LINE-STRENGTH GRADIENTS IN EARLY-TYPE GALAXIES

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ABSTRACT. We have measured line-strength gradients in a sample of 15 early-type galaxies. The line-strength measures include the Mg_2 index and the equivalent widths of Hβ and two iron blends at 5270Å and 5335Å. In most of the galaxies we find gradients in the metallic line-strengths. However, the gradients vary markedly from object to object and do not correlate strongly with other parameters such as total luminosity, rotation, etc. A comparison of the line-strengths in the outer parts of these galaxies with galactic globular clusters suggests relatively modest abundance gradients in early-type galaxies.

1. INTRODUCTION

It is now clear that the stellar populations in globular clusters and elliptical galaxies do not simply represent a one parameter family in which metal abundance is the key variable (see Burstein, 1985 for a detailed review, Pickles 1986 in this volume). We mention here just a few of the developments which have led to this conclusion: (a) although in integrated colours galactic globular clusters appear as a one parameter family, their horizontal branch morphologies require at least two additional parameters (Freeman and Norris 1981); (b) M31 globular clusters which have similar metal line-strengths to those of galactic globular clusters generally have stronger Balmer lines (Burstein et. al. 1984, hereafter BFGK); (c) The Balmer lines in the nuclei of elliptical galaxies are stronger than expected in synthesis models of old (~15Gyr) metal rich stellar population (O'Connell 1976; Gunn, Stryker and Tinsley 1981) and do not match continuously with those of metal rich galactic globular clusters (BFGK). (d) M31 globular clusters have stronger CN features when compared to elliptical galaxy nuclei with similar values of magnesium line-strength (BFGK). The reasons for these differences are not well understood. Gunn, Stryker and Tinsley have suggested that the enhanced Balmer line-strengths in elliptical nuclei might be caused by a modest rate of current star formation; O'Connell (1980), Pickles (1985) and Rose (1985) argue that the stellar populations in elliptical galaxies contain a substantial intermediate

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age component (~5-10Gyr). However, other possibilities such as blue stragglers cannot be convincingly ruled out.

In this article, we investigate another aspect of old stellar populations, namely line-strength gradients in early-type galaxies. The existence of radial abundance variations in elliptical galaxies and the bulges of spirals has been suspected ever since early work on colour gradients (eg. de Vaucouleurs 1961, Tifft 1961). More recent work (see Gallagher 1984; Cohen 1986) has shown that the colours in the halos of giant elliptical galaxies are generally redder than those of metal poor galactic globular clusters. At face value, these colour gradients suggest relatively weak abundance gradients. Further progress in understanding these gradients requires spectroscopic data. As indicated above, spectroscopic studies have revealed a number of intriguing differences between spheroidal stellar populations. Line-strength variations **within** elliptical and other early-type galaxies provide a further test of the nature of these populations.

Previous line-strength studies have been reviewed by Faber (1977). They have provided unambiguous evidence of gradients in strong absorption features such as CN and Mg. However, only a few features, in a small sample of early-type galaxies, have been studied and the results have left a number of important questions unanswered (see below). This lack of data is not altogether surprising. High precision measurements at large distances from the centres of elliptical galaxies require long exposures and careful data reduction. A "two-dimensional" detector is essential if a large body of homogeneous data is to be obtained on a reasonable time scale. Our own results are based on spectra obtained with the Image Photon Counting System (IPCS) at the Anglo-Australian Telescope in a number of observing runs between 1979 and 1982. The observations were made primarily for dynamical studies of early-type galaxies and details may be found in various published papers (Efstathiou, Ellis and Carter 1980, 1982; Davies et. al., 1983; Carter et. al., 1985). Our sample spans a range of morphological types (ellipticals, S0's and cD's), absolute magnitudes and ellipticities and thus provides a starting point for a more systematic analysis of line-strength gradients.

We first outline a number of interesting problems which remain to be solved:

1. Are there any regularities in line-strength gradients? For example, do gradients correlate with parameters such as absolute magnitude, surface brightness, ellipticity, etc. Such correlations could provide important clues to the formation of elliptical galaxies (eg. Carlberg 1984). The available results are ambigous. Strom and Strom (1978) found that colour gradients vary strongly from galaxy to galaxy and presented evidence that gradients correlate with total luminosity. Burstein (1979) found indications of a correlation between central line-stength and gradients while Spinrad et. al. (1972) argued that CN gradients along the major axes of highly flattened galaxies are weaker than those in round galaxies. However, Faber (1977) found that gradients in CN, Mg and NaD in 8 early-type galaxies of widely different ellipticities were all roughly similar.

2. It is well known that line-strengths in the centres of ellipticals and S0's are strongly correlated with total luminosity, suggesting that the stars in the inner parts of giant galaxies are more metal rich than those in low mass galaxies (Faber 1973, Burstein 1979, Terlevich et al 1981, Tonry and Davis, 1981). If the stellar populations in ellipticals were governed by only one parameter, the mean metallicity of the system, then the gradients in all features within a galaxy should follow the same set of relations as those obeyed by the nuclei.

3. Do line-strength gradients correlate with morphological type? Wirth and Shaw (1983) find that colour gradients in spiral bulges are steeper than those in elliptical galaxies and argue that these systems must have formed in differents ways. It clearly important to check this result in more detail. There is now considerable speculation on the formation mechanism of cD galaxies. If galactic cannibalism (Hausman and Ostriker 1978) or cooling flows (Fabian et. al. 1984) are responsible for their high luminosities, it may be possible to detect anomalies in the spectral properties when compared to giant ellipticals.

4. Larson (1975) presented detailed models of the dissipative collapse of elliptical galaxies and predicted that the isoabundance contours ("isochromes") would be flatter than the isophotes. Results on this point remain ambiguous. Strom and Strom (1978) found supporting evidence from their study of colour gradients. Faber (1977) also measured such an effect but concluded that "the behaviour is quite variable from feature to feature and from object to object". Recently, Carlberg (1984) has presented a dissipative scheme for the formation of slowly rotating ellipticals which does not lead to a strong flattening of the isochromes.

In this article, we present results on line-strength gradients in 15 early-type galaxies. Our discussion will be focussed primarily on points (1) and (2) described above. An important aspect of our study is that we have adopted the line-strength system described by BFGK, thus allowing direct comparison with their extensive results for globular clusters and the nuclei of ellipticals. A more complete discussion of our work is given elsewhere (Gorgas and Efstathiou 1986).

2. Mg_2 GRADIENTS

We have measured the Mg_1, Mg_2, Hβ , Mgb, Fe5270 (henceforth Fe52) and Fe5335 (henceforth Fe53) indices defined by BFGK. We will not discuss the lengthy details of the data reduction here, but it is important for the reader to be aware that the the main sources of error in our line-strengths arise from a number of systematic effects associated with the instrument configuration. These include, S-distortion, non-uniformities in the response of the IPCS and saturation of the detector at high count rates. In addition, the Mgb, Fe52 and Fe53 indices are affected by velocity dispersion broadening which we have calibrated by convolving spectra of G and K giants with Gaussian distributions. Our line indices have been corrected to a fixed resolution corresponding to a Gaussian distribution of 220 km s^{-1} to match the resolution used by BFGK. The spectra were calibrated to an absolute scale using Oke (1974) flux standards observed during each run. This differs from the absolute calibration used by BFGK who calibrated with respect to a tungsten lamp. The absolute calibration is important in determining the zero point of the Mg_2 and Mg_1 indices, which have widely separated side bands, but is unimportant for the other indices. An important check that our results are on the same system as that of BFGK is provided by comparing our nuclear values with their relations for elliptical nuclei. This is shown in Figure 1 for all the ellipticals in our sample together with an additional 8 ellipticals for which short exposures were taken (Davies et. al., 1983). The nuclear values of BFGK were determined using a 1.4"x4" aperture, while we have binned our data to simulate an aperture of sx4" where s denotes the slit width in arcsec (between 2" and 3" depending on the observing run). The nuclear values shown in Figure 1 obey similar relations to those found by BFGK. In fact the scatter in the Fe lines is nearly twice as small as theirs. The scatter that we observe in Figure 1 is compatible with our estimated measurement errors with perhaps the exception of the Hβ-Mg_2 relationship. NGC 4742 provides an extreme example of a discrepancy since this galaxy has a central H equivalent width of 3.8Å which is nearly twice as large as the average value for an elliptical with similar nuclear metal line-strengths.

In Figure 2, we show how the major axis Mg_2 gradients vary for 10 ellipticals and 2 bulge dominated S0 galaxies. We have presented the Mg_2 gradients since this index is more accurately measured than the others. Gradients in the other indices will be discussed in Section 3. The triangles in Figure 2 show Burstein and Faber's measurements for NGC 4472 (Faber, 1977) which are in good agreement with those presented here.

Figure 2 shows that the Mg_2 gradients vary substantially from galaxy to galaxy. For example, NGC3904 appears to have a strong gradient while NGC 4478 does not possess a significant gradient. Our results do not support Faber's (1977) conclusion that early-type galaxies have similar gradients. We have fitted a straight line to each of the line-strength profiles shown in Figure 2 and tested for correlations between the slopes and other parameters by applying the Spearman rank-correlation test. The parameters chosen were: blue absolute magnitude, mean surface brightness within r_e, mean velocity dispersion within $0.5r_e$, ellipticity, ratio of maximum rotational velocity to central velocity dispersion, velocity dispersion gradient and central Mg_2 value. The strongest correlation (−0.50 for the 12 galaxies shown in Figure 2, −0.66 if the two S0's are excluded) is with velocity dispersion (in the sense that galaxies with large velocity dispersions have steeper gradients)- but the result is significant at less than the 95% level. We therefore conclude that Mg gradients do not correlate strongly with other parameters. The mean of the

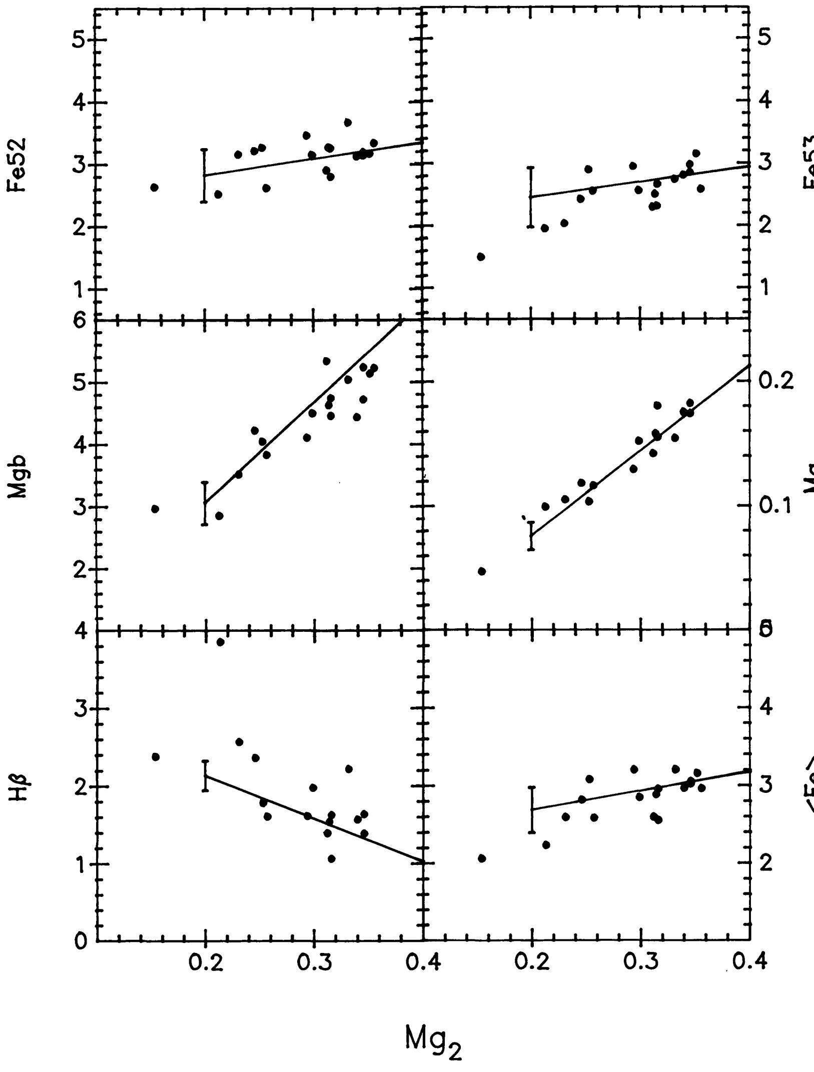

Figure 1. Comparison of nuclear line-strengths for elliptical galaxies in our sample with the mean relations (solid lines) determined by Burstein et. al. (1984). Their rms scatter is indicated by the error bars. <Fe> is the average of the two iron indices Fe52 and Fe53. The units of Fe52, Fe53, <Fe>, Mgb and Hβ are in Angstroms and those of Mg_1 and Mg_2 are in magnitudes.

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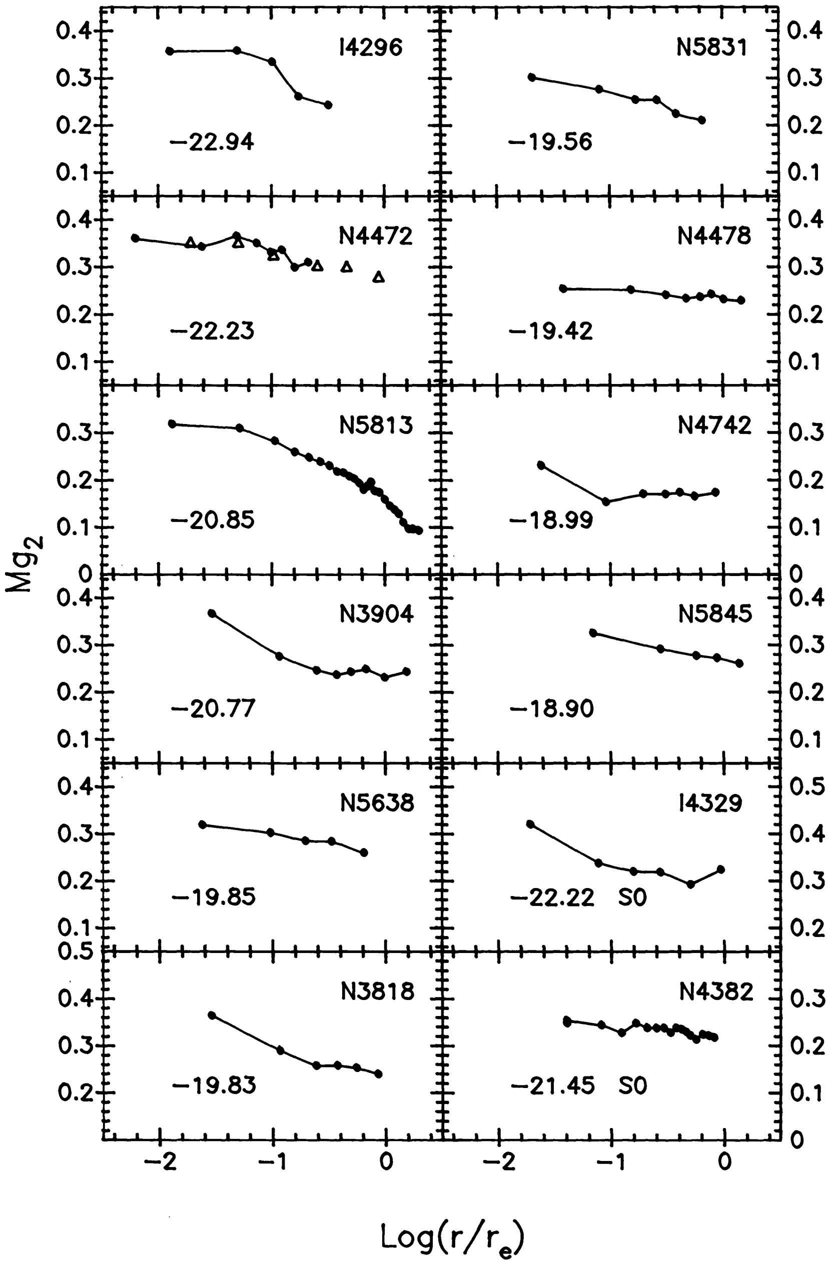

Figure 2. Major axis Mg_2 gradients for 12 early-type galaxies. We have plotted Mg_2 against $\log(r/r_e)$ where r_e is de Vaucouleurs' effective radius as listed in the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs et. al. 1976). For each galaxy we give the absolute magnitude in the B_T system assuming a Hubble constant of H_o = 50 km s^{-1} Mpc^{-1}.

gradients for this sample is

$$Mg_2 = -(0.06 \pm 0.03) \log(r/r_e) + \text{constant} \qquad (1)$$

where the error represents one standard deviation. Converting such results into true metallicity gradients remains a major unsolved problem which we will not address in detail in this article (see the reviews by Burstein 1985, Pickles 1986 this volume, and references therein). In Figure 3, we show Mould's (1978) theoretical computation (as recalibrated by Terlevich et. al., 1981) for the relation between the Mg_2 index and [Fe/H] for an old (13Gyr) stellar population ([Fe/H] = $3.9Mg_2 - 0.9$). In addition, we have plotted Mg_2 values for galactic globular clusters measured by BFGK against estimates of [Fe/H] from Table 6 of Zinn and West (1984) (which gives [Fe/H] = 11.551 Mg_2 - 2.274). If Mould's calibration is correct then elliptical galaxies generally have weak metallicity gradients with [Fe/H] ~ -0.22 $\log(r/r_e)$.

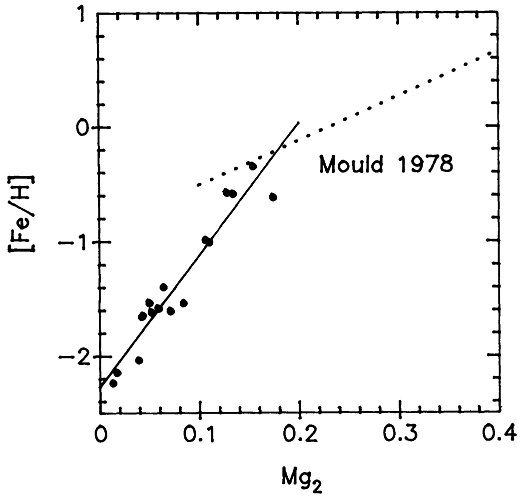

Figure 3. Mg values for galactic globular clusters (from BFGK) plotted against estimates of [Fe/H] from Zinn and West (1984). The solid line shows a least squares fit. The dotted line shows a calibration of the Mg_2 index at high metallicities for a 13 Gyr stellar population.

Gradients for three cD galaxies are presented in Figure 4. Our results show that these galaxies also possess modest Mg_2 gradients. The cD's all have shallower gradients than the mean given in equ. (1), but a larger sample is required to test whether this represents a systematic trend rather than a statistical fluctuation.

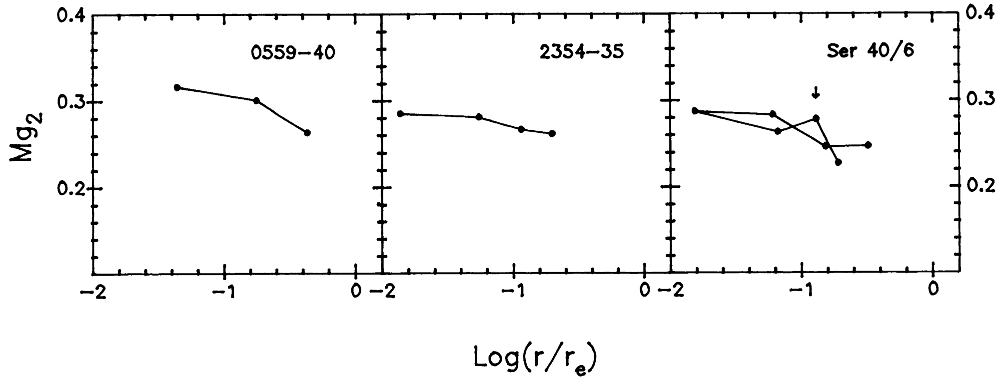

Figure 4. Major axis Mg_2 gradients in three cD galaxies. Sersic 40/6 is a dumbell galaxy and the position of the secondary nucleus is indicated by the arrow.

3. GRADIENTS IN OTHER FEATURES

For one galaxy, NGC 5813, we have particularly high signal-to-noise spectra extending out to large radii. We therefore present results for this galaxy separately in Figure 5 where we compare our line-strength estimates with those measured by BFGK for galactic globular clusters and for the nuclei of elliptical galaxies (see also Efstathiou and Gorgas 1985). This Figure shows that the line-strengths in the outer regions of NGC 5813 match continuously with those of metal rich galactic globular clusters. Notice that the Hβ index is nearly constant with radius outside the nuclear regions of the galaxy and thus the stellar population at large radii does not obey the same Mg_2-Hβ relationship as do the nuclei of elliptical galaxies. Previous studies of line-strength gradients have been based on changes in strong CN, Mg and Na features. Faber (1982) has stressed the importance of detecting changes in iron-peak features as a way of distinguishing between selective overenhancements in some elements and true abundance gradients. As Figure 5 shows, we do detect significant radial gradients in the iron features.

A similar comparison is shown in Figure 6 for elliptical galaxies from the sample of Davies et. al. (1983). The observational data for each of these galaxies are less extensive than for NGC 5813 so the line-strengths at large radii are less well determined. We have therefore averaged the results in the outer parts of each galaxy (typically between $0.5r_e$ to r_e). These points are plotted as the crosses in Figure 6. They have been connected to the nuclear line-strengths to give an impression of the gradients within each galaxy. These galaxies show similar trends to those found in NGC 5813.

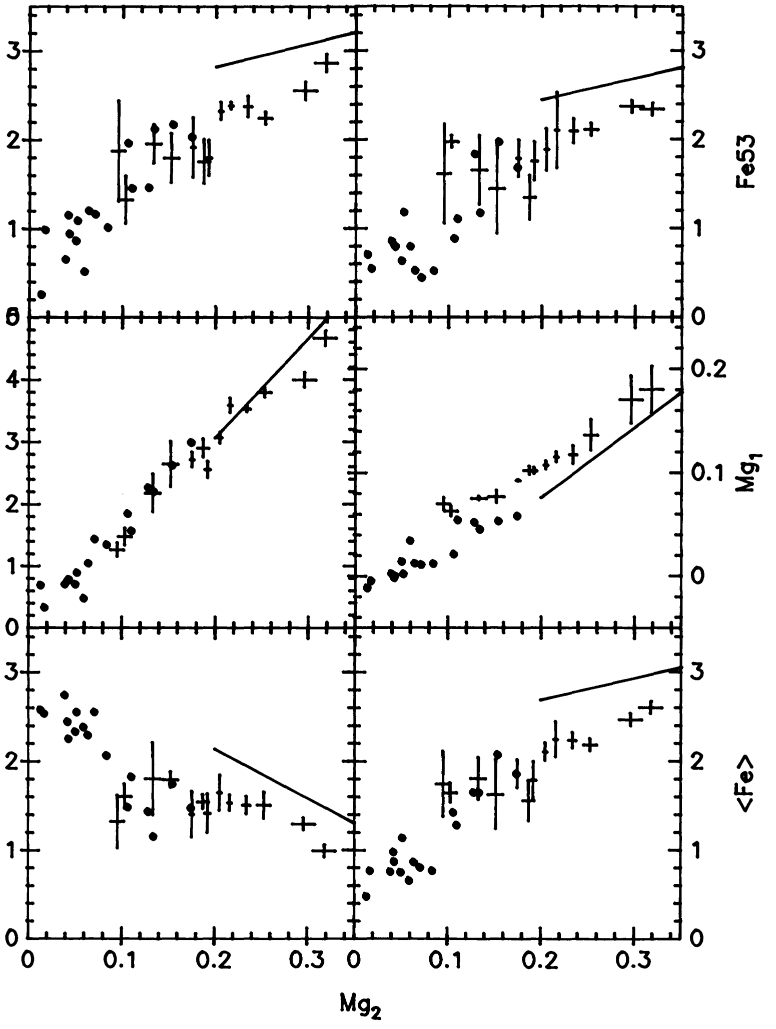

Figure 5. A comparison of the line-strengths in NGC 5813 (crosses) with those of galactic globular clusters (filled circles). The sizes of the crosses give estimates of 1σ random errors. We estimate that inaccuracies in sky subtraction could lead to systematic errors of up to 0.03-0.04 mag in Mg_2 for the outermost points. The solid lines show the mean relations deduced by BFGK for the nuclei of ellipticals.

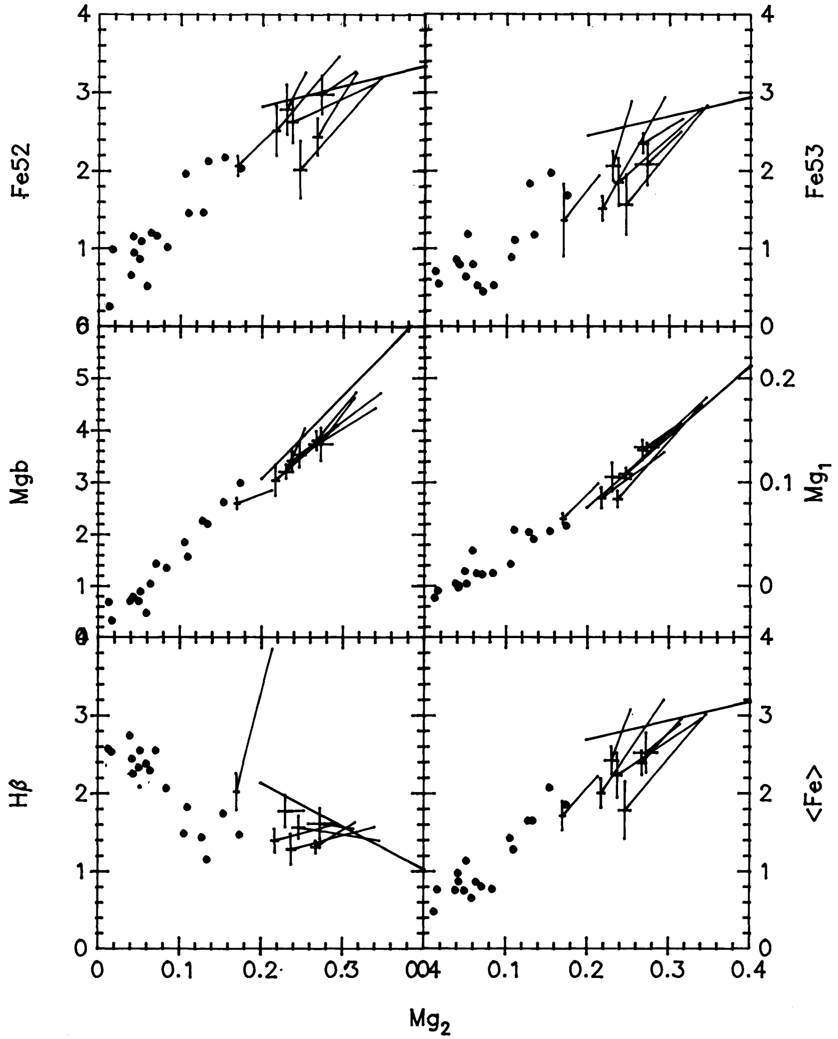

Figure 6. As for Figure 5 except we show our results for ellipticals from the sample of Davies et. al. (1983). The crosses show line-strengths in the outer parts of each galaxy (typically $0.5r_e$ - r_e). The crosses have been connected to the nuclear line-strengths by straight lines.

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Hβ in the outer parts of these galaxies is lower than would have been inferred from the relation obeyed by elliptical galaxy nuclei. In addition the iron features, particularly Fe53, show quite steep gradients.

A detailed interpretation of these results in terms of stellar population models is beyond the scope of this article. The deviations shown in Figures 5 and 6 from a one parameter relation for the stellar populations in elliptical galaxies, especially in the Hβ-Mg_2 relation, may be indicative of variations in both age and metallicity. This possibility is explored further in the discussion following Pickles' contribution to these proceedings.

4. CONCLUSIONS

Our results show that most early-type galaxies, including cD's, possess line-strength gradients within one effective radius but the indices do not generally attain values as low as those of metal rich galactic globular clusters. This, in turn, suggests that typical abundance gradients are quite weak. The relative line-strengths in the outer parts of ellipticals appear to obey a different set of relations when compared to the nuclei of elliptical galaxies indicating that these stellar populations do not represent a one parameter family.

We have addressed only a few of the points raised in the introduction. Much more work needs to be done and we anticipate that this will be forthcoming as CCD/spectrograph combinations become more readily available on large telescopes. We have emphasised the inter-relationships between line-strength gradients and the variations seen amongst stellar populations in the nuclei of elliptical galaxies. More detailed work along these lines may help determine whether these relations can be understood in terms of a combination of age and metallicity variations.

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DISCUSSION

White: Is it fair to say on the basis of your data that more than half of the stars in these relatively bright ellipticals (those outside r_e) have lower metallicities than the more metal-rich galactic globular clusters?

Efstathiou: We overlap with the metal-rich galactic globulars in one galaxy, NGC 5813, and here the inferred metallicity is about [Fe/H] $\sim$ -0.5 at $r \sim 1.5 - 2r_e$. The line-strengths for the rest of the galaxies in our sample are still larger than those of metal-rich galactic globulars at the outermost points that we have measured ($< r_e$). Data at larger radii are needed to fully answer your question. However, results on colour gradients, in particular recent work by Cohen, suggest that the halos of ellipticals are not extremely metal poor. I should add that we have checked the analysis of NGC 5813 and we do not think that errors in sky subtraction could eliminate the overlap with galactic globular clusters.

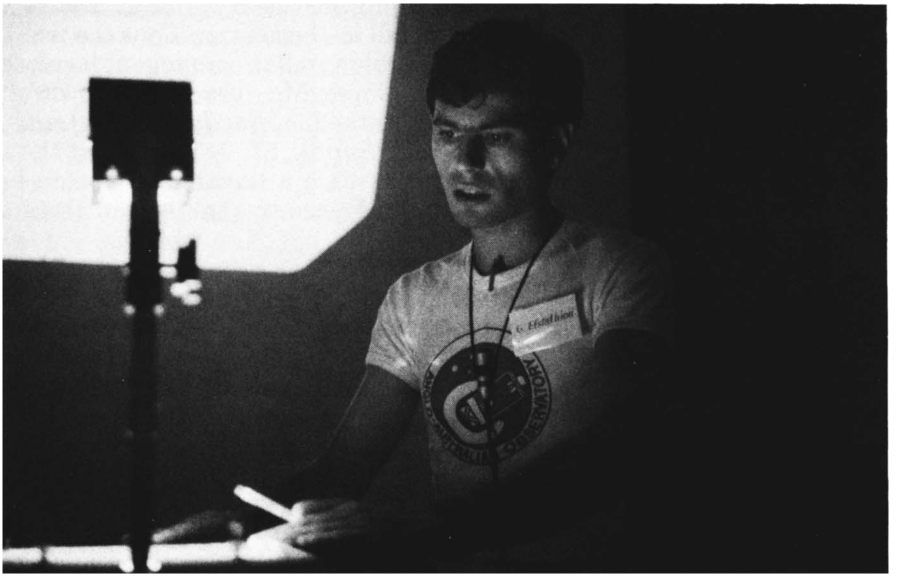
Davies: Sadler and I find weak emission filling in the $H\beta$ line in the centres of ellipticals, which causes the line–strength to fall in the centre. Thus the true central strength of $H\beta$ is stronger, and the need for a blue stellar component increased. We also find that the brighter galaxies have shallower Mg_2 gradients, however, given the work of Guinan and Smith (1984, *Publ. Astr. Soc. Pacific*, **96**, 354) and Faber, Friel, Burstein & Gaskell (1985, *Astrophys. J. Suppl.*, **57**, 711) showing the gravity sensitivity of this index, I see no reason to assume a linear relationship between Mg_2 and [Fe/H], especially as the gradients in Fe are so shallow and these are the only independent line–strengths measured.

Efstathiou: Let me take your points in turn: (i) your results on $H\beta$ are very interesting. We find that the $H\beta$ equivalent width falls in the very centre of NGC 5813 and the feature is essentially absent in the centre of the cD galaxy PKS2354–35, but in neither case can we tell whether this is caused by emission filling in the absorption feature (we find no evidence of [O III] emission lines. (ii) We do not find a statistically significant correlation between absolute magnitude and Mg_2 gradients. (iii) Our use of Mould's work is meant to be illustrative. A more extensive investigation between Mg_2 and metallicity would be worthwhile, though we have tried to stress the importance of looking at gradients in a variety of features. Our data do show substantial gradients in the Fe indices. In fact, the gradients in the two Fe blends are generally steeper than would have been inferred from the relations found for the nuclei of ellipticals.

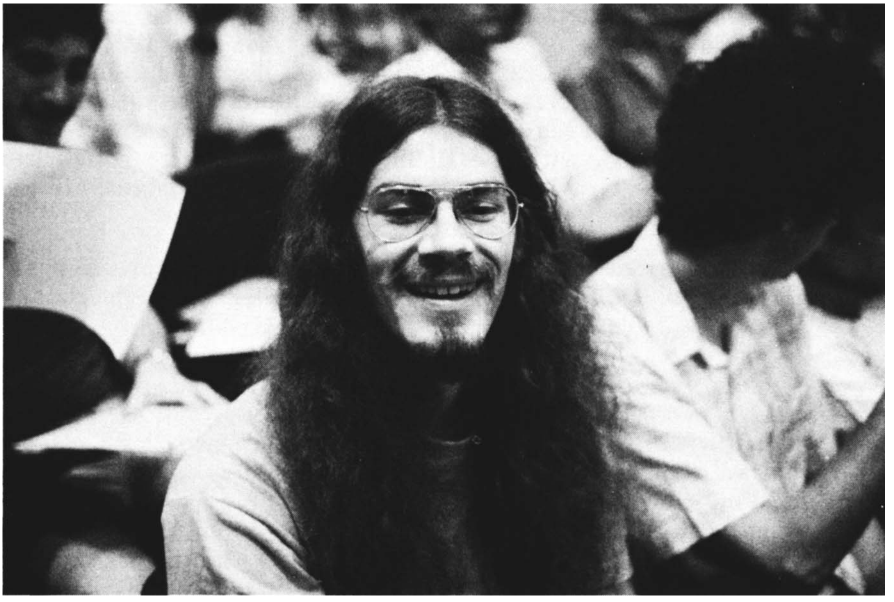
Peletier: Regarding the dust seen in the centre of NGC 5813 by, e.g., Jedrzejewski, how do you think dust affects the line–strength gradients?

Efstathiou: The sidebands span such a small wavelength range that I don't think there could be a significant effect.

Burstein: The correlation of Mg_2 with metallicity is still somewhat misunderstood. Although the Mg index does increase in strength with metallicity, the giant branch also becomes much redder and Mg_2 increases strongly with decreasing temperature. Much of the change of Mg_2 with [Fe/H] in integrated spectra comes from this temperature dependence. Gravity effects in Mg_2, while important, are less than these temperature effects.



George Efstathiou, with an advertisement for the AAT.



Josh Barnes took all the photos, except this one.

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