Gas properties of H\textsc{ii} and Starburst galaxies: relation with the stellar population

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ABSTRACT

We study the gas emission of galaxies with active star formation, consisting mostly of H\textsc{ii} galaxies and Starbursts, as well as some Seyfert 2’s, and determine chemical and physical parameters. The data consist of 19 high signal-to-noise ratio optical templates, a result of grouping 185 emission line galaxy spectra. Underlying stellar population models (Raimann et al., 1999) were subtracted from the templates in order to isolate the pure emission component.

We analyse the distribution of these improved signal-to-noise ratio emission spectra in diagnostic diagrams and find that the H\textsc{ii} templates show a smaller spread in \( \log([\text{O}\textsc{iii}]/\text{H}\beta) \) values than the individual galaxies, apparently due to the population subtraction and better signal-to-noise ratio. We thus suggest the template sequence as a fiducial observational locus for H\textsc{ii} galaxies which can be used as reference for models. The sequence of line ratios presented by the H\textsc{ii} galaxies in the diagram \( \log([\text{O}\textsc{iii}]\lambda5007/\text{H}\beta) \times \log([\text{N}\textsc{ii}]\lambda6584/\text{H}\alpha) \) is primarily due to the gas metallicity, of which the \( \log([\text{N}\textsc{ii}]/\text{H}\alpha) \) ratio is a direct estimator. We also study the properties of the Starburst galaxies and those intermediate between H\textsc{ii} and Starburst galaxies, which are more metal rich and sit on more massive galaxies.

We discuss the present results in the frame of a recently proposed equivalent width diagnostic diagram for emission line galaxies (Rola et al., 1997) and conclude that the observed ranges in \( W([\text{O}\textsc{ii}])/W(\text{H}\beta) \) and \( W(\text{H}\beta) \) are mostly due to the non-ionizing stellar population contribution. \( W(\text{H}\beta) \) can be used as an estimator of this contribution to the continuum, and briefly discuss implications to the cosmological use of H\textsc{ii} galaxies.

Key words: galaxies: abundances – galaxies: starburst – galaxies: compact – galaxies: stellar content – galaxies: ISM – galaxies: nuclei.

1 INTRODUCTION

The investigation of nearby star-forming galaxies plays an important role in the interpretation of the ever increasing data on distant galaxies, as the so-called Lyman-break galaxies seem to be well described by local Starburst galaxies (Meurer et al., 1999). Melnick et al. (1999) propose that H\textsc{ii} galaxies can be used as distance estimators over a wide range of redshifts.

H\textsc{ii} galaxies are among the less luminous star-forming galaxies. Their emission-line spectra and relatively low gaseous metallicities (\( \approx 0.1 \) to 0.25 solar, e.g. Peña et al., 1991) would be consistent with the idea that they are very young galaxies undergoing their first episodes of star formation. On the other hand, in a recent study, Schulte-Ladbeck and Crone (1998) have concluded that in the blue compact dwarf galaxy VII Zw 403 there are older stellar population components.

In a previous study (Raimann et al., 1999, hereafter Paper I) we have investigated the stellar population properties of a sample dominated by nearby H\textsc{ii} galaxies, but including also Starburst and Seyfert 2 galaxies for comparison purposes. We have considered their continuum and
emission/absorption line properties, grouped them into high signal-to-noise templates, and performed stellar population syntheses using a base of stellar cluster spectra (Bica, 1988; Bica and Alloin, 1986). We concluded that most HII galaxies present important flux contributions from populations as old as 500 Myr.

In the present paper, we investigate the gaseous properties of the templates obtained in Paper I, after subtraction of the underlying stellar population. We use the emission-line fluxes to classify the spectra according to their excitation characteristics in diagnostic diagrams, to calculate the gaseous abundance and to obtain the age of the last generation of (ionizing) stars. The role of the underlying stellar population, including its effect on the interpretation of data from distant star-forming galaxies and its relation to the emission line properties, is also explored.

We present the data set in section 2. The diagnostic diagrams are discussed in section 3. The gas metallicity, the age of the ionizing stellar population and relation between the metallicity and the non-ionizing stellar population are studied in section 4. Possible uses of emission-line galaxies for cosmological studies are discussed in section 5. The concluding remarks are given in section 6.

2 THE SAMPLE

The original sample consists of 185 emission-line galaxy spectra obtained by Terlevich and collaborators, most of them (156) discussed individually in Terlevich et al. (1991). The average aperture used in the observations corresponds to \( \approx 1.1 \times 1.9 \) kpc. More details can be found in Paper I, where we have grouped the spectra according to their continuum, absorption and emission line properties, in order to obtain improved signal-to-noise (S/N) ratio spectra. This strategy was necessary to constrain the stellar population syntheses, mainly for the HII groups. The resulting spectral groups are listed in Table 1 ordered from bluer spectra at the top to redder at the bottom of the table. The groups are named after the member galaxy with the best S/N ratio. The number of the galaxies in each group is shown in column 2. In two cases, GUM448 and G_NGC1510, there were no other similar spectra, and we have thus considered them as “groups” of only one galaxy. The spectral type, according to distribution of emission line spectra of the groups in the Baldwin, Phillips and Terlevich (BPT, 1981) diagnostic diagrams, is given in column 3. In column 4 we list the average absolute magnitudes \(<M_B>\), obtained using the apparent magnitudes and radial velocities from the NASA/IPAC Extragalactic Database (NED) [1] (see Paper I), for \( H_0 = 75 \) km s\(^{-1}\) Mpc\(^{-1}\), and in columns 5, 6 and 7 we provide the average H\(\beta\) emission line luminosities, average dimensions at the galaxy corresponding to the angular aperture and average H\(\beta\) equivalent width, respectively. In columns 8 and 9 we list the S/N ratios in the continuum of each template for spectral regions around \( \lambda 4200 \)\(\AA \) and \( \lambda 5400 \)\(\AA \).

† The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Figure 1. Representative spectral groups: (a) blue HII, (b) HII with Balmer jump in absorption, (c) Seyfert 2. In the bottom panels we present the dereddened spectra and the corresponding synthesized one (Paper I), while in the top panels we present the difference between the two.

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Table 1. Average properties of the groups.

| Groups              | Number of objects | Spectral Type | $<M_B>$ | $<\log(L(H\beta)>$ | $<\text{Aperture}>$ | $\log(W(H\beta))$ | S/N 4200 Å | S/N 5400 Å |
|---------------------|-------------------|---------------|---------|-------------------|-------------------|------------------|------------|------------|
| G_Cam1148-2020      | 9                 | HH            | -17.81 ± 1.08 | 40.66 ± 0.49 | 1.5 × 1.8 | 2.37 | 16 | 11 |
| G_Um461             | 9                 | HH            | -14.99 ± 2.68 | 39.27 ± 0.35 | 0.2 ± 0.3 | 2.33 | 21 | 17 |
| G_Tol1924-416       | 7                 | HH            | -19.96 ± 0.85 | 41.61 ± 0.32 | 2.5 ± 3.3 | 1.98 | 26 | 17 |
| G_NGC1487           | 6                 | HH            | -17.14 ± 1.07 | 39.17 ± 0.34 | 0.2 ± 0.3 | 1.43 | 19 | 15 |
| G_Tol1004-296       | 17                | HH            | -17.21 ± 1.17 | 39.92 ± 0.31 | 0.4 ± 0.6 | 2.03 | 38 | 29 |
| G_Um484             | 1                 | HH            | -19.46        | 41.16       | 1.8 ± 2.1 | 1.84 | 21 | 18 |
| G_Tol6440-381       | 18                | HH            | -16.83 ± 0.67 | 40.93 ± 0.38 | 1.5 ± 2.7 | 1.68 | 21 | 12 |
| G_Um504             | 15                | HH            | -15.86 ± 0.70 | 39.32 ± 0.22 | 0.4 ± 0.8 | 1.39 | 23 | 17 |
| G_Um71              | 36                | HH            | -17.68 ± 1.19 | 40.17 ± 0.26 | 1.1 ± 2.1 | 1.45 | 23 | 16 |
| G_NGC1510           | 1                 | HH            | -16.93        | 39.07       | 0.3 ± 0.4 | 1.19 | 26 | 26 |
| G_Cam0949-2126      | 9                 | HH/Starburst  | -19.73 ± 1.48 | 41.11 ± 0.26 | 2.5 ± 3.8 | 1.47 | 21 | 13 |
| G_Mrk711            | 5                 | HH/Starburst  | -19.81 ± 0.81 | 41.23 ± 0.21 | 1.4 ± 2.1 | 1.47 | 40 | 26 |
| G_Um140             | 15                | HH/Starburst  | -18.09 ± 0.85 | 39.73 ± 0.17 | 0.8 ± 1.5 | 1.07 | 19 | 14 |
| G_NGC3089           | 11                | HH/Starburst  | -19.29 ± 1.02 | 40.54 ± 0.23 | 1.1 ± 2.1 | 1.21 | 22 | 16 |
| G_Mrk710            | 2                 | Starburst     | -18.47        | 39.57 ± 0.32 | 0.2 ± 0.4 | 1.62 | 20 | 19 |
| G_Um477             | 8                 | Starburst     | -20.11 ± 0.94 | 40.23 ± 0.34 | 0.7 ± 1.4 | 1.10 | 24 | 26 |
| G_Um103             | 3                 | Seyfert 2     | -19.72 ± 0.39 | 40.46 ± 0.25 | 1.8 ± 3.7 | 1.18 | 13 | 11 |
| G_NGC4507           | 7                 | Seyfert 2     | -19.77 ± 0.79 | 40.95 ± 0.31 | 1.7 ± 3.5 | 1.42 | 15 | 19 |
| G_NGC3281           | 6                 | Seyfert 2     | -19.70 ± 0.96 | 40.06 ± 0.30 | 1.2 ± 2.4 | 0.88 | 13 | 18 |

The spectra of the groups were dereddened according to $E(B - V)$, the internal reddening affecting the stellar population which was obtained in the synthesis (Paper I). The synthesized stellar population from Paper I was then subtracted from the spectrum of each group. The importance of the subtraction of the underlying stellar population for emission line measurements has been discussed in detail by Bonatto et al. (1989). The main effect is on $H\beta$, with consequences on gas internal reddening determination and calculated emission line ratios involving this line. Three representative spectra are shown in Fig. 1. In the top of each panel we show the population-free spectrum and in the bottom the dereddened spectrum previously to stellar population subtraction together with the corresponding synthesized spectrum used in the subtraction. The emission spectra for the remaining groups were presented in Raimann (1998).

The emission-line fluxes of the population-free spectra were then measured and the corresponding values, relative to $H\beta$, are shown in Table 1. In the cases of line blending (e.g., $H\alpha + [NII] \lambda 6548, 84$ and $[SII] \lambda 6717, 31$) the profiles were constrained by adjusting Gaussians of the same width. We have then calculated the residual gas reddening assuming a Galactic reddening law (Seaton, 1979), case B recombination, and an intrinsic ratio $H\alpha / H\beta = 2.9$ (Osterbrock, 1989). Only two groups, $G_{NGC1510}$ and $G_{NGC3281}$, presented significant gas reddenings with $E(B - V)_{gas} = 0.24$ and 0.32, respectively. The other groups have $E(B - V)_{gas} \leq 0.05$, which are listed in column 2 of Table 1.

### 3 BPT DIAGNOSTIC DIAGRAMS

The reddening-corrected emission-line fluxes were used to locate the groups in the BPT diagnostic diagrams $log([OIII] \lambda 5007 / H\beta) \times log([NII] \lambda 6584 / H\alpha)$, $log([OIII] \lambda 5007 / H\beta) \times log([SII] \lambda 6717, 6731 / H\alpha)$ and $log([OIII] \lambda 5007 / H\beta) \times log([OII] \lambda 3700 / H\beta)$ (Baldwin et al., 1981; Veilleux and Osterbrock, 1987), shown in Figs. 2 and 3.

Fig. 2 contains the present galaxy data, together with those of Starburst Nuclear (therein referred to as MGB), Seyfert, LINER and HII galaxies from Coziol (1996). In this diagram the groups $G_{UM103}$, $G_{NGC4507}$ and...
Table 2. Emission line fluxes relative to H$\beta$.

| Group          | [OIII] $\lambda$4363 | [OIII] $\lambda$5007 | H$\beta$ | [OII] $\lambda$3727 | [NII] $\lambda$6584 | [SII] $\lambda$6717 | [SII] $\lambda$6731 |
|----------------|----------------------|----------------------|----------|---------------------|--------------------|---------------------|--------------------|
| G_Cam1148-2020| 0.89 0.48 0.50 0.13 1.00 6.25 0.02 2.67 0.04 | 0.07 0.05 |
| G_Um461       | 0.86 0.51 0.48 0.12 1.00 6.06 0.01 2.34 0.03 | 0.05 0.04 |
| G_Tol10924-416| 1.15 0.45 0.48 0.10 1.00 5.52 0.02 2.05 0.04 | 0.07 0.04 |
| G_Ngc1487     | 2.64 0.33 0.48 0.03 1.00 3.31 |
| G_Tol10904-296| 1.53 0.37 0.47 0.05 1.00 4.74 0.03 2.77 0.23 | 0.29 0.18 |
| G_Um448       | 2.95 0.22 0.51 0.02 1.00 2.85 0.05 2.69 0.32 | 0.21 0.17 |
| G_Tol5040-381 | 1.98 0.26 0.43 0.03 1.00 4.94 0.06 2.44 0.15 | 0.11 0.10 |
| G_Um504       | 2.48 0.22 0.54 0.03 1.00 3.64 0.05 2.30 0.21 | 0.17 0.10 |
| G_Um71       | 2.19 0.24 0.45 0.02 1.00 3.75 0.01 2.70 0.22 | 0.17 0.10 |
| G_Ngc1510     | 1.80 0.19 0.40 0.03 1.00 3.93 0.01 2.75 0.39 | 0.29 0.20 |
| G_Cam0949-2126| 2.19 0.09 0.38 0.01 1.00 1.83 0.01 2.58 0.42 | 0.16 0.21 |
| G_Mrk711      | 2.26 0.14 0.44 0.01 1.00 2.16 0.09 3.01 0.88 | 0.30 0.23 |
| G_Um140       | 2.75 0.01 0.44 0.01 1.00 1.35 0.01 2.87 0.59 | 0.27 0.34 |
| G_Ngc3089     | 2.03 0.01 0.43 0.01 1.00 1.09 0.01 3.04 0.96 | 0.38 0.27 |
| G_Mrk10       | 1.20 0.01 0.44 0.01 1.00 0.35 0.01 3.07 1.12 | 0.28 0.26 |
| G_Um477       | 1.05 0.01 0.43 0.01 1.00 0.26 0.01 3.06 1.46 | 0.35 0.33 |
| G_Um103       | 2.52 0.63 0.34 0.11 1.00 7.86 0.27 2.55 1.22 | 0.01 0.44 |
| G_Ngc4507     | 1.76 0.83 0.49 0.22 1.00 10.2 0.37 2.94 1.75 | 0.49 0.51 |
| G_Ngc3281     | 2.24 0.68 0.51 0.22 1.00 10.4 0.41 4.08 4.04 | 1.00 0.96 |

Note: The colon symbol indicates a large uncertainty.

NGC3281 are located in the region occupied by Seyfert 2 galaxies while G_Um477 and G_Mrk710 are in the Nuclear Starburst region. The groups G_Mrk711, G_Cam0949-2126, G_Um140 and G_Ngc3089 are located in a region intermediate between those of HII and Nuclear Starbursts. The remaining groups – the majority – are located in the HII galaxies’ region. The classification is shown in column 3 of Table 1. It can be observed that the HII galaxy groups are located closer to the HII region loci as defined by the dashed lines in this diagram than the individual HII galaxies of Caldwell’s (1996) sample.

Fig. 3 contains only our groups data, together with the HII models of McCall et al. (1985). In Fig. 3a the HII galaxy groups are also located close to the HII region loci as defined by the dashed line.

In order to check if the groups are indeed closer to the theoretical loci than the individual HII galaxies, we have plotted in Fig. 3b the groups data together with the original data for each individual galaxy (Terlevich et al., 1991). It can be observed that the effect is still present. Two factors contribute to this. The subtraction of the stellar population which increases the H$\beta$ emission (reducing $log([OIII]/H\beta]$) and the grouping of the individual spectra which produces higher S/N spectra. In HII galaxies with significant contribution of $t \geq 50$ Myr stellar populations the first effect is particularly important, because these components have strong Balmer absorption lines.

We conclude that with spectra of high S/N ratio and corrected for the stellar population absorptions the HII galaxies in the BPT diagnostic diagrams $log([OIII]/H\beta] \times log([NII]/H\alpha)$ and $log([OIII]/H\beta] \times log([SII]/H\alpha)$ get closer to the theoretical HII region loci presented by Evans and Dopita (1985) and McCall et al (1985). Previous works have proposed models with very high temperatures to cover the region occupied by HII galaxies (Tresse et al., 1996 and Rola et al., 1997). Our results suggest that this is not necessary and that HII galaxies behave similarly to HII regions. We therefore suggest this observational locus as reference for theoretical models of HII galaxies in the BPT diagrams.

In the diagnostic diagram $log([OIII]/H\beta] \times log([OIII]/H\alpha)]$ (Fig. 3b) the galaxy groups for which it was possible to measure [OIII]/H$\alpha$ are located close to the HII region loci as defined by the dashed line. However, for many groups – mainly those with the lowest [OIII]/H$\beta$ – we have obtained only upper limits for [OIII]/H$\alpha$; these limits suggest systematically lower values for the galaxies when compared to HII region models. On the other hand, there are not enough HII region data in the literature with low [OIII]/H$\beta$ and with measured [OIII]/H$\alpha$, so these models are difficult to be compared even with HII region data.

The only star forming group which approaches considerably the AGN region is the HII/Starburst group G_Mrk711. It would be interesting to study in detail galaxies in this group (Paper I), because they might contain intrinsically high temperature HII regions, or alternatively that locus might reflect a composite spectrum, i.e. AGN mixed to HII regions.

4. AGE AND METALLICITY EFFECTS

We now study the gas properties, using the population-free spectra, in order to investigate the gas metallicity and age of the ionizing stellar population, and their relation to the loci occupied by the groups in the BPT diagrams.

4.1 Metallicity

Since the metallicity is very sensitive to gas temperature, which is not uniform in the nebulae, it is important to consider the ionization structure (Garnett, 1992). We have
adopted the two-zone model of Campbell et al. (1986), where the emission-line ratio \([\text{[OIII]}]/\lambda4959, 5007/\lambda4363\) gives the temperature \(T^{++}\) of the high ionization species (like \(\text{O}^{++}\) and \(\text{Ne}^{++,++}\)) and the emission line ratio \([\text{[NII]}]/\lambda6548, 84/\lambda5755\) gives the temperature \(T^+\) of the low ionization species (like \(\text{O}^+, \text{N}^+\) and \(\text{S}^+\)). The density is obtained through the emission-line ratio \([\text{[SII]}]/\lambda6717/\lambda6731\).

We were able to measure \([\text{[OIII]}]/\lambda4363\) for the H\textsc{ii} galaxies and Seyfert 2’s, while for the remaining groups only upper limits could be obtained (column 5 of Table 3). For the latter groups we have used the empirical calibration of Pagel et al. (1979) extrapolated as described in Schmitt et al. (1994) and Storchi-Bergmann et al. (1996) to calculate \(T^{++}\). We could not detect \([\text{[NII]}]/\lambda5755\) in any of the spectra. We have thus used the relation of Campbell et al. (1986) to calculate \(T^+\). The ionic abundance calculations were performed using a three-level atom model (McCall, 1984).

The resulting \(T^{++}\), Ne and ionic abundances are shown in Table 3. The total oxygen abundance \((\text{O/H})\) was calculated by adding the contributions of \(\text{O}^0\), \(\text{O}^+\) and \(\text{O}^{++}\).
The nitrogen abundance was calculated by assuming that N/O=\text{N}^{+}/\text{O}^{+}, based upon the rough coincidences between the ionization potentials of the two ions (Storchi-Bergmann et al., 1994 and references therein).

The ten H\textsc{ii} galaxy groups (G\text{NGC}1510, G\text{UM}504, G\text{UM}71, G\text{Ton}1924-416, G\text{UM}448, G\text{NGC}1487, G\text{Ton}1004-296, G\text{Ton}0440-381 and G\text{Cam}1148-2020) span a range in oxygen abundance of 7.87 < 12 + log(O/H) < 8.32. With small variations, because of different methodologies and sample, these values agree with those of Peña et al. (1991) and Terlevich et al. (1991).

The relatively large metallicities attained by the H\textsc{ii} galaxies are consistent with the result found in Paper I, that most H\textsc{ii} galaxy groups are not single generation, but present previous generations of stars which have enriched the gas. The groups classified as Starbursts – G\text{UM}477 and G\text{Mrk}711 – have near solar metallicity, while the ones classified as intermediate between H\textsc{ii} and Starburst – G\text{Cam}949-2126, G\text{Mrk}711, G\text{UM}140 and G\text{NGC}3089 – have somewhat lower metallicity: 12+log(O/H)≈8.6.

It can be noticed in Table 3 that the Seyfert 2 groups G\text{UM}103, G\text{NGC}3281 and G\text{NGC}4507 have very high temperatures when compared with those predicted by photoionization models (Storchi-Bergmann et al., 1990) which make the calculated chemical abundances lower than expected. This result is typical of Seyfert galaxies and is due to density stratification, to the presence of matter-bounded clouds (Binette et al., 1996), collisional de-excitation and a hard ionizing continuum, effects not present in H\textsc{ii} regions (Viegas-Aldrovandi and Gruenwald, 1988), making the above temperature calibration not valid for the Seyferts. Besides, Storchi-Bergmann et al. (1996) have pointed out how critical is the stellar population subtraction to the measurement of the [O\text{iii}]\lambda4363 in Seyfert’s, which usually causes one to overestimate the strength of this line.

We have thus revised the metallicities of the Seyfert 2 groups using the calibrations of Storchi-Bergmann et al. (1998) for the narrow-line region (NLR) of active galaxies which do not depend on [O\text{ii}]\lambda4363. These calibrations are a function of the emission-line ratios [O\text{ii}]\lambda4959,5007/H\beta, [N\text{ii}]\lambda6548,84/H\alpha and [O\text{ii}]\lambda3727/[O\text{iii}]\lambda4959,5007. We find that the (O/H) abundance is solar for G\text{NGC}4507 and slightly below solar for G\text{UM}103 and G\text{NGC}3281.

In Fig. 5 we show log(N/O) plotted against 12 + log(O/H) for the H\textsc{ii} galaxies and Starbursts. The distribution of our galaxy groups is consistent with the relation found by Storchi-Bergmann et al. (1994) for star-forming galaxies covering 8.3 < 12+log(O/H) < 9.4 (solid line in this figure). This relation is predicted by a simple model of galactic chemical evolution with instantaneous recycling, in which nitrogen has a secondary origin and oxygen has primary origin (Storchi-Bergmann et al., 1994 and references therein). Vila-Costas and Edmunds (1993) have shown that the secondary behavior dominates for 12+log(O/H) > 8.2, while for lower abundances nitrogen has mainly a primary origin [log(O/N) is approximately constant]. We have too few galaxies in the low abundance end to reach any conclusion there, but we can say that the data are consistent also with the results of Vila-Costas and Edmunds, as all data points in the low metallicity end are located above the line denoting secondary behavior.

Finally, we notice that the BPT sequence of H\textsc{ii} galaxies is also a sequence of [N\text{ii}]/H\alpha values. We have thus plotted in Fig. 6 12 + log(O/H) × log([N\text{ii}]/H\alpha) and a linear regression to the data. Symbols as in Fig. 5.

This kind of relation has been found by Storchi-Bergmann et al. (1994) for a sample dominated by more...
metal-rich starbursts. The main difference encountered here is that, for the lower metallicity HII galaxies of Fig. [NII]/Hα shows a wider dynamical range as a function of $12 + \log(O/H)$ than do the more metal-rich Starbursts.

### 4.2 Age indicators

The equivalent width $W(\text{H}\beta)$, the $[\text{OIII}]$\,$\lambda4959,5007/\text{H}\beta$ ratio and relative volume $R$ of the $\text{He}^+$ and $\text{H}^+$ zones are age indicators for HII regions (Dottori, 1981, 1987). Dottori and Bica (1981) have shown that $W(\text{H}\beta)$ can be used to date HII regions of the Magellanic Clouds. Copetti et al. (1986) studied the evolution of the above properties with age through stellar evolution models with a single burst of star formation, which can be used to derive the age of the ionizing star clusters from $W(\text{H}\beta)$ or $[\text{OIII}]$/H$\beta$.

More recently, Stasińska and Leitherer (1996) constructed a new grid of models representing an HII region produced by an evolving starburst embedded in a gas cloud of the same metallicity. They concluded that both $W(\text{H}\beta)$ and $W([\text{OIII}])$ were good age indicators, but not $[\text{OIII}]$/H$\beta$. According to them, the $[\text{OIII}]/\text{H}\beta$ ratio is a poor chronometer because its time dependence is mild for ages smaller than 5 Myr and its behaviour is affected by the ionization parameter.

We have thus used the models of Stasińska and Leitherer (1996) to derive the age of the ionizing star cluster for the present HII galaxy groups from the measured $W(\text{H}\beta)$ and $W([\text{OIII}])$. In Figs. 4 and 5 we present a sequence of models (continuous line) in $W([\text{OIII}])$ and $W(\text{H}\beta)$ versus age diagrams together with the data from our groups (horizontal lines). The models with the parameters best suited to our data correspond to $Z = 0.25Z_\odot$.

In the above models the continuum is only due to the nebular and ionizing stellar population. As concluded in Paper I, in the galaxy groups there is additional contribution of older stellar populations to the continuum, so that it is necessary to subtract that contribution before calculating $W(\text{H}\beta)$ and $W([\text{OIII}])$. In order to illustrate the effect of this additional component in the derived ages, we present in Fig. 6 both the data previously to the subtraction as dashed lines, and the corrected data as solid lines.

The age derived from $W(\text{H}\beta)$ is plotted against the age derived from $W([\text{OIII}])$ in Fig. 7a. Although the ages derived from $W([\text{OIII}])$ are in most cases up to $\approx 1$ Myr larger than the ones from $W(\text{H}\beta)$, they are well correlated with Spearman rank correlation coefficient of 0.98. Using both diagrams (Figs. 7a and 7b) we derive an age range of $2.7$–$5.0$ Myr for the ionizing populations in the HII galaxy groups. This age range corresponds to the predicted Wolf-Rayet (WR) phase of a young star cluster (Schaerer & Vacca, 1998). Indeed, WR features have been detected in our HII galaxy spectra and were discussed in Paper I.

As the age does not vary much among the HII galaxy groups, the sequence defined in the BPT diagram must be dominated by a varying metallicity (Sect. 4.1).

An age effect is suggested when we investigate the relation between the gas metallicity and the contribution of the stellar population with ages $t > 100$ Myr to the spectra. This can be observed in Fig. 8 where we plot $12 + \log(O/H)$ against the percentage of stellar population with ages $> 100$ Myr. This diagram suggests that most of the gas enrichment has been produced by stellar populations older than 100 Myr. The HII galaxies are the ones with smallest contributions of stars older than 100 Myr and most metal-poor while the Seyfert’s have the largest contributions of older populations and are the most metal-rich. There are only two deviant points, corresponding to the Starbursts. These cases

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**Table 3. Analysis results.**

| Group          | $E(B-V)_{\text{gas}}$ | $E_{\text{gas}}$ ($\text{cm}^{-3}$) | $T^{+}\text{+(K)}$ | $(\text{N}^{+}/\text{H}^{+})^{a}$ | $(\text{S}^{+}/\text{H}^{+})^{a}$ | $(\text{O}/\text{H})^{b}$ | $(\text{Ne}^{+}/\text{H}^{+})^{a}$ | $(\log(N/O))^{b}$ |
|----------------|-----------------------|-----------------------------------|-------------------|---------------------------------|-------------------------------|-----------------|---------------------------------|------------------|
| $G_{\text{Cam1148-2020}}$ | 0.00                  | $\approx 100$                    | $15475$           | 5.52                            | 5.10                          | 7.87                         | 7.04               | -1.44                          |
| $G_{\text{UM461}}$          | 0.00                  | $\approx 100$                    | $15039$           | 5.29                            | 5.01                          | 7.89                         | 7.11               | -1.70                          |
| $G_{\text{Tol1924-416}}$     | 0.00                  | $300$                            | $14436$           | 5.56                            | 5.11                          | 7.92                         | 7.10               | -1.57                          |
| $G_{\text{NGC1487}}$        | 0.00                  | $\approx 100$                    | $11177$           | 6.51                            | 5.89                          | 8.19                         | 7.32               | -1.35                          |
| $G_{\text{Tol1004-296}}$     | 0.00                  | $\approx 100$                    | $11811$           | 6.17                            | 5.57                          | 8.14                         | 7.30               | -1.39                          |
| $G_{\text{UM448}}$          | 0.00                  | $258$                            | $10294$           | 6.75                            | 5.94                          | 8.32                         | 7.29               | -1.28                          |
| $G_{\text{UM103}}$          | 0.00                  | $151$                            | $10082$           | 6.57                            | 5.97                          | 8.23                         | 7.21               | -1.29                          |
| $G_{\text{NGC3281}}$        | 0.00                  | $755$                            | $17285$           | 6.52                            | 5.57                          | 8.32                         | 7.36               | -1.28                          |
| $G_{\text{NGC3089}}$        | 0.00                  | $10839$                          | $18125$           | 6.67                            | 5.87                          | 8.21                         | 7.20               | -1.13                          |
| $G_{\text{NGC1510}}$        | 0.24                  | $\approx 100$                    | $11011$           | 7.15                            | 6.27                          | 8.63                         | 7.45               | -1.26                          |
| $G_{\text{Mrk711}}$         | 0.03                  | $141$                            | $9109$            | 7.40                            | 6.28                          | 8.58                         | 7.58               | -0.87                          |
| $G_{\text{UM140}}$          | 0.00                  | $1354$                           | $7727$            | 7.30                            | 6.48                          | 8.65                         | -1.20              | -0.86                          |
| $G_{\text{NGC3089}}$        | 0.04                  | $\approx 100$                    | $7144$            | 7.56                            | 6.48                          | 8.61                         | -0.81              | -0.81                          |
| $G_{\text{Mrk710}}$         | 0.05                  | $350$                            | $4968$            | 8.00                            | 6.78                          | 8.99                         | 0.95               | -0.69                          |
| $G_{\text{UM477}}$          | 0.05                  | $330$                            | $4611$            | 8.19                            | 6.95                          | 8.92                         | 0.92               | -0.69                          |
| $G_{\text{NGC4570}}$        | 0.00                  | $3080$                           | $13475$           | 8.69                            |                               |                               |                    |                                |
| $G_{\text{NGC3281}}$        | 0.32                  | $755$                            | $17285$           | 8.83                            |                               |                               |                    |                                |

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$a$ In $12+\log$ units.

$b$ $12+\log(O/H)_\odot = 8.91$ and $\log(N/O)_\odot = -0.93$.

$c$ Calculated using a different method: the calibration of Storchi Bergmann et al. (1998; see text).
can be understood as due to exceptionally high star formation rates in luminous evolved galaxies, spiral or interacting, so that light from stars younger than 100 Myr dominate the observed fluxes of the galaxies.

5 POSSIBLE COSMOLOGICAL USES

Recently, Melnick et al. (1999) have called attention to the possible use of HII galaxies as cosmological probes. In principle (i) emission line velocity dispersions, (ii) HII galaxy luminosities as candles, and (iii) stellar population/emission line properties as probes of galaxy evolution would be important tools to explore. In the following we discuss the latter two possibilities.

As can be seen in Table 4 the \(<M_B>\) values vary a lot among HII galaxy groups. Although the sources of B magnitudes are heterogeneous we do not expect that broad band magnitudes be useful as candles, since the contribution from underlying stellar populations of different ages varies considerably, as found in the population syntheses (Paper I). However, Hβ emission line luminosities appear to be less dispersed both within and among groups. This is especially so, by considering aperture effects among groups (Table 4). In order to further explore this possibility it would be im-

Figure 7. Model sequences (continuous lines) of (a) W([OIII]) and (b) W(Hβ) as a function of age of the ionizing stellar population (Stasińska and Leitherer, 1996) together with the values of W([OIII]) and W(Hβ) for the present sample (horizontal solid lines) used to derive the ages of ionizing stellar population. In (b) we also show the data previously to the stellar population subtraction (horizontal dashed lines). The age derived with W([OIII]) is plotted against the age derived with W(Hβ) in (c).
important to observe whole sets of local calibrators by means of narrow filter CCD imaging in emission lines and neighbouring continuum.

For high redshift galaxies, many lines used in the traditional diagnostic diagrams move out of the optical spectral range and typically the spectra have a low S/N ratio in the continuum. Frequently, in these cases, the two strongest emission lines observable in the optical window are [OII]λ3727 Å and Hβ. Rola et al. (1997, hereafter R97) used the equivalent widths of these lines to construct new diagnostic diagrams in order to classify the spectra of distant emission-line galaxies observed in deep galaxy redshift surveys.

Our data in the diagnostic diagram W([OII])/W(Hβ) × log(W(Hβ)) are shown in Fig. 8. In agreement with R97, the Seyfert galaxies occupy the region with W([OII])/W(Hβ) ≥ 3.5 while the Starbursts and HII galaxies occupy the region with W([OII])/W(Hβ) ≤ 3.5 and log(W(Hβ)) > 1.0. Although this diagram segregates AGNs from HII/Starburst galaxies we find that it does not segregate between HII and Starburst galaxies.

We have investigated the effect of the stellar population contribution in the above diagram, by subtracting the contribution of the older age components to the continuum of the HII and Starburst galaxies, and leaving only the ionizing continuum for the calculation of the equivalent widths. The result is presented in Fig. 9 which shows a shift in the loci of the galaxies with W(Hβ) as low as ≈ 10 Å to values larger than 50 Å, and for the W([OII])/W(Hβ) from values as large as ≈ 3 down to values lower than 1.5. It can be concluded that equivalent widths W([OII]) and W(Hβ) of Starburst and HII galaxies show a much smaller range of values once the older stellar population contributions are subtracted, which means that the intrinsic properties of star forming regions do not vary as much as suggested by the diagram before subtraction (Fig. 8). In fact, we conclude that the value of log(W(Hβ)) can be used as an indicator of the percentage contribution of the non-ionizing stellar population to the continuum. In Fig. 10 we plot this percentage P against log(W(Hβ)) together with a linear regression to the data:

\[ P(\%) = 153.04(±8.76) - 56.52(±5.31) \times \log(W(H\beta)), \]

for W(Hβ) in Å.

The Spearman rank correlation coefficient to this correlation is -0.90. W(Hβ) is thus a powerful tool for estimating the contribution of older stars to the spectrum of a galaxy. The relation above is very useful, especially for distant galaxies, for which W(Hβ) can be obtained once a continuum can be detected underneath Hβ.

On the other hand, back to the R97 diagram, we can conclude that the correction by the stellar population does not move the HII and Starburst galaxies to regions in the diagram outside the limits suggested by R97. But, for very distant galaxies, age ranges will necessarily become narrower and fractions of intrinsically young galaxies should increase; in both cases the lower right part of R97’s diagram should become more and more populated for such high redshift samples, as simulated in our analysis above.

6 CONCLUDING REMARKS

We have analysed the emission-line spectra of 19 galaxy templates, obtained from the grouping of 185 emission-line galaxy spectra, as described in Paper I. After correction for internal reddening and subtraction of the synthesized population spectrum, both from Paper I, the emission-line fluxes of each template were measured and corrected for additional
gaseous reddening, when present. According to the corresponding locus of each template in the BPT diagrams, the present sample comprises 10 groups of HII galaxies, 3 groups of Seyfert 2, 2 groups of Nuclear Starbursts and 4 groups of intermediate cases between Nuclear Starbursts and HII galaxies.

The HII galaxy groups define a much tighter sequence in the BPT diagrams than the individual galaxies, suggesting that the spread obtained in previous studies is due to a combination of lower S/N ratio spectra and of not taking into account the contribution of the underlying stellar population. With population subtraction in spectra of improved S/N ratio, the HII galaxy groups get closer to the theoretical sequences of HII regions presented by Evans and Dopita (1985) and McCall et al. (1985), suggesting that they are more similar to HII regions than concluded in previous works. The resulting sequence of HII templates in the BPT diagram is suggested as a fiducial observational locus for future models of HII galaxies.

From the emission-line ratios, we calculate the gas metallicity and age of the ionizing stellar population, and investigate the effect of these two parameters in the BPT diagram above. We conclude that the sequence defined by the HII galaxy templates is primarily due to metallicity, which spans the range $7.87 < 12 + \log(O/H) < 8.32$ ($\approx 1/11$ to $1/4$ solar), while the age of the ionizing stellar population ranges only from 2.7 to 5.0 Myr.

A connection with age is suggested when we relate the gas metallicity with the percentage contribution of stellar population components older than 100 Myr, which may indicate that the metal enrichment is mostly due to previous stellar generations, whose signatures are present in the spectral distribution even for the bluest HII galaxies, as discussed in Paper I. The larger the contribution of older stellar components, the more metal rich is the gas. We find a good correlation between $\log([\text{N}II]/H\alpha)$ and $12 + \log(O/H)$ and propose a calibration to obtain the latter from the former.

We also explore the effect of the stellar population contribution to the equivalent width diagnostic diagrams of Rola et al. (1997). We conclude that the observed ranges in $W([\text{O}II])/W(H\beta)$ and $W(H\beta)$ are essentially due to the non-ionizing stellar population contribution. By relating $\log(W(H\beta))$ to the percentage contribution of this population, we conclude that there is a tight correlation between these two quantities. We thus propose a calibration which can be used to estimate the non-ionizing stellar population contribution to the spectra from the measured $W(H\beta)$, which is particularly useful for probing properties of distant galaxies.

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