SPECTROSCOPY OF DWARF GALAXIES IN THE VIRGO CLUSTER. I. DATA, CHEMICAL ABUNDANCES, AND IONIZATION STRUCTURE

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ABSTRACT

Long-slit spectroscopy has been obtained for a sample of 22 blue dwarf galaxies selected in the direction of the Virgo Cluster, as part of a larger sample of Virgo blue dwarf galaxies for which deep Hα imaging has been collected. Most of the galaxies in the present sample are classified as BCDs or dwarf Irregulars in the Virgo Cluster Catalog. Line fluxes, Hβ equivalent widths, extinction coefficients, spatial emission profiles, ionization structure, and physical conditions are presented for each galaxy. Chemical abundances have been derived either using a direct determination of the electron temperature or after detailed examination of the predictions of different abundance calibrations. The oxygen abundances derived for the sample of Virgo dwarf galaxies span the range 7.6 ≤ 12 + log(O/H) ≤ 8.9, and the corresponding nitrogen-to-oxygen abundance ratio ranges from values typical of low-metallicity field BCD galaxies to near solar.

Subject headings: galaxies: abundances — galaxies: clusters: individual (Virgo) — galaxies: dwarf — galaxies: ISM — H II regions

On-line material: machine-readable table

1. INTRODUCTION

Within the study of the evolution of galaxies it now appears well established that the environment plays a significant role. From theoretical grounds, it is expected that galaxies located in high-density regions such as clusters of galaxies may suffer the effects of interactions, giving rise to mass loss or mass redistribution. Also, after the interaction with the (hot) intracluster medium (ICM), the gaseous component of galaxies may be affected by ram pressure stripping or evaporation (Haynes et al. 1984). The relatively high density of the ICM together with the higher probability of encounters in (rich) clusters may produce selective loss of gaseous galactic material. In this respect, the existence of a morphology-density relation is in the line of the observed deficit of gas-rich dwarf galaxies in dense environments (e.g., Binggeli et al. 1987).

A direct environmental impact is expected to be observed in the activity of star formation in galaxies (e.g., Hashimoto et al. 1998; Iglesias-Páramo & Vílchez 1999). This fact is of particular relevance for the issue of galaxy evolution, owing to the strong implications that gas flows (in/outflows), as well as gas stripping and/or pressure confinement, may have for the study of the chemical evolution of galaxies. The observational results available show a significant difference in the observed H I content between cluster and field spirals, the Virgo ones being H I deficient (e.g., Cayatte et al. 1990; Solanes et al. 2001). Other results obtained for the molecular component, however, show that the cold molecular clouds located near the center of these galaxies, which contain large amounts of H₂ and CO, do not appear to be lost to the ICM (Kenney & Young 1988; Boselli et al. 1997).

Since gas-rich dwarf galaxies are fragile systems, because they have low-mass surface densities and rotation velocities (Gallagher & Hunter 1984, 1989), it is expected that the impact of the environment should be significant for these objects. However, Hoffman et al. (1988) studied a large sample of dwarf galaxies in Virgo and found that, on average, they were not more stripped than spirals. The sole existence of these H I-rich dwarf galaxies in such a hostile environment may pose serious questions.

Analysis of the spectroscopic properties of local and distant samples of emission-line galaxies in environments of different density, show that galaxies in higher density regions appear statistically associated with somewhat lower star formation rates (Hashimoto et al. 1998; Vílchez 1995). Similar studies of emission-line galaxies located in or near voids, especially at the lowest densities, point to levels of star formation activity comparable to, or slightly higher than, field galaxies (cf. Popescu et al. 1999; Grogin & Geller 2000). This raises the question as to whether other fundamental properties of dwarf galaxies, such as their metal content, may feel the impact of their environment. It has been claimed that this can be the case in the so-called tidal dwarf galaxies (Duc & Mirabel 1999; Vílchez 1999); nonetheless, the study of the global spectroscopic properties of a sample of star-forming dwarfs in different environments (Vílchez 1995) led to the conclusion that the majority of them follow rather well a metallicity-luminosity relation. Some of the Virgo dwarfs studied in the latter work presented distinct spectroscopic properties and it was suggested they may have a higher abundance, though no definitive conclusion could be reached. In the present work, new and better spectroscopic data have been collected for a sample of Virgo dwarfs. Chemical evolution, the impact of environmental effects, and the relative contribution of these galaxies to the metal enrichment of the ICM and to the overall metallicity-mass-luminosity relation will be presented in a forthcoming paper (J. M. Vílchez et al. 2003, in preparation, hereafter Paper II).
Several Virgo dwarf galaxies have been already studied spectroscopically (Gallagher & Hunter 1989; Izotov & Guseva 1989; Lee et al. 2000; Lee 2002) or using multiwavelength analysis (e.g., Brosch et al. 1998). The present work attempts to produce a systematic spectroscopic study of a large sample of star-forming dwarf galaxies in the Virgo Cluster. Previous results for dIrrs in Virgo (e.g., IC 3475, Vignoux et al. 1986; UGC 7636, Lee et al. 2000) and, more recently in A1367 (CGCG 97–073 and CGCG 97–079, Gavazzi et al. 2001, Iglesias-Páramo et al. 2002) have shown direct evidence that ram pressure stripping is at work for cluster dwarf galaxies.

Finally, the location of our sample dwarfs in the Virgo cluster allows the star-forming regions to be spatially resolved and, since all are at approximately the same distance, distance-dependent uncertainties are minimized in the analysis. In 2 we report on the observations and data obtained for the sample galaxies. In 3, the results are presented derived for the ionization structure, physical properties, and chemical abundances. The discussion and conclusions from the analysis of the results are presented in 4. Further work including the implications of these results for the evolution of the sample of Virgo dwarf galaxies, and a global discussion of their properties will be presented in Paper II.

2. OBSERVATIONS AND DATA REDUCTION

Within an ongoing project of deep imaging of the BCD and Irregular galaxies in the Virgo Cluster Catalog (VCC; Binggeli et al. 1985), a total sample of 22 objects (21 Virgo plus 1 background), most of them classified as blue compact dwarf galaxies, were selected for our spectroscopic study. All the galaxies were selected in the direction of the Virgo central field (sampling within a radius ~ 5′ from M87) for which our Hα survey is being carried out (Boselli et al. 2002). The majority of the objects in the sample belong to VCC morphological classes BCD, Im/BCD; some of them appear classified as Im, Sm, and a few other are noted as peculiar Sp/BCD, dSph/BCD?, or amorphous (cf. Gallagher & Hunter 1989).

The observations were carried out at the Observatorio del Roque de los Muchachos (ORM, La Palma) during two three-night runs (1993 and 1994), using the 4.2 m William Herschel Telescope (WHT) with the ISIS double-arm spectrograph at the Cassegrain focus. For each slit position two spectra, one in the red and one in the blue, were taken simultaneously using a dichroic. Typical seeing values were around 0′′8 to 1′′ throughout most of the runs, and degraded to 2′′ during the second part of the 1994 run. During the first part of the 1993 run light high cirrus were present. All the exposures during both runs were made as closer to the zenith as possible (air masses were always ≤1.3 except in one case, VCC 428, observed at 1.5) in order to minimize any differential atmospheric refraction effects.

The 1280 × 1180 EEV3 detector with 22.5 μm pixels was used in the red arm, and a 1124 × 1124 TEK1 with 24 μm pixels in the blue arm. The effectively observed detector area was windowed to 1230 and 1020 pixels in the spectral direction for the EEV3 and TEK1 detectors, respectively, and to 600 pixels along the slit for both detectors. The spatial scale was of 0′.335 pixel−1 and 0′.357 pixel−1 for the EEV3 and TEK1 detectors, respectively, giving a total slit length of approximately 3′4.

The dichroic was set at an effective wavelength of 5400 Å (1993) and 5700 Å (1994) in order to separate the spectral ranges of the blue and red arms. The 316R grating used for the red arm had 316 lines mm−1 yielding a reciprocal dispersion of 60.4 Å mm−1. The 300B grating used for the blue arm had 300 lines mm−1 yielding a reciprocal dispersion of 62.2 Å mm−1. A similar effective spectral resolution of 4 Å FWHM was reached for both arms.

An additional spectral range in the near-infrared was observed for two of the galaxies, VCC 1699 and VCC 144, centered at 9100 Å. This observational set up gave us a total spectral coverage which includes lines from [O II] λ3727 up to [S II] λ9532.

The journal of observations is shown in Table 1. For each galaxy the VCC number (col. [1]), other name (col. [2]), morphological type1 (col. [3]), 1950 coordinates (cols. [4] and [5]), slit position angle (col. [6]), central wavelength (col. [7]), total exposure (col. [8]), and date of the observation (col. [9]) are presented.

The data reduction was performed at the IAC using the standard software package IRAF,2 following the standard procedure of bias correction, flat-fielding, wavelength calibration, sky subtraction, and flux calibration. The correction for atmospheric extinction was performed using an average curve for the continuous atmospheric extinction at the ORM (King 1985); flux calibration was achieved using repeated observations of the standards sp1446+259 and sp0642+021 from the La Palma spectrophotometric set (Sinclair 1996) which were observed throughout both runs. The sky-subtraction process was effective for most of the spectra, though the proximity of the Na D feature (sky and Galactic) to the emission of He I λ5876 in some spectra might contaminate the flux measured for this line.

Figure 1 shows the spatial profiles of the galaxies (line plus continuum flux) along the slit position, extracted from the two-dimensional spectra at the wavelength corresponding to the Hα line for each galaxy. Many of the spatial profiles are consistent with a single central source of emission, though some galaxies present a rich spatial structure. This is the case of VCC 848 for which up to four emission peaks can be seen in the spatial profile. For this galaxy, three spectra were extracted, labeled (a), (b), and (c) in Figure 1 [not the fourth because of the low signal-to-noise (S/N) of the emission lines], in addition to the integrated spectrum.

In this work an integrated spectrum has been analyzed for each galaxy, extracted adding the flux in the set of spatial increments under the corresponding Hα and Hβ spatial profiles, in order to maximize the final S/N ratio. Representative spectra of all the galaxies of the sample are shown in Figure 2.

3. RESULTS

3.1. Line Intensities

Line intensities were measured using the task SPLOT in the IRAF environment, marking a continuum point, on each side of each line, and adding the total excess flux over the continuum level within the two points. Errors were

1 For a definition of the morphological types see Binggeli, Sandage, & TAMMANN (1985), Sandage (1961), Sandage & TAMMANN (1981), and Sandage & Binggeli (1984).

2 Image Reduction and Analysis Facility, written and supported at the National Optical Astronomy Observatories.
determined for each line by taking into account the Poisson error associated with the total number of counts in the line plus its continuum, the dispersion (rms) of the nearby continuum, the effect of background subtraction, as well as the error associated with the exact placement of the local continuum. Independent measurements of the spectra were carried out in order to produce final error estimates. We believe that, though the relative sources of error are of varying importance for each line, absolute errors in the flux of faint lines are dominated by the continuum subtraction. We have not given a formal error for the absolute flux calibration of the spectra; we estimate an average error in the range 15%–20%.

| VCC (1) | Other Name (2) | Type (3) | $\alpha$ (B1950) (4) | $\delta$ (B1950) (5) | P.A. (deg) (6) | $\lambda$ (Å) (7) | Exposure (s) (8) | Date (9) |
|--------|----------------|----------|----------------------|---------------------|----------------|----------------|----------------|---------|
| 1699...| IC 3591        | SBmIII   | 12 34 30.3           | 07 12 10            | 237            | 4228          | 1400           | 1993 May 25 |
| 144... | Haro 6         | BCD      | 12 12 45.1           | 06 02 24            | 310            | 4228          | 2400           | 1993 May 25 |
| 1313...| RMB 132        | BCD      | 12 28 16.6           | 12 19 20            | 266            | 4228          | 2400           | 1993 May 25 |
| 562... | RMB 175        | BCD      | 12 20 03.3           | 12 26 05            | 138            | 4228          | 3400           | 1993 May 24 |
| 2033...| A1243+08       | BCD      | 12 43 32.8           | 08 45 02            | 237            | 4228          | 1183           | 1993 May 25 |
| 324... | Mrk 49         | Epec/BCD | 12 16 36.6           | 04 07 59            | 3              | 4228          | 2200           | 1993 May 24 |
| 848... | A1223+06       | ImIIIpec/BCD | 12 23 19.5       | 06 05 11            | 24             | 4223          | 2400           | 1993 May 26 |
| 1437...| A1230+09       | BCD      | 12 30 01.5           | 09 26 58            | 57             | 4223          | 1800           | 1993 May 26 |
| 841... | RMB 46         | BCD      | 12 23 15.9           | 15 13 45            | 344            | 4223          | 1800           | 1993 May 26 |
| 334... | RMB 56         | BCD      | 12 16 41.7           | 12 26 05            | 3              | 4228          | 2000           | 1993 May 24 |
| 1374...| IC 3453        | IBm/BCD  | 12 31 37.8           | 14 51 38            | 345            | 4382          | 1400           | 1994 Mar 10 |
| 655... | NGC 4344       | SpN/BCD  | 12 23 37.5           | 17 32 27            | 69             | 4382          | 1600           | 1994 Mar 10 |
| 1725...| A1235+08       | SmIII/BCD| 12 37 41.2           | 08 33 33            | 116.5          | 4382          | 1400           | 1994 Mar 12 |
| 135... | IC 3063        | Spec/BCD | 12 15 06.7           | 12 01 01            | 20.5           | 4382          | 1243           | 1994 Mar 12 |
| 1486...| IC 3483        | Spec?.N  | 12 30 38.1           | 11 37 22            | 170.5          | 4382          | 1400           | 1994 Mar 12 |
| 1955...| NGC 4641       | Spec/BCD | 12 43 97.6           | 12 03 03            | 28             | 4382          | 1400           | 1994 Mar 12 |
| 2037...| 10°71          | ImIII/BCD| 12 46 15.3           | 10 12 12            | 156            | 4382          | 1800           | 1994 Mar 11 |
| 72...  | 15°9           | ImIII/BCD| 12 13 02.0           | 14 55 58            | 134.5          | 4382          | 1800           | 1994 Mar 10 |
| 428... | BB 18          | BCD      | 12 20 40.2           | 13 53 20            | 29             | 4382          | 1500           | 1994 Mar 11 |
| 802... | BO 146         | BCD      | 12 25 28.7           | 13 29 50            | 61.9           | 4382          | 1800           | 1994 Mar 11 |
| 213... | IC 3094        | dS7/BCD? | 12 16 56.0           | 13 37 33            | 90             | 4382          | 1600           | 1994 Mar 11 |
| 1179...| IC 3412        | ImIII/BCD| 12 29 22.6           | 09 59 17            | 18             | 4382          | 1700           | 1994 Mar 11 |

**Notes.**—Col. (1): VCC name. Col. (2): Other name. Col. (3): Type. Cols. (4) and (5): B1950 coordinates. Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (6): Position angle of the slit. Col. (7): Central wavelength of the observation. Col. (8): Exposure time. Col. (9): Date of the observation.
Fig. 1.—Spatial emission profiles of the sample galaxies in a wavelength window centered in Hα. The spatial scale is 0.7335 pixel$^{-1}$. 
Fig. 1.—Continued
Each arm of the spectrograph was independently flux calibrated; and the matching of the corresponding extremes of the blue and red spectra was fairly good, except in the case of VCC 848 (1993 run) and VCC 1437, for which the flux match between the spectra of both arms was rather poor, so they were rescaled. The spectra of the galaxy VCC 848, which was independently observed (at slightly different positions) during the two runs, give results consistent within the errors.

In order to minimize the error associated with the relative (to H\textsc{ii}) flux calibration over the full wavelength range (especially for faint lines), whenever possible line ratios were derived with respect to the flux of the nearest Balmer line, H\textsc{ii} or H\alpha.

In Figure 2 all the spectra of the sample are shown. As illustrated in the figure, the spectra do not fit into a homogeneous class. They cover a wide range in spectral properties, such as the equivalent width of the emission lines, the strength and shape of the underlying stellar continua, as well as the strength of the Balmer lines in absorption and/or emission. Two illustrative examples of spectra of our sample are VCC 428, which shows the typical spectrum of an H\textsc{ii} region with a very faint continuum and strong emission lines, and VCC 1179, which shows strong apparent absorption in the Balmer series and very faint emission lines.

Underlying Balmer absorption is clearly present in the spectra of many galaxies of the sample. In order to correct line fluxes from this effect, a self-consistent procedure has been applied in which a fit was made to the Balmer decrement taking into account the contributions of the extinction and the underlying absorption. In this procedure the equivalent width in absorption was assumed to be the same for all the Balmer lines used (from H\textsc{δ} to H\alpha), as expected for
young ionizing clusters. The correction for underlying absorption ranges from equivalent widths equal to zero (e.g., for VCC 1313, VCC 802) up to values around 9 Å in some objects showing a strong continuum contribution (e.g., VCC 1179, VCC 135, VCC 1437). This range of values of the Hβ equivalent width in absorption were found to be enough to make the observed Balmer ratios agree with the theoretical values, within the errors. All the spectra were
corrected for reddening using the value of the Balmer decrement. The reddening coefficient, \( C(H\beta) \), was derived using the ratios of the optical Balmer recombination lines after correcting for underlying absorption, compared to the theoretical values for case B recombination (\( H\alpha/H\beta = 2.85 \), \( H\gamma/H\beta = 0.469 \), and \( H\delta/H\beta = 0.260 \), Hummer & Storey 1987), and taking into account the S/N ratios and appropriate baseline corrections. The values derived for \( C(H\beta) \) vary
from 0 to 0.5; and a typical error for the reddening coefficient is estimated to be around ±0.1.

Measurements of the flux in the [O III] λ4363 line were obtained from nine spectra of the sample, from which a direct determination of the electron temperature was performed. Whenever possible, upper limits to the flux in the [O III] λ4363 line were computed for each spectrum as 3 σ of the flux observed at this wavelength. The electron tempera-
3.2. Physical Conditions and Abundance Analysis

Electron densities, $N_e$, have been derived from the [S $\text{II}$] $\lambda 6717/6731$ ratio using standard algorithms (e.g., McCall 1984; Aller 1984). All the regions studied give values typical of low-density H $\text{II}$ regions. For the objects in common this result is consistent with previous work (Gallagher & Hunter 1989; Izotov & Guseva 1989).

For those galaxies with a measurement of the [O $\text{III}$] $\lambda 4363$ line flux, the electron temperature of the high-ionization zone, $T_{[O \text{III}]}$, was derived using FIVEL (Shaw & Dufour 1995) assuming the low-density limit. The temperature of the low-ionization zone, $T_{[S \text{II}]}$, has been determined assuming the relation with $T_{[O \text{III}]}$ from photoionization models (Pagel et al. 1992). For the galaxies VCC 1699 and VCC 144 the [S $\text{II}$] $\lambda 6312$ line was measured; from the ratio of its intensity to the flux of the nebular [S $\text{II}$] lines a value of the $T_{[S \text{II}]}$ temperature has been obtained, which appears consistent with $T_{[O \text{III}]}$ to within the errors. Although the appropriate temperature for the [S $\text{III}$] and [Ar $\text{II}$] lines is better represented by intermediate values between $T_{[O \text{III}]}$ and $T_{[O \text{II}]}$ (Garnett 1992), for the purpose of this paper we have used $T_{[O \text{III}]}$ to derive their corresponding abundances.

For the galaxies with a direct determination of the electron temperature, the following ionic and total abundances and abundance ratios: O$^{++}/H^+$, O$^+$/H$^+$, O/H, N$^+$/O$^+$, S$^{++}$/H$^+$, S$^+$/H$^+$, S/H, Ne$^{++}$/O$^{++}$, and Ar$^{++}$/O$^{++}$ have been computed using FIVEL (Shaw & Dufour 1995) assuming the low-density limit, and these are presented in Table 4.

For those galaxies without a direct measurement of the flux of a temperature sensitive line, the abundance of oxygen was derived using the predictions of several different abundance calibrations. The behavior of optical oxygen line intensities in H $\text{II}$ regions as a function of oxygen abundance has been studied via semiempirical methods (e.g., Pagel et al. 1979; Alloin et al. 1979; Edmunds & Pagel 1984; Skillman 1989; Zaritsky et al. 1994; Pilyugin 2000) and also using theoretical photoionization models (e.g., Dopita & Evans 1986; McGaugh 1991; Olofsson 1997; Dopita et al. 2000; Charlot & Longhetti 2001).

Several abundance calibrations can be found in the literature that make use of different ratios of relatively bright nebular lines. Among these empirical abundance parameters are $R_{23}$ (Pagel et al. 1979), $P$ (Pilyugin 2000), and $S_{23}$ (Vilchez & Esteban 1996). Additional empirical calibrations make use of the line ratios [O $\text{III}$] $\lambda 4959, 5007$/[N $\text{II}$] $\lambda 6548, 6584$/H$\alpha$, and [N $\text{II}$] $\lambda 6548, 6584$/[O $\text{II}$] $\lambda 3727$ (van Zee et al. 1998b).

The optical oxygen lines [O $\text{II}$] and [O $\text{III}$] are sensitive to both oxygen abundance and electron temperature. At low metallicities, H $\text{II}$ region cooling appears dominated by collisional excitation of H Ly$\alpha$. Within this regime the total oxygen line intensity increases with abundance. At high metallicities, the oxygen abundance becomes the main coolant, and the bulk of the cooling is then transferred from the optical to the infrared fine-structure lines [O $\text{III}$] $\lambda 52, 88\mu$. Correspondingly, in this regime the intensities of the optical oxygen lines decline as the oxygen abundance increases.

On this basis, the abundance parameter $R_{23}$, defined by Pagel et al. (1979) as $R_{23} = ([\text{O III}] \lambda 3727 + [\text{O II}] \lambda 4959, 5007)/H\beta$ has been widely used in the literature as an
| Line          | $\lambda$ (Å) | $f(\lambda)$ | VCC 1699 | VCC 144 | VCC 1313 | VCC 562 | VCC 2033 | VCC 324 |
|--------------|---------------|--------------|----------|---------|----------|---------|----------|---------|
| [O ii]       | 3727          | 0.26         | 1.260    | (0.018) | 2.541    | (0.031) | 1.102    | (0.032) | 2.656    | (0.076) |
| H12          | 3751          | 0.20         | 0.019    | (0.001) | ...      | ...     | ...      | ...     | ...      | ...     |
| H11          | 3770          | 0.26         | 0.033    | (0.002) | ...      | ...     | ...      | ...     | ...      | ...     |
| H10          | 3798          | 0.25         | 0.042    | (0.002) | ...      | ...     | ...      | ...     | ...      | ...     |
| H9           | 3835          | 0.24         | 0.067    | (0.003) | ...      | ...     | ...      | ...     | ...      | ...     |
| [Ne iii]     | 3868          | 0.23         | 0.364    | (0.007) | 0.270    | (0.006) | 0.338    | (0.014) | ...      | (0.005) |
| H8 + He i    | 3889          | 0.22         | 0.177    | (0.004) | 0.154    | (0.005) | 0.167    | (0.010) | 0.100    | (0.012) |
| He + [Ne iii]| 3969          | 0.21         | 0.264    | (0.005) | 0.194    | (0.005) | ...      | (0.005) | ...      | (0.005) |
| H6           | 4000          | 0.18         | 0.261    | (0.005) | 0.264    | (0.005) | 0.251    | (0.008) | 0.263    | (0.008) |
| H7           | 4340          | 0.14         | 0.471    | (0.008) | 0.469    | (0.008) | 0.469    | (0.015) | 0.466    | (0.015) |
| [O iii]      | 4363          | 0.13         | 0.041    | (0.002) | 0.024    | (0.002) | 0.095    | (0.005) | <0.008   | <0.008   |
| He i         | 4471          | 0.10         | 0.036    | (0.002) | 0.028    | (0.003) | 0.027    | (0.003) | ...      | (0.002) |
| [Ar iv]      | 4713          | 0.04         | 0.005    | (0.001) | ...      | ...     | ...      | ...     | ...      | ...     |
| Hβ           | 4861          | 0.00         | 1.000    | (0.013) | 1.000    | (0.013) | 1.000    | (0.024) | 1.000    | (0.038) |
| He i         | 4922          | −0.01        | 0.007    | (0.001) | ...      | ...     | ...      | ...     | ...      | ...     |
| [O iii]      | 4959          | −0.02        | 1.819    | (0.022) | 1.177    | (0.015) | 1.570    | (0.034) | 0.948    | (0.036) |
| [O iii]      | 5007          | −0.03        | 5.531    | (0.052) | 3.605    | (0.037) | 4.637    | (0.081) | 2.906    | (0.079) |
| He i         | 5876          | −0.23        | 0.113    | (0.003) | 0.098    | (0.003) | 0.085    | (0.006) | ...      | (0.009) |
| [O i]        | 6300          | −0.30        | 0.016    | (0.002) | 0.054    | (0.003) | 0.017    | (0.003) | ...      | (0.002) |
| [S ii]       | 6312          | −0.30        | 0.016    | (0.001) | 0.012    | (0.001) | ...      | ...     | ...      | ...     |
| [N ii]       | 6548          | −0.34        | 0.025    | (0.001) | 0.069    | (0.003) | ...      | ...     | 0.025    | (0.003) |
| Hβ           | 6563          | −0.34        | 2.868    | (0.031) | 2.859    | (0.030) | 2.861    | (0.051) | 2.848    | (0.080) |
| [N ii]       | 6584          | −0.34        | 0.079    | (0.003) | 0.205    | (0.003) | 0.031    | (0.003) | 0.146    | (0.012) |
| He i         | 6678          | −0.35        | 0.033    | (0.002) | 0.030    | (0.002) | 0.023    | (0.002) | ...      | (0.002) |
| [S ii]       | 6717          | −0.36        | 0.104    | (0.002) | 0.181    | (0.004) | 0.116    | (0.005) | 0.298    | (0.017) |
| [S ii]       | 6731          | −0.36        | 0.077    | (0.003) | 0.211    | (0.004) | 0.085    | (0.005) | 0.196    | (0.017) |
| He i         | 7065          | −0.40        | 0.026    | (0.001) | 0.019    | (0.002) | 0.023    | (0.003) | ...      | (0.003) |
| [Ar iii]     | 7135          | −0.41        | 0.105    | (0.003) | ...      | ...     | 0.046    | (0.004) | 0.007    | (0.004) |
| P14           | 8598          | −0.62        | 0.005    | (0.001) | ...      | ...     | ...      | ...     | ...      | ...     |
| P13           | 8665          | −0.63        | 0.005 a  | (0.001) | ...      | ...     | ...      | ...     | ...      | ...     |
| P10           | 9014          | −0.67        | 0.013    | (0.002) | ...      | ...     | ...      | ...     | ...      | ...     |
abundance index. The $12 + \log(O/H)$ versus $R_{23}$ relation is double valued, presenting an ambiguity between the high and low abundance branches, together with a turnover region centered around $12 + \log(O/H) \approx 8.2–8.3$ (McGaugh 1991, 1994; Miller & Hodge 1996; Olofsson 1997). $R_{23}$ has been calibrated by different authors (e.g., Edmunds & Pagel 1984; McCaill et al. 1985; Dopita & Evans 1986; see a comparison in McGaugh 1991). These calibrations differ systematically at high-metallicity by up to 0.2–0.3 dex, and there are some claims that the empirical abundance in this range might be overestimated (e.g., Castellanos et al. 2002; Pilyugin 2001; Kinkel & Rosa 1994; see also Bresolin & Kennicutt 2002). The typical uncertainties quoted for $R_{23}$ empirical abundances are between 0.1 dex at low metallicity, up to 0.2 dex in the turnover region and the abundance high end.

The parameter $S_{23}$, defined as $S_{23} = ([S\ II] \lambda 6716, 6731 + [S\ III] \lambda 9069, 9532)/H\beta$ (Vilchez & Esteban 1996) has been calibrated by Díaz & Pérez-Montero (2000) as an empirical abundance index, in analogy to $R_{23}$. Spectroscopically, the sulfur lines defining $S_{23}$ are analogous to the optical oxygen lines in $R_{23}$ though, given their longer wavelengths, their contribution to the cooling becomes important at lower temperatures (Díaz & Pérez-Montero 2000). Thus, $S_{23}$ appear to show a monotonic behavior over a larger range of oxygen abundance. Kennicutt et al. (2000) have found that $S_{23}$ can show considerable scatter within H II region and suggested it should be applied to integrated spectra; nonetheless the dispersion they derived in the abundances when using $S_{23}$ was only slightly larger than using $R_{23}$. This calibration can provide more accurate abundances for objects with oxygen abundances between $12 + \log(O/H) = 7.20$ (0.02 $Z/\odot$) and $12 + \log(O/H) = 8.80$ (0.75 $Z/\odot$) (cf. Díaz & Pérez-Montero 2000).

Pilyugin (2000, 2001) has proposed a new empirical method for the determination of the oxygen abundance in H II regions based on the definition of the parameter $P = ([O\ III] \lambda 4959, 5007/H\beta)/R_{23}$. Following earlier suggestions by McGaugh (1991) that the strong oxygen lines of $[O\ III]$ and $[O\ II]$ have enough information for the determination of abundances in H II regions, he compared oxygen abundances in bright H II regions derived from direct determination of the electron temperature with those derived through the proposed $P$-method. He has found that the precision of the oxygen abundances derived with the $P$-method is comparable to the one obtained using a direct determination of the electron temperature. Two abundance relations were obtained: one for low-metallicity H II regions, lower than $12 + \log(O/H) \approx 8.1$, and another one for high-metallicity H II regions with $12 + \log(O/H) \geq 8.2$ (i.e., similar to the upper and lower abundance branches of the $O/H$ vs. $R_{23}$ relationship).

In his theoretical work, McGaugh (1991) produced an extensive grid of H II region models parameterized by the shape of the ionizing spectrum, the geometry of the nebula, and the abundance of the gas. He found that the behavior of the strong oxygen lines can be modeled by taking into account the softening of the ionizing spectra produced by stars of increasing metallicity. In these models, the ratios $[O\ III] / [O\ II]$ versus $R_{23}$ surface predicted by the models is double valued due to the two cooling regimes described above operating at high and low abundance. This theoretical calibration appears consistent with recent observations and photoionization models of high abundance objects (Castellanos et al. 2002 and references therein), and it has an estimated mean uncertainty of 0.1 dex. Overall, we should bear in mind that different geometry and aging of the H II regions could introduce some scatter in the calibration (e.g., Stasińska 1999).

Dopita et al. (2000) theoretically recalibrated the extragalactic H II region sequence and defined the theoretical boundary between H II regions and active galactic nuclei. They used the PEGASE (Fioc & Roca-Volmerange 1997) and STARBURST99 (Leitherer et al. 1999) codes to generate the spectral energy distribution of the ionizing star clusters, and MAPPINGS3 (Sutherland & Dopita 1993) was used to compute photoionization models, including a self-consistent treatment of dust physics and chemical depletion. The extragalactic H II region sequence of observations is well reproduced by these models, assuming that the ionizing clusters are all young ($\leq 2$ Myr) (these authors point out this is likely a selection effect). They proposed that the ratio $[N\ II] \lambda 6548, 6584/[O\ III] \lambda 3727$ gives the best diagnostic of abundance, being monotonic between 0.1 $Z/\odot$ and over 3.0 $Z/\odot$.
More recently, Charlot & Longhetti (2001) combined recent population synthesis and photoionization codes to compute the line and continuum emission from star-forming galaxies. They calibrate the nebular properties of the models using observations of line ratios for a sample of star-forming galaxies. From optical spectral fits they are able to constrain the star formation history, the gas abundance, and the absorption by dust.

For the determination of abundances in this paper we have used (i) the analytical expression of the McGaugh (1991) theoretical models reported in Kobulnicky et al. (1999); (ii) the theoretical calibration of [N ii]/[O ii] after Dopita et al. (2000); (iii) the empirical calibration of $\Delta_{23}$ (Diaz & Perez-Montero 2000); and (iv) the empirical calibration of the parameter $P$ (Pilyugin 2000, 2001). For each galaxy, an average oxygen abundance, $(12 + \log(O/H))$, and N/O abundance ratio, $(\log(N/O))$, has been adopted.

In the next section we discuss the results of the abundance analysis and present the adopted abundances for the sample galaxies.

### 4. DISCUSSION AND CONCLUSIONS

In this work oxygen abundances and N/O abundance ratios have been derived for 21 dwarf galaxies in the Virgo Cluster, these are presented in Tables 5A and 5B. These results show that the oxygen abundances of the galaxies span the metallicity range $0.05 \leq Z \leq 1.5$. The nitrogen-to-oxygen ratios derived range from values typical of low-metallicity, field BCD galaxies up to near solar

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**TABLE 2B**

Reddening-Corrected Line Intensities Relative to H$\beta$ for the Sample of Virgo Dwarf Galaxies: VCC 848, VCC 1437, VCC 841, and VCC 334

| Line | $\lambda$ (Å) | $f(\lambda)$ | VCC 848 a | VCC 848b | VCC 848c | VCC 848b | VCC 1437 | VCC 841 | VCC 334 |
|------|--------------|--------------|-----------|----------|----------|----------|----------|----------|----------|
| [O ii] | 3727 | 0.26 | 1.989 | 2.968 | 2.573 | 3.410 | 4.816 | 2.714 | 3.725 |
| [Ne iii] | 3868 | 0.23 | 0.233 | (0.074) | (0.460) | (0.276) | (0.111) | (0.187) | (0.133) | (0.123) |
| H$\delta$ | 3889 | 0.22 | 0.115 | (0.031) | ... | ... | ... | ... | ... |
| H$\epsilon$+[Ne iii] | 3969 | 0.21 | 0.160 | (0.032) | ... | ... | ... | ... | ... |
| H$\gamma$ | 4100 | 0.18 | 0.261 | 0.262 | ... | 0.247c | 0.263 | 0.264 | 0.181 |
| H$\epsilon$ | 4340 | 0.14 | 0.467 | 0.468 | 0.470c | 0.472 | 0.466 | 0.466 | 0.473 |
| [O iii] | 4363 | 0.13 | 0.046 | <0.079 | <0.040 | 0.041 | <0.014 | <0.014 | <0.018 |
| H$\beta$ | 4861 | 0.00 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| [O ii] | 4959 | -0.02 | 1.158 | 0.416 | 0.580 | 1.072 | 0.791 | 0.722 | 0.596c |
| [O ii] | 5007 | -0.03 | 3.526 | 1.524 | 1.180 | 3.211 | 2.482 | 2.448 | 2.005 |
| H$\epsilon$ | 5876 | -0.23 | 0.060 | ... | ... | 0.104 | 0.095 | 0.084 | ... |
| [O i] | 6300 | -0.30 | 0.030 | ... | ... | 0.082 | ... | ... | 0.024 |
| [N ii] | 6548 | -0.34 | 0.091c | 0.111 | ... | 0.085c | 0.145 | 0.102c | 0.040c |
| H$\alpha$ | 6563 | -0.34 | 2.851 | 2.851 | 2.864 | 2.849 | 2.851 | 2.850 | 2.873 |
| [N ii] | 6584 | -0.34 | 0.177 | 0.369 | 0.373 | 0.196 | 0.515 | 0.370 | 0.223 |
| H$\epsilon$ | 6678 | -0.35 | ... | ... | ... | ... | 0.017 | ... | ... |
| [S ii] | 6717 | -0.36 | 0.136 | 0.591 | 0.899 | 0.361 | 0.361 | 0.401 | 0.504 |
| [S ii] | 6731 | -0.36 | 0.107 | 0.448 | 0.474 | 0.253 | 0.276 | 0.280 | 0.358 |
| [Ar iii] | 7135 | -0.41 | ... | ... | ... | 0.085 | 0.074 | 0.088 | ... |
| C(H/β) | 0.07 | 0.12 | 0.06 | 0.22 | 0.43 | 0.40 | 0.13 |
| F(H/β) | 6.71 | 2.11 | 1.55 | 14.2 | 12.4 | 7.76 | 8.31 |

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*a* Spectra of knots a, b, and c (Fig. 1); 1993 run.

*b* Integrated spectrum; 1994 run.

*c* Uncertain value.
ratios. Comparison with previous work on abundances of Virgo dwarfs is a difficult task due to the shortage of papers devoted to this subject. Previous spectroscopy of several star-forming Virgo dwarfs has been done by Gallagher & Izotov & Guseva (1989). Bright line ratios such as \( R_{\text{Hunter}} \) (1989) and Izotov & Guseva (1989) have been devoted to this subject. Previous spectroscopy of several Virgo dwarfs is a difficult task due to the shortage of papers presenting in Pagel et al. (1979). These abundance values appear consistent, within the errors, with the values derived here for the same objects.

In order to adopt the final oxygen abundance and nitrogen-to-oxygen abundance ratio for each galaxy of the sample, we have proceeded as follows:

1. For the nine objects with an electron temperature measurement, the abundances derived using the electron temperature, as quoted in Table 4, have been finally adopted. They are presented in Tables 5A and 5B and, in the following, we will refer to these abundances as “direct” abundances.

2. For each of the 13 remaining objects an average abundance value, or the corresponding abundance interval, has been finally adopted, and it is presented in Tables 5A and 5B. This average value for each galaxy was derived from the predictions of the corresponding abundance calibrations used in this work (see §3) as it is described below. In this respect, the dispersion among the abundance predictions for each object can be seen as an indicator of the uncertainty in the derivation process. We believe that the advantage of using several calibrations, instead of choosing a single one, is that we can obtain a more realistic estimate of the uncertainty (e.g., Zaritsky et al. 1994).

At this point it is important to emphasize the role that the \([\text{N} \text{II}] / [\text{O} \text{II}]\) ratio plays for the abundance calibrations. This...
line ratio has been shown to be monotonic with oxygen abundance from 0.2 Z\textsubscript{\odot} up to 3.0 Z\textsubscript{\odot} (Dopita et al. 2000), a metallicity range where nitrogen behaves as a secondary element. It is also important to bear in mind that the [N\textsc{ii}]/[O\textsc{ii}] ratio depends on both electron temperature and N/O abundance ratio. Thus, choosing a different formula accounting for the dependence of N/O on O/H would lead, in principle, to different values for this ratio. For example, Stasińska et al. (2001) adopted a mild dependence of N/O on O/H abundance \[\log(N/O) = 0.5 \log(O/H) + 0.4]\, leading to smaller predictions of [N\textsc{ii}]/[O\textsc{ii}].

In addition, as originally proposed by Edmunds & Pagel (1978), N/O may also change with time as a consequence of delayed production of nitrogen. This fact has relevance for the process of abundance determination, when comparing with the predictions for the zero-age case. Indications of such behavior have been pointed out by looking at the N/O versus O/H plot for H\textsc{ii} regions and star-forming galaxies (e.g., van Zee et al. 1998a; Henry et al. 2000), for abundances in the range 0.1 to 0.5 Z\textsubscript{\odot}. On the other hand, variations in the N/O ratio can also be produced by the effects of gas inflow or outflow in the galaxy and/or self-enrichment (Henry et al. 2000). For primary nitrogen, N/O can be affected only in the case of a differential outflow (i.e., different outflow for oxygen than for nitrogen); when nitrogen is secondary, N/O can be affected by an unenriched inflow in addition to differential outflow (see Henry et al. 2000, Köppen & Edmunds 1999, and references therein).

The [N\textsc{ii}]/[O\textsc{ii}] ratio presents a single parameter sequence from high to low abundances (e.g., van Zee et al. 1998b; Dopita et al. 2000). As commonly accepted, we have assumed that all the H\textsc{ii} regions with log ([N\textsc{ii}]/[O\textsc{ii}]) < −1.0 correspond to the lower oxygen abundance

### Table 2D

Reddening-Corrected Line Intensities Relative to H\textsc{ii} for the Sample of Virgo Dwarf Galaxies: VCC 2037, VCC 72, VCC 428, VCC 802, VCC 213, and VCC 1179

| Line | \(\lambda (\text{Å})\) | VCC 2037 | VCC 72 | VCC 428 | VCC 802 | VCC 213 | VCC 1179 |
|------|---------------------|---------|--------|--------|--------|--------|--------|
| [O\textsc{ii}] | | 3727 | 0.26 | 5.438 | 3.424 | 2.128 | 2.696 | 2.361 | 9.503 |
| [Ne\textsc{iii}] | | 3868 | 0.23 | ... | ... | 0.214 | 0.303 | ... | ... |
| H\textsc{ii} + He\textsc{i} | | 3889 | 0.22 | ... | ... | 0.150 | 0.203 | ... | ... |
| He\textsc{i} + [Ne\textsc{iii}] | | 3969 | 0.21 | ... | ... | 0.188 | ... | ... | ... |
| H\textsc{ii} | | 4100 | 0.18 | ... | 0.261\textsuperscript{a} | 0.262 | 0.259\textsuperscript{a} | 0.261 | 0.262 |
| H\textsc{ii} | | 4340 | 0.14 | (0.109) | (0.017) | (0.036) | (0.044) | ... | 0.469\textsuperscript{a} |
| [O\textsc{iii}] | | 4363 | 0.13 | <0.047 | <0.063 | 0.072 | 0.031 | <0.028 | <0.055 |
| H\textsc{ii} | | 4861 | 0.00 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 | 1.000 |
| [O\textsc{iii}] | | 4959 | −0.02 | 0.682 | ... | 0.963 | 0.700 | 0.109 | 0.471 |
| [O\textsc{iii}] | | 5007 | −0.03 | 1.812 | 0.477 | 2.910 | 2.150 | 0.336 | 1.525 |
| He\textsc{ii} | | 5876 | −0.23 | ... | ... | ... | ... | 0.219 | ... |
| [O\textsc{ii}] | | 6300 | −0.30 | ... | ... | ... | ... | ... | ... |
| [N\textsc{ii}] | | 6548 | −0.34 | ... | 0.315\textsuperscript{a} | ... | 0.103 | 0.259 | 0.216\textsuperscript{a} |
| H\textsc{i} | | 6563 | −0.34 | 2.863 | 2.861 | 2.871 | 2.858 | 2.858 | 2.864 |
| [N\textsc{ii}] | | 6584 | −0.34 | 0.354 | 0.729 | 0.072 | 0.355 | 0.910 | 0.434 |
| [S\textsc{ii}] | | 6717 | −0.36 | 0.781 | 1.525\textsuperscript{a} | 0.173 | 0.481 | 0.473 | 0.710 |
| [S\textsc{ii}] | | 6731 | −0.36 | 0.630 | 0.445 | 0.135 | 0.355 | 0.364 | 0.559 |
| He\textsc{i} | | 7065 | −0.40 | ... | ... | 0.037 | ... | ... | ... |
| [Ar\textsc{iii}] | | 7135 | −0.41 | ... | ... | 0.061 | ... | ... | 0.209 |
| C(H\textsc{ii}) | | 7135 | −0.41 | ... | ... | 0.23 | 0.25 | 0.48 | 0.04 |
| F(H\textsc{ii}) | | 7135 | −0.41 | ... | ... | 0.10 | 0.10 | 0.209 | 0.099 |

\textsuperscript{a} Uncertain value.
predictions of $R_{23}$ and $P$, and conversely, the high abundance branch of these calibrations correspond to H ii regions showing log ([N ii]/[O ii]) $\geq -1.0$ (e.g., McGaugh 1994; Miller & Hodge 1996; van Zee et al. 1998b; Contini et al. 2002). In Tables 5A and 5B the value of log ([N ii]/[O ii]) has been quoted for each galaxy, together with the parameters log ([O iii]/[O ii]) and log $R_{23}$. These line ratios are used in the computation of the abundance predictions from the different calibrations selected, as described in § 3.

For each galaxy, in Tables 5A and 5B we show the abundance predictions for $12 + \log(O/H)$ that have been obtained using the different calibrations:

1. $P_{\text{upper}}$ and $P_{\text{lower}}$ are the upper and lower oxygen abundance, respectively, predicted from the empirical calibration of Pilyugin (2000, 2001).
2. $R_{23\text{lower}}$ and $R_{23\text{upper}}$ are the lower and upper oxygen abundance, respectively, predicted by the McGaugh (1991) theoretical models, computed using the algorithms reported in Kobulnicky et al. (1999).
3. [N ii]/[O ii]: represents the oxygen abundance obtained from the theoretical calibration of the [N ii]/[O ii] diagnostic by the Dopita et al. (2000) models.
4. $S_{23}$ is the abundance predicted by the empirical calibration of the $S_{23}$ ratio after Díaz & Pérez-Montero (2000).

In Tables 5A and 5B all the abundance predictions, from the different calibrations, have been quoted for every object. However, in the computation of the average abundance of each galaxy we have used only those predictions within the allowed range of application of each calibration (see § 3) and following the [N ii]/[O ii] criterion as indicated above.

As an additional constraint, from the spectra with appropriate S/N, lower limits to O/H were computed using the estimated upper limits to the [O iii] A4363 line flux. The lower limits to O/H are quoted also in Tables 5A and 5B. This constraint supplied information on the abundance regime.

In Figure 3 we present the diagnostic diagram of log ([O iii]/[O ii]) versus log ([N ii]/[O ii]) with the points of our sample of Virgo galaxies; superposed is the model grid of Dopita et al. (2000) for abundances 0.2 up to 2 Z$_\odot$. Triangles and circles correspond to objects with log ([N ii]/[O ii]) $\leq -1.0$ and $\geq -1.0$, respectively. Filled points represent those objects for which a “direct” determination of the abundance has been obtained. A sequence of points can be seen in the figure, where the highest abundances, between 1 and 1.5 Z$_\odot$, are predicted for four objects in the sample. Many points cluster around the 0.5 Z$_\odot$ line, while only three points, spanning the whole range in ionization parameter $[3.5 \leq \log(u) \leq -2.3]$ shown in the plot, appear consistent with the lowest abundance predictions for 0.2 Z$_\odot$ (note that, according to Fig. 6 in Dopita et al. 2000 these points could be consistent also with the locus of the 0.1 Z$_\odot$ models). A comparison between the abundances predicted from these models and the “direct” abundances, for the three objects in Table 4 with $12 + \log(O/H) \geq 8.2$, tell us that model and “direct” abundances appear consistent, within the errors. The remaining galaxies have “direct” abundances lower than 0.2 Z$_\odot$, which are out of the range allowed for these models.

The log ([O iii]/[O ii]) versus log $R_{23}$ diagnostic diagram is presented in Figures 4 and 5. McGaugh (1991) models, as reported in Kobulnicky et al. (1999), are shown for the lower (Fig. 4) and higher (Fig. 5) abundance regimes. The points are coded as in Figure 3. Model predictions for different values of the oxygen abundance are shown in Figure 4 as continuous lines, starting from $12 + \log(O/H) = 7.4$, each line increasing the abundance by 0.1 dex. In Figure 5, the corresponding models for high abundances are shown by dotted lines, starting from $12 + \log(O/H) = 8.2$, the abundance of each line increasing by 0.1 dex. As stated before, triangles represent objects analyzed using the low abundance models (Fig. 4), whereas circles represent objects corresponding to high abundance models (Fig. 5). The somewhat larger uncertainty expected in the turnover region, pointed out in § 3, is apparent extrapolating model predictions toward $12 + \log(O/H) = 8.2$. Looking at Figures 4 and 5 and Tables 5A and 5B we can see that, for most of the objects with a “direct” oxygen abundance, these abundances are consistent with the model predictions, within a nominal error of 0.2 dex. It is striking, however, the large discrepancy that appears between model and “direct”

### Table 3: Comparison of Values of log $R_{23}$ with Previous Works

| VCC (1) | IG89 (2) | GH89 (3) | This Work (4) |
|--------|---------|---------|--------------|
| 144    | 0.86    | 0.89    | 0.865        |
| 324    | 0.72    | 0.88    | 0.817        |
| 334    | ...     | 0.91    | 0.80         |
| 848    | ...     | 0.73$^a$| 0.824        |
| 1374   | ...     | 0.92$^a$| 0.85         |
| 1437   | 0.74    | ...     | 0.908        |
| 1725   | ...     | 0.81    | 0.74         |
| 2033   | 0.89    | 0.91    | 0.665        |

Notes.—Col. (1): Galaxy VCC number. Col. (2): IG89—Izotov & Guseva 1989. Col. (3): GH89—Gallagher & Hunter 1989. Col. (4): This work.

$^a$ Uncertain value.
TABLE 4
DIRECT DETERMINATION OF PHYSICAL CONDITIONS AND ABUNDANCES

| Parameter                   | VCC 1699          | VCC 144          | VCC 1313         | VCC 848\(^a\)   | VCC 848\(^b\)   | VCC 1374         | VCC 1725         | VCC 428         | VCC 802         |
|-----------------------------|-------------------|------------------|------------------|-----------------|-----------------|-----------------|-----------------|----------------|----------------|
| \(T_{\text{e}}\) (10^4 K) \(\pm\) | 1.048 ± 0.021     | 1.014 ± 0.037    | 1.542 ± 0.038    | 1.278 ± 0.132   | 1.265 ± 0.131   | 0.929 ± 0.090    | 1.481 ± 0.150   | 1.696 ± 0.10    | 1.33 ± 0.14    |
| \(T_{\text{S}}\) (10^4 K) \(\pm\) | 1.06 ± 0.03       | 1.15 ± 0.03      | ...              | ...             | ...             | ...             | ...             | ...             | ...             |
| \(\log N_{\text{S}}\) (cm\(^{-3}\)) \(\pm\) | 1.9               | 1.8              | 1.8              | 2.2             | \(\leq 2\)     | \(\leq 2\)      | \(\leq 2\)      | 2.1             | 1.8             |
| \(12 + \log (O^+/H^+)\) \(\pm\) | 7.61 ± 0.05       | 8.00 ± 0.07      | 7.08 ± 0.07      | 7.57 ± 0.15     | 7.72 ± 0.16     | 7.94 ± 0.16      | 7.54 ± 0.16     | 7.30 ± 0.10     | 7.58 ± 0.16     |
| \(12 + \log (O^{++}/H^+)\) \(\pm\) | 8.23 ± 0.06       | 8.09 ± 0.05      | 7.67 ± 0.05      | 7.76 ± 0.12     | 7.74 ± 0.16     | 8.14 ± 0.10      | 7.31 ± 0.11     | 7.36 ± 0.08     | 7.50 ± 0.14     |
| \(12 + \log (O/H)\) \(\pm\)       | 8.32 ± 0.06       | 8.35 ± 0.07      | 7.77 ± 0.06      | 7.98 ± 0.14     | 8.03 ± 0.16     | 8.35 ± 0.14      | 7.74 ± 0.14     | 7.64 ± 0.09     | 7.84 ± 0.15     |
| \(\log (N^+/O^+)\) \(\pm\)        | −1.46 ± 0.05      | −1.39 ± 0.04     | −1.63 ± 0.08     | −1.22 ± 0.08    | −1.37 ± 0.11    | −1.33 ± 0.09     | −0.97 ± 0.10    | −1.53 ± 0.10    | −1.0 ± 0.12     |
| \(12 + \log (S^+/H^+)\) \(\pm\)   | 5.58 ± 0.05       | 6.04 ± 0.04      | 5.36 ± 0.06      | 5.58 ± 0.14     | 5.90 ± 0.16     | 6.31 ± 0.12      | 6.00 ± 0.11     | 5.39 ± 0.11     | 6.02 ± 0.17     |
| \(12 + \log (S^{++}/H^+)\) \(\pm\) | 6.57 ± 0.08       | 6.40 ± 0.09      | ...              | ...             | ...             | ...             | ...             | ...             | ...             |
| \(12 + \log (S/H)\) \(\pm\)       | \(\geq 6.61\) ± 0.08 | \(\geq 6.56\) ± 0.08 | ...              | ...             | ...             | ...             | ...             | ...             | ...             |
| \(\log (Ne^{++}/O^{++})\) \(\pm\) | −0.70 ± 0.03      | −0.64 ± 0.06     | −0.74 ± 0.07     | −0.74 ± 0.08    | ...             | ...             | −0.74 ± 0.10    | −0.46 ± 0.17    | ...             |
| \(\log (Ar^{++}/O^{++})\) \(\pm\) | −2.29 ± 0.08      | ...              | −2.42 ± 0.09     | ...             | −2.06 ± 0.09    | −2.16 ± 0.10     | −1.62 ± 0.12    | −2.06 ± 0.10    | ...             |

\(^a\) Knot a, 1993 run.
\(^b\) Integrated spectrum, 1994 run.
abundances for VCC 802, VCC 848, and VCC 1725. For these three galaxies $R_{23}^{\text{upper}}$ was selected since all show $\log ([\text{N} \, \text{II}]/[\text{O} \, \text{II}]) > -1.0$. However, it is interesting to note that this discrepancy could be minimized if $R_{23}^{\text{lower}}$ had been selected instead of $R_{23}^{\text{upper}}$. This situation could be understood if we adopt the hypothesis that these galaxies show a $[\text{N} \, \text{II}]/[\text{O} \, \text{II}]$ ratio higher than the one expected for dwarf galaxies with a similar oxygen abundance.

A comparison between “direct” and empirical abundances derived using Pilyugin (2000, 2001) for the galaxies in Table 4 give a smaller difference, typically comparable to the nominal error of the calibration. From Tables 5A and 5B we can notice again the striking cases of VCC 802, VCC 848, and VCC 1725 for which we find differences between “direct” and predicted abundances of $-0.56$, $-0.35$, and $-0.66$ dex, respectively. As in the case of the McGaugh models previously discussed, if we had selected $P_{\text{lower}}$ instead of $P_{\text{upper}}$ for these three galaxies, under the hypothesis mentioned above, these differences would have diminished to “direct” $-P_{\text{lower}} = -0.06$, $-0.05$, and $-0.26$ dex, respectively, comparable to the nominal error of the calibration. In the case of VCC 1699 we find a somewhat large

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**TABLE 5A**

**Adopted Abundances and Ionization Structure Parameters for Virgo Dwarf Galaxies: VCC 1699, VCC 144, VCC 1313, VCC 562, VCC 2033, VCC 324, VCC 848, VCC 1437, VCC 841, and VCC 334**

| Parameter | VCC 1699 | VCC 144 | VCC 1313 | VCC 562 | VCC 2033 | VCC 848 | VCC 1437 | VCC 841 | VCC 334 |
|-----------|----------|---------|----------|---------|----------|---------|----------|---------|---------|
| $\log R_{23}$ | $0.935$ | $0.865$ | $0.864$ | $0.814$ | $0.665$ | $0.817$ | $0.824$ | $0.908$ | $0.770$ | $0.80$ |
| $\log ([\text{O} \, \text{III}]/[\text{O} \, \text{II}])$ | $0.688$ | $0.275$ | $0.751$ | $0.162$ | $-0.274$ | $0.292$ | $0.372$ | $-0.168$ | $0.067$ | $-0.156$ |
| $\log ([\text{N} \, \text{II}]/[\text{O} \, \text{II}])$ | $-1.10$ | $-0.96$ | $-1.40$ | $-1.15^a$ | $-0.96^b$ | $-0.92$ | $-0.92$ | $-0.85$ | $-0.77$ | $-1.15$ |

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* $^a$ Uncertain value or calibration.
* $^b$ At the 1 $\sigma$ error level, $[\text{N} \, \text{II}]/[\text{O} \, \text{II}] < 0.1$ could be compatible, leading to $(12 + \log (\text{O}/\text{H})) = 8.0$, $(\log (\text{N}/\text{O})) = -1.4$.
* $^c$ Direct abundance determination (or lower limit) from the $[\text{O} \, \text{III}] 4363$ line flux.
* $^d$ Abundances derived from the integrated spectrum of VCC 848, in parenthesis.
* $^e$ Empirical abundance calibration using the P-method: upper-lower branch after Pilyugin 2000, 2001.
* $^f$ Theoretical abundance calibration of $R_{23}$ (cf. Pagel et al. 1980) according to the models of McGaugh 1991; upper-lower branch as parameterized in Kobulnicky et al. 1999.
* $^g$ Theoretical abundance calibration of $[\text{N} \, \text{II}]/[\text{O} \, \text{II}]$ abundance diagnostic according to the models of Dopita et al. 2000.
* $^h$ Empirical abundance calibration using sulfur lines, after Díaz & Pérez-Montero 2000.
difference between its “direct” abundance and $P_{\text{lower}}$ or $R_{23\text{ lower}}$. However, since VCC 1699 has log $R_{23} > 0.9$, it would be located in the turnover region of the calibrations. As discussed below, the oxygen abundance adopted for the turnover of the calibration is then in good agreement with the “direct” abundance computed for VCC 1699.

As already pointed out in § 3, both calibrations, $R_{23}$ and $P$, enter a region around $12 + \log(O/H) = 8.2$ to 8.3, corresponding to log $R_{23} > 0.9$, for which abundance predictions become more uncertain. This region represents the turnover between the low and high abundance branches of both calibrations. From this metallicity, the theoretical calibration of [N ii]/[O iii] of Dopita et al. (2000) can be used up to over solar values. Nonetheless, the models for 0.1 and 0.2 Z$\odot$ predict nearly the same locus in the log ([N ii]/[O iii]) versus log ([O iii]/[O ii]) diagram (Fig. 6 in Dopita et al. 2000) implying, in practice, that we cannot discriminate between these two abundances. Thus, in this work we have adopted a conservative abundance of $12 + \log(O/H) = 8.2 \pm 0.2$ for all the objects in the sample showing log $R_{23} > 0.9$ without a “direct” determination of the abundance.

The $S_{23}$ parameter seems to be monotonic across this abundance region, but it was available only for two objects of the Virgo sample: VCC 144 and VCC 1699. For these two galaxies, as can be seen in Tables 5A and 5B, the oxygen abundances provided by the $S_{23}$ calibration (Diaz & Perez-Montero 2000) are in good agreement with the “direct” abundances, within the errors.

For some of the objects without a “direct” abundance we have adopted an interval in $12 + \log(O/H)$, instead of a single value, with the aim of encompassing the range in O/H predictions (typically between the McGaugh and Pilyugin calibrations). The use of strong line diagrams, notably at high abundance, is subject to large uncertainties (see Stasińska 1999 for a review). The models of McGaugh (1991) assume unevolving ionizing stellar clusters, whereas it is known that both the ionization parameter as well as the shape of the ionizing spectrum may evolve (e.g., Stasińska & Leitherer 1996; Olofsson 1997). The effect of cluster evolution on the oxygen line fluxes is expected to be important especially at high metallicity, where diagnostic diagrams could change as a function of age (Stasińska 1999). On the other hand, using the best empirical fit to the samples of abundances derived from temperature-sensitive lines, as in the Pilyugin $P$ calibration, could lead to lower values of oxygen especially at high abundance (Stasińska 2002).

There have been some suggestions that the $R_{23}$ calibration may provide abundances systematically higher by 0.2–0.3 dex in the high abundance regime, probably depending on the excitation conditions (e.g., Castellanos et al. 2002; Pilyugin 2001; Kinkel & Rosa 1994; see also Bresolin & Kennicutt 2002). The effect of excitation has been taken into account by McGaugh (1991), Pilyugin (2000), and Dopita et al. (2000). On the other hand, for two of the objects showing [N ii]/[O iii] $\gtrsim 1$, their errors could allow the lower branch to be chosen at the 1σ level; in these two cases, VCC 562 and VCC 2033, the abundance of the lower branch of $12 + \log(O/H)$ has also been indicated in Tables 5A and 5B.

The average N/O abundance ratio, $\log(N/O)$, has been derived for each galaxy of the sample. In doing this, an “average” electron temperature was assumed for each object, corresponding to the temperature for which the derived oxygen abundance can be reproduced from the observed [O iii] and [O ii] fluxes within the errors. From photoionization models, it is well known that for temperatures $t_{\text{O iii}} \geq 1.2$ (in units $10^4$ K), $t_{\text{O iii}}$ is higher than $t_{\text{O ii}}$ and the opposite is found for $t_{\text{O iii}}$ below this value (Peimbert 2002 and references therein). Using an average temperature would introduce an error when deriving the nitrogen-to-oxygen ratio (e.g., van Zee et al. 1998b). For an average difference of 1000 K between $t_{\text{O iii}}$ and $t_{\text{O ii}}$ in the average temperature range used, an error of 0.06 dex in $\log(N/O)$ would be obtained, within the nominal error budget of the calibrations.

All the objects with $12 + \log(O/H) \lesssim 8.2$ in Tables 5A and 5B show nitrogen-to-oxygen ratios consistent with the typical values of low-metallicity dwarf galaxies. There are two notable exceptions to this behavior: VCC 1725 and

| Parameter | VCC 1374 | VCC 655 | VCC 1725 | VCC 135 | VCC 1486 | VCC 1955 | VCC 2037 | VCC 428 | VCC 802 | VCC 213 | VCC 1179 |
|-----------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| $log R_{23}$ | 0.85 | 0.36 | 0.74 | 0.22 | 0.69 | 0.37 | 0.90 | 0.78 | 0.74 | 0.45 | 1.06 |
| $log([O ii]/[O iii])$ | 0.13 | −0.93 | −0.07 | −0.64 | −0.54 | −0.70 | −0.34 | 0.26 | 0.02 | −0.73 | −0.68 |
| $log([N ii]/[O iii])$ | −0.98 | −0.28 | −0.77 | −0.06 | −0.69 | −0.37 | −1.07 | −1.35 | −0.77 | −0.30 | −1.22 |
| $12 + log(O/H)$ | 8.35 | 7.74 | $\geq 7.3$ | $\geq 7.7$ | 7.64 | 7.84 | $\geq 7.7$ | | | | |
| $P_{upper}$ | 8.3 | 8.6 | 8.4 | 8.7 | 8.3 | 8.6 | 8.1 | 8.5 | 8.4 | 8.5 | |
| $P_{lower}$ | 8.0 | 8.5 | 8.0 | 7.9 | 8.4 | 8.2 | 8.5 | 7.8 | 7.9 | 8.4 | |
| $R_{23 upper}$ | 8.5 | 8.9 | 8.6 | 9.0 | 8.6 | 8.9 | 8.4 | 8.6 | 8.6 | 8.9 | 8.2 |
| $R_{23 lower}$ | 8.1 | 7.75 | 8.0 | 7.5 | 8.1 | 7.7 | 8.3 | 7.9 | 7.9 | 7.8 | 8.2 |
| $[N ii]/[O iii]$ | 8.6 | 8.8 | 8.7 | 9.0 | 8.7 | 8.9 | 8.4 | 8.1 | 8.7 | 8.9 | 8.0 |
| Adopted | $12 + log(O/H)$ | 8.35 | 8.9–8.6 | 7.74 | 9.0–8.7 | 8.7–8.3 | 8.9–8.6 | 8.3 $\pm$ 0.2 | 7.64 | 7.84 | 8.9–8.5 | 8.2 $\pm$ 0.2 |
| $log(N/O)$ | $\leq -1.33$ | $-0.9$ | $-0.97$ | $-0.75$ | $-1.2$ | $-1.0$ | $-1.5$ | $-1.0$ | $-0.9$ | $-1.5$ | |
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VCC 802, which deserve independent confirmation and further study. Our data for these two galaxies indicate oxygen abundances below one-tenth solar and N/O ratios close to the Orion value log (N/O)_{Orion} = -0.85 \pm 0.10 (Esteve et al. 1998) which appears high for low abundance dwarfs. Among the galaxies with 12 + log(O/H) \geq 8.2, a significant fraction have high abundances with O/H and N/O close to or larger than the solar values 12 + log(O/H)_{\odot} = 8.71 \pm 0.05 and log (N/O)_{\odot} = -0.78 \pm 0.12 (Holweger 2001; Allende Prieto et al. 2001).

Finally, near 50% of the galaxies in the Virgo sample have oxygen abundances between the abundance of the Large Magellanic Cloud 12 + log(O/H)_{LMC} = 8.39 \pm 0.12 (Pagel et al. 1979) and that of Orion 12 + log(O/H)_{Orion} = 8.64 \pm 0.06 (Esteve et al. 1998). Most of the galaxies with the larger O/H abundances and/or the higher N/O ratios tend to show spectra with an important continuum contribution and conspicuous absorption lines. These outstanding objects need further study. In particular, following the idea that the N/O ratio could be a measure of the time elapsed since the bulk of star formation (Edmunds & Pagel 1978; Matteucci & Tosi 1985), the dwarfs with the highest N/O ratios could be good candidates to be post-starburst galaxies. Therefore, these objects may provide interesting hints for the chemical evolution models of dwarf galaxies in dense environments. A detailed study of the results obtained in this work will be presented in Paper II. In the framework of the metallicity-(mass)-luminosity relation (Skillman et al. 1989; Richer et al. 1998; Hidalgo-Gámez & Olofsson 1998; Pilyugin 2001), Paper II is aimed to analyze the relationship between metallicity and the fundamental properties and chemical evolution of Virgo dwarf galaxies.

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