A CONSTRAINT ON THE FORMATION OF DWARF ELLIPTICAL GALAXIES IN THE DENSE COMA CLUSTER CORE

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Received 1996 June 14; accepted 1996 July 16

ABSTRACT

Deep CCD photometry and positions for a new sample of ~250 dwarf elliptical (dE) galaxies in the Coma cluster core are analyzed. A significant color gradient is detected in their projected radial distribution, given by \( \Delta(B-R)/\Delta(\log R_e) = -0.08 \pm 0.02 \) mag. Calibrating these dE galaxies against Galactic globular clusters yields a corresponding metallicity gradient which goes as \( Z \propto R_e^{-0.29} \). Simulations reveal that this gradient in the projected radial distribution corresponds to a true (three-dimensional) radial color gradient which goes as \( \Delta(B-R)/\Delta(\log r) \approx -0.20 \) mag, or \( Z \propto r^{-0.69} \) over the same radial range. If this radial gradient is a primordial one, it is consistent with a model in which the intracluster gas exerted a significant confinement pressure, impeding the outflow of supernovae-driven metal-rich gas from the young dE galaxies.

Subject headings: galaxies: clusters: individual (Coma) — galaxies: dwarf: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Early-type dwarf-elliptical (dE) galaxies are a class of diffuse, low-luminosity, low surface brightness galaxies with luminosities in the range \( -18 \lesssim M_B \lesssim -8 \) mag, and colors typically near \( (B-R) \approx 1.4 \) mag. They are characterized by smooth surface brightness profiles, and the nonnucleated dE galaxies are well described by a single exponential or a modified-exponential profile (e.g., Ichikawa, Wakamatsu, & Okamura 1986; Ferguson & Binggeli 1994; Cellone, Forte, & Geisler 1994). Color gradients are observed in some dE galaxies, yet there does not appear to be any preference for red or blue color gradients (Caldwell & Bothun 1987; Vager et al. 1988; Cellone et al. 1994; Durrell 1996). Dwarf elliptical galaxies appear to be dominated by extensive dark matter halos, with a mass-to-light ratio that varies as \( M/L \propto L^{-0.4} \) (Ferguson & Binggeli 1994), consistent with the models of Dekel & Silk (1986). With a typical mass on the order of \( 10^8 \) \( M_{\odot} \), dE galaxies may be the evolved state of primeval protogalactic fragments, the first self-gravitating systems formed in a CDM cosmology (e.g., Searle & Zinn 1978; Larson 1985). While the formation of dE galaxies is not completely understood, the review by Ferguson & Binggeli (1994) provides an excellent overview of this field.

In a recent simulation, Moore et al. (1996) illustrated that a large fraction of a cluster's dE galaxy population can arise as remnants of late-type galaxies, which are harrassed as they infall to the cluster. In these simulations, the primary infalling galaxy is tidally disrupted and stripped by the mean cluster field and by encounters with individual cluster galaxies. The result is one primary dE galaxy (corresponding to the remnant core of the late-type galaxy), with the possibility that additional bound stellar systems (presumably dwarf galaxies) can form in the tidally stripped galaxy debris. In comparison, traditional formation scenarios relevant to dE galaxies in a cluster environment assume that they are primeval and attribute their observed characteristics to an interdependence between external and internal factors. For a dense environment such as the Coma cluster, the dominant external factors would include: a confinement pressure exerted by the intracluster medium, ram-pressure stripping of galactic gas due to motions through the intergalactic medium, and tidal destruction of low-mass dE galaxies in the dense cluster core. The internal factors relevant to dE galaxy formation include extensive dark matter halos and an expulsion of residual gas via supernovae-driven winds (e.g., Wyse & Silk 1985; Dekel & Silk 1986; Silk, Wyse, & Shields 1987, hereafter SWS87; Babul & Rees 1992, hereafter BR92; Marlowe et al. 1995; Babul & Ferguson 1996). The combined result is expected to be a single major star formation epoch, a stellar population similar in age and integrated light to globular clusters, with a galaxy mass and metallicity dependent upon location with respect to the cluster center.

The Coma cluster (e.g., Thompson & Gregory 1993; Colless & Dunn 1996) is the nearest of the very rich Abell clusters (\( cz \approx 7200 \) km s \(^{-1} \), Abell richness class 2), and the core of this dense environment provides an excellent location in which to study the properties of dE galaxies. An analysis of the photometric colors of dE galaxies can provide valuable insights into the properties of individual galaxies, and can also reveal statistical correlations for populations of galaxies (Caldwell & Bothun 1987; Evans, Davies, & Phillipps 1990; Garilli et al. 1992; Cellone et al. 1994). In this Letter, the distribution of \( (B-R) \) color for individual dE galaxies is analyzed as a function of their clustercentric radius, and a significant radial gradient in this color is detected. This new finding is then discussed in the context of dE galaxy formation and evolution in a gas-rich, ultradense environment such as the Coma cluster.

2. ANALYSIS

The data sample used here is a subset of the full data sample presented in Secker (1995; 1996) and Secker & Harris (1996, hereafter SH96). Briefly, a 700 arcmin\(^2\) region of the Coma cluster core was mosaic-imaged in two colors \( (R, B) \) with the KPNO 4 m, in 1.7'1-1.7'3 seeing. The three cluster fields considered here together span a range in
clustercentric radius of \( 1.33 \leq R_{cc} \leq 23.33 \), with \( 1' \approx 20.9 h^{-1} \) kpc. \( R \)-band magnitudes were derived with Kron’s \( 2r_1 \) aperture (e.g., Bershady et al. 1994) and corrected to true total magnitudes with simulations (Secker 1995, 1996). Constant aperture magnitudes (\( r_{ap} \approx 0.56 h^{-1} \) kpc) were used to calculate accurate \( (B-R) \) colors, prior to which the seeing was matched between the corresponding \( R \) and \( B \) images. Our cluster membership is based upon the object’s \( (B-R) \) color: the dE galaxy population is clearly evident on a \( R \), \( (B-R) \) color-magnitude diagram as a narrow sequence not present on the control field (SH96). As illustrated by Biviano et al. (1995) and SH96, this technique enormously reduces contamination due to background galaxies. In this Letter, I restrict the analysis to objects in the dE color range \( 1.05 \leq (B-R) \leq 1.6 \) mag, while in magnitude, the sample is restricted to the range \( 15.5 \leq R \leq 20.0 \) mag. (A value of \( H_0 = 75 \) gives a distance modulus of 34.9, for which \( R = 15.5 \) mag corresponds to \( M_R = -19.4 \) mag, an upper limit for dE galaxies.) Above \( R = 19.5 \) mag, dE galaxies are clearly resolved as nonstellar, and all stellar objects have been excluded. In this color and magnitude range there are 340 objects on the program field (dominated by cluster dE galaxies), compared to 87 objects (scaled to the same area) on the control field. At \( R = 20.0 \) mag, the sample is \( \approx 90\% \) complete in magnitude, and \( \approx 100\% \) complete in color, with a typical color uncertainty of \( \pm 0.03 \) mag.

In Figure 1, the \( (B-R) \) color for each of the 340 program field objects is plotted versus the logarithmic projected clustercentric radius, adopting NGC 4874 as the cluster center. Superimposed upon the scatterplot of Figure 1 are larger solid circles representing the trimmed mean \( (B-R) \) color in 2’ radial annuli, plotted at the geometric mean radius of the bin. The uncertainty estimates on these points correspond to the standard error of the mean. Initially evident in Figure 1 is the trend for decreasing mean color with increasing radius, although obscured to some degree by the scatter in the binned values.

The solid line in Figure 1 is the result of a weighted least-squares fit to the mean \( (B-R) \) colors. The slope and intercept for this regression line are given by \( \Delta (B-R)/\Delta (\log R_{cc}) = -0.08 \pm 0.02 \) and \( (B-R) = 1.46 \pm 0.02 \) mag at \( R_{cc} = 1' \). This is a radial color gradient, significant at the 4 \( \sigma \) level, which corresponds to a decrease of 0.10 mag in the mean color of dE galaxies over the radial range \( 1.33 \leq R_{cc} \leq 23.33 \). Thus, we detect a significant gradient in the distribution of galaxy color versus projected clustercentric radius, which works in the sense that dE galaxies at smaller clustercentric radii are redder in the mean.

The \( (B-R) \) color index, like \( (B-I) \) and the Washington \( (C-T_i) \) color, is a sensitive and accurate estimator of the total heavy element abundance (metallicity) for old stellar populations (Geisler & Forte 1990; Couture, Harris, & Allwright 1991; Secker et al. 1995). Several of the Local Group dwarfs show evidence for more than one episode of star formation (e.g., Caldwell & Bothun 1987; Sarajedini & Layden 1995; Smecker-Hane, Stetson, & Hesser 1995), and this may be true for a fraction of the early-type dE galaxies located in the environment of rich clusters. However, it is a fair assumption that the majority of these cluster dE galaxies are composed of a metal-poor stellar population, similar in age to globular clusters (Ferguson & Binggeli 1994). While both age and metallicity affect absorption features in the spectra (and therefore the integrated color) for systems of old stars, the effect of metal abundance dominates over age effects in the observed \( (B-R) \) color (Worthy 1994). As well, changes in the integrated color induced by starbursts are short lived (about 10^9 yr), after which the integrated colors return to normal (Charlot & Silk 1994). Thus in this sample of Coma cluster dE galaxies, I assume that the redder dE galaxies are more metal rich than the bluer dE galaxies.

In order to quantify this metallicity scale, I adopt a color-metallicity relationship derived from metallicities and integrated \( (B-R) \) colors for 82 Galactic globular clusters (from Harris 1996), given by \[ \text{[Fe/H]} = (3.44 \pm 0.09) (B-R) - (5.35 \pm 0.10). \] This color-metallicity relationship is calibrated over the range \( 0.85 \leq (B-R) \leq 1.45 \) mag, which I linearly extrapolate to \( (B-R) = 1.6 \) mag. In this analysis, the observed \( (B-R) \) colors are used, uncorrected for a foreground reddening of \( E_{B-V} \approx 0.02 \) mag. Combined uncertainties in the photometric calibration, reddening, and the metallicity calibration give rise to typical external uncertainties for \text{[Fe/H]} on the order of 0.2 dex.

The right-side axis of Figure 1 labels this metallicity scale, which is valid for the 340 program field objects and the mean values in the radial annuli. In terms of metallicity, the slope and intercept of the regression line are given by \[ \Delta \text{[Fe/H]}/\Delta (\log R_{cc}) = -0.29 \pm 0.07 \] and \[ \text{[Fe/H]} = -0.32 \pm 0.02 \text{ dex at } R = 1'. \] This slope indicates a significant radial metallicity gradient, which goes as \( Z \propto R^{-0.29}. \) Thus, for the population of bright dE galaxies in the Coma cluster core, dE galaxies closer to the cluster center are more metal rich in the mean. Considering the extreme nature of the environment in which these dE galaxies formed and have evolved, a metallicity near \( \text{[Fe/H]} \approx -0.32 \) dex for the most luminous dE galaxies is not inconceivable.

3. DISCUSSION

3.1. Primordial Origin for the Radial Color Gradient

Is this detected radial metallicity gradient a manifestation of primordial differences in the dE galaxies (a result of their
location within the cluster), or is this gradient due to an effect of different origin? The primary factor to be considered is the presence of intracluster dust. Ferguson (1993) examined the relation between the Mg$_2$ index and (B−V) colors for elliptical galaxies: he determined that there is a measurable quantity of dust in the Coma intracluster medium, and estimated $E_{B-V} \approx 0.05$ mag, such that $E_{B-V} \approx 0.08$ mag. Via simulations, he determined that a King model with a core radius of 0.5 Mpc was plausible for the dust distribution. Assuming $E_{B-V} \approx 0.08$ mag at the cluster center, one would estimate a total $\Delta E_{B-V} \approx 0.04$ mag out to the core radius. Our data spans nearly the same radial range, and from the analysis of the projected radial color distribution we estimate $\Delta(B-R) = 0.10$ mag. Thus, while the intracluster dust may contribute significantly to our radial color gradient, it cannot be the sole cause of the observed color gradient.

As detected by SH96, there exists a strong color-luminosity correlation in this same data set, which works in the sense that the more luminous dE galaxies are redder (in the mean); the detected color gradient therefore also corresponds to a luminosity gradient. Thus, we may question whether any mass-dependent dynamical relaxation of the dE galaxy orbits could have occurred. For dE galaxies in a rich cluster environment, both two-body relaxation and dynamical friction occur over a timescale much greater than the Hubble time (Bahcall 1977; Merritt 1985). West & Richstone (1988) proposed that in a simulated galaxy cluster, what is the effect of projection to two dimensions (Fig. 2), such that...
medium (see discussion below). These secondary effects were not included in our simulation.

3.3. Interpretation

Any successful model for the formation of dE galaxies in a cluster environment, regardless of the mechanism or epoch, must naturally account for the radial metallicity gradient described in the previous section. The “late- accretion” model of SWS87 postulates that the intracluster gas was enriched by the metal-rich gas outflows from dE galaxies at an early epoch (i.e., $10 \approx z \approx 5$). Then during the epoch of cluster formation, this diffuse gas is compressed and cools, subsequently infalling and accreting onto the halos of the most massive dwarf galaxies; vigorous starbursts can then follow. SWS87 assume that the star formation within a dwarf galaxy is governed by the gas accretion rate, which is regulated by the proximity of the dwarf galaxy to a more massive companion; i.e., the tidal field of a large central galaxy effectively strips gas from the nearest dwarf galaxies, such that the star formation rate decreases toward the cluster center.

The SWS87 model is applicable to dwarf galaxies in a cluster environment, and it describes a transition from dE galaxies to dIr galaxies during the present epoch of galaxy cluster formation. They also postulate that this accretion mechanism could supply the gas necessary for star formation in the nucleus of the more massive dE galaxies, thus explaining the presence of a nucleus in the brighter dE galaxies. If this is indeed the case, an observable metallicity gradient within the dE galaxy population would ensue, with those further from the cluster center being more metal rich in the mean. The sample of 340 objects that are analyzed above includes all detected dE galaxies in the absolute magnitude range $-19 \approx M_B \approx -14.5$ mag. Within this magnitude range, and within our sample, we expect the fraction $N(\text{dE, N})/N(\text{dE})$ to vary from nearly 100% for the brightest down to 20% or 30% for the fainter dwarfs (van den Bergh 1986); that is, the sample of bright dE galaxies will be dominated by nucleated dE galaxies. If these dE,N galaxies result from this late accretion, SWS87 predict that a positive radial metallicity gradient would be observed, which is not consistent with the radial metallicity gradient we detect.

The model introduced by BR92 naturally explains the observed negative metallicity gradient. BR92 postulate that the intracluster medium (ICM) played a dominant role in the evolution of dwarf galaxies, as an external pressure which confined the supernova-driven gas, preventing gas loss in a way that the dark halos themselves could not. BR92 postulate that if this ICM pressure dominated over the counter effect of ram-pressure stripping, it could halt the outflow of metal-rich gas from the young dE galaxies. This metal-rich gas would then cool and fall back onto the galaxy core; this gas would then be available for subsequent star bursts. They attribute the paucity of field dE galaxies at the present time to the lack of confinement pressure; the field dE galaxies more easily expelled their gas, inhibiting further star formation, and have subsequently faded away. In fact, BR92 and Babul & Ferguson (1996) have proposed that the faint blue galaxies (e.g., Koo & Kron 1992) are a field population of star-bursting dE galaxies at redshifts $0.5 \approx z \approx 1$, which will subsequently fade.

This ICM is an integral component of rich galaxy clusters like Coma, and while it is diffuse (i.e., $n \approx 10^{-2}$–$10^{-3}$ cm$^{-3}$ in the core), the total mass of the ICM is comparable to the total mass in luminous matter throughout the cluster. With a temperature near $T \approx 10^3$–$10^4$ K (Fabian et al. 1994), the ICM pressure in the cluster core is on the order of $(nT)_{\text{ICM}} \approx 10^5$ cm$^{-3}$ K, sufficient to confine the outflowing gas within the dark matter halos of the dE galaxies. Thus the dense core of the Coma cluster provides an excellent laboratory in which to study the effects of variation in the density of the ICM on dE galaxy metallicity. Following the logic of BR92, and since the ICM density peaks in the cluster core near NGC 4874 (White, Briel, & Henry 1993), the dE galaxies nearest to the cluster center should be on average both more massive and more metal rich, than dE galaxies farther from the cluster core. Thus the detection of a negative radial metallicity gradient within the dE galaxy population of the Coma cluster core is consistent with the model of BR92.

This research was supported by an NSERC operating grant to W. E. Harris, by the Ontario Ministry of Colleges and Universities (a 1994/1995 scholarship to the author), and by the Department of Physics and Astronomy at McMaster University. I would like to thank Arif Babul, Pat Durrell, Doug Geisler, Bill Harris, and Dean McLaughlin for their helpful comments and discussions.

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