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GRADIENTS OF METAL LINE INDICES IN A SAMPLE OF EARLY TYPE GALAXIES

L.J. Danziger[1], C.M. Carollo[1], L. Buson[2], F. Matteucci[1,3], E. Brocato[4]

[1] European Southern Observatory
Karl-Schwarzschild-Str. 2
W-8046 Garching bei München, Germany

[2] Osservatorio Astronomico di Padova
Vicolo dell'Osservatorio 5 Padua Observatory
I-35100 Padova, Italy

[3] Istituto di Astrofisica Spaziale Frascati, Lab Astrofis. Spaziale
Consiglio Nazionale delle Ricerche
I-00044 Frascati, Italy

[4] Osservatorio Astronomico "V. Cerulli"
Collurania
I-64100 Teramo, Italy

Collurania Observatory

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Introduction

Observational attempts to define parameters which contain information pertinent to galaxy formation and chemical enrichment, have usually concentrated on the nuclear regions of early-type galaxies. This is most noticeable for chemical line indices and marginally less so for velocity dispersions and rotation curves. The number of galaxies for which the radial dependence of the above parameters extends to 0.5 R_e is small, albeit growing. The work described here is an attempt to use data for extended regions in galaxies generated for a sizeable sample in order to study statistically significant trends.

The Data

During the period 1985–87 the La Silla 3.6 m telescope equipped with the Boller and Chivens spectrograph was used to obtain long slit spectra of 42 early type galaxies, 24 of which are classified as ellipticals, 15 as SO, one as cD, and 2 as spirals which excludes them from further discussion. Since the spectra were taken for another different program, we generally obtained observations with the slit at two position angles north-south and east-west always passing through the nucleus with exposure times not exceeding 20 minutes. The resolution of these spectra lay in the range 7–8.5 Å. Spectra of a series of G and K giants were also taken to be used as templates, and the usual flux standards to ensure that all measurements were made on flux calibrated spectra. Special care was taken with sky subtraction to ensure we made measurements inside radii where a 10 percent change in the sky level caused not more than a 10 percent variation in the Mg_2 absorption line index.

Using the fourier quotient technique (Bertola *et al.* 1984) we have determined velocities and velocity dispersions as a function of radius of the galaxy. For several nights we lacked template spectra and used stellar spectra from other runs, sometimes corrected by gaussian convolution for a slightly different resolution. A comparison of results from spectra obtained in different runs showed that good agreement was always obtained for galaxies in common. In addition

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different templates gave similar results. Central velocity dispersions obtained by averaging all measurements inside the inner 5 arcseconds were in good agreement with those found by Davies *et al.* (1987).

We estimate that our velocity dispersions were measured with 10% uncertainty down to 150 km/sec, and with 20% uncertainty down to 100 km/sec.

Using the same spectral data we computed the following indices defined by Burstein *et al.* (1984) as a function of radial distance — Mg_2, Mg_1, $H\beta$, NaD, TiO, and TiO_2. In general, in order to treat data of comparable accuracy, we have summed spectra along the slit to keep formal errors within a given amount for all radial distances. All indices have been corrected for velocity dispersion by using the central velocity dispersion for each galaxy. The corrections were negligible for the molecular bands and reach 20 percent at $\sigma \sim 300$ km/s for both the $H\beta$ and NaD indices.

Radial logarithmic gradients for the velocity dispersions and the line indices have been computed using a linear least squares fit to all the data points. We stress here that for the present set of data these gradients apply on the average to regions of the galaxy in the range $0.2R_e \leq r \leq 1.5R_e$ with 75 percent grouping in the range 0.3 R_e - 1.5 R_e. Gradients computed for significantly smaller or larger radii may well be different because these indices are known to change at differing rates in many cases with radial distance. Clearly the linear fitting used here contains an assumption about radial dependence which may be abandoned when more extensive accurate data becomes available.

Results

From the kinematical data we have been able to detect possible signs of decoupled cores in 6 objects including IC 1459 (see Figure 1). Since we use only the gradient of Mg_2 in the following

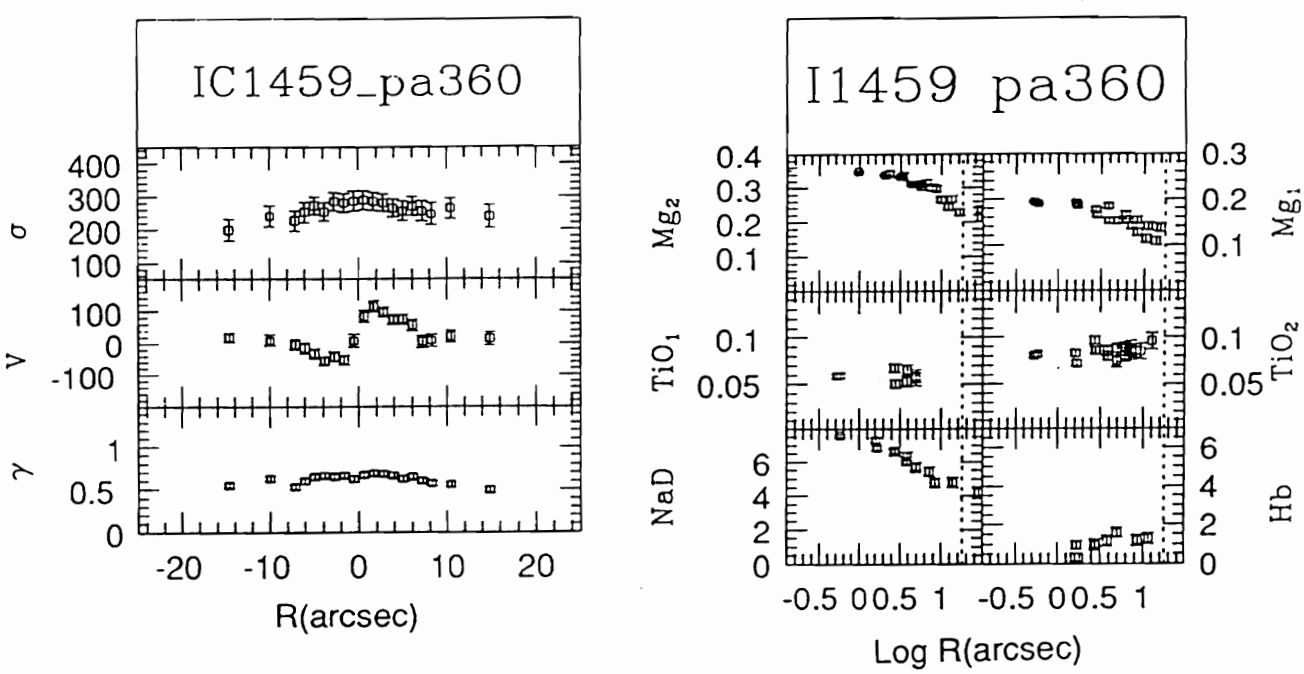

Fig. 1. The left hand side shows a plot of velocity dispersion σ, velocity v and line strength γ versus radius for IC 1459. The right hand side shows the line indices as a function of log R (radius) where the vertical dashed line marks the position of 1/2 R_e. Position angle is marked.

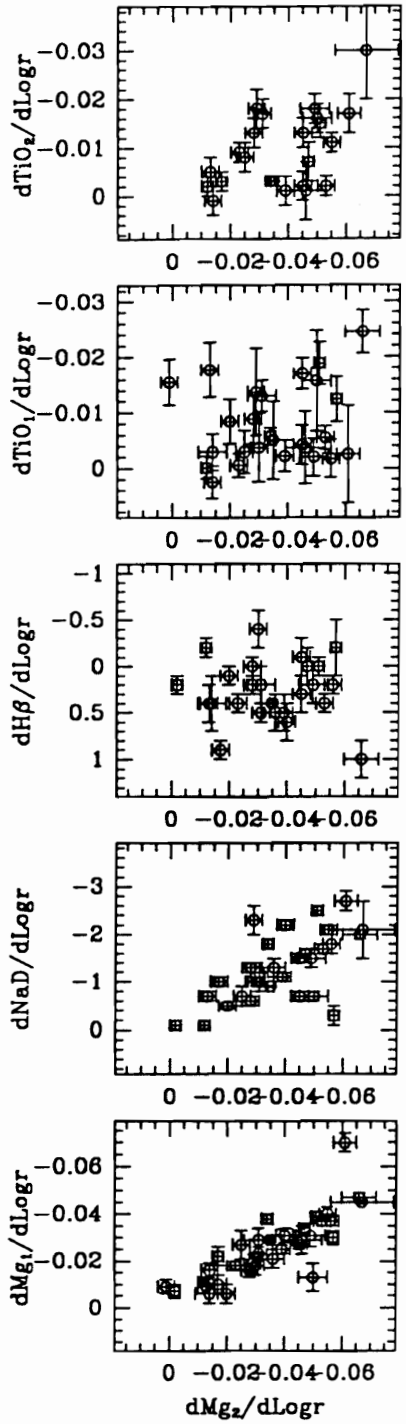

Fig. 2. Shows plots of the various gradients of line strengths versus the Mg_2 gradient.

analysis and interpretation it is worth noting beforehand how the gradients of the other indices mentioned above correlate with that of Mg_2. The results are summarized in Figure 2. To a high level of significance the gradients of Mg_1 and NaD correlate positively with that of Mg_2, and TiO_2 correlates weakly, while the gradients of $H\beta$ and TiO_1 show no significant correlation. While a correlation or lack thereof between these 3 indices and Mg_2 may have an astrophysical origin and consequence, any such relationship is obscured for technical reasons. In the case of the $H\beta$ index the bandwidths defining this index are narrow and therefore not well sampled in our spectra; in addition because of the nature of our sample, in many cases $H\beta$ emission may fill in the absorption. For TiO_1 and TiO_2 the absorption feature is so weak that our accuracy may not be adequate to the task.

Before discussing gradients we can assess the quality of our data by comparing it with published material. In Figure 3 we plot our nuclear values of Mg_2 versus published values for galaxies in common taken from Davies *et al.* (1987). Good global agreement is apparent with no evidence for systematic differences.

In Figure 4 we plot the nuclear values of Mg_2 versus the nuclear value of the velocity dispersion. Since both these parameters are related to the absolute luminosity of a galaxy a correlation is expected and observed. This agrees with the statement of Gorgas *et al.* (1990) and the result of Bender (1992) although over a more restricted range. Why this correlation obtains over the complete range of elliptical galaxy systems, if galaxies in different luminosity (and mass) ranges are formed by different mechanisms, is not straightforwardly obvious.

In Figure 5 we plot luminosity versus σ (the Faber Jackson relationship). We have not attempted to correlate residuals in this correlation versus residuals from other correlations because many of the galaxies in our sample have been incorporated into other studies with larger samples.

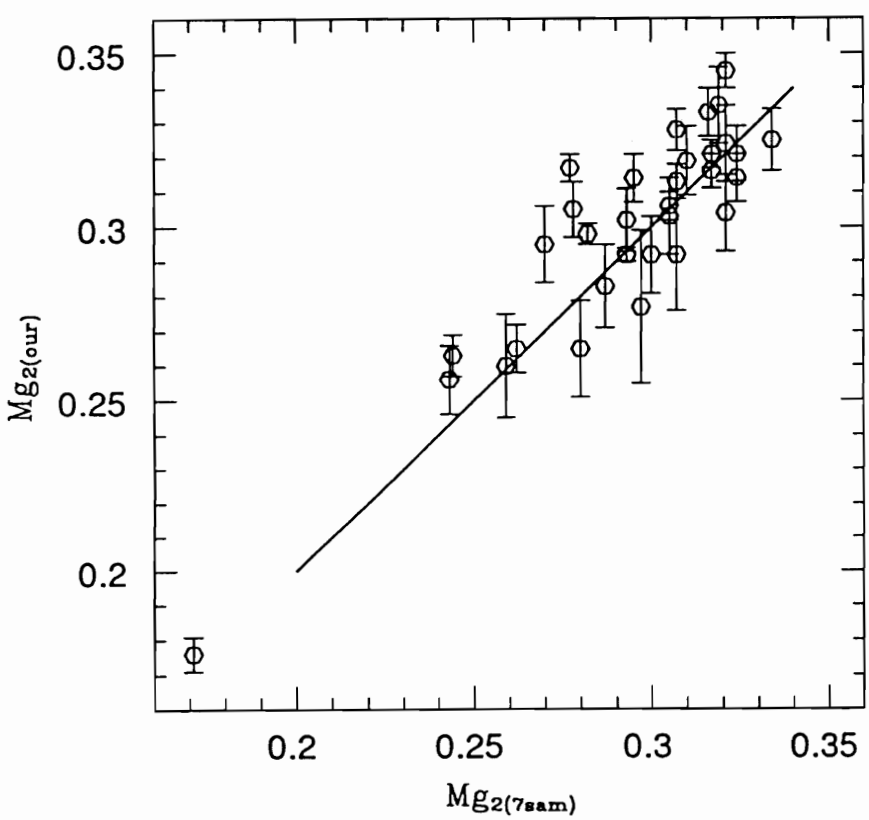

Fig. 3. Shows a plot of our central Mg_2 line strengths versus those of Davies *et al.* (1987) for galaxies in common.

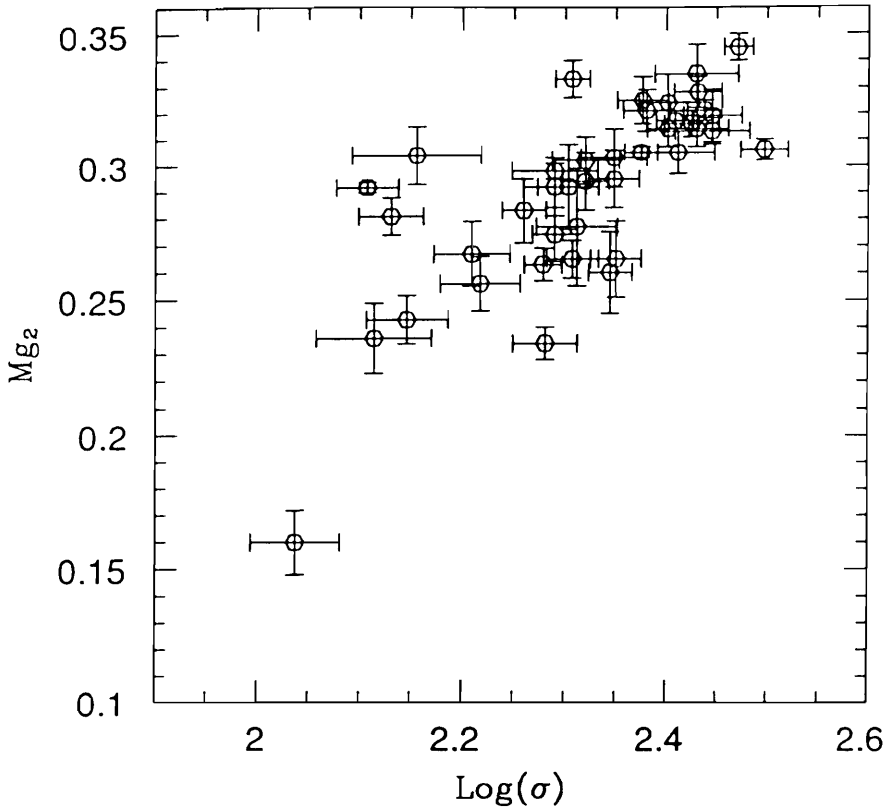

Fig. 4. Central Mg_2 line strength is plotted against central σ (velocity dispersion) using data from our sample.

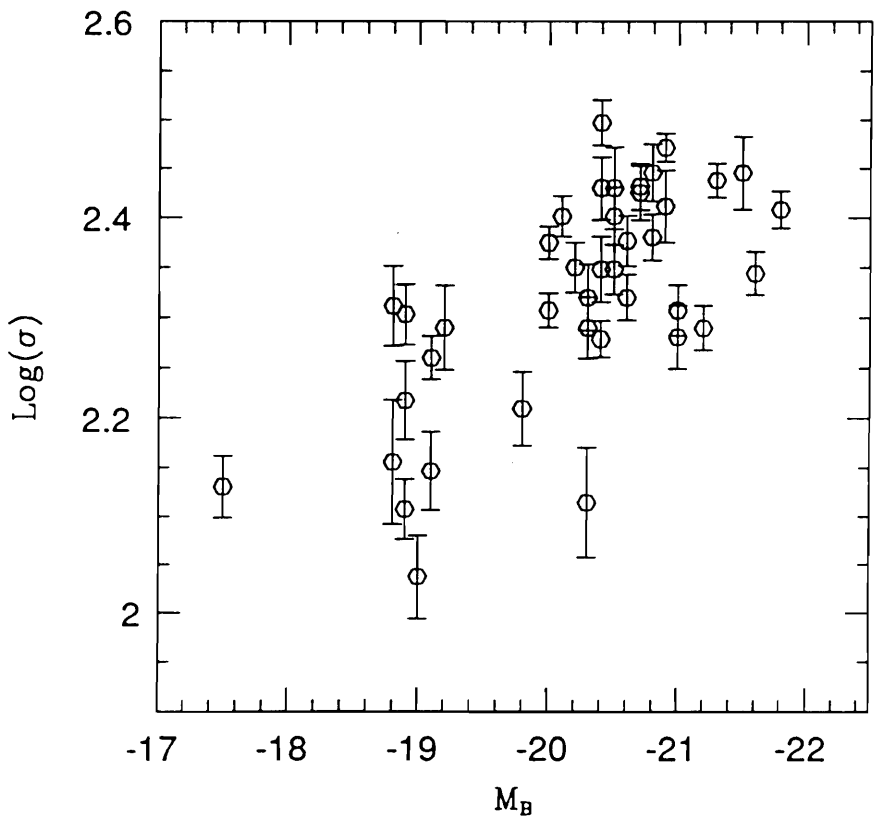

Fig. 5. Central σ is plotted against absolute B magnitude M_B using our data for our sample.

Before proceeding to discuss statistical relationships formed from the ensemble of data, it is worth looking at data for some individual galaxies. In Figure 1 the Mg_2 gradient for IC 1459 changes with radial distance as does the NaD gradient. Indeed there is a suggestion that a rapid change occurs at the point where the counter rotating core manifests itself (10 arcsec), in the manner pointed out by Bender (1992) for other systems with decoupled cores.

A comparison of Figure 1 with Figure 6 shows that in NGC 1052 which has almost no gradient in σ, while the radial trend of Mg_2 is similar to that in IC 1459, the gradient of NaD is much greater.

A comparison of Figure 6 with Figure 7 shows that both NGC 5846 and NGC 1052 have similarly flat σ curves. However in contrast to NGC 1052, NGC 5846 has a negligible gradient in Mg_2 and a very shallow gradient in NaD.

By making linear fits to determine gradients it is clear that we are losing details in the radial properties that may contain important clues for understanding galaxy formation and chemical evolution. The current data is not adequate for a more sophisticated analysis.

Having stressed the potential limitations in defining linear gradients, we note that there are 4 objects in our sample for which data exists over a radial distance $< 0.2\ R_e$. These have been excluded from the following analyses which use gradients. Gradients for a galaxy have been obtained by combining results from either side of the nucleus and different position angles when available. In fact there was in all galaxies good agreement between the individual values and the average.

We have found no effects on chemical gradients that distinguish galaxies with shells, dust lanes, emission lines, X-ray emission, or radio emission.

Any correlation of Mg_2 gradient with σ gradient is weak or non-existent.

In Figures 8 and 9 we show plots of the Mg_2 gradient versus maximum rotational velocity and ellipticity respectively. The available data is restricted in Figure 8 because we observed only a few of our objects on the major axis and these had to be supplemented with data from the literature. The presence of galaxies classified as lenticular in this plot certainly strengthens the correlation, as it does for a correlation between Mg_2 gradient and $V_{\rm rot}/\sigma$. This is probably true for the apparent correlation with ellipticity, where one should be aware that unknown projection effects complicate a ready interpretation.

There appears to be a significant correlation between the Mg_2 gradient and central values of Mg_2 and the velocity dispersion σ_0 but only for the lenticular or lower mass objects.

There appears to be some, though not large, correlation between the Mg_2 gradient and the B absolute magnitude of these galaxies. Separation into lenticular and elliptical types has an affect on this conclusion.

We have used the Jaffe (1983) density law under the assumption of spherical symmetry to compute the mass of all the galaxies. Using the isothermal sphere approximation our final expression for the mass is

$$M_{\rm total} = 3{\times}10^3 \sigma_0^2 D R_e\ M_\odot$$

where σ_0 is in km/s
D in Mpc
and R_e in arcseconds.

The plot of Mg_2 gradient versus $M_{\rm total}$ is shown in Figure 10. Once again there appears to be a positive correlation between these 2 quantities when the lenticular or lower mass objects are considered alone. When all objects are considered any suggestion of a correlation disappears. A negative correlation may be marginally present when only ellipticals are considered. A similar structure appears in a plot of Mg_2 gradient versus M/L ratio. This presumably is a reflection

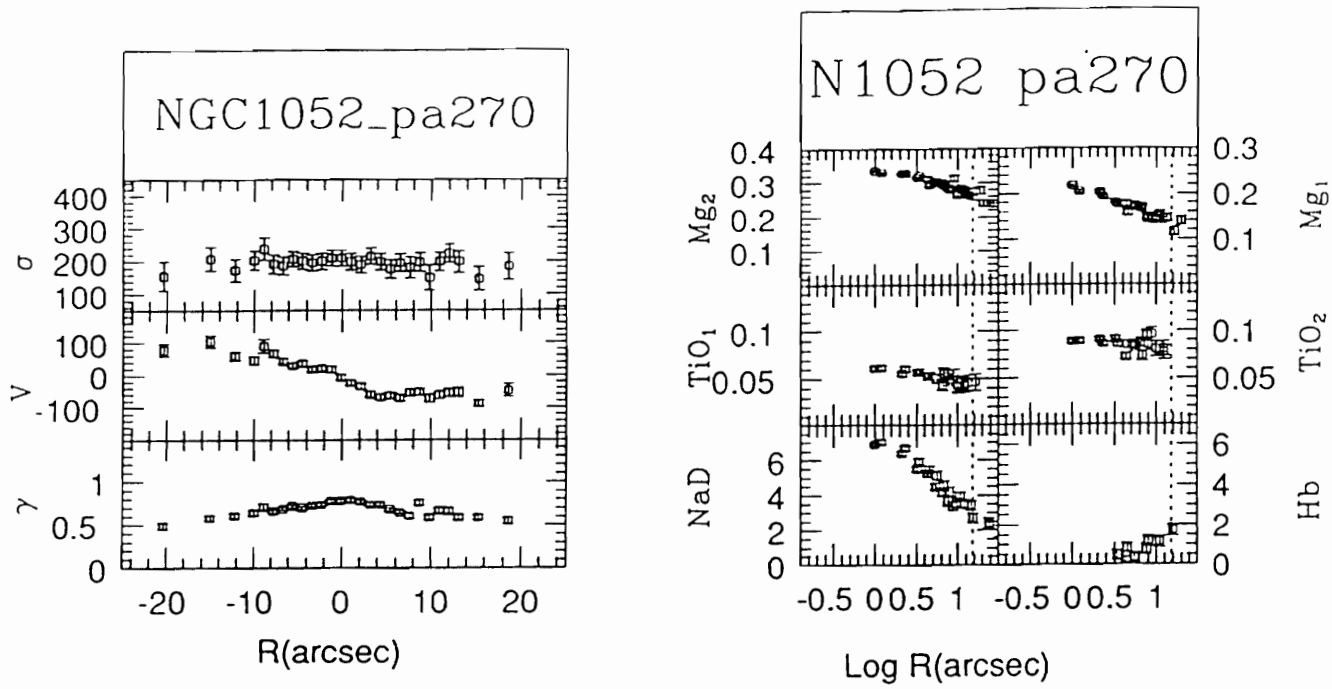

Fig. 6. Similar plots to those in Fig. 1 for NGC 1052.

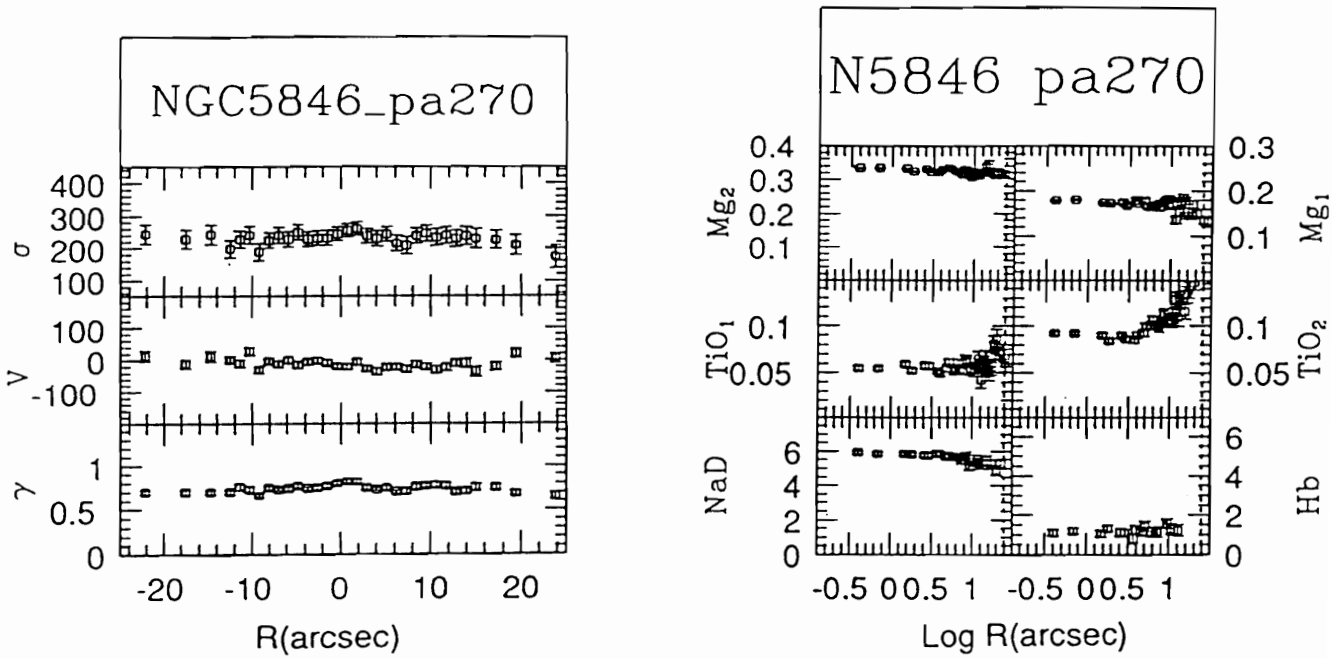

Fig. 7. Similar plots to those in Fig. 1 for NGC 5846.

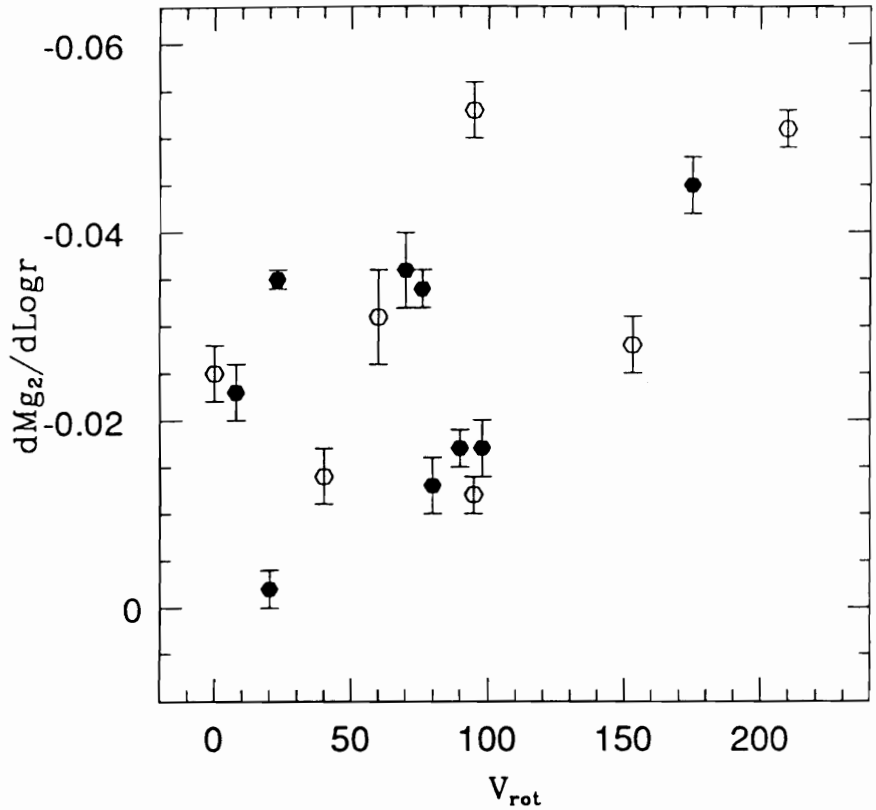

Fig. 8. A plot of the Mg_2 gradient versus maximum rotational velocity V_{rot}. Lenticulars are indicated by open circles in this and the following plots.

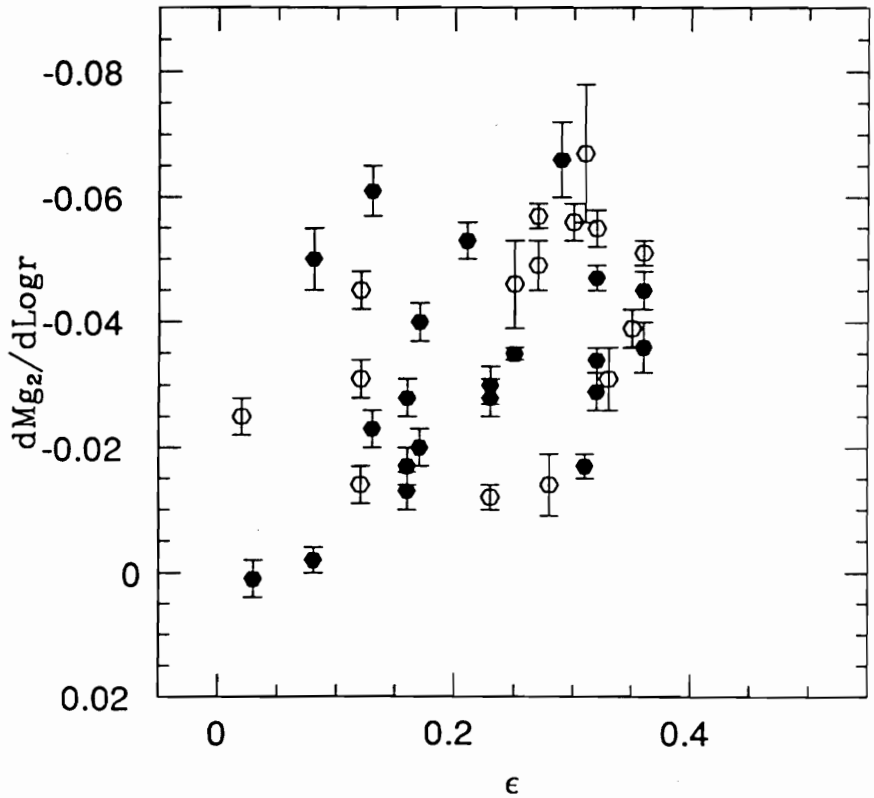

Fig. 9. A plot of the Mg_2 gradient versus ellipticity ϵ.

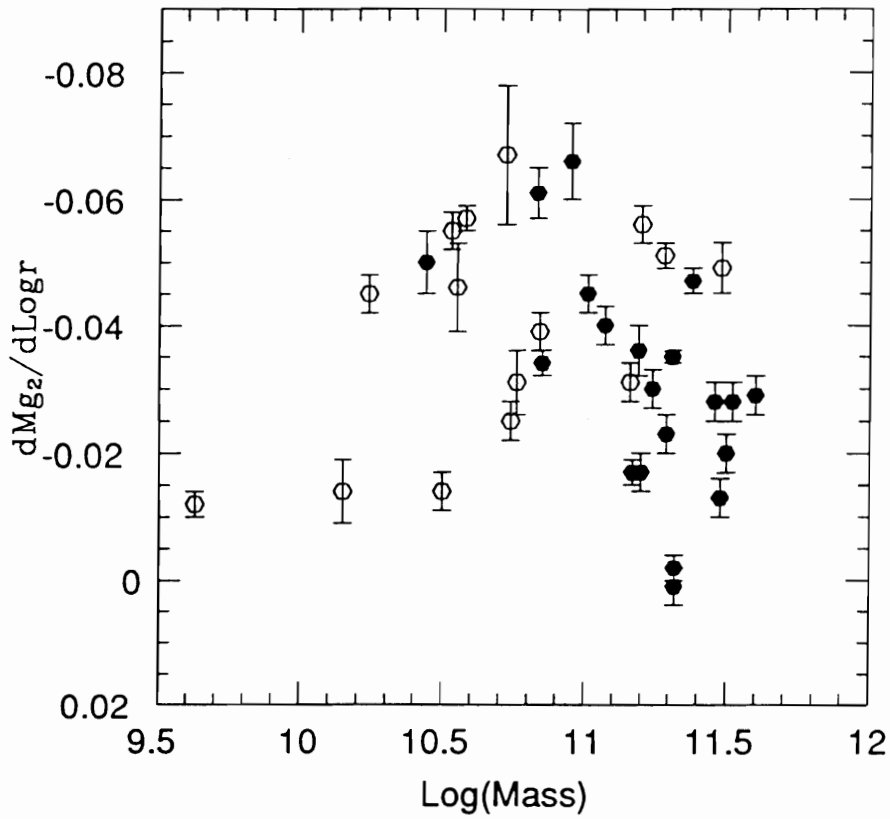

Fig. 10. A plot of the Mg_2 gradient versus the log (Mass). See text for details of the mass derivation.

of the pattern seen in Figure 10 because, as noted before, there was only a small apparent correlation of Mg_2 with absolute luminosity.

Discussion

We believe that it is premature to draw strong conclusions on the basis of the present data. This is because, as indicated earlier, we have been able to derive gradients only over a restricted range of radial distance, and that with only a linear fitting routine. Clearly there is much more structure in the radial variations of Mg_2 gradient (and σ gradient) to be elucidated with better data. For example we already know, because we now have better data extending to much larger radii for NGC 2663 (Carollo and Danziger 1992), that we would derive a significantly different (larger) gradient of Mg_2 by making a linear fit over this more extended distance. It is not yet clear what is an appropriate way to measure these gradients.

Nevertheless some qualitative conclusions may indicate future directions to go with better data. We have pointed out that in plots of Mg_2 gradient versus $V_{\rm rot}$, ellipticity e, $V_{\rm rot}/\sigma$, log Mass, central Mg_2, and central σ_0, there is always a correlation (albeit of varying degrees of confidence) for lenticular or lower mass objects, or a correlation is strengthened by their inclusion. This seems to be qualitatively consistent with a dissipative collapse model for galaxy formation first proposed by Larson (1974), and elaborated upon by Tinsley (1980), Carlberg (1984), Arimoto and Yoshii (1987), Matteucci and Tornambè (1987) and Brocato *et al.* (1990). A metallicity gradient is expected to form as a consequence of gas dissipation, and it should increase with increasing mass and luminosity due to the dependence of the time of onset of galactic winds on the mass of the galaxy. Also larger rotation and greater flattening would imply greater dissipation. However this would seem to apply only to galaxies in our data set with masses $\leq 10^{11}\ M_\odot$, a very approximate limit at this stage.

When we consider higher masses the situation is less clear — either no correlation or negative correlations exist. Could this be due to the fact that for galaxies of higher mass, the dominant mechanism of galaxy formation is due to merging? We note that Gorgas *et al.* (1990) pointed out that in their sample of galaxies, the cD galaxies appeared to have lower than average gradients of Mg_2. We also note that it is in this mass domain that Capaccioli *et al.* (1991) have noted a division in characteristics of galaxies in the surface-brightness versus effective radius R_e plane. One might wonder whether the 2 observed effects stem from a common origin. Clearly an unambiguous classification of galaxies into lenticular or elliptical may be fundamental to our understanding. Ambiguity probably still exists in our sample.

Merging of spirals to form ellipticals can result in a lessening of gradients seen in the original galaxies (White 1980). This type of modelling is still undeveloped and spiral-spiral merging is not accepted universally as a viable mechanism of E galaxy formation. In addition, as mentioned previously, the continuity seen in the tight sequence observed in the Mg_2 versus log σ_0 plane is not obviously explained if 2 different mechanisms of galaxy formation dominate in different domains of mass.

One way forward observationally is to obtain gradients of Mg_2 at much larger radii. This should also be combined with good quality colour data, because there is a hint from the work of Peletier *et al.* (1990) that the structure observed by us in the Mg_2 gradient versus log M diagram is seen in their diagram of (U–R) gradient versus M_B. It may also exist in the plots of (B–R) gradient versus M_B presented by Kormendy and Djorgovski (1989). Since it is known that Mg is created mostly in intermediate mass stars and Fe mostly in low mass stars, one should attempt to gather information not only on elements such as Mg but on elements such as Fe, in order to unravel how chemical evolution proceeded with galaxy evolution. We mentioned earlier that in our data we see apparently quite different behaviour for NaD (and probably TiO) relative to Mg_2. Unexpected differences are already beginning to emerge in the behaviour of Fe relative to Mg_2 as shown by the work of Worthey *et al.* (1992) and Carollo and Danziger (1992).

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