significantly

FIG. 12.— Mg_2 gradients of early-type galaxies

steeper beyond $z \simeq 0.5$ and become almost vertical at $z \simeq 1$. Obviously, seven ellipticals in the HDF do not agree with an evolution of the age sequence at all but show quite excellent agreement with theoretical evolutionary loci of the metallicity sequence. Therefore, the color gradients of ellipticals certainly reflect the gradient of stellar metallicity. Then, why would the line-strength gradients not also reflect the stellar metallicity gradient?

6. CONCLUSIONS

We have restudied line-strength gradients of 80 elliptical galaxies. Our sample galaxies show a very similar central

$(Mg_2)_0$ distribution to that of 572 ellipticals studied by Davies et al. (1987). We assume that the gradients of metallic lines, such as Mg_2 , Mg_b , Fe_1 , and Fe_2 , all originate from the gradient of mean stellar metallicity in elliptical galaxies, and we have applied the Worthey (1994) index-metallicity relations to get $\Delta[Fe/H]/\Delta \log r = -0.30 \pm 0.12$ (Mg_2), -0.34 ± 0.16 (Mg_b), -0.28 ± 0.16 (Fe_1), and -0.25 ± 0.13 (Fe_2) and find that more than 80% of elliptical galaxies show metallicity gradients in the range $-0.6 \leq \Delta[Fe/H]/\Delta \log r \leq -0.1$. The typical gradient, $\Delta[Fe/H]/\Delta \log r \simeq -0.3$, is flatter than the gradients predicted by monolithic collapse simulations

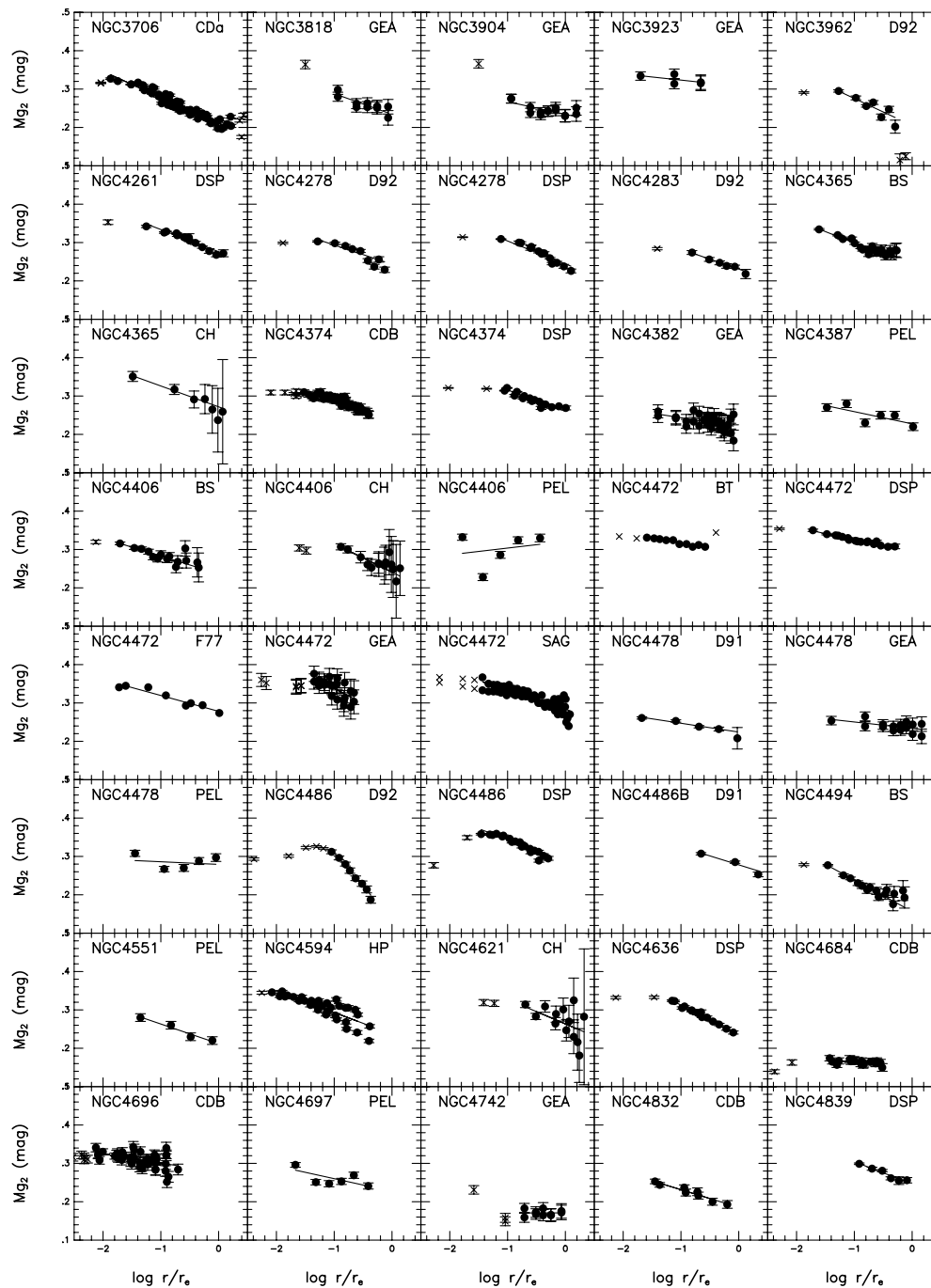


FIG. 12.—Continued

(Larson 1974a; Carlberg 1984). The metallicity gradients do not correlate with any physical properties of galaxies, including central and mean metallicities, central velocity dispersions σ_0 , absolute B magnitudes M_B , absolute effective radii R_e , and dynamical masses of galaxies. Unless there are significant unknown errors in the measurements of line-strength gradients, elliptical galaxies have different metallicity gradients, even if they have nearly identical properties such as masses and luminosities. This rather surprising behavior of the line-strength gradients has never been taken into account in modeling the formation of elliptical galaxies.

By using the metallicity gradients, we have calculated mean stellar metallicities for individual ellipticals. The average metallicities of our sample are $\langle [\text{Fe}/\text{H}] \rangle = -0.18 \pm 0.19$ (Mg_2), -0.15 ± 0.24 (Mg_b), -0.37 ± 0.17 (Fe_1), and -0.36 ± 0.18 (Fe_2), and the typical metallicity is one-half solar, $\langle [\text{Fe}/\text{H}] \rangle \simeq -0.3$. Contrary to the claim of Gonzalez & Gorgas (1996), the mean metallicities of ellipticals are not universal but range from $\langle [\text{Fe}/\text{H}] \rangle \simeq -0.8$ to $+0.3$. Since the mean metallicity of 19 elliptical galaxies with $\sigma_0 \geq 250 \text{ km s}^{-1}$ is $\langle [\text{Fe}/\text{H}] \rangle \simeq -0.04 \pm 0.11$, a claim made by Arimoto et al. (1997) remains unexplained; i.e., the iron abundance of the inter-

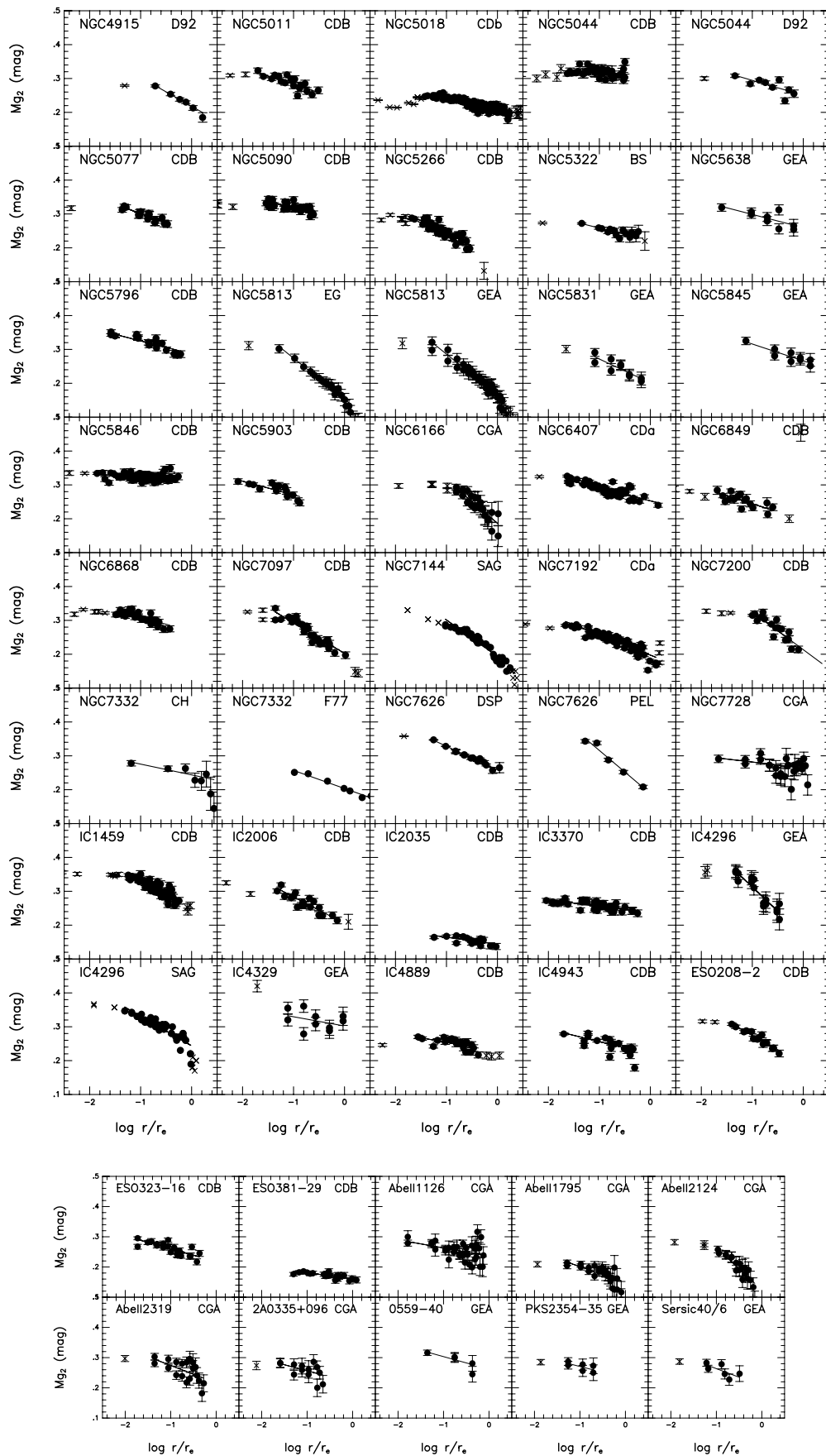


FIG. 12.—Continued

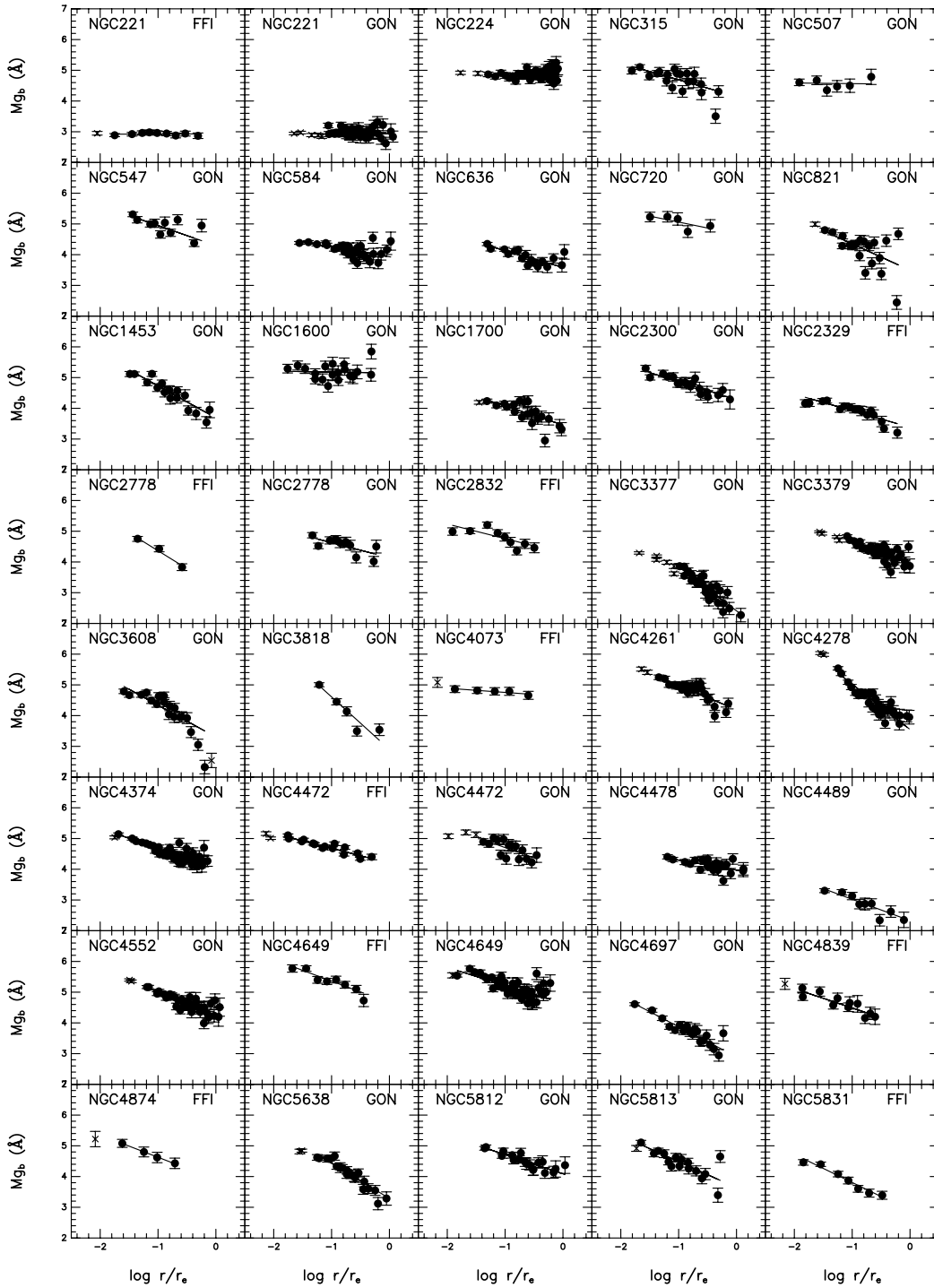


FIG. 13.— Mg_b gradients of early-type galaxies

stellar mediums of luminous elliptical galaxies, as derived from *ASCA* X-ray observations of the iron L complex, is at variance with the abundance expected from the stellar populations. $\langle [Fe/H] \rangle$ correlates well with σ_0 and dynamical mass, though relations for M_B and R_e include significant scatters. We find the fundamental planes defined by surface brightnesses SB_e , $\langle [Fe/H] \rangle$, and R_e (or M_B), the scatters of which are much smaller than those of the $\langle [Fe/H] \rangle - R_e$ (or M_B) relation. The $\langle [Fe/H] \rangle - \log \sigma_0$ relation is nearly parallel to the $[Fe/H]_0 - \log \sigma_0$ relation but systematically lower

by 0.3 dex; thus the mean metallicities are about one-half of the central values. The metallicity-mass relation, or equivalently, the color-magnitude relation of ellipticals holds not only for the central parts of galaxies but also for entire galaxies.

Assuming that Mg_2 and Fe_1 give $[Mg/H]$ and $[Fe/H]$, respectively, we find $\langle [Mg/Fe] \rangle \simeq +0.2$ in most elliptical galaxies. $\langle [Mg/Fe] \rangle$ shows no correlation with galaxy mass tracers such as σ_0 , in contrast to what was claimed for the central $[Mg/Fe]$. This can be most naturally explained if

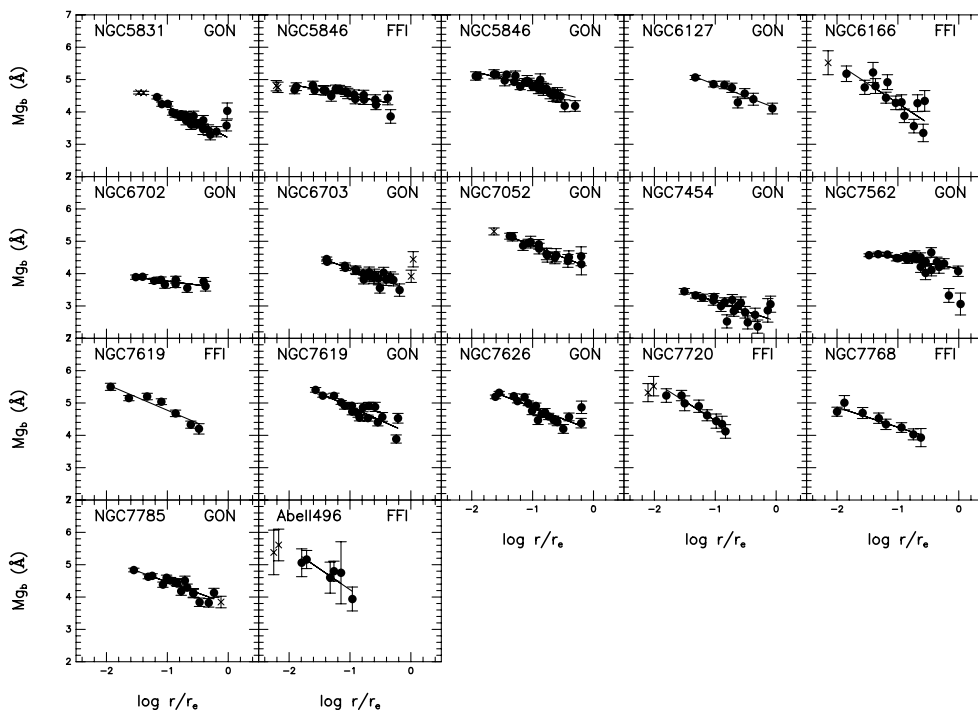


FIG. 13.—Continued

star formation had stopped in elliptical galaxies before the bulk of SNe Ia began to explode.

Elliptical galaxies can have significantly different metallicity gradients and $\langle [\text{Fe}/\text{H}] \rangle$ even if they have the same galaxy mass. This may result from different history of galaxy mergers, as suggested by the White (1980) simulation. However, we fail to find any evidence suggesting the same origin for the dispersion of metallicity gradient, the scatter around the metallicity-mass relation, and the dynamical disturbances; none of available data of Σ , a_4 , and $(v/\sigma)^*$ show a correlation with the gradients and the scatters. The scatters of both gradient and metallicity-mass relation might come from dust obscuration, but contrary to broadband colors, line strengths are far less sensitive to dust. Another possibility is that the scatters are due to different ages and age gradients. However, the scatters are

affected little by the age and the age gradient that we derive from $\text{H}\beta$, although $\text{H}\beta$ may not be a good age indicator. If it turns out that these galaxies are old and have no peculiar age gradients, the scatters discussed in this paper should have their origin at the formation epoch of galaxies.

We would like to express our heartfelt thanks to our anonymous referee whose critical reading of our draft significantly improved the paper. We are grateful to C. M. Carollo, J. Gorgas, and R. P. Saglia for providing us the machine readable data of their line-strength gradients. We thank T. Yamada, K. Ohta, and N. Tamura for fruitful discussions. This work was financially supported in part by a Grant-in-Aid for the Scientific Research (No. 0940311) by the Japanese Ministry of Education, Culture, Sports and Science.

APPENDIX

Mg_2 AND Mg_b GRADIENTS OF EARLY-TYPE GALAXIES

To give a comprehensive view of the line-strength gradients, we show in Figures 12 and 13 the Mg_2 and Mg_b gradients of 133 early-type galaxies, including compact ellipticals, S0 galaxies, and bulges of spirals. Filled circles and crosses represent the observational data taken from F77, EG, CH, PEL, GEA, BT, D91a, D91b, BS, D92, CDB, DSP, GON, HP, SAG, CDa, CDb, SPD, CGA, and FFI. We plot the data taken along several position angles, after correcting for the eccentricity. The solid lines show regression lines that are calculated by using only filled circles.

REFERENCES

- Arimoto, N., Matsushita, K., Ishimaru, Y., Ohashi, T., & Renzini, A. 1997, *ApJ*, 477, 128
 Arimoto, N., & Yoshii, Y. 1987, *A&A*, 173, 23
 Barbuy, B. 1994, *ApJ*, 430, 218
 Baugh, C. M., Cole, S., Frenk, C. S., & Lacey, C. G. 1998, *ApJ*, 498, 504
 Bender, R., Burstein, D., & Faber, S. M. 1992, *ApJ*, 399, 462
 ———. 1993, *ApJ*, 411, 153
 Bender, R., & Surma, P. 1992, *A&A*, 258, 250 (BS)
 Binggeli, B., & Jerjen, H. 1998, *A&A*, 333, 17
 Boroson, T. A., & Thompson, I. B. 1991, *AJ*, 101, 111 (BT)
 Bower, R. G., Lucey, J. R., & Ellis, R. S. 1992, *MNRAS*, 254, 601
 Bressan, A., Chiosi, C., & Tantalo, R. 1996, *A&A*, 311, 425
 Burstein, D. 1979, *ApJ*, 232, 74
 Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R., & Wegner, C. 1988, in *Towards Understanding Galaxies at Large Redshift*, ed. R. G. Kron & A. Renzini (Dordrecht: Kluwer), 17
 Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Stone, R. P. S., Lynden-Bell, D., Terlevich, R., & Wegner, C. 1987, *ApJS*, 64, 601

- Burstein, D., Faber, S. M., Gaskell, C. M., & Krumm, N. 1984, *ApJ*, 287, 586
- Butcher, H. R., & Oemler, A. 1978, *ApJ*, 219, 18
- . 1984, *ApJ*, 285, 426
- Buzzoni, A., Gariboldi, G., & Mantegazza, L. 1992, *AJ*, 103, 1814
- Caon, N., Capacciolo, M., & D'Onofrio, M. 1993, *MNRAS*, 265, 1013
- Cardiel, N., Gorgas, J., & Aragón-Salamanca, A. 1995, *MNRAS*, 277, 502 (CGA)
- Carlberg, R. G. 1984, *ApJ*, 286, 403
- Carollo, C. M., & Danziger, I. J. 1994a, *MNRAS*, 270, 523 (CDa)
- . 1994b, *MNRAS*, 270, 743 (CDB)
- Carollo, C. M., Danziger, I. J., & Buson, L. 1993, *MNRAS*, 265, 553 (CDB)
- Casuso, E., Vazdekis, A., Peletier, R. F., & Beckman, J. E. 1996, *ApJ*, 458, 533
- Ciotti, L., D'Ecceole, A., Pellegrini, S., & Renzini, A. 1991, *ApJ*, 376, 380
- Cole, S., Aragón-Salamanca, A., Frenk, C. S., Navarro, J. F., & Zepf, S. E. 1994, *MNRAS*, 271, 781
- Couture, J., & Hardy, E. 1988, *AJ*, 96, 867 (CH)
- Davidge, T. J. 1991a, *AJ*, 101, 884 (D91a)
- . 1991b, *AJ*, 102, 896 (D91b)
- . 1992, *AJ*, 103, 1512 (D92)
- Davies, R. L., Burstein, D., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R. J., & Wegner, G. 1987, *ApJS*, 64, 581
- Davies, R. L., Efstathiou, G., Fall, S. M., Illingworth, G., & Schechter, P. L. 1983, *ApJ*, 266, 41
- Davies, R. L., & Sadler, E. M. 1987, in *IAU Symp. 127, Structure and Dynamics of Elliptical Galaxies*, ed. T. de Zeeuw (Dordrecht: Reidel), 441
- Davies, R. L., Sadler, E. M., & Peletier, R. F. 1993, *MNRAS*, 262, 650 (DSP)
- de Carvalho, R. R., & Djorgovski, S. 1989, *ApJ*, 341, L37
- Dickinson, M. 1996, in *ASP Conf. Ser. 86, Fresh Views of Elliptical Galaxies*, ed. A. Buzzoni, A. Renzini, & A. Serrano (San Francisco: ASP), 283
- Djorgovski, S., & Davis, M. 1987, *ApJ*, 313, 59
- Dressler, A. 1980, *ApJ*, 236, 351
- . 1984, *ApJ*, 281, 512
- Dressler, A., & Gunn, J. E. 1983, *ApJ*, 270, 7
- . 1992, *ApJS*, 78, 1
- Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R. J., & Wegner, G. 1987, *ApJ*, 313, 42
- Dressler, A., et al. 1997, *ApJ*, 490, 577
- Driver, S. P., Windhorst, R. A., & Griffiths, R. E. 1995, *ApJ*, 453, 48
- Efstathiou, G., & Gorgas, J. 1985, *MNRAS*, 215, 37 (EG)
- Faber, S. M. 1973, *ApJ*, 179, 731
- . 1977, in *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley & R. B. Larson (New Haven: Yale Univ. Press), 157 (F77)
- Faber, S. M., Dressler, A., Davies, R. L., Burstein, D., Lynden-Bell, D., Terlevich, R., & Wegner, G. 1987, in *Nearly Normal Galaxies, from the Planck Time to the Present*, ed. S. M. Faber (New York: Springer), 175
- Faber, S. M., Friel, E. D., Burstein, D., & Gaskell, C. M. 1985, *ApJS*, 57, 711
- Faber, S. M., & Jackson, R. E. 1976, *ApJ*, 204, 668
- Fisher, D., Franx, M., & Illingworth, G. 1995a, *ApJ*, 448, 119 (FFI)
- Fisher, D., Illingworth, G., & Franx, M. 1995b, *ApJ*, 438, 539
- Forbes, D. A., Brodie, J. P., & Grillmair, C. J. 1997, *AJ*, 113, 1652
- Franceschini, A., Silva, L., Fasano, G., Granato, G. L., Bressan, A., Arnouts, S., & Danese, L. 1998, *ApJ*, 506, 600
- Franx, M., & Illingworth, G. 1990, *ApJ*, 359, L41
- Franx, M., Kelson, D., van Dokkum, P., Illingworth, G., & Fabricant, D. 1996, in *Galaxy Scaling Relations, Origins, Evolution, and Applications*, eds. L. N. Da Costa & A. Renzini (Berlin: Springer), 185
- Gonzalez, J. J. 1993, Ph.D. thesis, Univ. California (GON)
- Gonzalez, J. J., & Gorgas, J. 1996, in *ASP Conf. Ser. 86, Fresh Views of Elliptical Galaxies*, ed. A. Buzzoni, A. Renzini, & A. Serrano (San Francisco: ASP), 225
- Gorgas, J., Efstathiou, G., & Aragón-Salamanca, A. 1990, *MNRAS*, 245, 217 (GEA)
- Graham, A., & Colless, M. 1997, *MNRAS*, 287, 221
- Harris, W. E. 1991, *ARA&A*, 29, 543
- Hes, R., & Peletier, R. F. 1993, *A&A*, 268, 539 (HP)
- Kauffmann, G., & Charlot, S. 1998, *MNRAS*, 294, 705
- Kauffmann, G., & White, S. D. M. 1993, *MNRAS*, 261, 921
- Kelson, D. D., van Dokkum, P. G., Franx, M., Illingworth, G. D., & Fabricant, D. 1997, *ApJ*, 478, L13
- Kobayashi, C., Tsujimoto, T., Nomoto, K., Hachisu, I., & Kato, M. 1998, *ApJ*, 503, L155
- Kodama, T., & Arimoto, N. 1997, *A&A*, 320, 41
- . 1998, *MNRAS*, 300, 193
- Kodama, T., Arimoto, N., Barger, A. J., & Aragón-Salamanca, A. 1998a, *A&A*, 334, 99
- Kodama, T., Bower, R. G., & Bell, E. F. 1998b, preprint (astro-ph/9810138)
- Kormendy, J., & Djorgovski, S. 1989, *ARA&A*, 27, 235
- Larson, R. B. 1974a, *MNRAS*, 166, 585
- . 1974b, *MNRAS*, 169, 229
- . 1975, *MNRAS*, 173, 671
- Maeder, A. 1992, *A&A*, 264, 105
- Matsushita, K. 1997, Ph.D. thesis, Univ. Tokyo
- Matteucci, F. 1994, *A&A*, 288, 57
- Michard, R. 1980, *A&A*, 91, 122
- Mould, J. R. 1978, *ApJ*, 220, 434
- Ostriker, J. 1980, *Comm. Astrophys.*, 8, 177
- Peletier, R. F. 1989, Ph.D. thesis, Univ. Groningen (PEL)
- Saglia, R. P., et al. 1993, *ApJ*, 403, 567 (SAG)
- Sansom, A. E., Peace, G., & Dodd, M. 1994, *MNRAS*, 271, 39 (SPD)
- Schade, D., Barrientos, L. F., & Lopez-Cruz, O. 1997, *ApJ*, 477, L17
- Schechter, P. L. 1980, *AJ*, 85, 801
- Schweizer, F., & Seitzer, P. 1992, *AJ*, 104, 1039
- Schweizer, F., Seitzer, P., Faber, S. M., Burstein, D., Ore, C. M. D., & Gonzalez, J. J. 1990, *ApJ*, 364, L33
- Stanford, S. A., Eisenhardt, P. R. M., & Dickinson, M. 1998, *ApJ*, 492, 461
- Tamura, N., Kobayashi, C., Arimoto, N., Ohta, K., & Kodama, T. 1999, in preparation
- Terlevich, R., Davies, R. L., Faber, S. M., & Burstein, D. 1981, *MNRAS*, 196, 381
- Toomre, A., & Toomre, J. 1972, *ApJ*, 178, 623
- Trager, R. C., Worthey, G., Faber, S. M., Burstein, D., & Gonzalez, J. J. 1998, *ApJS*, 116, 1
- Tripicco, M. J., & Bell, R. A. 1995, *AJ*, 110, 3035
- Vader, J. P. 1986, *ApJ*, 305, 669
- . 1987, *ApJ*, 317, 128
- van den Bergh, S. 1982, *PASP*, 94, 459
- . 1990, in *Dynamics and Interaction of Galaxies*, ed. R. Wielen (Berlin: Springer), 492
- Vazdekis, V. A., & Arimoto, N. 1999, *ApJ*, 525, 144
- White, S. D. M. 1980, *MNRAS*, 191, 1P
- Whitmore, B. C., & Schweizer, F. 1995, *AJ*, 109, 960
- Worthey, G. 1994, *ApJS*, 95, 107
- Worthey, G., Faber, S. M., & Gonzalez, J. J. 1992, *ApJ*, 398, 69