SPATIALLY RESOLVED SPECTROSCOPY AND CHEMICAL HISTORY OF STAR FORMING GALAXIES IN THE HERCULES CLUSTER: THE EFFECTS OF THE ENVIRONMENT

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ABSTRACT

Spatially resolved spectroscopy has been obtained for a sample of 27 star-forming (SF) galaxies selected from our deep Hα survey of the Hercules cluster. We have applied spectral synthesis models to all emission-line spectra of this sample using the population synthesis code STARLIGHT and have obtained fundamental parameters of stellar components such as mean metallicity and age. The emission-line spectra were corrected for underlying stellar absorption using these spectral synthesis models. Line fluxes were measured and O/H and N/O gas chemical abundances were obtained using the latest empirical calibrations. We have derived the masses and total luminosities of the galaxies using available Sloan Digital Sky Survey broadband photometry. The effects of cluster environment on the chemical evolution of galaxies and on their mass–metallicity (MZ) and luminosity–metallicity (LZ) relations were studied by combining the derived gas metallicities, the mean stellar metallicities and ages, the masses and luminosities of the galaxies, and their existing H1 data. Our Hercules SF galaxies are divided into three main subgroups: (1) chemically evolved spirals with truncated ionized-gas disks and nearly flat oxygen gradients, demonstrating the effect of ram-pressure stripping; (2) chemically evolved dwarfs/irregulars populating the highest local densities, possible products of tidal interactions in preprocessing events; and (3) less metallic dwarf galaxies that appear to be “newcomers” to the cluster and are experiencing pressure-triggered star formation. Most Hercules SF galaxies follow well-defined MZ and LZ sequences (for both O/H and N/O), though the dwarf/irregular galaxies located at the densest regions appear to be outliers to these global relations, suggesting a physical reason for the dispersion in these fundamental relations. The Hercules cluster appears to be currently assembling via the merger of smaller substructures, providing an ideal laboratory where the local environment has been found to be a key parameter in understanding the chemical history of galaxies.

Key words: galaxies: clusters: general – galaxies: clusters: individual (Abel 2151)

Online-only material: color figures

1. INTRODUCTION

The star formation history (SFH), gas content, and mass exchange with the environment (infall of metal-poor gas and/or outflow of enriched material) are fundamental variables that regulate the chemical evolution of a galaxy. Clusters of galaxies host large numbers of galaxies of various sizes, luminosities, and morphologies as well as a large mass of gas confined within a given volume of space. Thus, galaxy clusters can provide an excellent place to study the impact of the environment on the aforementioned fundamental variables regulating the metal content of a galaxy.

The relation between stellar mass and metallicity is fundamental to constraining galaxy evolution scenarios in dense environments. From the observational point of view, Lequeux et al. (1979) were the first to point out that metallicity is strongly correlated with galaxy stellar mass or luminosity, with the more massive galaxies being richer in metal. Since then much work has been done to extend these correlations to large samples of galaxies (Skillman et al. 1989; Zaritsky et al. 1994; Lamareille et al. 2004, among others). This holds at all redshifts, although for a given stellar mass, more distant galaxies appear to have a lower metal content than local galaxies (e.g., Savaglio et al. 2005; Erb et al. 2006). Maiolino et al. (2008) argue that both the zero point and the slope of the mass–metallicity (MZ) relation are a function of redshift.

Many different scenarios have been proposed for the physical mechanisms underlying such a relation. According to Finlator & Davé (2008), the chemical evolution of galaxies is governed by momentum-driven gas outflows, which are more efficient in expelling metal-enriched gas in dwarf galaxies than in giant galaxies. Spitoni et al. (2010) also support the ejection scenario caused by galactic winds. Köppen et al. (2007) claim that the MZ relation is linked to the initial mass function (IMF), which in turn presents a higher upper mass cutoff in more massive galaxies. Calura et al. (2009) advocate that the MZ relation is intrinsically related to the mass and morphological type of the galaxies. They support an increasing efficiency of star formation with mass without any need to invoke galactic outflows. The inflows scenario, whether smooth or in the form of gas-rich satellites, has been explored by Davé et al. (2010).

In this context, several cluster-related environmental processes can affect the SFH or the gas exchange between the galaxy and its environment and, as a consequence, could alter the chemical evolution of cluster galaxies. Some processes mainly affect the gaseous content of a galaxy, such as the ram-pressure stripping (Gunn & Gott 1972; Kenney et al. 2004; van Gorkom 2004), re-accretion of the stripped gas (Vollmer
et al. 2001), turbulence and viscosity (e.g., Quilis et al. 2000), and starvation/strangulation (Larson et al. 1980). Other processes can affect both the gaseous and the stellar properties of a galaxy, ranging from low-velocity tidal interactions and mergers (e.g., Mamon 1996; Barnes & Hernquist 1996; Conselice 2006) to high-velocity interactions between galaxies and/or clusters (“harassment”); Moore et al. 1998, 1999; Struck 1999; Mihos 2004); see Boselli & Gavazzi (2006) for an extensive review on this subject.

A number of works have been devoted to searching for the possible effects of cluster environment on the chemical properties of spiral galaxies in the Virgo cluster (Shields et al. 1991; Henry et al. 1992, 1994, 1996; Skillman et al. 1996; Pilyugin et al. 2002). The spirals at the periphery of the cluster are indistinguishable from the field galaxies, whereas for the H\textsc{i}-deficient Virgo spirals near the core it has been claimed that their abundances are higher than those for the spirals located at the periphery of the cluster or in a field with comparable luminosity or Hubble type. On the other hand, several works devoted to the study of the star formation and the metal content of dwarfs in nearby clusters such as Virgo, Coma, and Hydra have revealed that some of them show different behavior with respect to field galaxies, and this fact has been attributed to the effect of the cluster environment (Vilchez 1995; Duc et al. 2001; Igalias-Páramo et al. 2003; Vilchez & Igalias-Páramo 2003; Lee et al. 2003; Vaduvescu et al. 2007; Smith et al. 2009; Mahajan et al. 2010).

In the era of the large surveys, observational clues that constrain galaxy evolution scenarios in dense environments have lately been investigated on the basis of large samples of galaxies. Mouhcine et al. (2007) suggested that the evolution of SF galaxies is driven primarily by their intrinsic properties and is largely independent of their environment over a large range of local galaxy density. On the contrary, Cooper et al. (2008) find a strong relationship between metallicity and environment, such that more metal-rich galaxies favor regions of higher overdensity. Ellison et al. (2009) also support the environmental influence, especially of the local density, on the MZ relation. It is clear that a full understanding of the role played by the environment on galaxy evolution still remains a major issue. All these works based on Sloan Digital Sky Survey (SDSS) spectroscopic data present a deficit of important observational information on dwarf cluster galaxies. In addition, SDSS provides apertures spectroscopy, thus missing spatially resolved information that can be much needed, e.g., to analyze the spatial properties of galaxies in clusters.

In this paper, we focus our attention on the nearby Hercules (A2151) cluster of galaxies and investigate the impact of the cluster environment on the chemical history of galaxies. The Hercules cluster shows an amazing variety of environments found in different parts of the cluster, which makes it one of the more interesting nearby (at a distance of 158.3 Mpc) dense environments. It has never before been studied from the chemical evolution point of view. It is the richest and densest among the three members of the Hercules supercluster (A2151, A2147, and A2152; Barmby & Huchra 1998) and appears to be a collection of groups, gravitationally bound but far from dynamical relaxation (Bird et al. 1995; Maccagni et al. 1995). Sánchez-Janssen et al. (2005) report the presence of at least three distinct regions with a varying dwarf to giant galaxy ratio within the A2151 cluster. Giovannelli et al. (1981) studied the supercluster neutral hydrogen content and found that A2147 is clearly deficient in contrast with A2151, which shows a normal to mildly gas-deficient galaxy population, indicating that A2151 may still be in the process of formation. Dickey (1997) reported the presence of strong environmental effects on the mass of H\textsc{i} in the A2151 cluster. High-resolution ROSAT data (Huang & Sarazin 1996; Bird et al. 1995) reveal an irregular X-ray emission pattern that divides this cluster into two main components, which correspond to two groups of galaxies in the region. The maximum of the cluster galaxy distribution is not coincident with the primary X-ray maximum, but with a secondary one located 10–15 arcmin to the east of the primary. This implies that most A2151 galaxies are not expected to be embedded in a hot X-ray intracluster medium (ICM). Thus, the Hercules cluster provides an ideal case in which the different effects of the cluster environment on the evolution of the galaxies can be studied as “caught in the act.”

In this work, we have benefited from our deep search for H\textalpha emitting galaxies in the Hercules cluster (Cedrés et al. 2009, C09 hereafter) to define a new sample of SF galaxies. Tracing H\textalpha emission in order to study the population of galaxies with recent star formation has two important advantages: (1) it is not aperture biased as many of the spectroscopic studies using fibers are, and (2) it reveals star-forming (SF) dwarfs that would not have been classified as SF galaxies with an optical flux criterion. We investigate gas-phase metallicities and stellar properties of galaxies that span a large range of magnitudes (−21 ≤ M\textsubscript{B} ≤ −16.5 mag) and morphologies (from grand design spirals to blue compacts and tidal dwarfs).

The present paper is organized as follows. In Section 2 we present the characteristics of our spectroscopic sample, the observations, and the data reduction. In Section 3, we present the spectral synthesis techniques performed to compute characteristic properties of the underlying stellar population. In Section 4, we derive the chemical and physical properties of our sample of galaxies, and in Section 5 we discuss the environmental effects on the Hercules cluster galaxies. Section 6 summarizes the overall picture of the Hercules cluster as revealed from the chemical evolution point of view.

2. OBSERVATIONS

2.1. The Galaxy Sample

Spatially resolved spectroscopy has been obtained for 27 Hercules SF galaxies of the C09 Hercules sample.7 We complement our sample with two more galaxies of the C09 sample, which have SDSS spectroscopy. In addition, two more galaxies are considered from the Igalias-Páramo et al. (2003, IP03 hereafter) A2151 sample of dwarf galaxies (see Section 4.2 for more details). Thus, our spectroscopic sample comprises a total of 31 galaxies and our spectroscopic follow-up of the C09 sample is completed up to an absolute magnitude M\textsubscript{B} = −17 mag. To illustrate this, in Figure 1 we show the histogram of the C09 sample of SF galaxies as a function of their M\textsubscript{B} absolute magnitude and the fraction of the galaxies with no spectroscopic data.

Our sample is composed of 15 luminous SF galaxies (M\textsubscript{B} ≤ −19) and 16 dwarf and Magellanic type irregular galaxies (M\textsubscript{B} > −19). Among the spiral/irregular galaxies, nine show discernible spatial structure and therefore their different parts

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7 From our spectroscopic data it is shown that the radial velocity of one (SDSS J160547.17+173501.6) of the C09 galaxies is out of the velocity range of the Hercules cluster, rendering its membership to the cluster unlikely. The various SDSS photo-z estimates were consistent with the criteria adopted by C09 for cluster membership. More details are given in the Appendix.
have been analyzed independently (see also Section 2.3 and Figure A2). For three luminous galaxies and three dwarfs/irregulars, we have gathered together evidence that they are affected/perturbed by galaxy–galaxy interactions, either being members of mergers, being tidal dwarf candidates (TDCs), or through their H I morphology showing evidences of interaction (we give details of these objects in the Appendix).

The Hercules cluster shows abundant substructures seen in X-ray emission and broadband imaging (Huang & Sarazin 1996). The galaxy surface density as well as the velocity space reveals the presence of subclusters in the galaxy distribution (Maccagni et al. 1995; Bird et al. 1995). The extended X-ray emission coming from the hot intracluster gas shows an irregular pattern that divides the cluster into two components. Most He emitters are located around the secondary X-ray maximum in the higher-density regions of the A2151 galaxies. The blue cross indicates the position of the cluster center given in NED. See the text for details.

Figure 1. Histogram of the C09 sample of SF galaxies as a function of their $M_B$ absolute magnitude. We show the fraction of galaxies with no spectroscopic data (filled region). Our spectroscopic follow-up of the C09 Hercules SF galaxies is complete up to absolute magnitude $M_B = -17$ mag.

Figure 2. Superposition of the map of galaxy density of the Hercules cluster (red) and the ROSAT All-Sky Survey X-ray map (blue). The density map includes all Hercules galaxies with SDSS spectroscopy. The SF galaxies of the present sample are indicated by pluses and squares. Open squares indicate dwarf galaxies with $\text{abs}(\Delta V) > \sigma_V$. The surface density of galaxies reveals the presence of subclusters. The extended X-ray emission coming from the hot intracluster gas shows an irregular pattern that divides the cluster into two components. Most He emitters are located around the secondary X-ray maximum in the higher-density regions of the A2151 galaxies. The blue cross indicates the position of the cluster center given in NED. See the text for details.

(A color version of this figure is available in the online journal.)

2.2. Optical Spectroscopy

Long-slit spectroscopy was carried out at the 4.2 m WHT and the 2.5 m Isaac Newton Telescope (INT) at the Observatorio del Roque de los Muchachos (ORM) in Spain. Table 1 shows the journal of the spectroscopic observations. We present for each galaxy the object name as quoted by C09, R.A., decl., observation date, telescope, effective wavelength range, slit position angle, and total exposure time. Most of the galaxies were observed as close to the zenith as possible, always with airmass less than 1.3, in order to minimize any differential atmospheric refraction effects, except in four cases, as indicated in Table 1, for which the paralactic angle was used.

Observations at the William Herschel Telescope (WHT) were performed during two observing runs in 2009 June and July, using the double arm spectrograph Intermediate Dispersion Spectrograph and Imaging System (ISIS) with slightly different instrumental setups. In 2009 June, the dichroic splitting the beam was set at 5300 Å and the gratings used were R300B and R158R, giving nominal dispersions of 0.86 Å pixel$^{-1}$ and 1.82 Å pixel$^{-1}$, respectively, and a spectral coverage of $\sim$3600–9230 Å. In 2009 July, the dichroic was set at 5700 Å and the gratings used were R300B and R316R, giving respective dispersions 0.83 and 0.89 Å pixel$^{-1}$ and a spectral coverage $\sim$3160–8263 Å. During both runs the CCD setup was the same: on the blue arm the EEV12 detector, providing a spatial scale 0.19 arcsec pixel$^{-1}$, and on the red arm the RED+ detector sampling 0.22 arcsec pixel$^{-1}$. Observations at the INT were also performed during two observational runs, in 2008 June and 2009 May, using the Intermediate Dispersion Spectrograph (IDS) with the EEV12 detector and R300V grating, giving a nominal dispersion of 1.86 Å pixel$^{-1}$ and a spatial scale of 0.4 arcsec pixel$^{-1}$. The total wavelength coverage free of
vignetting with this setup was \( \sim 3400-7700 \, \text{Å} \). In both ISIS and IDS spectra the slit width was set to 1.5 arcsec. The orientation of the slit, as listed in Table 1, was selected to cover the maximum surface of the Hz emission detected by Cedrés et al. (2009), with a few exceptions that were observed on the parallactic angle.

### 2.3. Data Reduction

The spectra were reduced in the standard manner using IRAF routines. First, the two-dimensional (2D) spectra were bias subtracted and flat-field corrected. For this, dome flat exposures were used to remove pixel-to-pixel variations in response. Wavelength calibration was achieved using spectra of CuNe and CuAr comparison lamps, reaching an accuracy of \(~0.3 \, \text{Å}\) for IDS and less than 0.1 Å for ISIS spectra. Several exposures were taken for each object in order to remove cosmic ray hits. The spectra were corrected for atmospheric extinction using an extinction curve for ORM (King 1985) and all observing nights were photometric, according to Carlsberg Meridian Telescope records. Enough slit length free of any object permitted an adequate sky subtraction. For the flux calibration, during the observational runs each night at least three spectrophotometric standard stars were observed, varying in color, except during 2009 June 26 and 27 when we observed two and one stars, respectively. The expected spectrophotometric error is estimated as 10% (2008 June), 8% (2009 May), 3% (2009 June), and 2% (2009 July). ISIS matching between red and blue arm spectra was successful, as can be seen in the spectra shown in Figure A1 in the Appendix.

From the 2D frames an integrated 1D spectrum was produced for those galaxies showing no significant spatial structure. Conversely, for galaxies showing rich spatial structure, their 2D spectrum is divided into 1D spectra corresponding to their different sub-regions. For these galaxies, in Figure A2 in the Appendix we show \( g-i \) color maps produced using SDSS images and Hz equivalent-width (EW) maps using our data, with the precise position of the slit overplotted on both maps. We also give the spatial profiles of the Hz line and the nearby continuum emission along the slit position extracted from the 2D spectra. On these profiles the different galaxy parts considered in our analysis are highlighted. All the 1D spectra extracted in this study are presented in Figure A1 in the Appendix.

### 3. SPECTRAL SYNTHESIS MODEL FITTING

We use the population synthesis code STARLIGHT to fit spectral synthesis models to all our spectra and compute some characteristic properties of the underlying stellar component as the luminosity-weighted and mass-weighted stellar age and metallicity (see, e.g., Asari et al. 2007). We also use the model fits to correct our spectra for underlying stellar absorption. Our galaxy sample spans a considerable range in its emission-line properties, from systems with Balmer emission lines with large EWs to systems where the H\( \beta \) is just detectable above a high

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**Table 1**

| Galaxy | R.A. (J2000.0) | Decl. (J2000.0) | Date | Tel. | Range | P.A. | Exp. |
|--------|---------------|----------------|------|------|-------|------|------|
| PGC057185 | 16 06 48.2 | 17 38 51.6 | 2008 Jun 6 | INT | 3500–7730 | 13 | 3600 |
| IC1173 | 16 05 12.6 | 17 25 22.3 | 2008 Jun 6 | INT | 3500–7730 | 45 | 3600 |
| KUG1603+179A | 16 05 30.6 | 17 46 07.2 | 2008 Jun 6 | INT | 3500–7730 | 30 | 4500 |
| NGC 6050A,B | 16 05 23.4 | 17 45 25.8 | 2008 Jun 6 | INT | 3500–7730 | 67 | 3600 |
| LEDA1543586 | 16 05 10.5 | 17 51 16.1 | 2008 Jun 7 | INT | 3500–7730 | 297 | 5300 |
| NGC 6045 | 16 05 07.9 | 17 46 31.6 | 2008 Jun 7 | INT | 3500–7730 | 75 | 4500 |
| KUG1602+174A | 16 04 39.0 | 17 20 59.9 | 2008 Jun 7 | INT | 3500–7730 | 59 | 5400 |
| LEDA084719 | 16 05 07.1 | 17 38 57.8 | 2008 Jun 7 | INT | 3500–7730 | 67 | 4200 |
| PGC057077 | 16 05 34.2 | 17 46 11.8 | 2008 Jun 8 | INT | 3500–7730 | 297 | 4500 |
| UGC10190 | 16 05 26.3 | 17 41 48.6 | 2008 Jun 8 | INT | 3500–7730 | 150 | 4500 |
| LEDA140568 | 16 06 00.1 | 17 45 52.0 | 2008 Jun 8 | INT | 3500–7730 | 10 | 5400 |
| [DKP87]160310.21+175956.7 | 16 05 25.0 | 17 47 02.0 | 2008 Jun 8 | INT | 3500–7730 | 66 | 5400 |
| LEDA057064 | 16 05 27.2 | 17 49 51.6 | 2008 Jun 9 | INT | 3500–7730 | 115 | 5400 |
| LEDA084703 | 16 03 05.7 | 17 10 20.4 | 2008 Jun 9 | INT | 3500–7730 | 82 | 5400 |
| KUG1602+175 | 16 04 45.4 | 17 26 54.3 | 2009 May 26 | INT | 3400–7630 | 315 | 3600 |
| LEDA084710 | 16 04 20.4 | 17 26 11.2 | 2009 May 26 | INT | 3400–7630 | 105 | 3600 |
| CGGC108–149 | 16 06 35.3 | 17 53 32.2 | 2009 May 26 | INT | 3400–7630 | 172 | 3600 |
| KUG1602+174B | 16 04 47.6 | 17 20 52.0 | 2009 May 26 | INT | 3400–7630 | 67 | 2400 |
| LEDA084724 | 16 05 45.5 | 17 34 56.7 | 2009 Jun 26 | WHT | 3600–9230 | 0 | 3000 |
| SDSS J160556.98+174304.1 | 16 05 57.0 | 17 43 04.1 | 2009 Jun 26 | WHT | 3600–9230 | 90 | 3600 |
| [DKP87]1606310.21+175956.7 | 16 05 25.0 | 17 51 50.6 | 2009 Jun 26 | WHT | 3600–9230 | 114 | 3600 |
| SDSS J160524.27+175329.3 | 16 05 24.3 | 17 53 29.4 | 2009 Jun 27 | WHT | 3600–9230 | 102 | 3600 |
| SDSS J160547.17+173501.6 | 16 05 47.2 | 17 35 01.7 | 2009 Jun 27 | WHT | 3600–9230 | 170 | 3600 |
| SDSS J160523.66+174832.3 | 16 05 23.7 | 17 48 32.3 | 2009 Jun 27 | WHT | 3600–9230 | 140 | 3600 |
| IC1182 | 16 05 36.8 | 17 48 07.5 | 2009 Jul 19 | WHT | 3160–8263 | 127 | 3000 |
| IC1182+[S72]d | 16 05 41.9 | 17 47 58.4 | 2009 Jul 19 | WHT | 3160–8263 | 96 | 3600 |
| SDSS J150531.84+174826.1 | 16 05 31.8 | 17 48 26.2 | 2009 Jul 19 | WHT | 3160–8263 | 66 | 3600 |

**Notes.** Column 1: Galaxy name following Cedrés et al. (2009); Column 2: right ascension in hours, minutes, and seconds; Column 3: declination in degrees, arcminutes, and arcseconds; Column 4: observation date; Column 5: telescope used; Column 6: wavelength range coverage in Å; Column 7: position angle in degrees; and Column 8: exposure time in seconds.

a This pair is also known as Arp 272.
b Observed at parallactic angle through airmass \( \geq 1.3 \).
level of stellar continuum. Especially in the latter cases, an accurate correction for underlying stellar absorption is crucial. The usual practice of adopting an $\text{EW}_{\text{abs}}$ of $\sim$2 Å for stellar Balmer lines, though generally justifiable, bears the risk of introducing significant systematic errors in the analysis of systems with faint emission lines. This is because the exact value for $\text{EW}_{\text{abs}}$ depends on the stellar population mixture, i.e., the SFH of a galaxy. For example, Gonzalez Delgado et al. (1999) infer for a single stellar population (SSP) a monotonous increase of the $\text{EW}_{\text{abs}}$ for the Balmer $\text{H}$ through $\text{H}$ lines from $\lesssim$3 Å at an age $\lesssim$3 Myr to $\geq$10 Å at ages $\sim$0.5 Gyr, followed by a decrease for older ages. SF galaxies, consisting of different SSPs of young to intermediate age, in addition to a (significantly) older underlying host galaxy, likely follow a considerably more complex time evolution in their luminosity-weighted $\text{EW}_{\text{abs}}$. This issue has been explored in much detail by, e.g., Guseva et al. (2001), who have considered a variety of SFHs and mass proportions between the young and older stellar components in SF dwarf galaxies. Obviously, for systems with low emission-line EWs, improper correction for underlying stellar absorption may propagate significant errors in, e.g., the intrinsic extinction or spectroscopic classification using BPT (Baldwin et al. 1981) diagrams. For example, for an intermediate luminosity-weighted age of 0.2–0.6 Gyr, where Balmer $\text{EW}_{\text{abs}}$s are largest, the underestimation of Balmer line fluxes due to incomplete correction for underlying stellar absorption may shift an SF galaxy on the $\log((\text{O III}) \lambda 5007/\text{H} \beta)$ versus $\log((\text{N II}) \lambda 6583/\text{H} \alpha)$ BPT diagram into the zone of active galactic nuclei (AGNs).

The determination of the $\text{EW}_{\text{abs}}$ may be carried out by simultaneous fitting of two Gaussians to each emission and absorption Balmer line profile. Another adequate, and arguably more efficient, technique for correcting for underlying stellar absorption is the fitting and subsequent subtraction of the observed spectrum of a synthetic stellar spectrum in order to isolate the net nebular line emission fluxes. To this end, we used the population synthesis code STARLIGHT (Cid Fernandes et al. 2004, 2005a, 2005b; Garcia-Rissmann et al. 2005). This code synthesizes the observed stellar continuum as due to the superposition of SSPs of different ages and metallicities. The SSP library used is based on stellar models by Bruzual & Charlot (2003) for a Salpeter IMF for three metallicities ($Z_{\odot}/5$, $Z_{\odot}/2.5$, and $Z_{\odot}$) and 59 ages (between 0.25 Myr and 13 Gyr). Output of the model is the list of those SSPs with a mass contribution $M_i > 0$ (%) and their luminosity contribution $L_i$ (%) to the wavelength interval to which the input spectra have been normalized (5100–5300 Å here).

Prior to modeling, the observed spectra were de-redshifted and resampled to 1 Å pixel$^{-1}$. Additionally, emission lines and residuals from the night sky subtraction were identified and interactively flagged using a code we developed. Throughout, we preferred not to correct the input spectra for intrinsic extinction or to strongly constrain its allowed range in the STARLIGHT models for two reasons. First, the extinction coefficient $C(\text{H} \beta)$ computed prior to correction of Balmer emission-line fluxes for underlying stellar absorption is, especially for galaxies with faint nebular emission, uncertain. An a priori de-reddening of the input spectra using this approximate $C(\text{H} \beta)$ value would therefore yield no advantage toward reliability and computational expense. For the same reason, and in order to minimize biases in the STARLIGHT solutions, we have allowed the intrinsic extinction to vary between $+4.5$ and $-0.7$ V mag. The allowance for a negative $A_V$ is justified by possible uncertainties in flux calibration, the (partial) coverage of the physical spatial area of the galaxy, and the incompleteness of the SSP library. As evident in Table 2, solutions with $A_V \leq 0$ are the exception in our analysis. Second, fixing the intrinsic extinction in the STARLIGHT models to the observed $C(\text{H} \beta)$ would imply that ionized gas and stars are subject to equal extinction. No compelling evidence exists for this as yet. On the other hand, for the sake of simplicity and to keep computational time low, we have throughout assumed a single foreground extinction model, although provision is given in STARLIGHT to solve for a different extinction in the young ($\lesssim$10 Myr) and older stellar populations.

A typical example of the spectral synthesis for a galaxy with relatively faint nebular emission in our sample is shown in Figure 3. The left panel shows the observed, normalized
determination and correction for underlying absorption. The stellar absorption features well, thus permitting an adequate fit.

It may be seen from the left panel that synthetic spectra fit broad features well, thus permitting an adequate fit.

The shaded area in the lower diagram shows the smoothed spectrum (orange color) with the best-fitting synthetic spectrum overlaid (blue color). Flagged intervals in each spectrum are marked with shaded vertical bars. The smaller panels to the right show the age distribution of the SSPs evaluated by STARLIGHT as a function of, respectively, luminosity and mass fraction in percent. Thin vertical lines in the right panel indicate the ages of the library SSPs. The shaded area in the lower right panel shows the smoothed M/L distribution and is meant as a schematic illustration of the SFH. It may be seen from the left panel that synthetic spectra fit broad stellar absorption features well, thus permitting an adequate determination and correction for underlying absorption. The corrected emission-line fluxes, as measured from the observed spectra after subtraction of the synthetic stellar spectra, are listed in Table 3 (see Section 4 for a detailed discussion).

Although an elaborate study of the SFH of the sample galaxies is beyond the scope of this paper, we have included some characteristic properties of our sample galaxies. These include the luminosity-weighted and mass-weighted metallicity Zₖ,L and Zₖ,M along with their standard deviations and the intrinsic extinction AV of the stellar component as given by fitting STARLIGHT models.

Table 2

| Galaxy       | Zₖ,L  | Zₖ,M  | τₖ,L (Gyr) | τₖ,M (Gyr) | AV (mag) |
|--------------|-------|-------|------------|------------|---------|
| PGC05185b    | 0.016 ± 0.002 | 0.005 ± 0.001 | 2.56 ± 0.51 | 6.68 ± 0.54 | 1.19    |
| D97ce000     | 0.005 ± 0.001 | 0.010 ± 0.002 | 1.97 ± 0.61 | 1.86 ± 0.64 | 0.64    |
| LEDA14007b   | 0.006 ± 0.001 | 0.007 ± 0.001 | 2.68 ± 0.50 | 6.26 ± 0.62 | 0.84    |

Notes. The luminosity-weighted and mass-weighted stellar metallicity (e.g., the mass fraction of metals over H, where the solar value is assumed to be Z☉ = 0.019) Zₖ,L and Zₖ,M and stellar age τₖ,L and τₖ,M along with the standard deviations and the intrinsic extinction AV of the stellar component as given by fitting STARLIGHT models.
| Line     | $f(\lambda)$ | PGC057185 | IC1173 |
|----------|--------------|-----------|--------|
|          | $a$          | $b$       | $c$    |
|          | $a$          | $b$       | $c$    |
| 3727 [O II] | 0.271 | 305 ± 20 | 231 ± 5 | 239 ± 53 | 206 ± 37 | 991 ± 131 | 118 ± 9 |
| 3869 [Ne III] | 0.238 | ... | ... | ... | ... | ... | ... |
| 3889 He II + H8 | 0.233 | ... | ... | ... | ... | ... | ... |
| 3968 [Ne III] + H7... | 0.216 | ... | ... | ... | ... | ... | ... |
| 4069 [S II] | 0.195 | ... | ... | ... | ... | ... | ... |
| 4102 Hβ | 0.188 | ... | 26 ± 5 | ... | ... | ... | 48 ± 2 |
| 4340 Hγ | 0.142 | 50 ± 16 | 47 ± 8 | ... | ... | ... | ... |
| 4861 Hβ | 0.00 | 100 ± 8 | 100 ± 9 | 100 ± 18 | 100 ± 13 | 100 ± 12 | 100 ± 7 |
| 4959 [O III] | −0.024 | ... | 12 ± 2 | ... | ... | ... | ... |
| 5007 [O IV] | −0.035 | 57 ± 4 | 36 ± 2 | 54 ± 10 | 25 ± 15 | 236 ± 18 | 88 ± 6 |
| 5876 He I | −0.209 | ... | 11 ± 1 | ... | ... | ... | ... |
| 6300 [O I] | −0.276 | 21 ± 5 | 16 ± 1 | ... | ... | 71 ± 15 | ... |
| 6548 [N II] | −0.311 | 31 ± 3 | 39 ± 6 | 30 ± 7 | 62 ± 11 | 180 ± 26 | ... |
| 6563 Hα | −0.313 | 302 ± 14 | 294 ± 8 | 282 ± 54 | 285 ± 40 | 285 ± 1 | 287 ± 15 |
| 6584 [N II] | −0.316 | 85 ± 5 | 113 ± 7 | 94 ± 18 | 140 ± 21 | 492 ± 68 | 103 ± 10 |
| 6717 [S II] | −0.334 | 64 ± 4 | 46 ± 4 | 50 ± 11 | 38 ± 7 | 157 ± 24 | 84 ± 3 |
| 6731 [S II] | −0.336 | 55 ± 4 | 41 ± 4 | 44 ± 11 | 54 ± 19 | 152 ± 24 | 63 ± 8 |
| $F(H\beta)$ | 4.8 ± 0.4 | 15.7 ± 1.5 | 2.1 ± 0.4 | 1.7 ± 0.2 | 2.3 ± 0.3 | 2.2 ± 0.2 |
| EW($H\beta$) | 6.5 ± 0.8 | 5.5 ± 0.6 | 3.0 ± 0.6 | 1.9 ± 0.3 | 1.6 ± 0.4 | 8.1 ± 1.6 |
| c($H\beta$) | 0.70 ± 0.06 | 1.09 ± 0.02 | 1.29 ± 0.26 | 1.02 ± 0.19 | 0.96 ± 0.19 | −0.21 ± 0.29 |
| Velocity | 11403 ± 27 | 11204 ± 19 | 11122 ± 30 | 10617 ± 15 | 11204 ± 19 | 10248 ± 44 |

**Note.** $F(H\beta)$ in $10^{-16}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$; EW($H\beta$) in Å; Velocity in km s$^{-1}$.

### Table 3 (Continued)

| Line     | $f(\lambda)$ | KUG1603 + 179A | NGC 6050A | NGC 6050B |
|----------|--------------|--------------|-----------|-----------|
|          | $a$          | $b$          | $c$      | $a$       | $b$      |
|          | $a$          | $b$          | $c$      | $a$       | $b$      |
| 3727 [O II] | 0.271 | 205 ± 5 | 133 ± 11 | 172 ± 7 | 151 ± 16 | 128 ± 15 | 176 ± 45 |
| 3869 [Ne III] | 0.238 | ... | ... | ... | ... | ... | ... |
| 3889 He II + H8 | 0.233 | ... | 24 ± 1 | ... | 35 ± 2 | ... | ... |
| 3968 [Ne III] + H7... | 0.216 | 17 ± 3 | ... | ... | 18 ± 2 | ... | ... |
| 4069 [S II] | 0.195 | 14 ± 2 | ... | ... | ... | ... | ... |
| 4102 Hδ | 0.188 | 25 ± 4 | 28 ± 5 | ... | 27 ± 8 | ... | ... |
| 4340 Hγ | 0.142 | 46 ± 2 | 41 ± 5 | 49 ± 2 | ... | 43 ± 8 | 48 ± 11 |
| 4861 Hβ | 0.00 | 100 ± 3 | 100 ± 3 | 100 ± 3 | 100 ± 10 | 100 ± 5 | 100 ± 5 |
| 4959 [O III] | −0.024 | ... | 13 ± 3 | 17 ± 3 | ... | 38 ± 6 | ... |
| 5007 [O IV] | −0.035 | 43 ± 2 | 37 ± 4 | 48 ± 2 | 61 ± 5 | 33 ± 3 | 107 ± 6 |
| 5876 He I | −0.209 | 12 ± 2 | ... | 9 ± 1 | ... | ... | ... |
| 6300 [O I] | −0.276 | 8 ± 1 | 16 ± 2 | ... | 41 ± 0 | 5 ± 1 | ... |
| 6548 [S II] | −0.311 | 36 ± 2 | 44 ± 5 | 40 ± 1 | 53 ± 8 | 34 ± 3 | ... |
| 6563 Hα | −0.313 | 279 ± 4 | 261 ± 23 | 306 ± 10 | 286 ± 38 | 285 ± 15 | 293 ± 9 |
| 6584 [N II] | −0.316 | 105 ± 2 | 148 ± 13 | 116 ± 4 | 184 ± 23 | 100 ± 6 | 82 ± 7 |
| 6717 [S II] | −0.334 | 46 ± 1 | 36 ± 4 | 47 ± 2 | 36 ± 7 | 37 ± 3 | 45 ± 4 |
| 6731 [S II] | −0.336 | 39 ± 1 | 47 ± 5 | 38 ± 2 | 69 ± 11 | 36 ± 3 | 65 ± 10 |
| $F(H\beta)$ | 11.2 ± 0.4 | 16.0 ± 0.5 | 14.4 ± 0.5 | 8.0 ± 0.8 | 10.2 ± 0.4 | 7.7 ± 0.4 |
| EW($H\beta$) | 9.3 ± 0.7 | 4.9 ± 0.3 | 10.4 ± 0.7 | 2.6 ± 0.3 | 15.1 ± 1.5 | 4.9 ± 0.5 |
| c($H\beta$) | 0.49 ± 0.02 | 1.25 ± 0.12 | 0.35 ± 0.05 | 0.32 ± 0.17 | 0.57 ± 0.07 | 0.16 ± 0.03 |
| Velocity | 11280 ± 30 | 11162 ± 20 | 11121 ± 27 | 9524 ± 38 | 9686 ± 37 | 11134 ± 39 |

### 4. RESULTS

#### 4.1. Line Fluxes

Line fluxes were measured in the spectra after subtracting the best-fitting spectral energy distribution (SED) of the underlying stellar population (see Section 3) using the SPLOT task of IRAF. Line fluxes were measured integrating the flux under the line profile over a linearly fitted continuum. In order to account for the main source of error in our data, driven by the continuum placement, five independent measurements of the emission-line flux were carried out for each line, and we assumed the mean and the standard deviation as the flux measurement and the corresponding statistical error.

The reddening coefficients $c(H\beta)$ were calculated adopting the galactic extinction law of Miller & Mathews (1972) with $R_V = 3.2$, as presented in Hägeler et al. (2008), using the expression

$$
\log \left[ \frac{I(\lambda)}{I(H\beta)} \right] = \log \left[ \frac{F(\lambda)}{F(H\beta)} \right] + c(H\beta) f(\lambda),
$$

where $I(\lambda)/I(H\beta)$ is the theoretical and $F(\lambda)/F(H\beta)$ is the observed Balmer decrement. The theoretical Balmer decrement
depends on electron temperature and density, and we used the data for Case B assuming low-density limit and 10,000 K (Storey & Hummer 1995). In those cases in which we measured at least three Balmer lines with signal-to-noise ratio (S/N) > 5 we have performed a least-squares fit to derive \( \phi(H\beta) \), and the corresponding error was taken to be the uncertainty of the fit. When only \( H_\alpha \) and \( H\beta \) were available, \( \phi(H\beta) \) was derived applying expression (1) and its error was calculated as the \( \text{rms} \) of a Gaussian error distribution produced by a random sampling simulation, taking into account the errors in the line fluxes of \( H_\alpha \) and \( H\beta \).

Reddening-corrected line fluxes and reddening coefficients \( \phi(H\beta) \) are presented in Table 3. The errors quoted account for the uncertainties in the line flux measurement and in the extinction coefficient. Table 3 also presents the \( H\beta \) flux not corrected for extinction and EW, as well as the galaxy recessional velocity, as derived by our spectroscopic data. The \( H\beta \) EW quoted was determined from the net emission spectrum, i.e., the observed spectrum after subtraction of the best-fitting stellar SED, and the level of the adjacent continuum in the original spectrum.

Figure 4 shows the extinction of the gas-phase component \( A_{V,\text{gas}} \approx 2.18 \times \phi(H\beta) \) as a function of the intrinsic extinction of the stellar component derived by STARLIGHT in the previous section. A linear fit, considering the (relatively) small errors in the extinction coefficients, yields the relation 

\[
A_{V,\text{gas}} = 2.18 \times \phi(H\beta) + A_{V,\text{star}} < -0.1
\]
Table 3 (Continued)

| Line       | f(\lambda) | LEDA140568 | [D97]ce-200 | PGC057064 | LEDA084703 |
|------------|-------------|------------|-------------|-----------|------------|
|            | a           | b          |             | a         | Int a      |
| 3727 [OIII] | 0.271       | 314 ± 20   | 326 ± 23    | 256 ± 23  | 636 ± 21   | 331 ± 5    | 339 ± 10   |
| 3869 [NeII] | 0.238       | 44 ± 9     | ...         | ...       | 22 ± 1     | 22 ± 2     |
| 3968 [NeIII]+H\beta | 0.216       | ...         | ...         | ...       | 22 ± 1     | 15 ± 2     |
| 4069 [SII]  | 0.195       | ...         | ...         | ...       | 18 ± 1     | 20 ± 3     |
| 4102 H\alpha | 0.188       | ...         | ...         | ...       | ...        | ...        |
| 4340 H\gamma | 0.142       | 47 ± 10    | 46 ± 3     | 46 ± 8   | 49 ± 1     | 49 ± 1     |
| 4861 H\beta | 0.000       | 100 ± 6    | 100 ± 8    | 100 ± 7  | 100 ± 5   | 100 ± 1   | 100 ± 1     |
| 4959 [OIII] | -0.024      | 70 ± 4     | 53 ± 6    | 41 ± 10  | 57 ± 5    | 61 ± 2     |
| 5007 [OIII] | -0.035      | 214 ± 5    | 163 ± 4    | 45 ± 4  | 134 ± 8  | 177 ± 1   | 187 ± 2     |
| 5876 HeII  | -0.209      | ...         | ...         | ...       | 14 ± 1     | 14 ± 2     |
| 6300 [OII] | -0.276      | ...         | 20 ± 1    | 13 ± 4  | 16 ± 2     | 14 ± 1     | 12 ± 1     |
| 6584 [NII] | -0.311      | ...         | 12 ± 3    | 44 ± 4  | 56 ± 3     | 16 ± 2     | 11 ± 2     |
| 6563 HeI  | -0.313      | 286 ± 20   | 286 ± 2    | 286 ± 19 | 282 ± 6   | 292 ± 6   | 219\*       |
| 6584 [NII] | -0.316      | 16 ± 5     | 35 ± 2    | 126 ± 10 | 155 ± 5  | 43 ± 2     | 31 ± 1     |
| 6717 [SII] | -0.334      | 39 ± 3     | 60 ± 1    | 48 ± 4  | 77 ± 5     | 55 ± 2     | 39 ± 2     |
| 6731 [SII] | -0.336      | 23 ± 3     | 51 ± 1    | 27 ± 2  | 64 ± 6     | 40 ± 2     | 29 ± 1     |

Note. \* Uncertain value.

Table 3 (Continued)

| Line       | f(\lambda) | LEDA084703 | KUG1602 + 175 | LEDA084710 | CGCG108–149 | KUG1602 + 174B |
|------------|-------------|------------|---------------|-------------|--------------|----------------|
|            | b           | c          |               |             |              |                |
| 3727 [OIII] | 0.271       | 360 ± 8    | 514 ± 10      | 159 ± 12    | 361 ± 110   | 159 ± 53      | 164 ± 18    |
| 3869 [NeII] | 0.238       | 21 ± 2     | ...           | ...         | ...         | ...            |
| 3968 [NeIII]+H\beta | 0.216       | ...         | ...         | 22 ± 4    | ...         | ...            |
| 4069 [SII]  | 0.195       | ...         | ...         | ...        | ...         | ...            |
| 4102 H\alpha | 0.188       | 24 ± 1     | 25 ± 3     | ...        | ...         | ...            |
| 4340 H\beta | 0.142       | 47 ± 1    | 47 ± 8    | 47 ± 5    | ...         | 46 ± 7        |
| 4861 H\beta | 0.000       | 100 ± 1   | 100 ± 2    | 100 ± 8   | 100 ± 11    | 100 ± 17     | 100 ± 6     |
| 4959 [OIII] | -0.024      | 57 ± 1    | 44 ± 2    | ...       | ...         | ...            |
| 5007 [OIII] | -0.035      | 186 ± 2   | 131 ± 3    | 56 ± 7    | 82 ± 9     | 53 ± 4        | 50 ± 5      |
| 5876 HeI  | -0.209      | 13 ± 2    | 11 ± 1    | ...        | 7 ± 4     | ...            |
| 6300 [OII] | -0.276      | 13 ± 1    | 20 ± 5    | ...       | 15 ± 4    | ...            |
| 6584 [NII] | -0.311      | 14 ± 1    | 20 ± 1    | 37 ± 2    | 30 ± 5    | ...            |
| 6563 HeI  | -0.313      | 280 ± 7   | 290 ± 3    | 282 ± 7   | 285 ± 34    | 283 ± 52     | 283 ± 6     |
| 6584 [NII] | -0.316      | 42 ± 1    | 49 ± 2    | 103 ± 6   | 89 ± 12    | 165 ± 32     | 97 ± 5      |
| 6717 [SII] | -0.334      | 48 ± 1    | 84 ± 2    | 45 ± 3    | 63 ± 9    | 50 ± 14     | 55 ± 4      |
| 6731 [SII] | -0.336      | 38 ± 1    | 48 ± 2    | 23 ± 4    | 36 ± 6    | 54 ± 15     | 44 ± 4      |

| F(H\beta)  | 17.0 ± 0.0   | 3.7 ± 0.1   | 27.2 ± 2.1   | 10.0 ± 1.1  | 4.1 ± 0.7 | 11.6 ± 0.7 |
| EW(H\beta) | 16.5 ± 0.8   | 6.2 ± 0.6   | 4.2 ± 0.4    | 3.3 ± 0.5  | 1.4 ± 0.2 | 4.8 ± 0.5 |
| c(H\beta)  | 0.59 ± 0.03  | 0.50 ± 0.01 | 0.45 ± 0.03  | 1.18 ± 0.16 | 1.16 ± 0.25 | 0.48 ± 0.02 |
| Velocity   | 10032 ± 11   | 10087 ± 16  | 10574 ± 20   | 10781 ± 32 | 11121 ± 15 | 10622 ± 15 |

0.81 ± 0.89A_V,star. We find that stars suffer less extinction than gas; this can be explained if the dust has a larger covering factor for the ionized gas than for the stars (Calzetti et al. 1994). In the same line are recent results presented by Monreal-Ibero et al. (2010) and Alonso-Herrero et al. (2010), who explore the relation between the extinction suffered by the gas and by the stellar populations in the central regions of SF galaxies using integral field unit (IFU) spectroscopic data.

4.2. Comparison with Previous Data

SDSS spectroscopic data exist for 22 out of the 43 SF galaxies of the C09 sample. In most of the cases the SDSS fiber covers the central 3 arcsec of the galaxy; for three galaxies, NGC 6050, NGC 6045, and PGC057064, SDSS provides two different aperatures on each of them. We applied the same procedure to these spectra as to our spatially resolved spectra, removing the continuum emission by fitting STARLIGHT and measuring line fluxes on the subtracted emission-line spectrum as described in Sections 3 and 4.1. We then compared these line fluxes with our line fluxes for 19 galaxies for which we have ORM long-slit spectra. We checked first whether the SDSS aperture position matches the long-slit locus and then extracted the spectrum from the corresponding area of the long slit. The comparison is shown in Figure 5 where the principal emission lines are
shown as measured, without applying any reddening correction to them (cyan: [O III] 3727, red: Hα 6563, blue: [O II] 5007, pink: [N II] 6583, green: [S II] 6717, and yellow: [S II] 6731). Despite the fact that the covered regions are not identical (this could be due to the inhomogeneous nature of SF regions), we can see that line ratios show a good agreement. While most of the points lie within the 0.2 dex scatter region from the 1:1 line, there are some emission features that display larger discrepancies. This mostly happens in the cases of galaxies in which the SDSS fiber is placed in the center of the galaxy, where the covered regions are not identical (this could be due to the inhomogeneous nature of SF regions).

In addition, IP03 have spectroscopic data for seven galaxies belonging to the C09 sample in the Hercules cluster. We compared the line fluxes, before the reddening correction, for five galaxies for which we have spectra in common (Figure 5, open circles). We also see very good agreement, with a small variation expected given the different position angles and different data analyses.

The galaxies SDSSJ160304.20+171126.7, SDSSJ160520.58+175210.6, and SDSSJ160305.24+171361.6, quoted in the C09 sample, only have SDSS spectroscopy. The same procedure described in Sections 3 and 4.1 was applied to these galaxies. For the latter, even after applying STARLIGHT to the SDSS spectrum, we do not glean any emission line because the SDSS fiber is placed in the center of the galaxy, where no Hα emission is present. The other two are included in our sample; their STARLIGHT outputs and line flux measurements are also quoted in Tables 2 and 3, respectively. Finally, in this work are also incorporated two galaxies (LEDA085054 and D97ce-143), which belong to the C09 sample and for which
Figure 4. Gas-phase extinction estimated using the Balmer emission lines vs. the extinction of the stellar component derived by STARLIGHT model fits on the continuum emission. A weighted linear fit to the data (solid line) yields the relation $A_{V,\text{gas}} = 0.81 + 0.89 A_{V,\text{star}}$.

Figure 5. Emission-line ratios $I(\lambda)/I(H\beta)$ for the principal emission lines (without applying reddening correction) as derived by the ORM long-slit spectra observed for this work vs. corresponding ratios from SDSS (filled points) or IP03 spectra (open cycles) for the same galaxy regions. Cyan: [O II] $\lambda$3727, red: Hα 6563, blue: [O III] $\lambda$5007, pink: [N II] $\lambda$6583, green: [S II] $\lambda$6717, and yellow: [S II] $\lambda$6731. The continuous line is the line of equality and the dotted lines indicate a variation by $\pm 0.2$ dex.

(A color version of this figure is available in the online journal.)

spectroscopic data are available by IP03; all these spectra give a final coverage of the C09 sample of 72%.

4.3. Abundance Derivation

The radiation emitted by a nebula depends on the abundances of the chemical elements and the physical state of the gas, especially its average temperature and density. Physical and chemical properties of nebulae can be derived by measuring the intensities of collisionally excited emission lines. After hydrogen and helium, the most abundant element in the universe is oxygen. Additionally, oxygen presents bright emission lines in the optical range when H II regions of the local universe are observed. In practice, the metallicity of SF galaxies is quantified via the oxygen abundance, as $12 + \log(O/\text{H})$.

Prior to the determination of the gas-phase chemical abundances, the excitation conditions of the gas have to be explored. In order to do that we use the BPT diagrams (Baldwin et al. 1981). The derivation of gas-phase metal abundances is constrained to nebular emission-line spectra generated by photoionization from massive stars. Non-stellar ionizing sources, such as AGNs, produce generally distinctive emission-line ratios compared to ordinary H II regions. In Figure 6, we present the BPT diagram with Kauffmann et al. (2003) empirical demarcation curve with a continuous blue line, and Kewley et al. (2001) theoretical upper limit for starburst galaxies with a dashed black line, in order to identify non-stellar ionizing sources. We use four distinctive colors/symbols for our sample of galaxies. With blue filled circles we plot the 16 integrated dwarf/irregular galaxies ($M_B > -19$) of our sample. With red stars we plot the nuclei of six spirals and with green triangles their corresponding disk regions. Magenta squares are used for luminous ($M_B < -19$) galaxies for which we integrate the 2D long-slit spectrum into one 1D spectrum (PGC057077 is plotted with magenta squares and PGC057064 with blue filled circles). We mark with a square the galaxy SDSS J160531.84+174826.1, which has been claimed (Dong et al. 2007) hosts a Seyfert 1 AGN.

(A color version of this figure is available in the online journal.)
for different reasons; see the Appendix for details). Although we have divided the spectrum of the irregular galaxy LEDA084703 into three parts, from now on we consider the integrated values because they show homogeneous chemical composition (see the Appendix for details on this galaxy). In Figure 6, we see that the nuclei of NGC 6045, NGC 6050A, KUG1602+175A, galaxy CGCG108+149, and the southeastern part of the peculiar object PGC057064 (see the Appendix for special notes on this object) belong to the transition zone between the two separation curves. IC1182 lies on the separation curve of Kauffmann et al. (2003), and there is a controversy in the literature whether there is an AGN hosted in the nucleus of this merger (see Radovich et al. 2005 and references therein), but our long-slit spectrum is slightly off-set from the optical center. A detailed investigation of the nature of this peculiar object is out of the scope of the present paper and will be presented in a forthcoming work (V. Petropoulou et al. 2011, in preparation). The nucleus of IC1173 clearly lies in the AGN region; we do not include it in our abundance analysis. We mark with a square the galaxy CGCG108+149, and the southeastern part of the peculiar object PGC057064 (see the Appendix for special notes on this object) as a possible consequence of the bi-valuated nature of the O/III abundance in HII regions. The direct method is founded on the collisionally excited lines such as [OIII] λ4363, [NII] λ5755, [SII] λ6312 are measured. We do not detect any of the temperature diagnostic lines in our spectra. In addition, considering Hercules distance and the resolution of our observations, we are constrained to integrate galaxy spectra over large spatial scales, in some cases containing several HII regions.

In Figure 7, we show the histograms of the distribution of the N2S2 and R23 parameters for our sample of galaxies, using the same colors to separate our sample into four categories as in Figure 6. The histograms in both the left and right panels correspond to, from top to bottom: dwarf/irregulars, disks of spirals, integrated spirals, and nuclei of spirals.

**Figure 7.** Histogrames of the distribution of the N2S2 (left) and R23 (right) parameters for our sample of galaxies, using the same colors to separate our sample into four categories as in Figure 6. The histograms in both the left and right panels correspond to, from top to bottom: dwarf/irregulars, disks of spirals, integrated spirals, and nuclei of spirals.

(A color version of this figure is available in the online journal.)

N2S2 = −0.4, although there are few objects sorting out to higher values. These high values, as we will see later in the discussion, seem consistent with the properties of these galaxies. Spiral galaxies are separated into three categories. The galaxies for which we only have an integrated spectrum (magenta line, third from the top) show N2S2 values extending up to 0.4, and the most populated range is around 0.1–0.2. The other two categories correspond to massive galaxies divided into nuclei (red line, fourth from the top) and disks (green, second from the top). Although both distributions show a common range of N2S2 values from 0.0 to 0.3, there is a tendency for the spectra of the central parts to present higher N2S2 than the disks, which can reach values as low as −0.3. In the same line for the R23 distribution, the dwarfs (right panel, first histogram from the top, with blue line) present the larger values of R23 up to 8 with few objects presenting values as low as R23 = 1–3 (as we will show later, this is a hint on the nature of these objects). However, as a possible consequence of the bi-valuated nature of the O/H versus R23 function, the separation among the bright galaxies is not as clear as in the left panel. Nonetheless it can be seen that, for integrated bright galaxies (magenta, third from the top), the R23 distribution shows a large range with values from 2 to 7 with the most populated values close to 2; for the spatially resolved galaxies, the range of disks reaches higher values (up to 4) compared to nuclei (up to 3). This analysis highlights the fact that using SDSS spectroscopy, which most probably means sampling only galaxy centers (bottom histogram, with red line), could introduce a bias in the abundance results.

There are two commonly used methods to determine oxygen abundances in HII regions. The direct method is founded on a direct measurement of the electron temperature, applicable when the collisionally excited lines such as [OIII] λ4363, [NII] λ5755, [SII] λ6312 are measured. We do not detect any of the temperature diagnostic lines in our spectra. In addition, considering Hercules distance and the resolution of our observations, we are constrained to integrate galaxy spectra over large spatial scales, in some cases containing several HII regions.
regions, with potentially different ionization conditions. In these cases, the use of the direct method to derive abundances could be misleading (e.g., Kobulnicky et al. 1999).

The other way to determine oxygen abundances in H II regions is to use semi-empirical calibrations. There are two different types of calibrations: the empirical ones, based on fits to objects for which an accurate direct derivation of O/H is available (e.g., Pettini & Pagel 2004; Nagao et al. 2006; Pérez-Montero & Contini 2009; Pilyugin & Thuan 2005; Pilyugin et al. 2010) and the ones based on predictions of theoretical photoionization models (e.g., McGaugh 1991; Kewley & Dopita 2002; Tremonti et al. 2004). For an extensive review, see Lopez-Sanchez & Esteban (2010) and Kewley & Ellison (2008).

It has been shown recently (Bresolin et al. 2009) that model calibrations show a positive shift of 0.3 dex compared to oxygen abundances derived with the direct method, whereas the latter agree very well with oxygen abundances derived for the massive young stars. For our sample we also find a 0.3 dex positive shift between the abundances predicted using McGaugh (1991) model calibration (formulated by Kobulnicky et al. 1999) and the empirical calibration calculated by Pilyugin et al. (2010). Taking this into account, in this analysis we have chosen empirical calibrations.

Our sample spans from very low metallicity dwarfs to evolved disks and galaxy centers, with an important fraction lying in the turnover region of the R23 versus oxygen abundance relation (see Figure 7). For the empirical calibrations we use the N2 calibration given by Pérez-Montero & Contini (2009, hereafter PMC09) and the recent calibration by Pilyugin et al. (2010, hereafter P10) because they have the advantage of being valid along the entire metallicity range of our sample. The N2 parameter shows a monotonic relation with oxygen abundance, thus avoiding the degeneracy problem of R23; though this calibration involves a large rms error of up to ∼0.3 dex. In order to circumvent this problem P10 has provided a new improved calibration, which uses a multiparametric function of P, R2, R3, S2, N2 parameters and produces a very small rms error ∼0.07 dex. In Table 4, we give the oxygen abundance derived using both abundance calibrations. We are aware that using nitrogen as an abundance indicator from which to derive oxygen abundances can be potentially dangerous in case of objects with particular evolution, for example, for nitrogen-enriched galaxies (see PMC09). Comparing both abundance calibrations, we interpret PMCO9 abundances as an upper estimate and P10 as a lower estimate and, being conservative, we have adopted the mean of the two oxygen abundances. For each galaxy of our sample the adopted O/H value is consistent with the prediction of both calibrations within the statistical errors. For each O/H determination we have estimated the corresponding error as the rms of a Gaussian error distribution produced by a random sampling simulation taking into account the errors of the P, R23, R2, R3, S2, and N2 parameters. This error estimation has been adopted in all cases except in those cases for which it is lower than the statistical error provided by the P10 calibration (∼0.07 dex), which was finally adopted. As can be noted in Table 4, the error adopted is very close to half of the difference in O/H provided by both calibrations.

Nitrogen is also an important element in investigating galaxy evolution. Nitrogen abundance deserves a more thorough de-

\[15\text{Defined by MCOC9 as N2} = \log \left( \frac{I_{\text{[N} \alpha \text{]}6583}}{I_{\text{H} \beta}} \right)\]

\[16\text{Defined in P10 as N2} = \log \left( \frac{I_{\text{[N} \alpha \text{]}6548+6583}}{I_{\text{H} \beta}} \right) - S2 = \log \left( \frac{I_{\text{[N} \alpha \text{]}6548}}{I_{\text{H} \beta}} \right) - 1.04, \text{and} \ P = R3/R23 \text{. The theoretical ratio [N II] 6583/[N II] 6548 = 0.3 is assumed when necessary.}

\[\log \Sigma_{4,5} = \frac{1}{2} \log \left( \frac{4}{\pi d_V^2} \right) + \frac{1}{2} \log \left( \frac{5}{\pi d_V^2} \right), \quad (2)\]

considering all galaxies with SDSS spectra in the Hercules region at the corresponding redshift range, and presenting a difference in radial velocity smaller than 750 km s\(^{-1}\), a value approximately equal to \(\sigma_V\) of the cluster.

To account for possible fiber collisions that may lead to an underestimate of the local density in regions rich in projected galaxies as cluster centers, we calculate the local galaxy number density to the 10th nearest neighbor \(\Sigma_{10}\), using a magnitude-limited sample of galaxies taken from the SDSS database without velocity constrain. Counts of galaxies as a proxy of
Table 4

| GALAXY         | 12+log(O/H) | 12+log(O/H) | 12+log(O/H) | error | log(N/O) |
|---------------|-------------|-------------|-------------|-------|----------|
|               | PMC09       | P10         | adopted     |       |          |
| PGC057185a    | 8.64        | 8.48        | 8.56        | 0.07  | −1.04    |
| PGC057185b    | 8.74        | 8.53        | 8.63        | 0.07  | −0.72    |
| PGC057185c    | 8.69        | 8.50        | 8.60        | 0.12  | −0.86    |
| IC1173a       | 8.83        | 8.56        | 8.69        | 0.26  | −0.63    |
| IC1173c       | 8.72        | 8.57        | 8.65        | 0.07  | −1.05    |
| KUG1603+179Aa | 8.73        | 8.53        | 8.63        | 0.07  | −0.74    |
| KUG1603+179Ab | 8.88        | 8.57        | 8.72        | 0.07  | −0.54    |
| KUG1603+179Ac | 8.74        | 8.53        | 8.64        | 0.07  | −0.69    |
| NGC 6050Aa    | 8.92        | 8.53        | 8.72        | 0.07  | −0.55    |
| NGC 6050Ab    | 8.71        | 8.59        | 8.65        | 0.07  | −0.69    |
| NGC 6050B     | 8.63        | 8.52        | 8.58        | 0.07  | −1.02    |
| LEDA1543586   | 8.43        | 8.34        | 8.38        | 0.07  | −1.15    |
| NGC 6054Aa    | 8.77        | 8.49        | 8.63        | 0.09  | −0.71    |
| NGC 6054Ab    | 8.74        | 8.54        | 8.64        | 0.07  | −0.57    |
| NGC 6045c     | 8.95        | 8.54        | 8.75        | 0.07  | −0.36    |
| NGC 6045d     | 8.66        | 8.61        | 8.65        | 0.07  | −0.53    |
| NGC 6045e     | 8.74        | 8.46        | 8.60        | 0.07  | −0.74    |
| KUG1602+174A  | 8.72        | 8.58        | 8.65        | 0.12  | −0.81    |
| LEDA084568    | 8.08        | 8.05        | 8.07        | 0.11  | −1.60    |
| PGC057077a    | 8.75        | 8.46        | 8.61        | 0.26  | −0.69    |
| PGC057077b    | 8.73        | 8.46        | 8.60        | 0.07  | −0.64    |
| UGC10190a     | 8.70        | 8.54        | 8.62        | 0.07  | −0.63    |
| UGC10190b     | 8.72        | 8.58        | 8.65        | 0.07  | −0.86    |
| UGC10190c     | 8.61        | 8.50        | 8.55        | 0.07  | −1.27    |
| LEDA140568    | 8.08        | 8.05        | 8.07        | 0.11  | −1.60    |
| [D97]ce-200   | 8.35        | 8.19        | 8.27        | 0.07  | −1.49    |
| PGC57064a     | 8.79        | 8.50        | 8.64        | 0.07  | −0.58    |
| PGC57064b     | 8.86        | 8.35        | 8.61        | 0.07  | −0.81    |
| LEDA084703int| 8.41        | 8.28        | 8.35        | 0.07  | −1.29    |
| LEDA084703a   | 8.40        | 8.24        | 8.32        | 0.07  | −1.29    |
| LEDA084703b   | 8.42        | 8.29        | 8.35        | 0.07  | −1.25    |
| LEDA084703c   | 8.46        | 8.26        | 8.36        | 0.07  | −1.40    |
| KUG1602+175   | 8.72        | 8.54        | 8.63        | 0.07  | −0.63    |
| LEDA084710    | 8.67        | 8.44        | 8.56        | 0.27  | −0.92    |
| CGCG108-149   | 8.88        | 8.53        | 8.71        | 0.12  | −0.61    |
| KUG1602+174B  | 8.70        | 8.54        | 8.62        | 0.07  | −0.87    |
| LEDA084724    | 8.53        | 8.42        | 8.48        | 0.07  | −1.24    |
| SDSSJ160565.98+174304.1| 8.27 | 8.21 | 8.24 | 0.11 | −1.36 |
| [DKP87]160310.21+175956.7 | 8.61 | 8.50 | 8.56 | 0.07 | −1.19 |
| SDSSJ160524.27+175329.3 | 7.97 | 8.01 | 7.99 | 0.07 | −1.67 |
| SDSSJ160523.66+174832.3 | 8.54 | 8.28 | 8.41 | 0.07 | −1.30 |
| IC1182        | 8.61        | 8.41        | 8.51        | 0.07  | −1.19    |
| IC1182:[S72]d | 8.34        | 8.27        | 8.31        | 0.07  | −1.29    |
| SDSSJ160531.84+174826.1| 8.66 | 8.64 | 8.65 | 0.07 | −0.45 |
| SDSSJ160304.20+171126.7 | 8.62 | 8.44 | 8.53 | 0.07 | −1.10 |
| SDSSJ160520.58+175210.6 | 8.71 | 8.68 | 8.69 | 0.15 | −0.64 |
| [D97]ce-143   | 8.43        | 8.26        | 8.35        | 0.07  | −1.40    |
| LEDA3085054   | 7.43        | 7.58        | 7.58        | 0.07  | −0.86    |

Notes. The oxygen abundance is derived using Pérez-Montero & Contini (2009) and Pilyugin et al. (2010) calibrations. N/O is derived using N2S2 calibration by Pérez-Montero & Contini (2009).

* These values are given by the used calibration assuming upper limits for the [N II] and [S II] lines. The adopted O/H value is the one provided by Iglesias-Páramo et al. (2003) calculated using the P-method; we see that is in very good agreement with the O/H value that we calculate with the P10 method.

the local environment have the main weakness of missing the luminosity information of the counted galaxies. To account for this problem, we limit the count to luminous galaxies $M_r = -19, m_r = 17$ mag when corrected for galactic extinction. To correct for background and foreground galaxies, we use the field galaxy counts as given by Yasuda et al. (2001). The local galaxy number density is calculated to the 10th neighbor in order to improve statistics. As expected, the corresponding densities are higher, but they do not affect the conclusions of the $MZ$ relation analysis, as will be discussed in Section 5. The density estimates log $\Sigma_{14}$ and log $\Sigma_{10}$ are quoted in Table 5.

We then estimate the projected distance of our galaxies to the cluster center. As already mentioned in Section 1, Hercules is a peculiar cluster of galaxies, where the maximum of the cluster galaxy distribution ($16^d05''15''0 + 17^d44''55'') extracted from NED) is not coincident with the primary X-ray maximum found by Huang & Sarazin (1996). The center of the brightest X-ray component coincides with the brightest cluster galaxy.
NGC 6041A ($16^h04^m35^s  +17^d43^m18^s$). In Table 5, we give the projected distance of our sample galaxies to both centers in Mpc, referred to as the cosmological corrected distance of Hercules cluster 158.3 Mpc.

We calculate the star formation rate (SFR) of our galaxies from their Hα emission given by C09 using the Kennicutt (1998) calibration. We use $c$(Hβ) derived from our optical spectroscopy to correct Hα emission from extinction, assuming the Miller & Mathews (1972) extinction law with $R_V = 3.2$. When spectra of different parts of a galaxy are considered, the $c$(Hβ) used to calculate the global SFR of the galaxy is the mean value of all these $c$(Hβ) derived spectroscopically. We also correct the Hα flux from [N II] contamination using the empirical correction given by Reverte (2008):

$$\log \text{EW(H}_\alpha) = (-0.34 \pm 0.03) + (1.13 \pm 0.02) \log \text{EW(H}_\alpha + \text{[N II]}) \quad (3)$$

This empirical correction was derived using line fluxes integrated for entire galaxies, extracted from the extended spectrophotometric galaxy sample of Jansen et al. (2000), suitable for this kind of analysis. The errors on SFR quoted take into account only the Hα flux error.
Finally, we note that the H I survey of Dickey (1997) covers the whole central region of A2151, where all our SF galaxies lie. We have adopted the H I masses provided in that work (converting them to $M_{\odot}=73$ km s$^{-1}$ Mpc$^{-1}$).

Table 5 summarizes for each galaxy the physical properties calculated in this work and others extracted from the literature: the $M_b$ absolute magnitude, the galaxy radius at 25 mag arcsec$^{-2}$ in arcseconds (extracted from the SDSS iso$_{r}$ parameter for the $r'$ band), the local density estimates log$\Sigma_{2.5}$ and log$\Sigma_{10}$, the projected distance to the cluster center and the projected distance to the X-rays' center in Mpc, the stellar mass calculated with the kcorrect algorithm, the H I mass from Dickey (1997), and the SFR in $M_{\odot}$ yr$^{-1}$.

5. DISCUSSION

5.1. Metallicity versus Local Density

In this paper, we study the relation between metallicity and environment for our sample of SF galaxies in the Hercules cluster. We examine the potential impact of the environment on the $MZ$ and luminosity–metallicity ($LZ$) relations and investigate different evolutionary scenarios for these cluster galaxies.

The Hercules cluster 3D galaxy distribution is extremely clumpy (Bird et al. 1995), rendering it a very interesting and vivid environment difficult to disentangle only in the projected space without taking into account galaxy velocity. The local density of galaxies has been widely used as an indicator of their environments; in this work we have studied the behavior of metallicity versus local density. The local density $\Sigma_{2.5}$, derived to the fourth and fifth nearest neighbors, would describe the local environment at the group scale.

In Figure 10, we plot the galaxy gas-phase oxygen abundances versus the local density estimators $\Sigma_{2.5}$ (left) and $\Sigma_{10}$ (right) calculated in Section 4.4. We keep the same color/symbol distinction as in Figure 6. Additionally, the points corresponding to the same galaxy (nuclei and disks) are connected with straight lines. We see that for luminous galaxies, the oxygen abundance...
very high local densities

\[ \Sigma \]

metallicity (12 + log $\text{O}$

squares; similarly, both parts of PGC057064 are plotted in blue filled circles. parts and green triangles for their corresponding disk components (nuclei and disks are connected with lines). Both parts of PGC057077 are plotted in magenta filled squares; similarly, both parts of PGC057064 are plotted in blue filled circles.

Figure 10. Oxygen abundance of galaxies vs. their local densities. Left: O/H vs. $\Sigma_{4.5}$, the local galaxy number density to the average of the projected distances to the fourth and fifth nearest neighbors, where the galaxies considered are secure members of the Hercules cluster, as indicated by their SDSS spectroscopic redshift. Right: O/H vs. $\Sigma_{10}$, the local galaxy number density to the 10th nearest neighbor, where a magnitude limited sample ($M_B \leq -19$ mag) of galaxies is used and we remedy for background and foreground galaxies using the field galaxy counts of Yasuda et al. (2001). Colors and point features are as in Figure 11: blue filled circles for dwarf/irregular galaxies ($M_B > -19$), magenta squares for spirals ($M_B \leq -19$) integrated galaxies, red stars for the nuclei of six spirals that we divide into different parts and green triangles for their corresponding disk components (nuclei and disks are connected with lines). Both parts of PGC057077 are plotted in magenta filled squares; similarly, both parts of PGC057064 are plotted in blue filled circles.

(A color version of this figure is available in the online journal.)

does not show any significant dependence on the local galaxy number density. Luminous galaxies of this sample span the entire range of densities and are found to have nearly solar oxygen abundance. Dwarf galaxies show a noticeable variation: the $\sim 80\%$ of the less metallic dwarfs ($12 + \log O/H < 8.4$) are located at $\Sigma_{4.5} < 1.85$, whereas the $\sim 70\%$ of the higher metallicity ($12 + \log O/H > 8.4$) dwarf galaxies are located at very high local densities $\Sigma_{4.5} > 1.85$. A substantial fraction of these more metallic dwarfs have been identified to be affected by interactions; they are described in detail in the Appendix. This dual behavior is not so evident when the $\Sigma_{10}$ density estimator is used. The dependency observed in Figure 10 of the metallicity of dwarf/irregular galaxies on local density could be interpreted as follows: at the highest local densities, i.e., approaching the cluster center, only the more “robust”—i.e., more massive and more metallic—dwarf galaxies can survive. Conversely, the less metallic dwarf galaxies should have recently been incorporated to the cluster. This “newcomer” scenario for dwarfs is additionally supported by the fact that the majority of the low metallicity dwarf galaxies present radial velocities that differ from the radial velocity of the brighter cluster galaxy NGC 6041A—located at the X-ray maximum of the cluster—by more than $\sigma_V$, which is possible evidence of infall (Section 2.1).

One point worth mentioning here is that, in this work, we study the effect of local galaxy density by sampling environments much denser (from $\log \Sigma_{4.5} = 1.0$ to 2.5) than in previous works (Mateus et al. 2007; Mouchine et al. 2007; Cooper et al. 2008; Ellison et al. 2009) typically reaching $\log \Sigma \sim 1.5$. Additionally, the works mentioned above use the SDSS database and include few dwarf galaxies, mainly due to the magnitude limit of SDSS in combination with galaxy-size limits or redshift constraints applied in order to minimize possible aperture effects. This study, therefore, is complementary and goes beyond these previous works, dealing also with the dwarf galaxy population. In this sense, the Hercules cluster, being an ideal laboratory in which to study the environmental effects on SF galaxies, was not included in the SDSS-DR4 used in all these previous studies.

5.2. Mass and Luminosity versus Metallicity

Figure 11 (left) shows the gas-phase oxygen abundance versus galaxy stellar mass for our sample of galaxies (colors and point features as in Figure 10). We see that Hercules SF galaxies follow a well-defined sequence on this plot, which reaches a saturation value $\sim Z_\odot$ for galaxies with $\sim 10^{10} M_\odot$. We observe that the set of dwarfs/irregulars populating the higher local densities (i.e., $\log \Sigma_{4.5} > 1.85$; see Section 5.1), marked here with circles, appear shifted toward higher metallicities for their mass. This fact suggests a different evolution for these galaxies in the environment of the cluster, thus providing a physical reason for the dispersion in the $MZ$ relation. These findings are in line with the results of Cooper et al. (2008), who attribute $\sim 15\%$ of the measured scatter of the $MZ$ relation to the environment.

For the sake of clarity, in Figure 11 (right) we added the 15 Virgo dls and BCDs (light blue open circles) from Vaduvescu et al. (2007) and references therein (excluding VCC641 because of its uncertain oxygen abundance). For consistency with our data, when a direct abundance estimation is not available, we recalculate their abundances using the P10 method. We have recalculated the stellar mass for the Virgo dwarf galaxy sample using the kcorrect code (as for the Hercules sample) and found a good agreement with the mass estimate given by Vaduvescu et al. (2007), who calculated it using K-band photometry (we use the latter values in our Figure 11). We see that Virgo dwarf galaxies couple nicely with our Hercules data on the $MZ$ plot. We also compare with the extensive sample of SF galaxies used by Amorín et al. (2010), comprised of all the emission-line galaxies listed in the Max Planck Institute for Astrophysics/Johns Hopkins University (MPA/JHU) Data catalog of the SDSS DR 719, which covers a redshift range $0.03 \leq z \leq 0.37$. Oxygen abundances were calculated using the N2 calibration of PM09 and mass estimates were taken from the MPA/JHU catalog. On this plot Hercules SF galaxies lie within the same range as the emission-line galaxies of SDSS DR 7, except in the

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19 Available at http://www.mpa-garching.mpg.de/SDSS/.

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higher mass range, where our data show a shift toward lower metallicities by $\sim 0.15$ dex as compared to the Amorín et al. (2010) sample. We tentatively attribute this observed shift to the different oxygen abundance calibration used in each case; in addition, another important effect is the different spatial coverage of SDSS spectra versus the spatially resolved spectra used in this work.

In Figure 12 (left), we plot the gas-phase oxygen abundance versus galaxy $M_B$ absolute magnitude. Our galaxy sample follows an $LZ$ relation, where the same differential behavior identified in the $MZ$ relation is clear for the dwarf/irregular galaxies at high local densities (i.e., $\log \Sigma_{4.5} > 1.85$). On the plot to the right we show again the Virgo dI and BCDs (light blue open circles; Vílchez & Iglesias-Páramo 2003; Vaduvescu et al. 2007), and the (centers of) Virgo spirals (red open triangles) from Pilyugin et al. (2002) and references therein, and the Hydra dwarfs (green open squares) by Duc et al. (2001, 1999). All the abundances were recalculated using the $P_{10}$ method and $M_B$ of the Virgo spirals was derived from the $L_B$ given by Skillman et al. (1996). We see that SF galaxies of the Hydra, Virgo, and Hercules clusters appear to follow the overall $LZ$ relation, though it is apparent that the scatter has increased.

Moreover, Hercules SF galaxies also follow a well-defined sequence on the plots of the $N/O$ ratio versus galaxy stellar mass and galaxy $M_B$ absolute magnitude shown in Figure 13. In these plots, we can see how some of the dwarf galaxies shifted toward higher $O$ values in the $MZ$ relation appear overabundant in $N/O$ (see also Section 5.3.2). Additionally, the $N/O$ ratio makes evident a significant abundance difference between nuclei and disks (points connected with straight lines), which will be discussed in more detail in Section 5.4.

Very recent works (Mannucci et al. 2010; Lara-López et al. 2010) discuss the existence of a more general relation between stellar mass, gas-phase metallicity, and SFR in the local
universe. We have checked that, for the galaxy mass range we have in common, Hercules SF galaxies lie in the same range as the Lara-López et al. (2010) sample in the 3D plot, which combines stellar mass, gas-phase metallicity, and SFR. However, in this work we prefer not to extend this discussion until our spectroscopic study of several nearby clusters is finished (V. Petropoulou et al. 2011, in preparation). In that upcoming study, metallicities, stellar masses, and SFR are computed for a large sample of SF cluster galaxies. With this new data set a study of the fundamental plane for SF galaxies in clusters could be performed.

5.3. Environment and Chemical Enrichment in Hercules Galaxies

5.3.1. Comparison with the Closed-box Model

In order to study possible environmental effects on the (gas-phase) chemical enrichment in galaxies, it is useful to compare with the predictions of the so-called closed-box model (Edmunds 1990). According to this model, a galaxy consists initially of gas with no stars and no metals. The stellar IMF is assumed to be constant in time and the products of stellar nucleosynthesis are assumed to enrich the interstellar medium (ISM) instantaneously. Throughout its life, the metal content of a galaxy is neither diluted by infalling pristine gas nor lost via outflow of enriched gas. Hence, the metallicity at any given time is only determined by the fraction of baryons that remain in gaseous form. The model equation can be written as

$$Z_o = y_o \ln(1/\mu),$$

(4)

where $Z_o$ is the oxygen mass fraction, $y_o$ is the yield by mass, and $\mu$ is the ratio of the gas mass to the baryonic mass, $\mu = M_{\text{gas}}/M_{\text{bar}}$. The gas mass corresponds to the hydrogen atomic gas with a correction for neutral helium ($M_{\text{gas}} = 1.32 M_{\text{HI}}$; molecular gas mass was not taken into account here) and $M_{\text{bar}} = M_{\text{gas}} + M_*, $ where $M_*$ is the mass in stars.

Figure 14 compares the observed oxygen abundances for our sample galaxies to the prediction of the closed-box model, plotted with lines with different $y_o$. The green continuous line indicates the model with $y_o = 0.0074$, that is, the theoretical yield of oxygen expected for a Salpeter IMF and constant SFR, for stars with rotation following the Meynet & Maeder (2002) models (van Zee & Haynes 2006). Both infall and outflow of well-mixed material will result in effective yields that are lower than the true yields, as the enriched material is either diluted (infall) or lost from the system (outflow). A fraction of the sample of isolated dwarf irregular (dI) galaxies of van Zee & Haynes (2006) was found to follow the theoretical yield, and the rest appears consistent with a lower yield $y_o = 0.002$, almost 1/4 of the model prediction (blue dashed line in Figure 14). The gray strip indicates the relationship given by Lee et al. (2003) between oxygen abundance and the baryonic gas fraction for a sample of local universe dIs. The cyan open circles correspond...
to the Virgo dI and BCDs from Vaduvescu et al. (2007). Most of the Virgo dwarfs appear consistent with the Lee et al. (2003) locus for local dwarf galaxies, though some of them still present lower gas fractions.

We can see in Figure 14 that four of our low-mass galaxies for which we have H i measurements (Leda1543586, Leda140568, [D97]ce-200, and Leda3085054) are in agreement with the closed-box model predictions with $\gamma_0 = 0.0074$ (green line). This fact suggests that these galaxies are falling into the central region of the cluster and are now encountering the dense ICM gas for the first time; as a consequence, gas removal by ram-pressure stripping might not yet be observable. These four galaxies can be considered as prototypes of the “newcomers” to the cluster introduced in Section 5.1. This result is additionally supported by their disturbed H i characteristic morphologies (as seen in the Hα maps in C09) as described below. The Hα emission map of Leda140568 reveals a strong episode of star formation concentrated into an asymmetric arc located on the side of the galaxy facing the cluster center and almost no emission in the opposite side. This typical “bow” morphology has been observed in other cluster galaxies (e.g., Gavazzi et al. 2001) and is very suggestive of a ram-pressure event. After closer inspection of the C09 Hα maps we identify that the galaxy LEDA140568 also shows a “bow-shock” morphology on the side of the galaxy facing the cluster center. Additionally, the other two galaxies, [D97]ce-200 and Leda3085054, present strongly asymmetric Hα emission, one-sided and offset from the galaxy optical center. These starbursts could be the signature of pressure-triggered star formation by the ICM within the cluster environment (Treu et al. 2003). Additionally, these four galaxies have abs($A_V$) $> \sigma_V$ (see Section 2.1) and they have a median projected distance to the center of the X-ray distribution of $\sim 700$ kpc; thus they are approaching the edge of the main X-ray emitting region, which extends up to $R_X = 678$ kpc (Huang & Sarazin 1996).

The blue points close to the blue dashed line in Figure 14 ($\gamma_0 = 0.002$) correspond to the dwarf/irregular galaxies [D97]ce-143 and LEDA084703 (see the Appendix for details). [D97]ce-143 is located at high local density (Section 5.1) and Dickey (1997) reports that its corresponding H i emission map shows two elongations and is highly reminiscent of the Magellanic Stream. LEDA084703 shows a long H i plume (Dickey 1997) reaching about 1’ from the optical center to the southeast (also at the eastern part of this galaxy is located the supernova [SN] quoted by Zwicky et al. 1969). These peculiar H i morphologies suggest that some gas mass-loss effect has taken place, explaining their location in Figure 14.

A very interesting case is the galaxy IC1182:[S72]d labeled in Figure 14. This TDC (Iglesias-Páramo et al. 2003) shows an H I distribution that extends well beyond the galaxy disk (Dickey 1997). This morphology, combined with the information we obtained on its gas-phase chemical content (this galaxy lies above the MZ and mass–N/O relations) and with its old stellar population (see Section 5.3.2), indicates a particular formation scenario for this galaxy. This galaxy is probably the result of a “block” produced during the merger IC1182 and seems dominated by an old stellar population. This stellar “block” could have acquired a large mass of gas from the late-type galaxy of the merger IC1182. This formation scenario could explain why IC1182:[S72]d shows a much higher gas fraction than the value expected according to the closed-box model. Thus, the active environment of the cluster can provide an explanation for the location of a galaxy in such a forbidden region in Figure 14 (Edmunds 1990; van Zee & Haynes 2006). There exist examples of dwarf galaxies formed from the gas lost in a merger, e.g., the old TDG VCC 2062 in the Virgo cluster studied by Duc et al. (2007); according to these authors this galaxy has probably been formed out of the gas clouds lost by a gas-rich galaxy involved in a merger.

For the galaxies in our sample that were not detected in Dickey (1997) we assume an H i mass upper limit corresponding to the detection threshold of this survey ($\sim 2.6 \times 10^4 M_\odot$). In Figure 14, we add those galaxies with right pointing arrows (representative of the central oxygen abundance) to indicate the upper limit for their H i mass. Excluding the galaxies already discussed, the rest of the galaxies in Figure 14 (including upper limits) on average suggest effective yields below the closed box model and are consistent with the field sample of Lee et al. (2003). Finally, some points (few Virgo dwarfs and one Hercules upper limit for the IC1182 merger) still appear in Figure 14 displaced toward even lower values of gas fractions, as would be expected if these cluster galaxies suffered important environmentally induced gas removal (e.g., from ram-pressure stripping).

5.3.2. Gas-phase Metallicity versus Properties of the Underlying Stellar Component

In order to search for possible environmental footprints on the chemical history of our sample galaxies, we compare the stellar population properties, such as the mass-weighted stellar metallicity $Z_{\star,M}$ and mass-weighted stellar age $\tau_{\star,M}$, brought forth by the STARLIGHT model fitting (Section 3), with the gas-phase abundances derived in this work. The fact that these properties (for stars and gas) have been obtained following a completely different methodology should render our analysis more robust.

Figure 15 shows the gas-phase oxygen abundance (left) and the N/O ratio (right) versus the mass-weighted stellar age $\tau_{\star,M}$. We see an overall positive trend, more prominent for N/O, which should reflect the different timescales for the delivery of these two elements to the ISM. Oxygen, produced in Type II SNe, is released after $\sim 10$ Myr, while nitrogen is produced and released over a substantially longer period, $\gtrsim 250$ Myr. Overall, we can see how nitrogen abundance seems to correlate better with the mass-weighted stellar age. Additionally, the dispersion in N/O becomes smaller at an older age, possibly reflecting the averaging effects of many SF episodes, while the larger dispersion seen at young ages could reflect the stochastic effects of few episodes of SF or other possible environmental effects such as, e.g., gas inflows.

In Figure 15, we can see that $\gtrsim 85\%$ of the dwarf galaxies residing at high local density environments ($\log \Sigma_4.5 \gtrsim 1.85$) present old stellar populations of mass-weighted age $\gtrsim 6$ Gyr. Conversely, $\sim 70\%$ of the dwarfs located at density $\log \Sigma_4.5 < 1.85$ present mass-weighted ages below this value; a hint suggesting that only the more robust galaxies—e.g., more massive, evolved, and more metallic—could have survived in the environment of highest galaxy density. The outliers to this general correlation can also give us important clues to possible environmental effects on their chemical histories. On the right plot of Figure 15, we can identify the galaxy merger IC1182 and the two dwarfs associated with it (SDSS J150531.84+174826.1 and IC1182:[S72]d; see the Appendix). Interestingly enough, all these objects present almost the same (very old) stellar age. Moreover, the galaxy SDSS J150531.84+174826.1 appears to be more chemically enriched with respect to galaxies of similar mass (see also Figures 11 and 13). Taken altogether,
these properties of SDSS J150531.84+174826.1 recall those of the central part of a massive galaxy after having lost its outer parts (e.g., during a past interaction with the neighbor merger IC1182). The TDC galaxy IC1182[S72]d, despite hosting an old stellar population, does not seem to be that chemically evolved (especially in N/O) in accordance with the scenario already proposed for it: the accretion of a large mass of gas from the late-type galaxy of the merger IC1182. For IC1182, our spectrum sampled the slightly off-center starburst giving a gaseous oxygen abundance slightly lower than the average observed trend in the MZ relation. This fact, together with its low N/O ratio, suggests that this gas should have an origin external to the host underlying galaxy. A similar scenario has previously been invoked by Moles et al. (2004; see also Radovich et al. 2005), who claimed that this gas was provided by the late-type galaxy of the merger. A detailed study of this complex system is out of the scope of this work and will be presented in a forthcoming paper (V. Petropoulou et al. 2011, in preparation).

Two other objects can be seen above the correlation in Figure 15: the eastern part of the disk of NGC 6045 (NGC 6045e) and PGC057077b. Both galaxies appear affected by interactions and show intense SF (the highest SFR values measured for our sample after the merger IC1182). Though it has been shown that a high SFR can be a key ingredient in enhancing N/O (Mollá et al. 2006), what moves these two objects out of the general age–N/O relation seems to be related to their derived ages: the spectra of these objects are sampling just the starbursts, hence the derivation of $\tau_{\star,M}$ should then be dominated by the contribution of the young starburst; in contrast, the results derived for other parts of these two galaxies follow the general trend of N/O versus $\tau_{\star,M}$.

In Figure 16, we compare the gas-phase and the stellar oxygen abundances derived for the sample of galaxies. We compute the latter abundance using the mass-weighted metallicity, $Z_{\star,M}$, given by STARLIGHT, assuming $12 + \log(O/H)_{\odot} = 8.69$ (Asplund et al. 2009). We plot the difference between gas-phase and stellar oxygen abundance $\Delta \log(O/H)_{\text{gas}}$ versus the stellar oxygen abundance $12 + \log(O/H)_{\star}$. In this plot we can see two main behaviors. For luminous galaxies ($M_B \leq -19$), we can see the following correlation:

$$y = (7.99 \pm 0.47) - (0.925 \pm 0.055)x,$$

where $y = \Delta \log(O/H)_{\text{gas}}$, and $x = 12 + \log(O/H)_{\star}$ ($\chi^2 = 0.074$). Assuming our model fitting hypotheses, this “upper bound” correlation would mean that for a chemically evolved stellar population of order $\sim Z_{\odot}$, gas and stars present the same metallicity. However, even when the stellar metal content of these galaxies goes down, we can see that the observed gas abundance remains close to $\sim Z_{\odot}$ (see also Gallazzi et al. 2005; Asari et al. 2007). This behavior could reflect the fact that, for our more massive galaxies, gradients of stellar metallicity can be more conspicuous than those for gas, consistent with model predictions (Ferrini et al. 1994) suggesting that abundance gradients should flatten with age.

For the lower luminosity galaxies we can see that the two groups of dwarfs (referred to in Sections 5.2 and 5.3.1) also split up in Figure 16. The “newcomers” show similar oxygen abundances for gas and stars, whereas the more chemically...
evolved dwarfs found at high local densities (marked with circles), hosting older stellar populations (>6 Gyr), show that the gas oxygen abundance is higher than the abundance of the stars by up to 0.3 dex. An outlier to this relation, given that its peculiar formation is already unraveled, is the galaxy IC1182:[S72]d, for which the derived stellar metallicity is higher than the gaseous one. Whether these two behaviors, shown in Figure 16, result from different chemical evolutionary paths or rather reflect the environmental impact of the cluster remains to be disentangled.

5.4. Searching for the Cluster Influence in Hercules SF Galaxies

A considerable amount of work has been done in order to constrain the physical mechanisms that drive the SFH of galaxies, these mechanisms being either internal to the galaxy or related to the environment (Haines et al. 2007; Bretherton et al. 2010; Weisz et al. 2011). In the cluster environment it has been found that quenching mechanisms can even suppress the SF of galaxies with respect to their field counterparts and morphological changes can operate, converting spirals into anemic ones (Balogh et al. 2004). Various processes have been proposed to describe the environmental actions on cluster galaxies, these can be classified into three broad categories: (1) galaxy–ICM interactions, (2) galaxy–cluster gravitational interactions, and (3) galaxy–galaxy interactions (for a review see, e.g., Boselli & Gavazzi 2006; Treu et al. 2003).

In this work, we have searched for possible observable imprints of the cluster environment on the metallicity and the chemical history of a sample of SF galaxies in the Hercules cluster. Most of our sample galaxies are located within the central region of the Hercules cluster (< R200) where the cluster potential is expected to be steep, the ICM is measurable, and most of the physical mechanisms proposed above are effectively at work. We have examined the metal content of our sample galaxies as a function of local density, stellar mass, luminosity, and chemical evolution. On the basis of this analysis, three main subgroups of objects have emerged: (1) the more massive SF galaxies (including all spirals), (2) the set of dwarf/irregulars labeled “newcomers” in Section 5.3.1, and (3) a group of more chemically evolved dwarfs residing at the highest local densities observed in our sample. In addition, three dwarf/irregular galaxies, SDSS J160524.27+175329.3, SDSS J160556.98+174304.1, and LEDA084724, could not be fully ascribed to any of these groups (see the Appendix).

Massive galaxies (MR ⩽ −19) follow the global MZ/LZ relations, though they present evidence of being affected by the cluster environment, judging from their Hα structure/morphology and their abundance gradients. Most spirals in Hercules show Hα emission (see Hα maps in C09) less extended than their optical disks and sometimes offset from the center of the stellar continuum. This can be evidence of truncation of ionized gas in the disks of these cluster spirals, since we observe star formation occurring mostly in the inner parts. Gas removal from the outer parts of cluster spirals is believed to be a consequence of the ISM–ICM interaction. This effect has been observed, e.g., in the Virgo cluster spirals by Koopmann & Kenney (2004), with over half of their Virgo sample showing truncation of the star-formation in the disks. In fact, ram-pressure gas stripping could be effective on our Hercules spirals since all are located within R200.

The oxygen abundances derived for massive galaxies are close to solar, and for the more Hα extended spirals, mild or flat O/H abundance gradients have been obtained, a result in line with previous findings by Skillman et al. (1996) for Virgo spirals. In contrast, for the N/O ratio even oversolar values have been measured for the central part of some galaxies, showing prominent N/O spatial variations; this picture could result from the effect of gas infall in the center of these galaxies, suffering the action of the ICM (Vollmer et al. 2001). Such infall would dilute the abundance at the central parts of the galaxies, flattening the O/H gradient, while the N/O ratio is not expected to be affected. Overall, the question which remains to be explored is whether these spirals are chemically evolved because they reside in such high-density environments or we are just observing an effect of the morphology density relation (Dressler 1980). Further observations are needed to answer this question.

Regarding the dwarf/irregular galaxies, they appear to form two main groups with substantial differences as discussed in the previous sections. Overall, all the dwarfs present similar levels of SFR as derived from their Hα luminosities. The group of “newcomers” are the metal poor dwarfs; they present a young stellar population (Figure 15), and their stellar and gas metallicities are similar (Figure 16). They avoid the highest local densities (Section 5.1), appear located close to the boundaries of the X-ray cluster core, and show bow-shock/offset Hα morphologies. These structures host intense bursts of SF, possibly tracing the contact discontinuity of the ISM of the galaxy with the X-ray emitting ICM, an observable signature of pressure-triggered star formation. The “newcomers” do, however, follow the closed-box model predictions, suggesting that ram-pressure stripping has not yet substantially reduced their H1 gas. Ram-pressure stripping is expected to act on a timescale ∼5 × 10^7 yr (Abadi et al. 1999), while typical H1 region lifetimes are ∼(5–10) × 10^6 yr. Based on this scheme we should conclude that the “newcomers” are those dwarfs observed at the time when they are set to fire by their first encounter with the ICM, before removal of the galactic gas is accomplished by the ICM, and prior to subsequent quenching of SF rendering them undetectable in Hα.

The majority of the dwarf/irregulars populating the highest local densities of our sample (log S_15 > 1.85) show higher metallicities for their mass and luminosity, and they appear located above the overall MZ and LZ relations (see Figures 11 and 12). Their gaseous and stellar abundances differ by up to ∼0.3 dex, pointing toward a dominant old stellar population. Indeed, as seen in Figure 15 their stellar population presents ages exceeding ∼6 Gyr. These galaxies have been also found close to the X-ray cluster core, but their Hα morphologies do not suggest ISM–ICM interaction. However, we cannot discard the possibility that they could have been affected by ram-pressure stripping. Although H1 masses are not available for the vast majority of these objects, if we assume an H1 mass upper limit for them as in Section 5.3.1, many of these galaxies would be shifted in Figure 14 out of the canonical closed-box model, toward the zone of H1 deficiency.

We have seen that high local density is a key parameter that separates this group of chemically evolved dwarfs from the rest of the dwarfs. At these high-density environments preprocessing has been claimed to operate under the combined action of tidal forces among group members and the ram-pressure by the ICM (Cortese et al. 2006). We suggest that these dwarf galaxies—overmetallic for their masses—could originate from enriched material stripped by tidal forces among group
members, as has been suggested by Cortese et al. (2006) for the group of galaxies falling into A1367. Indeed we have identified a good number of these more metallic dwarfs affected by tidal interactions.

Mahajan et al. (2011) have found two sets of blue dwarf galaxies with different Hα emission properties in the Coma supercluster, presenting strong environmental dependence. These authors suggest that the more evolved dwarf population could be the progenitors of passive dwarf galaxies seen in the centers of clusters. The two dwarf galaxy groups we have identified in Hercules could match this scheme.

In this work we have studied SF galaxies located in the cluster central region (< R200), as a consequence, the discussion of the physical mechanisms affecting galaxies in the cluster environment is restricted to SF galaxies and could not by any means have been exhaustive. It would be necessary to study a larger sample covering a more extended area of the cluster in order to explore the full action of other processes able to suppress SF, such as starvation of the gaseous component, harassment, or interactions with the global cluster potential. An extended Hα survey reaching up to the Hercules cluster periphery is in progress. This will enable us to study in depth the interesting general environment of the Hercules cluster. Bird et al. (1995) using optical and X-ray data suggested the presence of at least three distinct subclusters in the Hercules cluster, the central A2151C, eastern A2151E, and northern A2151N (see Figure 2). These authors suggested that the A2151E and A2151N subclusters have recently undergone a merger event. Additionally, the velocity distribution of A2151C points toward the existence of two subgroups, one possibly originating from A2151N via infall. The X-ray emission is associated with the two galaxy groups in the central subcluster (Figure 2). All this information supports the idea that Hercules is at a relatively early stage of development.

6. SUMMARY

The Hercules cluster is one of the more exciting nearby dense environments, showing abundant sub-structures unraveled in X-ray emission and broadband imaging. This cluster constitutes an ideal laboratory in which to explore the effects of the environment on galaxy evolution. We have studied environmental effects on the metallicity and the chemical evolution of 31 SF cluster galaxies.

Spatially resolved spectroscopy has been obtained for a sample of SF galaxies and spectral synthesis model fitting has been performed for all the spectra analyzed in order to provide an effective correction of the underlying stellar absorption to emission-line spectra, as well as to derive the characteristic properties of the galaxy stellar populations. Line fluxes and chemical abundances of O/H and N/O have been obtained for all the galaxies, and whenever possible for different parts of galaxies, of the sample.

The main conclusions of this work can be summarized as follows.

1. From the study of the metallicity versus galaxy local density we have seen a dual behavior separating the dwarfs from the more luminous galaxies. The luminous galaxies have metallicities ~Z⊙ and reside at all densities studied in this work. The dwarfs found at higher local densities (log Σ_1.4 > 1.8) are found to be more metallic (12 + log (O/H) > 8.4), while the observed less metallic dwarfs (12 + log (O/H) < 8.4 are found preferentially at lower densities; some of them seem to be “newcomers” to the cluster.

2. We have found that our sample of Hercules SF galaxies shows well-defined sequences of blue luminosity versus metallicity and stellar mass versus metallicity (using both O/H and also the N/O ratio), following the general behavior found for SF galaxies. Besides this global behavior, we have found that dwarf/irregular galaxies populating the densest regions seem to crowd the upper part of the global sequences, thus providing a source for the dispersion observed in these relations. These more metallic dwarfs could be parts of more massive galaxies, fragmented by tidal interactions among group members.

3. Most of the luminous galaxies are chemically evolved spirals with oxygen abundance close to solar and truncated disks of ionized gas, possibly by the action of ram-pressure stripping. From our spatially resolved spectroscopy we have found that the Hα extended spiral galaxies present shallow oxygen abundance gradients, an expected result of possible gas infall at their centers. For the N/O ratio, even values over solar have been obtained for the central parts of some galaxies, and a significant spatial variation has been observed.

4. A detailed study of the chemical history of the sample galaxies has been performed, combining information on their gas-phase abundances, H i content, and stellar mass. Most of the dwarf galaxies with available H i mass seem to be “newcomers” to the cluster and appear consistent with the predictions of the closed box model. This fact agrees with the scenario in which these galaxies experience a pressure-triggered starburst right before the ram-pressure stripping sweeps away their gas component. The rest of the galaxies with H i measurement on average show lower values of gas fractions, though most of them are still consistent with the loci defined by samples of field galaxies.

5. The properties of the underlying stellar population, such as stellar age and stellar metallicity, have been explored and compared with the gas-phase metallicity. The “newcomer” dwarfs present a young stellar population, and their stellar and gas metallicities are similar. The more metallic dwarf galaxies host an old stellar population, resembling the evolved blue dwarfs referred to by Mahajan et al. (2011).

An overall positive trend has been found in the gas-phase oxygen abundance versus the mass-weighted stellar age τ⋆,M, which becomes more prominent in the case of the N/O ratio.

We have learned that the local environment of a galaxy is one of the key parameters in understanding its chemical history. In the variety shown in the Hercules cluster ecosystem we have seen galaxy–galaxy interactions, galaxy ISM–ICM interactions, and candidates of tidal dwarfs galaxies. Further observations are needed to disentangle the roles of all of these environmental effects from the expected intrinsic galaxy evolution.

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Figure A1. Integrated 1D observed spectra for each galaxy or part of a galaxy by INT and WHT.

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Facilities: ING:Newton, ING:Herschel
APPENDIX

NOTES ON INDIVIDUAL GALAXIES

A.1. Interacting Galaxies

IC1182, IC1182-[S72]d, and SDSS J160531.84+174826.1. IC1182 is a late merger that undergoes vigorous nuclear starburst activity with a star formation rate, estimated from its infrared and extinction-corrected Hα luminosity to be between 11 and $\sim 90 M_\odot$ yr$^{-1}$ (Radovich et al. 2005; Moles et al. 2004). IC1182 shows an extended ($\sim 60$ kpc) stellar tail to the east, where a tidal dwarf candidate IC1182-[S72]d is discernible (identified by Iglesias-Páramo et al. 2003; named ce-061 after Dickey 1997). To the north of the system and to a comparable distance there are also distinguished faint tidal features and plumes. In addition, to the west of the merging system, at a projected distance of $\sim 60$ kpc, there is the dwarf galaxy SDSS J160531.84+174826.1, which has been claimed (Dong et al. 2007) to be a Seyfert 1 AGN (but see Section 4). Dickey (1997) reports a long H1 structure extending northwest of IC1182, creating a bridge of H1 clumps toward SDSSJ150531.84+174826.1 (see Figure 3(a) of IP03), although the galaxy SDSSJ150531.84+174826.1 itself was not detected as a consequence of the velocity cutoff (9820 km s$^{-1}$) of the spectrometer used by Dickey (1997). These lines of evidence point toward a physical connection among the three galaxies. A forthcoming work will discuss the global picture of this system (V. Petropoulou et al. 2011, in preparation).
NGC 6050. It has long been considered a collision between two spiral galaxies (NGC 6050A and NGC 6050B). From our long-slit spectrum, we found that these two galaxies show important velocity differences (~1600 km s\(^{-1}\)) suggesting that they might represent simply a chance galaxy alignment. On the other hand, to the north of the system we have identified another galaxy on the basis of its underlying stellar component (clearly seen in the 2MASS imaging) and its SDSS spectrum. This galaxy is probably in interaction with NGC 6050A. Dickey (1997) quotes an H\(_i\) mass for the NGC 6050 system. We attributed the H\(_i\) mass exclusively to NGC 6050B because NGC 6050A is out of the velocity cutoff of the spectrometer used by Dickey (1997). The H\(_i\) distribution is centered on NGC 6050B.

NGC 6045. This edge-on spiral could be interacting with a smaller spiral companion located east of it. On its H\(_\alpha\) map (C09) we can see intense starburst activity on the east part of the galaxy disk, probably triggered by this interaction. Huang & Sarazin (1996) suggested a possible interaction of NGC 6045 with the radio galaxy NGC 6047, which is about 1.6 (~74 kpc) to the south. Dickey (1997) reports that in H\(_i\) only half of the disk is visible. From our long-slit spectroscopy we find a large velocity gradient along the disk of the galaxy, and half of the disk shows velocity out of the cutoff of the spectrometer used by Dickey (1997).

PGC057064. This peculiar galaxy, until now considered one galaxy, has turned out to be a merger of two galaxies, which on our long-slit spectrum show different rotation velocities.
We have considered the corresponding 2D spectrum parts separately. The 1D spectrum PGC057064a corresponds to the merger member located NW and PGC057064b corresponds to the merger member located SE. The two dwarf galaxies comprising this merger do not show any significant chemical variation.

A.2. Peculiar Galaxies

PGC057077. This is a peculiar galaxy previously cataloged as an elliptical in LEDA. The C09 Hα survey showed that PGC057077 is a very intense and compact Hα emitter with $f_{H\alpha} = 87 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ and EW = 148 Å. Although the galaxy is very compact and does not show any structural properties, we noted on its $g-i$ map, illustrated in Figure A2, a conspicuous color gradient. In our long-slit spectrum we were able to identify two regions with important differences in the continuum emission. In order to check for velocity gradients and differences in the chemical content between these two regions, we separated the 2D spectrum in two corresponding 1D spectra. The important continuum emission difference of the 1D spectra is shown in Figure A1. From our emission-line analysis we do not find any significant velocity variation between the two different galaxy parts, nor any difference in the chemical abundances. The difference in the continuum emission is attributed then to the high extinction suffered by both the stellar population and the gas in the NW part of the galaxy, which correspond to our (a) spectrum part. This peculiar galaxy is situated close to the edge of the principal X-ray emitting region, at 650 kpc from the X-ray center. In the NE part of the galaxy there is a low surface blue plume that could point toward the existence of a faint companion. The existing data are not conclusive as to whether it could have been the ICM–ISM interaction or...
a galaxy merger that triggered the unusual starburst of this galaxy. Further mid-infrared observations would be of interest there.

SDSSJ160520.58+175210.6 appears to be embedded into the H\textsubscript{i} structure assigned to the galaxy [D97]ce-200 (SDSSJ160520.64+175201.5); Dickey (1997) reports that this system looks like the Magellanic Clouds and the Magellanic Stream. However, these two galaxies have a velocity difference of 1300 km s\textsuperscript{-1}, a fact that renders unlikely an actual interaction between the two. The velocity of the H\textsubscript{i} cloud is very similar to the velocity of the galaxy [D97]ce-200.

LEDA084703. This is one of the two galaxies in this sample situated in the substructure almost one Abell radius SW of the cluster center. It is a quite blue galaxy, classified Sd/Irr, and it is situated almost one Abell radius away from the cluster center. There has been an SN explosion reported by Zwicky et al. (1969) in the east part of this irregular galaxy. There is a long plume extending toward the southeast detected in the optical images as well as in H\textsubscript{i} by Dickey (1997). The west part of the disk hosts a very intense starburst activity as can be seen in its H\textsubscript{α} EW map in Figure A2.

SDSSJ160524.27+175329.3. It has typical H\textsubscript{α} morphology and the colors of a blue compact galaxy. This compact starburst, located close to the X-ray maximum in the center of the Hercules cluster, could have resulted from the compression of the interstellar gas of a dwarf galaxy when entering the cluster core. Similar compact starburst galaxies have been found in the cores of other nearby clusters by Reverte et al. (2007).
**Figure A2.** First column shows the spatial profiles of the Hα line (continuous) and nearby continuum (dashed line) along the slit extracted from the 2D spectra for the galaxies showing rich spatial structure. The different sub-regions used to divide their 2D spectra into different 1D spectra are shown. The second and third columns show, respectively, the color (g′ − i′) maps and the Hα EW maps, with the slit position overplotted. (A color version of this figure is available in the online journal.)

**SDSS J160556.98+174304.1.** The Hα map of this dwarf galaxy shows an off-center starburst. Additionally, this galaxy is located close to the edge of the primary X-ray maximum in the cluster center and presents a large velocity difference with NGC 6041A. This evidence could suggest that the starburst has been triggered by the effect of the hot ICM. Dickey (1997) has not detected molecular gas for this galaxy, suggesting that the ram-pressure stripping could have already taken off its molecular gas.

**LEDA084724** presents an extended knotty Hα structure NW, in the direction toward the X-ray cluster center. This morphology could be suggestive of a starburst triggered by the ICM. Dickey (1997) has not detected molecular gas for this galaxy.

**SDSSJ160304.20+171126.7** is one of the two SF galaxies of this spectroscopic sample situated in the substructure almost one Abell radius SW of the cluster center. This galaxy has a close companion, the galaxy SDSS J160305.24+171136.1. The disturbed Hα structure of both could suggest a possible interaction.

**SDSSJ160523.66+174832.3** is located very close to the faint galaxy SDSSJ160523.67+174828.8 (22 and 23 in C09). The Hα map as well as the g − i color map of SDSSJ160523.66+174832.3 seem to reveal a disturbed morphology. It is possible that the two galaxies are interacting, although SDSSJ 160523.67+174828.8 does not have spectroscopic data and SDSS provides a photo-z estimate of z = 0.15 ± 0.02, nominally not consistent with the velocity range of the Hercules cluster.

**[DKP87]160310.21+175956.7.** The Hα map of this galaxy shows an intense starburst event to its southeast part. Towards this direction there is projected a faint galaxy. However, the close
Figure A2. (Continued)
companion galaxy has no spectroscopic data and the photo-z estimate provided by SDSS $z = 0.25 \pm 0.06$ is not consistent with the velocity range of Hercules cluster. 

SDSSJ160547.17+173501.6. This has turned out to be a background galaxy with $z = 0.12 \pm 0.01$. The various SDSS photo-z estimates were $0.06 \pm 0.01$, $0.06 \pm 0.05$ and $0.10 \pm 0.04$, thus the criteria adopted by C09 for cluster membership were fulfilled.

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Figure A2. (Continued)
