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DIFFERENCES IN CARBON AND NITROGEN ABUNDANCES BETWEEN FIELD AND CLUSTER EARLY-TYPE GALAXIES

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ABSTRACT

Central line-strength indices were measured in the blue spectral region for a sample of 98 early-type galaxies in different environments. For most indices (Mg *b* and ⟨Fe⟩ in particular), elliptical galaxies in rich clusters and in low-density regions follow the same index-σ relations. However, striking spectral differences between field elliptical galaxies and their counterparts in the central region of the Coma Cluster are found for the first time, with galaxies in the denser environment showing significantly lower C4668 and CN_2 absorption strengths. The most convincing interpretation of these results is that they represent a difference in abundance ratios arising from distinct star formation and chemical-enrichment histories of galaxies in different environments. A scenario in which elliptical galaxies in clusters are fully assembled at earlier stages than their low-density counterparts is discussed.

Subject headings: galaxies: abundances — galaxies: clusters: general — galaxies: evolution — galaxies: formation — galaxies: stellar content

1. INTRODUCTION

Despite the observational and theoretical efforts of the last few decades, the evolutionary status of early-type galaxies is still an unsolved problem. The stellar populations of nearby elliptical galaxies preserve a record of their formation and evolution. In particular, the study of their element abundance ratios should be a powerful discriminant between different star formation histories (e.g., Worthey 1998). However, this last approach is still in its infancy. The pioneering works of the late 1970s already revealed that abundance ratios in early-type galaxies are often nonsolar (O'Connell 1976; Peterson 1976). Since then, several studies have provided compelling evidence of Mg/Fe overabundances in massive elliptical galaxies as compared with the solar ratio (Worthey, Faber, & González 1992; Peletier 1989; Vazdekis et al. 1997), and they have been interpreted in the light of several possible scenarios based on the understanding that Mg is mainly produced in Type II supernovae (SNe; Faber, Worthey, & González 1992; Worthey et al. 1992; Matteucci 1994). However, in contrast to the above findings, another α-element (namely, Ca) seems to be underabundant in elliptical galaxies (O'Connell 1976; Saglia et al. 2002; Cenarro et al. 2003; Thomas, Maraston, & Bender 2003), challenging current chemical evolution models (Matteucci 1994; Mollá & García-Vargas 2000).

Several authors (Worthey 1998; Vazdekis et al. 2001) have also noted a strengthening in other absorption-line strengths, in particular, in the Lick/IDS C4668 and CN_2 indices, when compared with stellar population model predictions. The variations of these two indices are mainly driven by C and N (in the case of CN) abundances (Tripicco & Bell 1995), which could suggest a possible enhancement of these two elements relative to Fe when compared with the solar values. In contrast to Mg, C and N are mainly produced in low- and intermediate-mass stars (Renzini & Voli 1981; Chiappini, Romano, & Matteucci 2003), although there are recent suggestions that most of the C should come from massive stars. During the asymptotic giant branch (AGB) phase, these stars eject into the interstellar medium (ISM) significant amounts of ^{4}He, ^{12}C, ^{13}C, and ^{14}N, enriching the medium from which new stars will be formed. Therefore, it seems difficult to simultaneously reproduce the abundances of all these elements with a simple chemical evolution scenario.

The problem of C and N abundances has been more thoroughly studied in the field of globular clusters. An interesting, puzzling problem here is the existence of a CN dichotomy in Galactic and M31 globular clusters (Burstein et al. 1984). Although this is a controversial issue, recent works (Harbeck, Smith, & Grebel 2003) tend to favor the scenarios of different abundances in the parental clouds as opposed those that predict abundance changes produced internally by the evolution of the stars (see Cannon et al. 1998 for a review).

Given the expected sensitivities of relative abundances to the star formation history of elliptical galaxies, their study in galaxies within different environments should help us to discriminate between different formation and evolution models. For instance, hierarchical scenarios predict that elliptical galaxies in rich clusters assembled completely at high redshifts ($z > 3$), whereas field elliptical galaxies may have experienced an elapsed and more complex star formation history (Kauffmann & Charlot 1998). However, very little is known about the dependence of the relative abundances on environment. One piece of information is that there is no difference in the [Mg/Fe] ratio between cluster and field elliptical galaxies (Jørgensen 1999; Kuntschner et al. 2002). In this Letter, we study the behavior of several Lick/IDS indices (see Worthey et al. 1994 for definition) in a sample of low- and high-density environment galaxies (LDEGs and HDEGs, respectively), and, surprisingly, we do find systematic differences in the strength of C and CN features.

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2. OBSERVATIONS AND DATA ANALYSIS

2.1. *Observations*

Long-slit spectra of 98 early-type galaxies in different environments were taken in four observing runs with two different telescopes. The sample comprises 59 galaxies from the field and the Virgo Cluster (LDEGs) and 34 galaxies from the central region of the Coma Cluster (HDEGs), spanning a wide range of absolute magnitudes ($-22.5 < M_B < -16.5$, using $H_0 = 75$ km s^{-1} Mpc^{-1}) and central velocity dispersions (40 km s^{-1} < σ < 400 km s^{-1}, from dwarf elliptical galaxies, in Virgo and Coma, to giant galaxies).

In the first two runs (1998 January and 1999 August), we used the 3.5 m telescope at Calar Alto Observatory (Almería, Spain), employing the Twin Spectrograph. The observations of the third and fourth runs (1999 March and 2001 April) were carried out with the 4.2 m William Herschel Telescope (WHT) at the Roque de los Muchachos Observatory (La Palma, Spain) using the ISIS spectrograph. Spectral resolutions range from 2.6–4.0 Å (FWHM) for LDEGs to 8.6 Å for HDEGs, in a spectral range of 3600–5400 Å. Exposure times of 1200–3600 s per galaxy allowed us to obtain central spectra with signal-to-noise ratios (per angstrom unit) ranging from 25 to 250. We also observed several galaxies in common between runs to ensure that the measurements were in the same system. Eighty-five stars from the Lick/IDS library were included to transform the measured line-strength indices to the Lick system.

Standard data reduction procedures (flat-fielding, cosmic-ray removal, wavelength calibration, sky subtraction, and fluxing) were performed with REDUCEME (Cardiel 1999), which allowed a parallel treatment of data and error frames and provided an associated error file for each individual data spectrum.

2.2. *Velocity Dispersion and Line-Strength Indices*

For each galaxy, central spectra were extracted by co-adding within a standard metric aperture size corresponding to 4″ projected at the distance of the Coma Cluster (in this way simulating a fixed linear aperture of length 1.8 kpc in all the galaxies). Velocity dispersions were determined using the MOVEL and OPTEMA algorithms described in González (1993). We measured the Lick/IDS line-strength indices, although only CN_2, Mg *b*, C4668, and ⟨Fe⟩ are presented here (the rest of the indices, with a more detailed explanation of data handling, will be presented in a forthcoming paper). All the indices were transformed to the Lick spectrophotometric system using the observed stars and following the prescriptions in J. Gorgas, P. Jablonka, & P. Goudfrooij (2003, in preparation; see also Worthey & Ottaviani 1997). Using galaxies in common with Trager (1997) and with repeated observations between runs, we double-checked that there were no systematic errors in the indices of galaxies observed in different runs. All the indices presented in this work were transformed into magnitudes, following Kuntschner (1989): $I'(\mathrm{mag}) = -2.5 \log [1 - I(\mathrm{Å})/\Delta\lambda]$, where $\Delta\lambda$ is the width of the index bandpass.

2.3. *Results*

In Figure 1, we present the CN_2, C4668′, Mg *b*′, and ⟨Fe⟩′ indices versus the velocity dispersion (σ) for the 98 galaxies of the sample. The spectra of three dwarf galaxies from the Coma sample did not have enough signal-to-noise ratio to derive a reliable measurement of σ, and a typical value of 40 km s^{-1} was assumed. Also, for the rest of the galaxies with $\sigma < 60$ km s^{-1}, we adopted σ-values from Pedraz et al. (2002) and Guzmán et al. (2003). It is apparent from this figure that galaxies located in low- and high-density environments show systematic differences in C4668′ and CN_2, being that the indices in HDEGs are systematically lower than the indices in LDEGs. On the other hand, both galaxy subsamples seem to follow similar relationships in the ⟨Fe⟩′ and Mg *b*′ versus σ diagrams.

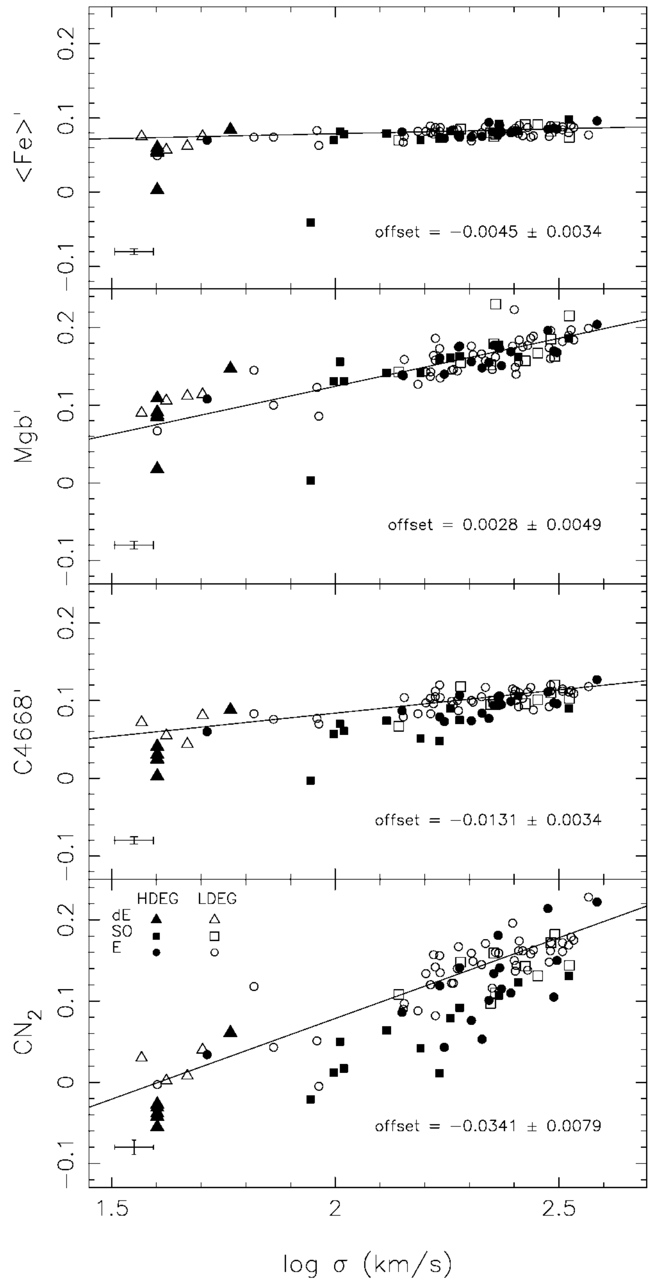

Fig. 1.—Relations of the line-strength indices analyzed in this Letter with the central velocity dispersions for HDEGs and LDEGs. LDEGs are represented as open symbols, whereas the filled symbols correspond to galaxies from the Coma Cluster. Dwarfs elliptical galaxies are plotted as triangles, S0 galaxies as squares, and E galaxies as circles. The lines represent error-weighted least-squares linear fits to the LDEG subsample. Typical errors in the indices and σ's are included at the bottom left of each panel. Labels indicate the mean offsets (and their corresponding errors) of the HDEGs with respect to the fits.

To quantify the possible systematic differences, we have performed a linear least-squares fit to the LDEG subsample and have measured the mean offsets (weighting with errors) of the Coma galaxies (HDEGs) from the fits. These differences

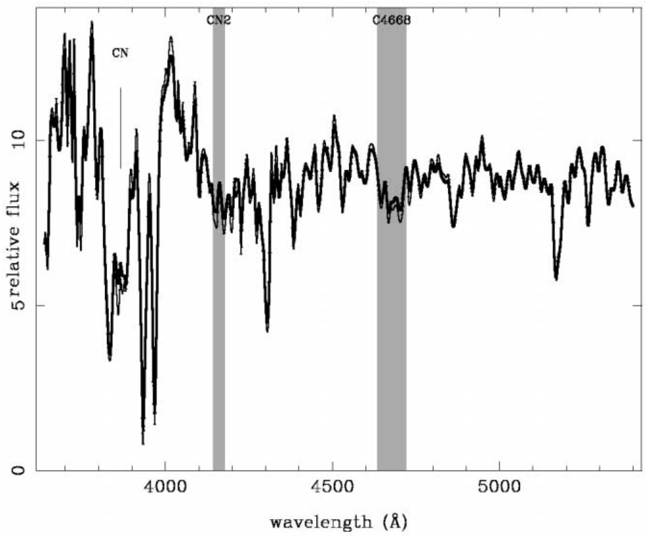

FIG. 2.—Co-added spectra for LDEGs and HDEGs, represented by thin and thick lines, respectively, in our spectral range. See text for details. The position of the CN band at around 4177 Å and the central bandpasses of the CN_2 and C4668′ indices are indicated. Besides these bands, a very consistent difference in the CN violet system (3850–3890 Å) is also evident.

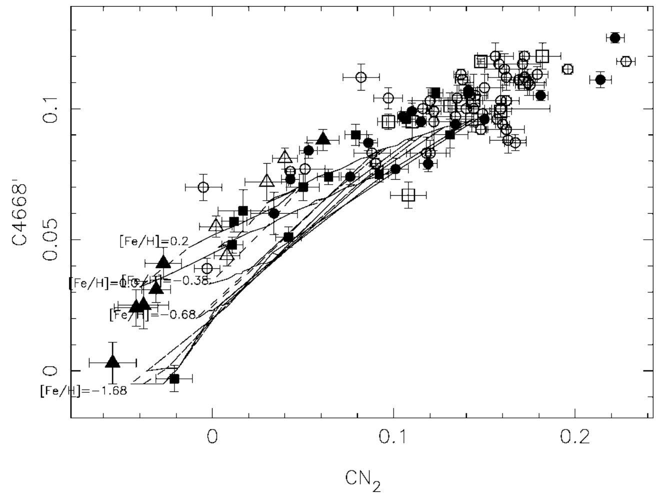

FIG. 3.—C4668′ line strengths vs. CN_2 for the complete samples of HDEGs and LDEGs. Overplotted are models by Vazdekis et al. (1996). Lines of constant [Fe/H] $= -1.68$, -0.68, -0.38, 0.0, and $+0.2$ are shown as solid lines. The dashed lines represent models of constant ages, from 1 to 17.78 Gyr, increasing from left to right. The symbols are the same as in Fig. 1.

and their errors are indicated within each panel, confirming the high significance of the systematic offsets in CN_2 and C4668′.

These systematic differences are also visible directly in the spectra of the galaxies. For illustration, Figure 2 shows the co-added spectra of LDEGs (*thin line*) and HDEGs (*thick line*) in the range 150 km $s^{-1} < \sigma < 250$ km s^{-1}, previously shifted to the same radial velocity and broadened to the maximum σ. The signal-to-noise ratios of the two combined spectra are above 300. It is evident that the offsets found in Figure 1 are due to real enhancements of the CN band at 4177 Å and the C_2 Swan band at 4735 Å in LDEGs compared with HDEGs. Note that this effect is also quite remarkable in the CN band around 3865 Å (not included in the Lick system).

3. DISCUSSION

Prior to interpreting the systematic differences in CN_2 and C4668′ as variations on element abundances (and since the indices are also sensitive to other physical parameters), we have explored the following possibilities:

1. Given the gravity dependences of the CN_2 and C4668′ indices (both are stronger in giant stars than in dwarf stars; Worthey et al. 1994), a decrease in the giant/dwarf ratio in HDEGs (with respect to LDEGs) would lead to lower index values. Using the models by Vazdekis et al. (1996), we have checked that a change in the exponent of the initial mass function (IMF) from 0.80 to 2.80 would decrease CN_2 and C4668′ by 0.033 and 0.009 mag, respectively, while the expected changes in Mg b' and $\langle Fe \rangle$ would be of 0.005 and 0.003, respectively, in the opposite sense (assuming an age of 10 Gyr and solar metallicity). These predictions are marginally consistent with our results (note that the above offsets for Mg b' and $\langle Fe \rangle$ are compatible with the measurements within the uncertainties); thus, we cannot reject this possibility. However, this result is in contradiction with other studies (Rose et al. 1994) that suggest a decrease in the giant/dwarf ratio in LDEGs compared with HDEGs and that would imply important changes in other observables. Measurements of the Ca triplet in the near-infrared (with a high sensitivity to the IMF; see Cenarro et al. 2003) should help to discard or confirm this scenario.

2. A difference in the (luminosity-weighted) mean age between HDEGs and LDEGs could also introduce systematic offsets in CN_2 and C4668′ between both galaxy samples. Under this scenario, and using the models by Vazdekis et al. (1996), the observed offsets could be accounted for if HDEGs were about 8 Gyr younger than LDEGs. This possibility can be rejected since it would imply a decrease in Mg b' and $\langle Fe \rangle$ of 0.026 and 0.014, respectively, in HDEGs compared with LDEGs, which is not observed. Furthermore, it contradicts previous findings that suggest that HDEGs are, in any case, older than LDEGs (Kuntschner et al. 2002).

Thus, the most plausible explanation for our results is that variations in the relative abundances of C and N with respect to Mg and Fe are responsible for the observed offsets between galaxies in different environments. Figure 3 compares the observed CN_2 and C4668′ with the predictions of stellar population models. This figure clearly shows that the previously found overabundances of C and N stand for LDEGs only; HDEGs tend to exhibit relative abundances closer to the solar partition.

The C4668′ index is extremely sensitive to carbon changes, so small variations in carbon abundance can change this index dramatically (Tripicco & Bell 1995). However, the variations of CN are mostly controlled by N because extra C is readily incorporated into CO but extra N makes more CN molecules. Therefore, a change in both C and N abundances is required to explain our results. Besides, if extra carbon is easily incorporated into CO, one should detect an enhancement in the strength of the CO bands in LDEGs compared with HDEGs. This effect has indeed been found by Mobasher & James (1996), who compared the CO band at 2.3 μm in galaxies from the field and from the Pisces and Abell 2634 clusters. They interpreted this difference as evidence of an intermediate-age stellar population in LDEGs (through a major contribution of AGB stars). Although we do not discard the larger contribution of younger populations in LDEGs compared with HDEGs, our results in the blue spectral range imply that their observations can be solely explained by a relative abundance difference. In any case, the observed offsets cannot be due to an age effect alone (see above).

The most plausible scenario to explain the differences in relative abundances is the one in which LDEGs and HDEGs have experienced different star formation histories. In particular, since the ISM is progressively enriched in C and N by low- and intermediate-mass stars, HDEGs should have been fully assembled before the massive release of these elements. The hierarchical clustering paradigm currently predicts that galaxies in clusters formed at different epochs than those of LDEGs. If the time that elapsed between the assembling of the former and the assembling of the later is enough to permit the C and N enrichment of the ISM of the premerging building blocks in LDEGs, then the stars formed in these galaxies during the merging events will be C- and N-enhanced. The constancy of the iron-peak elements could be understood if, in both environments, the mergers take place before Type I SNe can significantly pollute the ISM of the premerging blocks. Additionally, HDEGs could have experienced a truncated star formation and chemical-enrichment history compared with the more continuous time-extended history of their counterparts in low-density environments. However, under this hypothesis, there should be an increase of magnesium (produced by Type II SNe) in LDEGs; this is not detected. One way to understand the constancy of the Mg *b*′ index would be to invoke the IMF-metallicity relationship suggested by Cenarro et al. (2003), in which the successive episodes of star formation in LDEGs would take place with lower giant-to-dwarf ratios.

To conclude, we have noted for the first time a systematic difference in the element abundance ratios of galaxies situated in different environments. These differences impose strong constraints on models of chemical evolution and galaxy formation. It is clear that more work is still needed to completely understand the causes of the differences. In particular, it would be very interesting to compare the CN_2 and C4668′ indices between the central regions and the outskirts of the Coma Cluster, where Mobasher & James (2000) found differences in the strength of the near-IR CO molecule. Also, the detailed study of other dense clusters is very much needed to confirm whether or not this effect is particular to the Coma Cluster.

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