The Correlation of Metallicity Gradient with Galaxy Mass

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ABSTRACT

A number of previous studies have searched for a correlation between radial metallicity gradients and early-type galaxy mass – no convincing trends have been found. Here we re-examine this issue with several key enhancements: using total metallicity from studies that have broken the age-metallicity degeneracy, excluding galaxies with young stellar ages (i.e. those that have experienced a recent central starburst) and using the K-band to derive galaxy luminosities. We find that Coma cluster galaxies have metallicity gradients which correlate with galaxy mass. Furthermore, gradients have values similar to those of monolithic collapse models. The combination of dissipative formation and energy injection from supernova provides a mechanism for the trends with galaxy mass, however other explanations are possible. Additional high quality observational data is needed to further constrain the gas physics involved in galaxy formation.

Key words: galaxies: abundances; galaxies: clusters: individual: Coma; galaxies: elliptical and lenticular; galaxies: formation; galaxies: structure

1 INTRODUCTION

The nature of galaxy formation is one of the key questions in contemporary astrophysics. Within the Cold Dark Matter (CDM) paradigm (Blumenthal et al. 1984), two main scenarios for galaxy formation have been recognised. They are monolithic collapse at early epochs and hierarchical merging which can continue to later epochs.

A robust outcome of these early collapse models was the presence of radial metallicity gradients (Larson 1974; Carlberg 1984a,b). During the collapse, stars form from gas that is chemically-enriched as it flows towards the centre of the potential well, thus establishing a negative radial gradient in which the central stars are more metal-rich than those in the outer regions. Carlberg (1984b) showed that the injection of energy associated with galactic winds (from stellar mass loss or supernova) ultimately provides a pressure which drives the gas from the galaxy. The resultant metallicity gradients of ~0.5 dex per dex in the high mass galaxies, compared to low mass galaxies with almost zero gradient, is a result of deeper potential wells retaining more metals. More recent chemodynamical models, which include metallicity-dependent cooling and supernova feedback, also predict stronger metallicity gradients in more massive galaxies (Kobayashi 2004; Kawata & Gilson 2003; Chiosi & Carraro 2002; Kawata 1999, 1999; Bekki & Shioya 1999). Radial gradients in colour (Franx & Illingworth 1990), line indices (Carollo & Danziger 1994) and total metallicity (Mehlert et al. 2003; hereafter M03) have been shown to correlate with the local escape velocity or gradients in velocity dispersion. This has lead to a different interpretation of metallicity gradients by Martinelli et al. (1998) in which gradients are established by the onset of a galactic wind, which varies with the local depth of the potential well.

The formation of elliptical galaxies by a major merger also predicts metallicity gradients, however those gradients are expected to be significantly shallower than mentioned above, particularly for massive galaxies (e.g. White 1980; Barnes 1996; Bekki & Shioya 1999). Thus observations of radial metallicity gradients may offer a way of distinguishing between competing galaxy formation scenarios.

Several observational studies have examined metallicity gradients as a function of galaxy mass. Most previous work has focused on using colour (e.g. Peletier et al. 1990) or raw absorption line indices (e.g. Carollo et al. 1993; Davies et al. 1993; Fisher, Franz & Illingworth 1995) as a proxy for total metallicity. Carollo et al. (1993) claimed that a trend was present for low mass galaxies, but that gradients did not change with galaxy mass for the highest mass systems. From a literature compilation of 80 early-type galaxies, Kobayashi & Arimoto (1999) derived metallicity gradients from absorption line indices finding a typical gradient of ~0.3 dex per dex with an rms dispersion of about 0.15. They found no convincing trend of metallicity gradient with galaxy mass.

Both colour and raw line indices are affected by the age-metallicity degeneracy. So, in a given galaxy, they trace
some (unknown) combination of age and metallicity. In order to disintangle these effects, and hence break the age-metallicity degeneracy one requires a method such as the use of Lick line indices and single stellar population models (e.g. Proctor 2002; M03; Sánchez-Blázquez 2004; hereafter SB04) to derive independent metallicity and age gradients. (An alternative approach to break the degeneracy is to examine galaxies at higher redshift, e.g. Tamura et al. 2000.) In his thesis, Proctor (2002) found no obvious trend with velocity dispersion. M03 did not find any “significant evidence for correlations” between total metallicity gradient and galaxy mass in their study of 35 Coma galaxies. In her thesis, SB04 found a weak trend with velocity dispersion for Coma cluster galaxies but only when using the combination of Hβ and Fe4383 lines.

As measured gradients are luminosity-weighted and the central galaxy regions will be the focus of any merger-induced starburst (Hernquist & Barnes 1992), we would expect metallicity gradients to be artificially enhanced in the first few Gyrs following a central starburst. One example of this might be the field elliptical NGC 821. It has a central luminosity-weighted age of \( \sim 4 \) Gyrs indicating new star formation took place a few Gyrs ago, presumably induced by the accretion of gas into the galaxy central regions. It has a very steep metallicity gradient of \( \sim -0.8 \) dex per dex (Proctor et al. 2005). Thus previous observational studies which included galaxies with young central stellar populations (i.e. those that may have experienced a recent merger-induced central starburst), may therefore have introduced some scatter into any gradient versus mass correlation.

Here we revisit the important issue of early-type galaxy metallicity gradients. We use metallicity gradients derived from single stellar population models which break the age-metallicity degeneracy. We also exclude galaxies with measured young central ages, and use the K-band to derive galaxy luminosities. With these enhancements we find statistically significant correlations of metallicity gradients with galaxy mass for Coma cluster early-type galaxies.

2 RECENT MODEL PREDICTIONS

Kawata (1999) simulated the formation of a slowly rotating elliptical galaxy modelling the gas, stars and dark matter in a CDM cosmology. He followed the collapse of gas in a over-dense sphere from high redshift to \( z = 0 \). Star formation was essentially complete in the first 4 Gyrs (by \( z \approx 3 \)). Kawata & Gibson (2003) built on this work to simulate elliptical galaxies of three different masses (i.e. 40, 8 and \( 2 \times 10^{11} \) M⊙). They found steeper metallicity gradients in higher mass galaxies, which was due to the mass dependence of energy feedback from supernovae.

Chiosi & Carraro (2002) used a similar model which included supernova feedback to describe “...the monolithic collapse of gas inside non-rotating, viralized haloes of dark matter...”. Their galaxy assembly was largely complete by \( z = 2 \). They simulated high and low initial density galaxies over a range of total masses from \( 10^9 \) to \( 10^{13} \) M⊙. They also showed that the resulting metallicity gradients were stronger with increasing galaxy mass.

Recently, Kobayashi (2004) simulated the formation of elliptical galaxies in a CDM cosmology, focusing on internal metallicity gradients. Her models ranged from the assembly of tens of gas-rich subunits at high redshift (which she denoted as monolithic collapse) to the merger of equal mass gas-poor galaxies at low redshift (called major mergers). She found that galaxies of a given mass had steep metallicity gradients if formed by collapse and shallower gradients (after a few Gyrs had elapsed) if formed by a major merger. Thus variations in the formation history of galaxies will tend to cause scatter in any correlation of gradient with galaxy mass.

The galactic wind model of Martinelli et al. (1998) predicts stronger metallicity gradients in galaxies with larger internal velocities and hence galaxy mass. Quantitative gradient predictions, with galaxy mass, are not given in their paper.

A gaseous merger model was presented by Bekki & Shioya (1999). In their simulations, two gas-rich disk galaxies of varying mass collide to form an elliptical galaxy remnant. The gas and stellar masses were set equal so as to simulate mergers at high redshift. An additional key feature was the inclusion of supernova feedback. They examined the metallicity gradients in old merger remnants and found depend only weakly on the remnant galaxy mass.

3 OBSERVATIONAL DATA

We now turn to observations of early-type galaxies in the Coma cluster for which radial total metallicity gradients have been derived from single stellar population models. The samples we use are from M03 and SB04.

M03 used the Lick absorption lines (Worthey 1994) of Hβ, Mgb, Fe5270 and Fe5335 and the single stellar population models of Thomas, Maraston & Bender (2003) to derive metallicity gradients for early-type Coma galaxies. We take the central velocity dispersions and effective radii for this sample from Mehlert et al. (2000). The spectra of SB04 cover a large range of Lick lines. They derived metallicity gradients by fitting all available Lick indices with the single stellar population models of Vazdekis (1999). We also take central velocity dispersions and effective radii from the work of SB04.

For both samples total K-band apparent magnitudes come from the 2MASS survey, and we calculate absolute magnitudes assuming a distance modulus to Coma of 35.0. We have not corrected the magnitudes for Galactic extinction. This would have the effect of making each galaxy brighter by \( <0.01^m \) (Schlegel et al. 1998). We note that the K-band light traces the underlying mass better, and suffers less from extinction, than any optical passband.

Six of the Coma galaxies are in common between the two studies. We find a mean offset between the gradients of M03 and SB04 for these six galaxies of 0.25 ± 0.09 dex per dex. As the typical gradient in the SB04 study (–0.31) is similar to the average gradient (–0.30) in the compilation of Kobayashi & Arimoto (1999), we elected to subtract 0.25 from the values quoted by M03. We have implicitly assumed that a simple offset between the two studies is appropriate (with more data, a more sophisticated analysis could be carried out). Figure 1 shows the adjusted M03 gradients compared to the SB04 ones.

Next we exclude galaxies with central ages younger than
6 Gyrs from the metallicity gradient analysis. As mentioned earlier, such young galaxies are prime candidates for a recent gaseous merger which tends to make luminosity-weighted metallicity gradients initially much stronger.

We show the metallicity gradients for the 22 M03 and 13 SB04 Coma galaxies with ages \( \geq 6 \) Gyrs (our results reported below do not depend strongly on the exact age limit applied) against various proxies for galaxy mass in Figure 2. Each panel shows a different measure of galaxy mass, i.e. absolute K-band magnitude, central velocity dispersion and the \( \kappa_1 \) mass parameter (defined by Bender, Burstein & Faber 1992 as \( \kappa_1 = (2\log\sigma_o + \log r_e)/\sqrt{2} \)). Included are the collapse models of Kawata (1999, 2004) and the high mass model of Chiosi & Carraro (2002). We also show the predicted gradients for two merger remnant ellipticals several Gyrs after the merger event, from the simulations of Bekki & Shioya (1999). The models have been transformed from the B-band to the K-band assuming B–K = 4 as appropriate for old stellar populations.

The upper panels show the data of M03 (after applying the systematic offset mentioned above), the middle panels shows the data of SB04 and the lower panel the simple com-

**Figure 1.** Comparison of the metallicity gradients. The plot shows the gradients from Mehlert et al. (2003; M03), after an offset of 0.25 dex per dex has been applied, against the gradients measured by Sánchez-Blázquez (2004; SB04) for the six Coma cluster galaxies in common.
Figure 2. Metallicity gradients with galaxy mass for Coma galaxies. Each panel shows the metallicity gradient and a measure of galaxy mass using the data for old (age ≥ 6 Gyrs) early-type Coma cluster galaxies from Mehlert et al. (2003; M03) in the upper panels and from Sánchez-Blázquez (2004; SB04) in the middle panels. The lower panels show the combined data sets. Also shown are the three mass models from the dissipative collapse models of Kawata (2004) as open squares, the high mass collapse model of Chiosi & Carraro (2002) as an open circle, and the merger remnants of Bekki & Shioya (1999) as open triangles. The percentage shown is the probability of a correlation from the non-parametric Spearman rank test. Stronger gradients are generally present in higher mass galaxies.

We have tested the probability of a correlation between the metallicity gradient and the measures of galaxy mass in Figure 2 using a Spearman non-parametric rank test. We find that the metallicity gradient is correlated with the following probabilities: \( M_K \) (96%), \( \log \sigma \) (96%) and \( \kappa_1 \) (96%). Thus the exclusion of the young Coma galaxies from the M03 sample reveals correlations (at the 96% significance level) with mass which were not found in the full sample by M03.

For the SB04 data, the Spearman rank test gives correlation probabilities of: \( M_K \) (99%), \( \log \sigma \) (94%) and \( \kappa_1 \) (99%).

For the combined sample of 35 galaxies, the Spearman probabilities are all improved to: \( M_K \) (99.6%), \( \log \sigma \) (99%) and \( \kappa_1 \) (99.4%).

We note that the non-parametric Spearman rank test does not take into account the errors of the data points. To address this point, we performed 1000 Monte Carlo realizations of the data sample in which each point was perturbed randomly with a Gaussian distribution of width given by the errors. We ran the Spearman rank order test on each of the 1000 mock data samples and calculated the mode, i.e., the most probable value, of the distribution of probabilities. These tests reveal that the probability of a correlation is 99% or greater for all data sample-mass combinations (the only exception being the \( \log \sigma \) correlation for the SB04 sample, with 97% probability). This indicates that the claimed correlations are real and not due simply to errors in the data. An additional set of Monte Carlo simulations has shown that the results for the combined sample is not strongly dependent on the offset applied to the M03 data.

Thus we find strong statistical evidence for a correlation between galaxy metallicity gradients and galaxy mass. We also point out that the correlation is present with galaxy mass parameters that are measured completely independently of each other (e.g. luminosity and the \( \kappa_1 \) parameter). This further strengthens the case for a causal relationship.

The data scatter fairly evenly about the predictions from the dissipative collapse model of Kawata (1999, 2004),...
and are generally stronger (more negative) than the merger model predictions of Bekki & Shioya (1999).

4 DISCUSSION AND CONCLUSIONS

Using gradients derived from stellar population models (rather than simply colours or raw index measures) and by excluding young galaxies (i.e. allowing luminosity-weighted gradients to stabilise) we revisit the issue of radial metallicity gradients in early-type galaxies.

Our main result is that metallicity gradients for Coma cluster galaxies correlate with galaxy mass; with a statistical significance of >99% for the K-band luminosity, 99% for velocity dispersion and >99% for the κ1 mass parameter. In general, lower mass galaxies have shallower gradients. Such a trend is consistent with monolithic collapse models (Chiosi & Carraro 2002; Kawata 1999, 2004) which invoke gas dissipation and energy ejection (e.g. from supernova). It is also qualitatively consistent with the galactic wind models of Martinelli et al. (1998). The data of SB04, and M03 (after a systematic offset has been applied), have typical gradients that are more consistent with the monolithic collapse formation models than the gaseous merger model of Bekki & Shioya (1999). This suggests that the dominant formation mechanism for old, early-type Coma galaxies is one of monolithic collapse.

To confirm the reported mass trend and further constraint galaxy formation models, higher signal-to-noise spectra, which probe to large galactocentric radii, should be obtained. Also, samples of low luminosity (M_K ~ -22, M_B ~ -18, σ ~ 100 km/s) early-type galaxies at the same distance (e.g. within a nearby cluster) will be particularly useful to better define the metallicity gradient–mass correlation.

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