ABSORPTION-LINE SPECTRA OF ELLIPTICAL GALAXIES AND THEIR RELATION TO ELLIPTICAL FORMATION

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ABSTRACT. Recent spectral data strongly suggest that elliptical galaxies represent at least a two- and probably a three-parameter sequence: light-element abundance, iron-peak abundance, and probably age. These data are discussed in the context of new ideas about elliptical formation, including hierarchical clustering, merger-caused starbursts, and a variable IMF. Non-solar abundance ratios set important constraints on elliptical formation.

1. INTRODUCTION

The accuracy with which we need to model elliptical galaxy populations is conditioned by the use to which this knowledge will be put. Some applications are basically qualitative, others highly quantitative. An example of the latter is the use of models in cosmology to predict the statistical properties of populations of galaxies at large lookback times. The accuracy needed in this case is discouragingly high, roughly $\pm 20\%$ in age or $\pm 10\%$ in luminosity, if useful limits are to be set.

These two sorts of applications put vastly different demands on population models. In some ways, as we shall see, the quantitative situation now looks bleaker than before, and there is much work needed in stellar evolution and spectral synthesis before old stellar populations can be a truly quantitative tool. On the other hand, new data have yielded important qualitative insights to elliptical formation. This paper describes recent results on the spectra of elliptical galaxies and places them in the context of current thinking on how ellipticals formed.

2. NEW VIEWS ON ELLIPTICAL GALAXY FORMATION

The classical view of elliptical (and spheroid) formation held that these objects formed stars efficiently in the early universe and that their stellar populations can be modeled as an old, nearly coeval, single burst (Baade 1941; Morgan 1959; Eggen, Lynden-Bell, and Sandage 1962; Tinsley 1968; and Larson 1974a). A proto-elliptical was assumed to be a spherically symmetric, collapsing gas cloud, with successive generations of metal-enriched stars formed closer to the center, the observed metallicity gradient being built up by inflow of more enriched

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gas from the outer to the inner zones. Any later star formation was assumed to be describable by a simple, smooth mathematical function, such as $\exp[-t/\tau]$.

Over the past decade, evidence has been accumulating that this picture is too simple. We highlight briefly some of the major new ideas (and some speculations) that we think should be part of a more realistic picture of elliptical galaxy formation:

1.) *Hierarchical clustering:* Numerous evidence suggests that structure in the universe formed hierarchically through the merger of small bits and pieces to create larger units. Protogalaxies therefore had a clumpy substructure, with essentially no spherical symmetry. This hierarchical merging lasted many billions of years and continues on galaxy-sized scales at a low level even today. Galaxies are still colliding and merging to make yet larger galaxies. One therefore cannot speak, as we did earlier, of 'the epoch of galaxy formation'. Galaxy formation is a long-drawn-out process that continues to the present.

2.) *Mergers and starbursts:* Many gas-rich merging galaxies are sites of intense star formation. These starbursts appear to be stimulated by the collision of gas clouds in the two galaxies, and the remnant galaxies in many cases are expected to evolve in several billion years to look like normal ellipticals (*e.g.*, Toomre 1977; Schweizer 1982, 1987, Lutz 1991). We believe that the star formation and morphology of many nearby colliding galaxies provide a model - albeit at reduced intensity - for how stars actually formed in elliptical protogalaxies at high redshift. These nearby systems are an important window on the past.

3.) *Episodic star formation:* Merger-induced starbursts lead naturally to the notion that star formation in ellipticals is episodic, with long periods of quiescence punctuated by intense bursts. Since the entire process took billions of years, the stellar populations of spheroids encompass a wide range of ages, but the birthrate function was highly non-uniform. The usual, smoothly declining mathematical approximations do not apply.

4.) *The importance of metallicity:* There is a general lack of appreciation among cosmologists of how sensitively the evolution rates of old stellar populations depend on composition. Solar-abundance models are widely used for distant galaxies despite the fact that their spectra are potentially badly wrong. Observable parameters that correlate with age are colors, 4000 Å break, and Balmer line strength, all of which depend mainly on turnoff color. However, this is a strong function of Z as well as age: an error of 0.5 dex in Z translates to a factor of three in turnoff age, a huge error in cosmological terms. Getting evolutionary rates accurate to 20% requires metallicities accurate to 0.1 dex, which is currently quite beyond reach. The real situation is worse because of probable non-solar abundance ratios in giant E's (see below), necessitating models that vary these elements separately if high accuracy is to be achieved.

5.) *Bimodal star formation and a variable IMF:* This final notion is quite speculative. We noted above how rapid star formation is common in colliding galaxies and how it contrasts strongly with the sluggish, inefficient star formation in isolated galaxies. We suggest that this duality may be related to the theory of *bimodal star formation,* developed to account for star births in the Milky Way (see review by Shu et al. 1987). According to this theory, one mode is 'low-mass' or 'spontaneous' star formation, which is quiescent, continuous, widespread, and regulated by *internal* cloud parameters such as ionization and magnetic field. Opposed to this is 'high-mass' or 'induced' star formation, which is bursty, localized, and triggered by *external* factors such as passage through a spiral arm.

We speculate that the starbursts seen in merging galaxies are essentially just more intense versions of the high-mass process going on in spiral arms. Silk notes (this volume) how it is plausible theoretically that high-velocity cloud-cloud shocks could favor the formation of high-mass stars. The cloud-cloud shock environment in mergers may be similar to, yet more extreme, than the pressure jump across a spiral arm. Many authors (see review by Rieke 1988) have noted how the large mass requirements of certain starbursts could be eased if the initial mass function (IMF) were weighted toward high-mass stars. Moreover, it would not be surprising in this picture to find close ties between a galaxy's dynamics (especially the velocity dispersion) and such IMF-related quantities as mean metal abundance and certain abundance ratios. These trends are in fact observed and are discussed in more detail below.

3. THE LICK GALAXY PROJECT

Most of our results come from the library of galaxy and stellar spectra collected at Lick Observatory from 1972 to 1985. The spectra were taken with the Image-Dissector Scanner (IDS) on the Shane 3 m telescope and cover approximately 4000 Å to 6200 Å with 10 Å resolution (Faber et al. 1985, Burstein et al. 1984). The ultimate goal is to understand the compositions of elliptical galaxies well enough to use them as cosmological tools. The visible portion of the spectrum was selected because it is less sensitive than the blue to turnoff temperature and less sensitive than the red to the details of M giant evolution. The G- and K-type spectra of stars that dominate the visual region are amenable to calibration both theoretically and empirically, using samples of local stars.

Integrated line-strengths are calculated in two steps (Worthey, this volume). We utilize a set of empirical fitting functions (Gorgas et al. 1991) that model 11 strong lines as a function of stellar temperature ($V - K$), metallicity (taken to be [Fe/H]), and surface gravity. These functions were derived by fitting to a sample of ~300 field and cluster G and K stars. The fitting functions are coupled to published evolutionary tracks and isochrones (VandenBerg and Bell 1985, VandenBerg 1985, VandenBerg and Laskarides 1987, Green et al. 1987, Siedel et al. 1987, Swiegart 1987, Lattanzio 1991). The models are preliminary, lacking an accurate treatment of the M-giant tip and utilizing a provisional color-temperature calibration (Green 1988) and flux distributions (Bell and Gustafsson 1989). However, the basic conclusions are qualitative and should not be affected by these uncertainties.

Fitting functions are a novel approach in that they smooth over a stellar library in a controllable way and even allow limited creation (via interpolation) of certain stars that do not exist in the library (*e.g.*, very old super-metal-rich stars). However, there is an important limitation in that the fitting functions incorporate implicitly the *same abundance ratios* that are present in the calibrating stars. Since our calibrators are local, their abundances presumably reflect general solar-neighborhood values (*e.g.*, Wheeler et al. 1989). These ratios (and trends in these ratios) cannot be altered; they are locked into the mathematical coefficients. Our models are therefore potentially inconsistent, as they combine published evolutionary tracks for solar abundance ratios with fitting functions based on stars with ratios that may vary. This proves to be a crucial limitation in what follows.

4. IRON VS. MAGNESIUM

Our most important result concerns the strength of Fe vs. Mg in elliptical galaxies. Fe5270 vs. Mg_2 is shown for some well-observed ellipticals in Fig. 1a. An important feature is the large scatter. This is confirmed by residuals in other Fe lines and also by independent observations. We return to this point below.

A second feature is the rather shallow slope in Fe relative to Mg_2. Two squares indicate averages for typical ellipticals of high and low luminosity (termed 'giant' and 'compact' respectively). Mg_2 is 60% larger in giant E's, whereas Fe5270 is only 20% larger. This shallow slope is a distinct break from the globular clusters (Burstein et al. 1985), in which Fe5270 is linearly proportional to Mg_2 up to nearly the compact E level. The same break is seen also in Fe5335.

An Fe deficit (or Mg excess) is also indicated by the models shown in Fig. 1a. The models match globular clusters rather well up through nearly solar metallicity. The model lines also pass through the compact-E points, showing solar abundance ratios for these objects. The giant E's, however, show a systematic Fe deficit relative to Mg_2; their Fe5270 strengths rise only about half as fast as the models predict. A similar result was also noted by Peletier (1989). The star-cluster data of Bica and Alloin (1986) for our Galaxy, if extrapolated, also predict stronger Fe in giant E's than is seen.

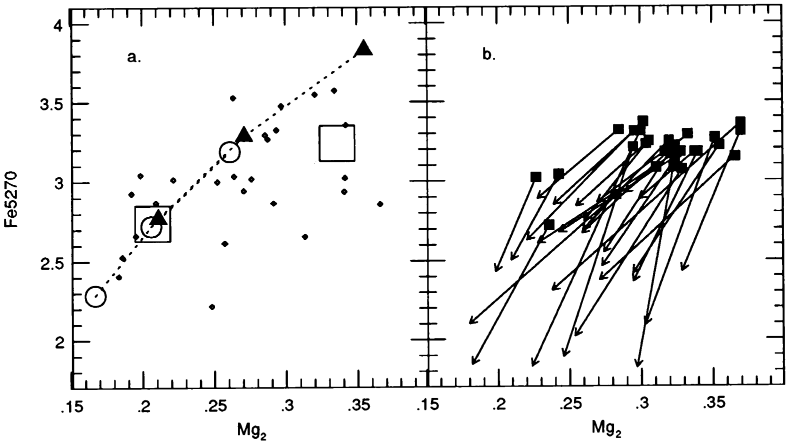

Figure 1a. Fe5270 vs. Mg_2 for Lick elliptical nuclei (small dots). Median loci for compact and giant E's are shown as large squares. Burst models for ages of 6 and 18 Gyr are shown as lines with symbols at [Fe/H] = -0.25, 0.0, and +0.25 dex. The triangles represent the older sequence. Figure 1b. CCD gradient data. Values for the central 5" of each galaxy are shown as black squares, and the averages of the furthest radii (typically 15-20") as the tips of the attached arrows.

The models in Fig. 1a show that the Fe/Mg_2 *ratio* is insensitive to both age and overall Z. Separate tests indicate that IMF is also unimportant. Since populations add vectorially in Fig. 1, the Fe discrepancy cannot be cured by invoking spreads in any of these quantities.

The only remaining option, it seems, is that giant E's have higher [Mg/Fe] than the most metal-rich stars of the solar neighborhood. Measuring this excess accurately is impossible, as we lack models with the proper abundance ratios. However, we can perhaps get a rough estimate from Fig. 1a. Hβ evidence (coming up) suggests that the average compact E is rather young, about 6 Gyr. Both Fe and Mg then agree in indicating a slight underabundance of $\sim$-0.1 dex relative to solar. This agrees well with the empirical fact that the spectra of compact E's can be closely matched using solar-neighborhood stars (Spinrad and Taylor 1968, Faber 1973, O'Connell 1980).

The giant E's are different. Regardless of whether an old or young age is chosen, the abundance from Mg_2 comes out 0.2-0.3 dex higher than from Fe5270. Interestingly, if an old age of 15 Gyr is selected, Fe is up by only +0.05 dex (and even Mg_2 is up by only +0.25 dex). These numbers might change with proper models, but it is possible that the absolute overabundance of Fe in giant E's is actually rather small.

These derived abundances are very sensitive to age, however; both Fe and Mg increase by +0.2-0.3 dex for an age increase of from 6 to 15 Gyr. Therefore, if these abundances were input back into evolving models, there would still be an uncertainty of a factor of 1.6-2 in the predicted rate of spectral evolution. Thus, we have not significantly sharpened our hold on metallicity by studying lines even in this (most favorable) part of the spectrum. The age-metallicity degeneracy can only be attacked, it seems, by modeling the near-UV spectrum between 2400 Å and 3200 Å (Fanelli et al. 1990), or perhaps from exquisitely accurate measurements of the Balmer line absorption (see below).

In an independent study, Gonzalez (1991) has measured Mg_2 and Fe gradients in 28 (mostly cluster) ellipticals using a high-accuracy CCD detector. His results are shown in Fig. 1b. Note that the trends *within* galaxies are steeper than the relation linking the nuclei. The same difference is seen in Fe5335 and was also detected by Efstathiou and Gorgas (1985), Peletier (1989), and by Gorgas et al. (1991) for a smaller sample of galaxies (but *cf.* Sadler and Davies 1991 for a different view).

These slopes help us to understand the scatter for the nuclei in Fig. 1a. Within a galaxy, Fe and Mg evidently vary in rough proportion; however, the *global average* of Mg to Fe is clearly varying from galaxy to galaxy. The collective Fe-Mg relationship for all populations is thus two-dimensional, with each galaxy following its own enrichment line. The precise nuclear location along this line depends on the maximum degree of nuclear enrichment achieved and on the spatial resolution of the observations.

Since Fe and Mg are made by two different types of supernovae - Type Ia vs. Type II - a change in their ratio could signal important differences in the nucleosynthetic enrichment process. Excess Mg could indicate an overabundance of *all* Type II-light elements in giant E's, relative to Fe. This possibility can be assessed by comparing the predicted impacts of the two element groups on the HR diagram and on the spectrum (Renzini 1977). The Fe-peak controls the temperature of the giant branch and thus the contribution of the coolest M giants. Fe should be tied to TiO strength, infrared spectral features, and M_I, the mean I-band brightness on the giant branch (Tonry et al. 1990). The rather small variations seen in these quantities are consistent with their being controlled by Fe.

Conversely, the impact of the Type II light elements should be be large and pervasive. Since O opacity largely controls the turnoff temperature, Type II abundances should couple closely to the blue-visual colors and Hβ line strength. Large variations are also expected in individual light-element features such as Mg b, MgH, NaD, and Na 8190 (Faber 1973, Bica and Alloin 1986, Deslisle and Hardy 1991). Production of C and N is less clear, but the strong CN excess suggests that these light elements, too, are also enhanced. The only known contradictions are the G-band (CH) and Ca (H-K and the IR triplet), but these are features that show little variation even in stars where Mg is strong (Faber et al. 1985, Díaz et al. 1989). Further checks are needed, but it appears plausible that the major driver of spectral variations in elliptical galaxies comes mainly from the light elements, not the Fe-peak.

5. Hβ VS. IRON AND MAGNESIUM: A THREE PARAMETER SCENARIO?

Hβ line strength may signal yet a third parameter in the system. Hβ is a difficult line because it is often filled in by emission. However, we have found that [O III] 5007 Å is a reliable flag for Hβ in nuclear spectra, and Gonzalez's long-slit data show this line clearly. Fig. 2 shows Hβ vs. Mg_2 for Gonzalez's nuclei, pruned of all suspected emission. The relation is exceptionally narrow, unlike Fe versus Mg_2. On it are superimposed Worthey's models. They overlap the galaxies but have a shallower slope at fixed age. The steepness of the galaxies reflects the fact that compact E's have high Hβ. Taken at face value, this suggests an age trend among Gonzalez's galaxies, with the compact E's some 5-6 Gyr old and the giant E's much older (these are mean ages only and are not meant to rule out that there could be a large age range within each type of system). Whether this result is general or merely reflects small-number statistics in Gonzalez's sample is not yet clear. However, it is interesting that the age for M32 estimated this way agrees well with detailed population synthesis (Faber 1973, O'Connell 1980).

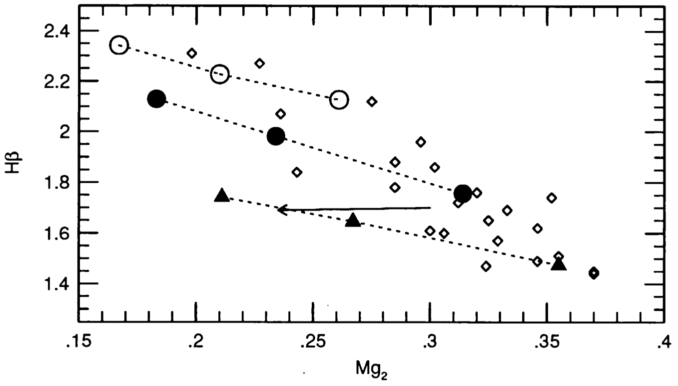

Figure 2. Hβ vs. Mg_2 for a sample of 28 nuclei without Hβ emission. The arrow shows a mean radial gradient. Model predictions appear as in Fig. 1a, except that a 9-Gyr locus is added as the middle line.

A mean radial $H\beta$ gradient is also indicated in Fig. 2. For clarity, we plot only an average of the best-measured 28 galaxies. The average gradient is flat, as was found also by Efstathiou and Gorgas (1985) and Gorgas et al. (1990). This flatness is surprising because of the steep gradients in both Fe and Mg_2. Worthey's models predict that, if all radii of a galaxy have the same age and differ only in Z, Hβ should *increase* slightly outward, not remain flat (see Figure 2).

These results are still preliminary, and the discrepancy may not be real. However, the implications are important and are worth a brief mention. To counteract metallicity, there would have to be a third parameter operating, most plausibly a gradient in the mean age. The sense is such that the centers of galaxies would have to be younger on average than the outer parts, by roughly one-quarter or one-third the total age.

This is interesting precisely because it agrees with the hierarchical merging picture. In this picture, a starburst is induced over a large volume while at peak intensity, but leftover gas eventually finds its way to the center, to be consumed there in the final stages of star formation. Actual starbursts follow this pattern. Young ones such as NGC 7252 show new stars over a large area (Schweizer 1982), while older bursts are strongly concentrated to the nuclei. Well known examples include NGC 205, NGC 1275, NGC 5102, NGC 2681, and M82. Among the Lick sample we have off-nuclear spectra of 8 early-type galaxies that show excess nuclear Hβ; in all of them, this excess declines away from the nucleus. The conclusion seems clear that the infusion of young stars from starbursts is relatively largest in the central regions. In merging and hierarchical clustering, then, elliptical galaxies form 'from the outside in', just as they do in the classic spherical collapse picture.

Growing evidence suggests that subtle age differences may in fact be common in ellipticals. Schweizer et al. (1991) showed that a sample of disturbed (mostly field) ellipticals tended to have systematically weak metal lines and strong Hβ for their luminosities, as though their spectra were diluted by young stars. Gregg (this volume) finds that the same galaxies yield systematically positive peculiar motions from the $D_n - \Sigma$ relation, due, he thinks, to enhanced surface-brightness. De Carvalho and Djorgovski (this volume) find a similar effect in field ellipticals from Faber et al. (1990), whereas cluster galaxies appear to be more homogeneous and dimmer. Gonzalez's very narrow $H\beta$ relation in Fig. 2 is consistent with these findings since his galaxies are mainly cluster members.

The evidence thus suggests that star formation continued for a long time in ellipticals but cut off sooner in clusters than it did in the field. An earlier cutoff in clusters is plausible if only moderate-velocity galaxy collisions are effective in producing mergers and starbursts. At the high encounter velocities in large clusters, two colliding systems will not coalesce, and shocked gas will be heated to escape velocity and will not form stars. Thus we have a natural cutoff in the age of stellar populations located in dense environments.

6. THREE WAYS TO VARY [Mg/Fe]

Three possible scenarios might account for variations in [Mg/Fe]. All utilize the fact that Mg is produced by Type II supernovae, whereas the bulk of Fe comes from Type Ia.

6.1. Different Star Formation Timescales

This first suggestion exploits the fact that Type II SNe come from massive stars with lifetimes shorter than 10^8 yr, while Type Ia SNe result from binary mass transfer, which sets in more slowly and lasts for Gyr. There results a well known time delay between the production of the light elements and the bulk of the Fe-peak, with the consequence that the first generations of stars have enhanced [Mg/Fe]. As applied to giant E's, however, this argument appears to have the wrong sign: star formation would need to occur faster to produce a higher yield of Mg, yet the evidence suggests that these systems actually took longer to accumulate. Longer timescales are suggested by the fact that the giants are larger objects (and hence in a hierarchy would have to form later) and also by their lower densities and longer dynamical timescales (a factor of 3 longer compared to compact E's [*e.g.* Blumenthal et al. 1984]). Giant E's are therefore required to accumulate their gas gradually, not making stars, and then make them all suddenly in a final burst. This scenario seems forced.

On the other hand, the argument can be turned around to exploit the observed fact that, for whatever reason, stellar populations in compact E's appear to be *younger* than those in giant E's. Smaller Es agglomerated their material quickly, so this argument goes, but turned it into stars more slowly. Perhaps slower star formation could be related to the lower cloud-cloud collision velocities in these systems.

6.2. Selective Loss of Mg vs. Fe

Modulating net yield by allowing metals to escape is the classic way to account for the higher metallicities of giant E's (Larson 1974a). The same mechanism has also been invoked to explain radial abundance gradients within galaxies (Franx and Illingworth 1990). To explain differences in Mg/Fe, we would need to appeal to the selective loss (or retention) of light vs. Fe-peak elements in galaxies of different sizes at different times.

To match the observations requires either that giant ellipticals lose more Fe or that compact ellipticals lose more Mg. The second choice is preferable, since it is hard to see how large galaxies with their deeper potential wells could lose more of anything. Preferential loss of light elements could have occurred early in compact ellipticals provided supernovae-driven winds were most intense at that time. However, in standard wind scenarios (Arimoto and Yoshii 1987, Matteucci and Tornambè 1987), the onset of winds is irreversible, so the loss of Fe always *exceeds* the loss of Mg. Winds do not appear to be the answer unless they can be shown to be more effective in giants than in compacts, which seems unlikely.

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6.3. Selective Production of Mg vs. Fe: Variable IMF

The final mechanism posits a difference in the IMF, with giant E's having more very massive stars, more Type II SNe, and more light element production. No conclusive evidence exists at this time to prefer this view over the others; however, it has no known drawbacks and fits rather neatly with the concept of bimodal star formation mentioned above. High-mass star formation, we recall, is triggered by external conditions such as passage through a spiral arm. A comparable external variable in ellipticals could be the ambient effective gas pressure due to cloud-cloud collisions. Since this scales roughly as the dispersion σ_{cl}^2, the effective ambient pressure in merging galaxies would be about 100 times higher than in spiral arms. Even among E's, there is a difference of a factor of ~10 between compacts and giants. If higher σ_{cl} favored more massive stars, the higher abundance of light elements in giant galaxies would be naturally explained.

The variable IMF theory also helps to explain another observational fact - the very tight correlation between Mg_2 and σ. Throughout this paper we have spoken loosely of 'giant' versus 'compact' E galaxies, tacitly implying that abundance scales best with galaxy mass. In fact, Mg_2 scales much more closely with *velocity dispersion* than it does with luminosity or any other parameter, in a relation that is closely obeyed over an astonishingly wide range of velocity dispersions (Bender et al., this volume). One explanation is that metal abundance is related to the local escape velocity, and thus to σ (Franx and Illingworth 1990). However, this idea is perhaps less attractive now that Fe is known to decouple from Mg - why should one element follow the escape velocity but not the other?

On the other hand, a tight Mg_2-σ correspondence is a natural consequence of the variable IMF scenario. High σ translates directly to high Mg_2 through the strength of the upper IMF, while Fe, being produced by lower-mass stars, is at best loosely correlated. In fact, an intimate relation between σ and *all* Type-II light elements is expected in this scenario, in agreement with the data.

Each theory makes distinct predictions, and it should be possible to choose among them by measuring accurate line strengths in the outer parts of ellipticals of different sizes and types. It is already clear, for example, that current standard enrichment models fail badly in predicting universally *more* Fe in giant E's rather than less (Matteucci and Tornambè 1987). As this result is generic under the simplest assumptions, the line strengths are clearly telling us something very fundamental and unexpected about elliptical formation. However, before accurate comparisons with models are possible, we must first learn how to translate line strengths reliably into age and element abundances. Before that can be done, 1) stellar evolutionary models must be broadened to include variable element ratios, and 2) spectral synthesis must be perfected to provide spectra of stars with non-solar abundance ratios. Our net reliance on theory will be vastly increased, and an extensive testing program will have to be undertaken before the results can be believed.

7. CONCLUSION

Although quantitative goals remain elusive, our qualitative understanding of ellipticals seems to be growing rapidly. IRAS and other facilities have shown conclusively that galaxy collisions trigger intense bursts of star formation. Many merging galaxies are today generating dynamically hot stellar populations that will evolve to look like ellipticals eventually. Some mergers are even forming proto-globular clusters (Lutz 1991, Holtzman et al. 1991).

This observational evidence is consistent with our growing theoretical understanding of merging and how it operates via hierarchical clustering to make structure in the universe (see review by Frenk 1988). Merging on galaxy-sized scales has passed its peak, and merging galaxies today are the last dregs undergoing this process. Though systematically less gas rich than earlier collisions, today's merging galaxies are nevertheless crucial because they show us, quite faithfully, what proto-spheroid formation must have looked like at high redshift. We see a close facsimile of it taking place now in the Galactic neighborhood.

Many of the early objections to formation of ellipticals by mergers (*e.g.*, Ostriker 1980) have been blunted by the realization that mergers often contain gas and that gaseous dissipation plays a major role in determining the final structure of the remnant. Thus, ten years ago, we witnessed a classic 'nature vs. nurture' debate on galaxy formation, whether protogalaxies were basically isolated structures, or whether their fate was determined mainly by interaction with the environment (*c.f.* White 1982). The realization that structure forms hierarchically and with gaseous dissipation is steadily erasing that distinction. On the one hand, the classic protogalaxy picture now takes clumpy substructure for granted, while, on the other, mergers now routinely include gaseous dissipation and star formation. Ironically, the two formerly opposing theories have themselves now merged!

The spectral data reported here are an important part of this picture. The knowledge that there are (probably) three parameters is crucial to making models. Moreover, all three parameters are intimately tied to exactly how and when these galaxies made stars. Merging predicts that in some galaxies there should exist subtle correlations between dynamical irregularities and spectral properties, depending on the time since the last major interaction. These correlations are now being discovered (Schweizer et al. 1991; Bender et al., this volume). The challenge in future is to make all this information quantitative.

In conclusion, we offer a caveat. Our whole approach here rests implicitly on the assumption that $H\beta$ is produced mainly by the turnoff stars and thus is simply related to age. Were it to be demonstrated that some other population, such as horizontal branch stars, contributes heavily to $H\beta$ (*e.g.*, Burstein et al. 1985), any simple three-parameter calibration involving Fe, Mg, and age would be threatened. The nearby galaxies M31 and M32 are the only stellar laboratories in which this possibility can be tested (using a repaired HST). Until this important loose end has been tied up, the basic calibration for old stellar populations will remain somewhat shaky.

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Discussion

J.P.Ostriker: A cautionary note on mergers. The thinness and coldness of spiral disks implies that recent merger activity is minimal. In recent calculations we found at Princeton that not more than 4% of the mass has been added (interior to our orbit) in the last 5 billion years.

Faber: Yes, I agree with that in the case of spirals. Even for ellipticals, I think it will turn out that a small percentage of them have undergone an interaction so recently as to sizeably perturb the colors and surface brightness. The real question for the typical elliptical is whether, via very careful observations of the line spectra or the dynamics, we can uncover evidence of even more ancient mergers. I think the answer with respect to the dynamics is incontrovertibly yes, and the line spectra are clearly tending in the same direction also.

D. Spergel: I want to reiterate your point about the role of magnetic fields. If magnetic fields grew by a dynamo mechanism, then the B field in the early universe was much weaker than today. Magnetic fields are believed to play an important role in transferring angular momentum from protostars to the molecular cloud. Without strong magnetic fields, old stars are much more likely to be rapidly rotating and much more likely to be in close binaries. These two effects need to be considered in models of stellar evolution.

Faber: Yes, I am particularly troubled by the role that binaries might play in massive star star evolution. Several people at this conference have privately noted that most Wolf-Rayet stars are close binaries. Might this fact influence the mass-loss process and hence the net yield of the various elements? Perhaps we should be thinking more closely about all these effects.

S.G. Djorgovski: A question and a comment: have you tried to divide your sample into the field and rich-cluster ellipticals and compared them? My comment is on M32. There is now a growing body of evidence that there are color and population gradients near the centers of highly concentrated globular clusters (bluer in the middle), which seem to involve changes in the horizontal branch and may be caused by dynamical processes. It is possible that similar phenomena may occur in high-density ellipticals like M32 and cause the 'inverse' UV color gradients, as seen in the ASTRO data.

Faber: On point one: yes, we did, and we found no net offset in predicted peculiar velocities between the field and clusters. However, we did not further subdivide the *field* sample according to environmental density, and this might reveal the effect that you and de Carvalho have found. On point two: that is an interesting suggestion that might perhaps be checked with the new HST images of M32 that have just been obtained.

Pagel: You mentioned the possibility that the universe could be only 10 Gyrs old. Recent development in Th/Nd/En chronology fully support ages up to 15-20 Gyrs deduced form HR diagrams in the conventional way.