The Astrophysical Journal, 614:L101–L104, 2004 October 20

EARLY-TYPE GALAXIES IN THE COMA CLUSTER: A NEW PIECE IN THE CALCIUM PUZZLE

A. J. Cenarro,[1] P. Sánchez-Blázquez, N. Cardiel,[2] and J. Gorgas
Departamento de Astrofísica, Facultad de Físicas, Universidad Complutense de Madrid, 28040 Madrid, Spain; cen@astrax.fis.ucm.es
Received 2004 January 16; accepted 2004 September 10; published 2004 September 16

ABSTRACT

We present measurements of the Ca II triplet and the Ca4227 Lick index for a sample of early-type galaxies in the Coma Cluster, deriving, for the first time, their corresponding relationships with velocity dispersion. Compared with a similar subsample of elliptical galaxies in the field, Coma galaxies with velocity dispersions in the range ≈180–270 km s^{-1} exhibit significant differences in the strengths of the Ca features, suggesting an influence of the environment on the star formation histories of these galaxies. We argue that the main scenarios previously proposed to explain the relatively low Ca II triplet of galaxies are not able by themselves to simultaneously reconcile the strengths of the two Ca indices in both environments.

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

1. INTRODUCTION

The near-infrared (NIR) Ca II triplet constitutes the strongest absorption feature in the integrated spectra around 8600 Å of relatively old stellar populations. Given its well-known capability to derive the metallicity of Galactic globular clusters (Armandroff & Zinn 1988, hereafter A88; Rutledge et al. 1997), this spectral feature was considered a useful tool to study the stellar populations of normal galaxies. However, the first observational work (Cohen 1979; Bica & Alloin 1987; Terlevich et al. 1990; Houdashelt 1995) reported only small differences among the integrated Ca II triplet of several types of galaxies, remarkably at variance with the trends found when using other metallicity indicators (e.g., the Mg triplet at 5175 Å). The difficulties of previous single stellar population (SSP) models to make reliable predictions of the Ca II triplet (due to severe deficiencies in the available stellar libraries) prevented an understanding of the above apparent inconsistency.

After a series of papers devoted to constructing realistic models for disentangling the actual behavior of the Ca II triplet in stellar populations (Cenarro et al. 2001a, hereafter C01; Cenarro et al. 2001b; Cenarro et al. 2002, hereafter C02; Vazdekis et al. 2003, hereafter V03), the above topic is being revisited and constitutes a controversial matter of debate. There exist recent evidences showing that, unlike other metal lines, the Ca II triplet is surprisingly anticorrelated with central velocity dispersion (σ_0) for several types of galaxies: elliptical galaxies (E's) in the field (Saglia et al. 2002, hereafter S02; Cenarro et al. 2003, hereafter C03), bulges of spiral galaxies (Falcón-Barroso et al. 2003, hereafter F03), and dwarf E's in the Fornax Cluster (Michielsen et al. 2003). Even more importantly, the measured values in giant E's lie well below model predictions for any reasonable choice of stellar population parameters (age and metallicity). A wide range of interpretations, like the existence of a dwarf-enriched stellar population, Ca underabundances, Ca depletion in the interstellar medium, or a composite stellar population have been discussed in the above references. Unfortunately, the lack of definitive evidences allows no consensus to exist at the moment.

In the blue spectral range, Ca4227 is considered the most Ca-sensitive Lick index (Tripicco & Bell 1995). Intriguingly, despite Ca being an α-element like Mg, the metallicities inferred for E's using Ca4227 suggest that Ca is not enhanced—it could be even depressed—with respect to Fe (Worthey 1992; Vazdekis et al. 1997; Worthey 1998; Trager et al. 1998; Vazdekis et al. 2001; Proctor & Sansom 2002, hereafter P02). Once again, the existence of Ca underabundances has been demanded to explain the low Ca4227 values (Thomas et al. 2003b, hereafter T03b).

It is well known that the environment is expected to play a decisive role in the assembling and star formation history of galaxies. Hierarchical scenarios predict that E's in rich clusters were mostly formed at high redshifts, whereas field E's may have experienced an extended and more complex star formation history (Kauffmann & Charlot 1998). Although no differences in the [Mg/Fe] ratios seem to exist between cluster and field E's (Jørgensen 1999; Kuntschner et al. 2002), Sánchez-Blázquez et al. (2003, hereafter S03) have recently found significant differences in C and N abundance ratios between Coma and field E's. These differences impose strong constraints to models of galaxy formation and chemical evolution.

The above picture motivated us to extend the previous work to the analysis of the Ca II triplet and the Ca4227 index in galaxies of different environments: first of all, because it might reveal new clues to the so confusing Ca II triplet behavior, and second, because the fact that Ca seems to be an anomalous α-element makes it especially interesting from the point of view of chemical evolution.

2. OBSERVATIONS AND DATA REDUCTION

This work makes use of long-slit spectroscopic data for two samples of galaxies: E's from the Coma Cluster and E's in the field. Both were observed during two different runs (1999 March and 2001 April) using ISIS, the double-arm spectrograph at the 4.2 m William Herschel Telescope (Observatorio del Roque de los Muchachos, La Palma). All details about the sample, observations, and data reduction for E's in the field are given in C03 and Sánchez-Blázquez (2004, hereafter S04) for the NIR and blue-arm data, respectively. We also refer the reader to S04 for a description of the reduction of the blue spectroscopic data for the Coma galaxies. In this section, we just concentrate on their NIR spectral range (8355–9164 Å).

[1] Also at UCO/Lick Observatory, University of California, Santa Cruz, CA 95064.

[2] Also at Calar Alto Observatory, CAHA, Apartado 511, 04044 Almeria, Spain.

Our sample of galaxies from the Coma Cluster consists of 28 early-type galaxies (E to S0) spanning a wide range of central velocity dispersions (80 km s^{-1} $\lesssim \sigma_0 \lesssim$ 370 km s^{-1}). We have rejected the faintest low-mass galaxies in S03 because of quite large errors. When it was feasible, the 3′.5 long slit (2″ width, providing 2.9 Å FWHM spectral resolution) was rotated to include two galaxies in the same exposure. Otherwise, single galaxies were observed by aligning the slit with the major axis. Exposure times of 1200–2000 s per galaxy led to signal-to-noise ratios from 30 to 120 Å^{-1} in a central aperture of radius $R_{\rm eff}/8$.

Standard spectroscopic reduction procedures were performed with REDUCEME (Cardiel 1999). Apart from an accurate correction for the fringe pattern, we took special care on the sky subtraction and the correction for telluric absorptions at $\lambda \gtrsim 8950$ Å (by using the telluric pattern derived from the spectra of flux standard stars). Both are especially critical for Coma galaxies since the redshift of the cluster ($z \sim 0.025$) places some index bandpasses in regions affected by atmospheric absorptions and strong sky emission lines. The availability of error spectra for each galaxy frame allowed us to estimate reliable uncertainties in the measurements of the indices. Index errors account for photon statistics, uncertainties in the flux calibration, and radial velocity determinations (see details in C01).

Final spectra were relative-flux–calibrated using spectrophotometric standard stars observed several times at different air masses. In order to transform the NIR spectra to the V03 spectrophotometric system, a sample of 39 stars (from B to late M spectral types) in common with C01 were observed during twilights. Following C03, they were also employed as templates for σ_0 determinations. Rather than using template-dependent polynomials, systematic differences between indices measured at different spectral resolutions were prevented by broadening all the spectra up to the largest σ_0 of the galaxy sample, namely, 370 km s^{-1}, corresponding to NGC 4889.

The observation of four E's in common with C03 allowed us to confirm a homogeneous spectrophotometric system for the blue and NIR spectra of both observing runs.

3. INDEX-σ_0 RELATIONS

We analyze, for the first time, the behaviors of the Ca II triplet, the H Paschen series (CaT*, CaT, and PaT line-strength indices; see definitions in C01), and the Ca4227 Lick index as a function of σ_0 for E's in the Coma Cluster. All the measurements correspond to a central aperture of radius $R_{\rm eff}/8$ (or 1″ for galaxies with $R_{\rm eff} < 8''$). There exists a database[3] listing the galaxy sample as well as the indices and σ_0 determinations.

Figure 1 shows the measurements of the above indices versus σ_0 for E's in the Coma Cluster and, for comparison, for a similar subsample of E's in the field. Error-weighted, least-squares linear fits to all data have been computed for both samples (see labels in Fig. 1). CaT* and CaT in Coma E's exhibit an anticorrelation with σ_0 (Figs. 1*a* and 1*b*), which is compatible with the one derived for field E's (C03). However, because of the errors of the computed slopes, we cannot rule out that a flat trend with σ_0 could exist for the Coma sample. As in the case of field E's, a flat behavior is derived for the PaT index (Fig. 1*c*), while both slightly positive and negative (nearly flat) trends are evidenced for the Ca4227 indices of field and Coma E's, respectively (Fig. 1*d*). In brief, as regards to the qualitative behaviors with σ_0 of the above indices, we find no important differences between field and Coma E's.

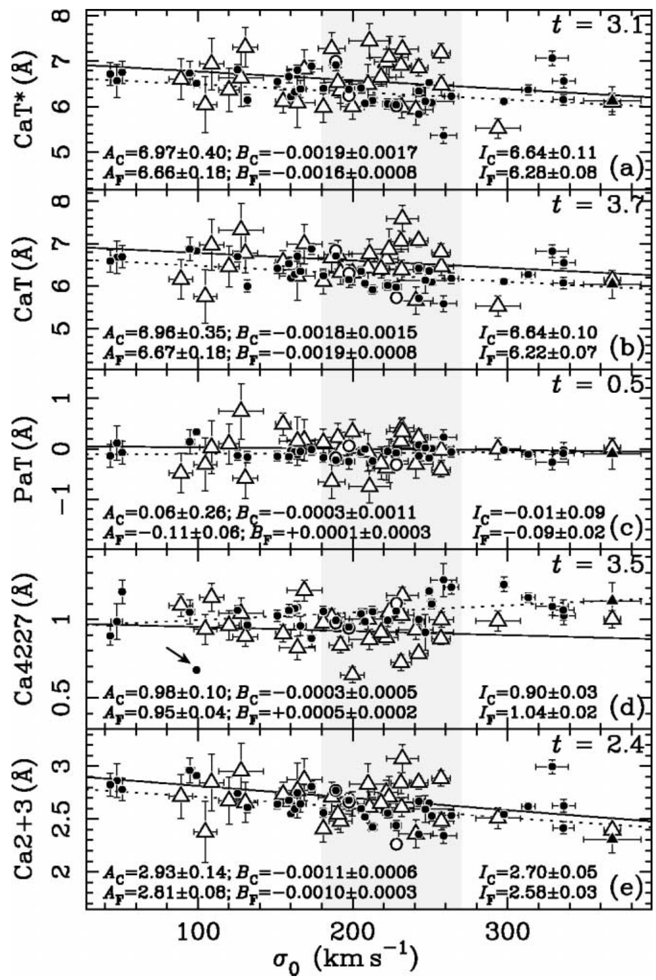

FIG. 1.—CaT*, CaT, PaT, Ca4227 and Ca2 + 3 (≡Ca2 + Ca3 indices by A88) vs. central velocity dispersion for E's in the Coma Cluster (*triangles*) and in the field (*circles*). For comparison, the indices of four galaxies in common between both runs are included (*open circles and filled triangle*). All the indices are measured at 370 km s^{-1} spectral resolution and corrected to the system defined by the models (V03). Solid (Coma) and dotted (field) lines represent error-weighted, least-squares linear fits to all data ($I = A + B\sigma_0$; see the labels, with C and F subscripts referring to Coma and field E's). $I_{\rm C}$ and $I_{\rm F}$ are error-weighted mean indices for Coma and field E's within the range 180 km s^{-1} $\lesssim \sigma_0 \lesssim$ 270 km s^{-1} (*shaded region*). A *t*-value larger than ∼1.96 indicates that $I_{\rm C}$ and $I_{\rm F}$ are statistically different. NGC 4742 (see arrow in panel *d*), with a very low Ca4227 because of a central young stellar population (see C03), has been rejected from the linear fits and the mean index computations.

The most striking differences between both samples arise from the mean absolute values of their Ca indices. In particular, although intermediate-low mass E's ($\sigma_0 \lesssim 180$ km s^{-1}) in both samples exhibit similar mean index values, we find clear differences for those E's within the range 180 km s^{-1} $\lesssim \sigma_0 \lesssim$ 270 km s^{-1} (in the following, we will refer to them as *massive* E's, the ones being the main subject of discussion in this Letter). Note that, other than visual inspection, no a priori argument exists to justify the above subsample selection. Interestingly, the fact that the differences in C4668 and CN_2 for Coma and field E's are also particularly evident in a similar range of velocity dispersion (S03) supports the idea that massive E's in different environments could indeed have different stellar population properties. Unfortunately, the scarcity of E's with $\sigma_0 \gtrsim 270$ km s^{-1} in our Coma sample prevents us from confirming whether the above behavior extends to the high-mass end of the E family.

[3] See http://www.ucm.es/info/Astrof/ellipt/CATRIPLET.html.

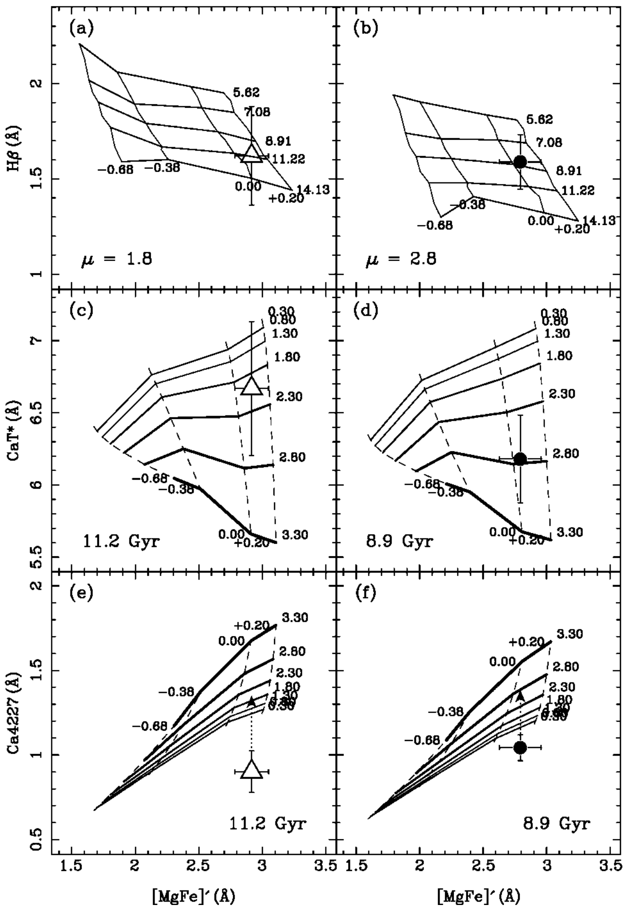

FIG. 2.—Mean values of Hβ, [MgFe]′, Ca4227, and CaT* for Coma (*open triangles*) and field (*filled circles*) E's within the range 180 km s^{-1} $\lesssim$ $\sigma_0 \lesssim$ 270 km s^{-1}. Rather than typical errors, error bars correspond to the rms standard deviation of the data (larger than the former ones). SSP model predictions by V03 and V99 at 370 km s^{-1} spectral resolution, respectively, are overplotted. In panels *a* and *b*, age and metallicity vary from 5.62 to 14.13 Gyr and from -0.68 to $+0.20$ dex at different Salpeter-like IMF slopes (μ; see the labels). Panels *c*–*f* exhibit model predictions at fixed age (see the labels) with varying μ (0.3–3.3) and metallicity (as in panels *a* and *b*). Arrows in panels *e* and *f* are explained in the text.

For this subsample of massive galaxies consisting of 17 Coma E's and 15 E's in the field, we have computed error-weighted means of the indices and their corresponding standard errors (see labels in Fig. 1). The statistical significance of the differences between the mean indices of both samples is studied by using a *t*-test (see Fig. 1; for a significance level of $\alpha =$ 0.05, *t*-values larger than 1.96 indicate that a significant difference exists). Apart from the fact that no significant differences are found for the PaT index (as expected for relatively old stellar populations; see V03), we determine the existence of an intriguing behavior: while field E's exhibit Ca4227 values significantly larger than Coma E's, the contrary occurs for the CaT* and CaT indices. In order to check that the above results are not driven by uncertainties in the correction for NIR telluric absorptions, we also measured the Ca2 and Ca3 classical indices by A88 (Ca2 + 3 ≡ Ca2 + Ca3). The high sensitivities of these indices to velocity dispersion and to the presence of Paschen lines (see C01) are not important when, as is the case, they are measured on the spectra of old stellar populations at equal spectral resolution. In turn, the major improvement lies in the fact that their continuum sidebands are located in regions free from telluric absorptions for the redshift of the cluster. The data in Figure 1 (panel *e*) prove that the trends and differences inferred from these indices are compatible with the ones derived for CaT* and CaT.

4. DISCUSSION

As it has been recently reported by S02, C03, and F03, single and composite stellar population models with solar abundance ratios ([α/Fe] $=$ 0.0) and a standard initial mass function (IMF) cannot reproduce the low Ca II values of massive galaxies by solely assuming age and metallicity variations. Among others, two alternate scenarios have been proposed: (1) the existence of Ca underabundances and (2) the existence of a dwarf-enriched stellar population. In the following paragraphs, we explore in turn whether the above scenarios are consistent enough to explain simultaneously the discrepancy with the model predictions and the differences between distinct environments.

1. Even though there exist no evolutionary synthesis models for the Ca II triplet in which nonsolar abundances ratios are considered, the Ca underabundant hypothesis has been proposed as a plausible scenario to explain the low CaT of massive galaxies (S02; F03). Making use of stellar population models with variable element abundance ratios for the Lick indices (Thomas et al. 2003a, hereafter T03a), T03b suggest the existence of a Ca depletion, with respect to the rest of α-elements, that increases with galaxy mass. Under this scenario, and assuming that the integrated Ca II triplet indeed traces the Ca abundance, the relative differences in the CaT of massive Coma and field E's should be naturally explained as differences in the levels of Ca underabundances, field E's being "more Ca underabundant" than Coma galaxies. However, there exists a strong contradiction in the fact that while mean Ca II indices of massive Coma E's are larger than of those in the field, the contrary occurs for Ca4227. Furthermore, taking into account that Ca4227 is affected by C and N abundances in the sense that the stronger CN is, the lower Ca4227 is (Schiavon et al. 2002; P02; T03a), and given that field E's exhibit CN overabundances larger than those in Coma E's (S03), the relative differences in Ca4227 cannot be explained by just CN effects either. In fact, if we consider such an effect, the actual difference between the Ca4227 strengths of both samples should be even larger than that in Figure 1*d*. In summary, just the existence of Ca underabundances and/or CN effects is unable to reconcile Ca4227 and CaT* at the same time.

2. Since the Ca II triplet of giant stars is stronger than that of dwarf stars, the existence of a dwarf-enriched stellar population could account for the low values of massive E's. This scenario can be parametrized by means of a variation of the IMF slope (μ; assuming a Salpeter-like IMF). The evolutionary synthesis models by V03 predict that, for old SSPs with intermediate-to-high metallicities, CaT* and CaT mainly depend on μ (they decrease with the increasing μ because of a larger dwarf-to-giant stars ratio). In the light of the above predictions, massive E's are interpreted to have both metallicities and dwarf-to-giant ratios larger than low-mass E's (C03).

In Figure 2, we make use of the models by Vazdekis (1999, hereafter V99) and V03 to compare Coma and field E's under this scenario. The only way to reconcile Hβ, [MgFe]′ (the one being independent of typical α/Fe ratios as defined by T03a), and CaT* at the same time is by invoking different ages, metallicities, and dwarf-to-giant ratios. In turn, the latter also affects the derived ages and metallicities because of the non-negligible dependence of Hβ to the dwarf-to-giant ratio. From

Figures 2*a*–2*d*, we derive similar metallicities (above solar) for both subsamples, a mean age for field E's lower (∼8.9 Gyr) than that for Coma E's (∼11.2 Gyr), and mean dwarf-to-giant ratios larger for the former ($\mu \simeq 2.8$) than for the latter ($\mu \simeq 1.8$). However, when this scenario is simultaneously applied to Ca4227, the model predictions fail to reproduce the locus of the galaxies (Fig. 2*c*). Therefore, even though relative differences between the Ca indices of Coma and field E's could be compatible with just variations of the dwarf-to-giant ratio (the larger μ is, the lower CaT* is, and the larger Ca4227 is; Figs. 2*c*–2*f*), this argument is not enough to reconcile absolute values of CaT* and Ca4227 by itself.

At this point, one notices that the current status is not quite optimistic. Could it be that both scenarios coexist, driving an apparent inconsistency? Even though the sensitivity of Ca4227 to unusual dwarf-to-giant ratios is not negligible, age and metal abundance effects are mainly expected to govern its behavior. The arrows in Figures 2*e* and 2*f* indicate the offsets in Ca4227—arising not only from the existence of Ca subabundances but also from possible dilution effects due to CN enhancements—required to reproduce the SSP properties in the previous panels. On the contrary, several arguments support the idea that the Ca II triplet is rather insensitive to Ca abundances. First, the CaT index does not correlate with stellar [Ca/Fe] abundance ratios (C02). Also, for SSPs older than ∼3 Gyr with intermediate-to-high metallicities, the integrated Ca II triplet saturates (or even decreases for dwarf-enriched SSPs) with increasing metallicity (V03). This is indeed a by-product of the increasing luminosity weight of late M stellar types (with very weak Ca II lines and strong TiO bands in their spectra) as the temperature of the isochrone becomes colder. Therefore, just because of temperature effects, very metal rich stellar populations with high Ca abundances are expected to exhibit CaT values lower than if, for example, they were solar-abundant (see more details in V03). In this sense, Ca II triplet indices are expected to be sensitive to global metallicity rather than to Ca abundances.

To conclude, we report, for the first time, systematic differences between the integrated Ca II triplet and Ca4227 of E's in the Coma Cluster and in the field, which are difficult to reconcile at the same time. Different abundance ratios and/or dwarf-enriched stellar populations could be conspiring to produce apparently inconsistent Ca indices. As proposed in S03, these kind of differences are probably driven by the effect of the environment on chemical evolution and galaxy formation. Unfortunately, we are far from determining any definitive proof for distinct star formation histories in massive E's located at different environments; the fact is that the current picture of calcium in galaxies seems to go beyond the capabilities of the available SSP models. An extensive effort in the field of nucleosynthesis and stellar atmospheres is in demand to help us understand how different abundance ratios affect not only line-strength indices but also the physics and temperature of isochrones. In the meantime, the collection of more and high-quality data of Ca line strengths is crucial for trying to understand the controversial Ca puzzle.

The authors are indebted to the referee, S. M. Faber, for useful comments and suggestions. A. J. C. acknowledges financial support from a Universidad Complutense de Madrid Fundación del Amo Fellowship. The William Herschel Telescope is operated on the island of La Palma by the Royal Greenwich Observatory at the Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias. This work was supported by the Spanish research project AYA2003-01840.

REFERENCES

Armandroff, T. E., & Zinn, R. 1988, AJ, 96, 92 (A88)
Bica, E., & Alloin, D. 1987, A&A, 186, 49
Cardiel, N. 1999, Ph.D. thesis, Univ. Complutense, Madrid
Cenarro, A. J., Cardiel, N., Gorgas, J., Peletier, R. F., Vazdekis, A., & Prada, F. 2001a, MNRAS, 326, 959 (C01)
Cenarro, A. J., Gorgas, J., Cardiel, N., Pedraz, S., Peletier, R. F., & Vazdekis, A. 2001b, MNRAS, 326, 981
Cenarro, A. J., Gorgas, J., Cardiel, N., Vazdekis, A., & Peletier, R. F. 2002, MNRAS, 329, 863 (C02)
Cenarro, A. J., Gorgas, J., Vazdekis, A., Cardiel, N., & Peletier, R. F. 2003, MNRAS, 339, L12 (C03)
Cohen, J. G. 1979, ApJ, 228, 405
Falcón-Barroso, J., Peletier, R. F., Vazdekis, A., & Balcells, M. 2003, ApJ, 588, L17 (F03)
Houdashelt, M. L. 1995, Ph.D. thesis, Ohio State Univ.
Jørgensen, I. 1999, MNRAS, 306, 607
Kauffmann, G., & Charlot, S. 1998, MNRAS, 294, 705
Kuntschner, H., Smith, R., Colles, M., Davies, R., Kaldare, R., & Vazdekis, A. 2002, MNRAS, 337, 172
Michielsen, D., De Rijcke, S., Dejonghe, H., Zeilinger, W. W., & Hau, G. K. T. 2003, ApJ, 597, L21
Proctor, R. N., & Sansom, A. E. 2002, MNRAS, 333, 517 (P02)
Rutledge, G. A., Hesser, J. E., & Stetson, P. B. 1997, PASP, 109, 907
Saglia, R. P., Maraston, C., Thomas, D., & Bender, R. 2002, ApJ, 579, L13 (S02)
Sánchez-Blázquez, P. 2004, Ph.D. thesis, Univ. Complutense, Madrid (S04)
Sánchez-Blázquez, P., Gorgas, J., Cardiel, N., Cenarro, J., & González, J. J. 2003, ApJ, 590, L91 (S03)
Schiavon, R. P., Faber, S. M., Castilho, B. V., & Rose, J. A. 2002, ApJ, 580, 850
Terlevich, E., Díaz, A. I., & Terlevich, R. 1990, MNRAS, 242, 271
Thomas, D., Maraston, C., & Bender, R. 2003a, MNRAS, 339, 897 (T03a)
———. 2003b, MNRAS, 343, 279 (T03b)
Trager, S. C., Worthey, G., Faber, S. M., Burstein, D., & González, J. J. 1998, ApJS, 116, 1
Tripicco, M. J., & Bell, R. A. 1995, AJ, 110, 3035
Vazdekis, A. 1999, ApJ, 513, 224 (V99)
Vazdekis, A., Cenarro, A. J., Gorgas, J., Cardiel, N., & Peletier, R. F. 2003, MNRAS, 340, 1317 (V03)
Vazdekis, A., Kuntschner, H., Davies, R., Arimoto, N., Nakamura, O., & Peletier, R. 2001, ApJ, 551, L127
Vazdekis, A., Peletier, R. F., Beckman, J. E., & Casuso, E. 1997, ApJS, 111, 203
Worthey, G. 1992, Ph.D. thesis, Univ. Calif., Santa Cruz
———. 1998, PASP, 110, 888