THE ASTROPHYSICAL JOURNAL, 466:831–839, 1996 August 1

OBSCURATION OF Lyα PHOTONS IN STAR-FORMING GALAXIES

MAURO GIAVALISCO,[1,2] ANURADHA KORATKAR, AND DANIELA CALZETTI
Space Telescope Science Institute, 3711 San Martin Drive, Baltimore, MD 21218
Received 1995 July 14; accepted 1996 February 29

ABSTRACT

We present a new study of the correlations between the Lyα emission, the UV extinction, and the metal content in a sample of 21 local, low-metallicity starburst galaxies from archival *IUE* spectra. We have consistently reextracted all the spectra using the optimal extraction algorithm by Kinney and coworkers, and we have also included galaxies not previously studied. In 40% of the cases our new measures of the Lyα equivalent width, W_α, differ from those reported in the literature by up to 50% of their value. The new measures show no significant correlation with either the obscuration of the UV continuum or the Balmer decrement, and only a very weak correlation with the metal index [O/H]. Using the flux ratio Lyα/Hβ instead of W_α to take into account differences in the ionizing conditions of the nebular gas does not change these results. This shows that the extinction vicissitudes of the Lyα and nonresonant radiations have been decoupled during their propagations through the ISM. We interpret this as evidence that the ISM in the sample galaxies is, on average, highly inhomogeneous and that the transport of Lyα photons is primarily controlled by the ISM geometry rather than by the amount of dust. If the ISM geometry is mainly the result of the energy release from the star formation activity, we speculate that a similar phenomenology was also present at high redshifts. As the median of the absolute value of W_α in our sample is relatively large, the line can be efficiently used to measure the redshifts of primeval galaxy candidates at redshifts $2 \lesssim z \lesssim 7$ via optical spectroscopy with the 10 m class telescopes.

Subject headings: dust, extinction — galaxies: starburst — H II regions — ISM: clouds — ISM: structure — stars: formation

1. INTRODUCTION

In star-forming galaxies, Lyα photons are produced by recombination of hydrogen atoms photoionized by O and B stars. Although line luminosities are expected to be large (Partridge & Peebles 1967; Charlot & Fall 1993), the amount of Lyα radiation observable from a galaxy can vary enormously. Resonant scattering by hydrogen atoms vastly increases the path length of the Lyα photons through the interstellar medium (Harrington 1973), making them more vulnerable than continuum photons to dust destruction, and quantitative calculations have shown that even relatively small amounts of dust can result in severe Lyα attenuation (Neufeld 1990; Charlot & Fall 1991). In principle, the topological structure of the different ionization phases of the ISM surrounding the production regions affects the net amount of Lyα radiation observable from a given direction (Neufeld 1991) so strongly that one can expect virtually any value for the Lyα equivalent widths W_α, from emission to absorption (Charlot & Fall 1993; Chen & Neufeld 1994).

Some empirical insight into the dominant mechanism governing the transport of Lyα photons in galaxies with active star formation can be gained by looking at the correlations between the amount of Lyα radiation and the reddening of nonresonant radiation or the dust content. If the Lyα photons are attenuated by dust because of the action of resonant scattering in a relatively uniform medium, then there should be a marked correlation between W_α and both the continuum reddening at UV wavelengths and the Balmer decrement. On the other hand, if the topology of the ISM is more complex, owing, for instance, to a clumpy distribution of gas and dust (Caplan & Deharveng 1986; Calzetti, Kinney, & Storchi-Bergmann 1994, hereafter CKS94), then the optical paths of the Lyα and the nonresonant photons will, in general, be decoupled and the net amount of Lyα radiation observable along a given line of sight will be determined primarily by the structure of the ISM. In this case, the observed Lyα equivalent width should be largely independent of the reddening of the nonresonant radiation. In any case, however, a correlation with the global dust content of the galaxies is still expected.

A sample of galaxies with redshifts large enough that their Lyα emission is separated from the geocoronal line has been observed with *IUE* over the years by several investigators (Meier & Terlevich 1981; Hartmann, Huchra, & Geller 1984; Deharveng, Joubert, & Kunth 1986; Hartmann et al. 1988; Terlevich et al. 1993). These works have shown that the Lyα emission is typically much weaker than that expected from the recombination theory in the case of no obscuration, even if the intense optical nebular lines show an abundance of ionizing photons. Furthermore, they have also shown a possible correlation between the Lyα intensity and the metallicity, expressed in terms of the ratio [O/H], suggesting that extinction by dust, traced by the metal abundance, is indeed responsible for Lyα obscuration (Hartmann et al. 1988; Charlot & Fall 1991). However, the effects of the ISM geometry on the Lyα propagation have not been addressed in these works.

Interestingly, the number of Lyα photons escaping from these galaxies seems, in general, to be larger than expected, if resonant scattering is effectively taking place in a homogeneous medium. By matching the aperture sizes of the UV and optical observations and correcting for normal extinction, Calzetti & Kinney (1992) showed examples of Lyα/Hβ ratios that are relatively well compatible with case B recombination theory, even in the presence of relatively high metallicity. On the other hand, *Hubble Space Telescope* (*HST*) observations by Kunth et al. (1994) of the galaxy I

[1] Observatory of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, CA 91101.
[2] Hubble Fellow.

Zw 18 provided no evidence for Lyα emission, although the galaxy seems to be one of the most metal-poor known, with $[O/H] \simeq 1/50[O/H]_\odot$ (see below).

These rather extreme behaviors of the Lyα emission are hard to explain in a simple model where the transport of the Lyα photons is primarily controlled by resonant scattering in a dusty homogeneous medium, and suggest that geometrical effects can play as large a role as that currently attributed to the galaxy dust content.

A knowledge of the typical structure of the ISM in star-forming galaxies is important for a deeper understanding of both the mechanisms that have triggered the star formation activity and the effects of the corresponding energy release. In addition, from a practical point of view, a knowledge of the phenomenology of the Lyα emission is very useful in optimizing observational strategies at very high redshifts. We now know that at redshifts $z \gtrsim 1.6$ a large fraction of the galaxy luminosity function is characterized by active star formation (Cowie et al. 1995). While for higher redshifts the traditional [O II] λ3727 emission line is redshifted out of the practical range for optical spectroscopy, to a region dominated by the intense OH night-sky emission lines, the Lyα has just entered the optical passbands and can be used effectively to secure redshifts of distant galaxies.

We present in this paper a study, based on archival and literature data, of the correlation between the intensity of the Lyα line, the extinction of nonresonant radiation, and dust content in a sample of 21 local star-forming galaxies that have been observed with *IUE* and (in one case) with *HST*. To minimize the uncertainties due to data reduction and analysis by different observers and to have a homogeneously reduced data set, we have reextracted and analyzed the original UV spectra from the *IUE* archive, obtaining new measures of equivalent width and UV spectral index. In addition, for 10 galaxies of the sample, the measures of extinction and dust content make use of the new spectroscopic data by CKS94. To account for variations of ionization conditions, due, for example, to aging of the bursting population, we have separately studied both the Lyα equivalent width and the ratio Lyα/Hβ. In § 2 we present the data set and discuss its properties. In § 3 we discuss several different methods for estimating the Lyα and nonresonant radiation extinction and discuss their relative merits. In § 4 we statistically analyze the relative obscurations of Lyα and continuum radiation, and in § 5 we discuss the implications of the results and present our conclusions.

2. THE DATA

Our sample includes 20 galaxies from the *IUE* archives, which have been selected for having redshifts high enough so that the Lyα line is separated from the geocoronal one and for having a relatively well detected UV continuum around the Lyα wavelength. This corresponds to selecting star-forming galaxies that are relatively unobscured and rejecting the heavily reddened ones. No additional selection criteria were applied to the sample, which also includes galaxy I Zw 18, observed with the Goddard High Resolution Spectrometer (GHRS) on the *HST* by Kunth et al. (1994).

All the *IUE* spectra have been obtained using the SWP camera in low-dispersion mode through the 10″ × 20″ aperture. Seventeen galaxies of the sample are the blue compact starbursts observed by Meier & Terlevich (1981), Hartmann et al. (1984), Deharveng et al. (1986), Hartmann et al. (1988), Calzetti & Kinney (1992), and Terlevich et al. (1993), as shown in Table 1. We add to this sample four new galaxies whose Lyα and dust extinction properties have not been included in previous studies, namely, Haro 15, IC 214, 1050+04, and MCG +6-28-44, and whose UV spectra have been published by Kinney et al. (1993). A summary of the sample is shown in Table 1, including the references to papers where the same galaxies were presented and/or

TABLE 1

THE DATA SET

Number	Galaxy	β	$E(B-V)$	[O/H]	Lyα/Hβ[a]	Lyα/$H\beta_C$[a]	W_α[a]	W_α[b]	F_α[c]	F_β[c]	Reference
1	Mrk 12	−0.75	...	...	0.167	...	...	19	...	...	1
2	Mrk 26	−1.40	0.16[b]	8.60[b]	−1.730	−4.720	−5.0	<6	−6.28	3.63[b]	2
3	Mrk 66	−1.60	0.00	8.39	1.249	1.249	5.5	6	5.61	4.49	3, 4
4	Mrk 309	1.40	0.70	9.19	0.000	0.000	0.0	6	0.00	1.41	3, 4
5	Mrk 347	−0.71	0.58	8.53	−2.046	−38.032	−7.7	7	−6.03	3.97	3, 4
6	Mrk 357	−1.19	0.12	8.53	1.957	4.155	9.4	10	12.4	8.14	2, 4, 5
7	Mrk 496	−0.78	0.60	8.77	0.572	24.662	8.0	5	7.21	12.6	2, 4, 5
8	Mrk 499	−1.02	0.45	8.47	−13.648	−229.641	−21.7	3	−20.6	1.94	3, 4
9	Mrk 702	−0.80	0.35[b]	8.40[b]	2.582	23.200	−32.0	<10	−27.8	12.4[b]	2
10	Pox 120	−1.50	0.10[b]	7.83[b]	11.672	21.857	50.0	76	27.8	2.70[b]	6
11	Pox 124	−1.00	0.00[b]	8.28[b]	0.000	0.000	0.0	<20	0.00	1.80[b]	6
12	BSO 234	−0.55	...	8.30[b]	1.961	...	24.0	30	2.85	1.50	3
13	C 0840+1201	−1.65	0.07[b]	7.90[b]	4.432	6.876	38.5	48	12.9	3.30[b]	7
14	Tol 41	−0.80	0.32[b]	7.98[b]	1.471	10.950	34.7	48	5.59	3.80[b]	5, 6
15	Tol 1924−416	−2.08	0.02	8.32	4.818	5.462	26.2	...	123	39.6	4, 5
16	Tol 1247−232	−1.25	0.21[b]	8.06[b]	2.615	9.763	23.3	29	25.8	13.5[b]	7
17	Haro 15	−1.33	0.00	8.57	0.787	0.787	4.0	...	5.58	8.04	4
18	IC 214	−0.26	0.53	8.68	−6.140	−170.648	−14.0	...	−11.7	2.30	4
19	I Zw 18	−2.36	0.04[b]	7.20[b]	<0.443	<0.569	...	<0.7	<1.00	2.40[b]	8
20	MCG +6-28-44	−1.61	...	...	...	...	−13.8	...	−29.2	...	9
21	1050+04	−1.05	0.55	8.57	−8.604	−271.094	−12.0	...	−20.5	2.84	4
22	1543+091	−1.90	0.10[b]	7.90[b]	7.181	13.447	59.0	120	27.8	4.60[b]	1

[a] Positive equivalent width values denote *emission*, negative values *absorption*. Unit of W_α in Å.

[b] Values from literature.

[c] Flux in units of 10^{-14} ergs s^{-1} cm^{-2}.

REFERENCES.—(1) Meier & Terlevich 1981; (2) Hartmann et al. 1984; (3) Hartmann et al. 1988; (4) Calzetti et al. 1994; (5) Calzetti & Kinney 1992; (6) Deharveng et al. 1986; (7) Terlevich et al. 1993; (8) Kunth et al. 1994; (9) Kinney et al. 1993.

studied. Note that Mrk 12, previously used in a similar analysis, has been excluded from our sample because its Lyα wavelength overlaps with the geocoronal line.

For all the *IUE* galaxies, we have reextracted the SWP spectra from each of the 40 IUESIPS line-by-line files using the optimal extraction technique of Kinney, Bohlin, & Neill (1991), which has been incorporated into the *IUE* final archive processing system, NEWSIPS, developed by NASA/ESA/SERC (Nichols et al. 1994). The new measures of W_α for the 20 galaxies are reported in Table 1, together with measures by other sources, when available. Interestingly, for about 40% of the common galaxies, the values we measure are rather different from those quoted in the literature. For instance, for Pox 120 and 1543+091, we measure values of W_α that are smaller than previously reported by a factor of 30%–50%. In a similar vein, our analyses of Mrk 26, Pox 124, and 0842+163 show either absorption or no emission at all, while the literature values are given as emission upper limits. Very likely, the discrepancies are due to the different error analysis and cosmic-ray removal technique. UV spectra of three galaxies of the sample (Mrk 66, Mrk 496, and 1050+04) have also been taken with the Hopkins Ultraviolet Telescope during the Astro-2 mission, and the measured Lyα equivalent widths are in good agreement with our values (H. Ferguson 1995, private communication).

Estimates of the dust extinction and content come from the UV spectral index β, the intrinsic reddening $E(B-V)$ derived from the Balmer decrement, and the oxygen abundance [O/H]. For each galaxy, we have measured β by fitting the function $F(\lambda) \propto \lambda^\beta$ to the UV continuum measured with *IUE* in the wavelength range 1250–2000 Å via a least-χ^2 technique, after removal of the regions corresponding to strong stellar and/or interstellar absorption lines (CKS94).

While the measures of the UV quantities, W_α and β, constitute a homogeneous and well-controlled set, those of Lyα/Hβ (via the Hβ fluxes), $E(B-V)$, and [O/H] come from different sources. For 10 galaxies of the sample, we have consistently measured these quantities from the *IUE* aperture-matched optical spectra of CKS94. In particular, $E(B-V)$ has been derived from the observed ratios Hα/Hβ/Hγ, which also allows the Balmer lines to be corrected for the underlying stellar continuum. Data for the remaining galaxies have been taken from published works, as detailed in Table 1, and in some cases they have also been obtained from matched optical spectra.

The ratio Lyα/Hβ is affected by the extinction suffered by the resonant photons relative to the nonresonant ones, but also by the standard differential extinction between $\lambda = 1216$ Å and $\lambda = 4861$ Å, which varies from galaxy to galaxy. To estimate the effects of this variation, we have also dereddened the Lyα/Hβ ratio, multiplying it by the factor

$$10^{0.4E(B-V)(k_{1216}-k_{4861})}, \quad (1)$$

where k_λ is the Milky Way extinction curve. If we neglect variations of the true extinction curve from galaxy to galaxy, the dereddened values, reported in Table 1 as Lyα/Hβ_C, are the flux ratios observed if the extinction curve were gray.

In almost all cases the measurements of the ratio [O/H] come from calibration diagrams that use the ratio ([O II] + [O III])/Hβ (Edmund & Pagel 1984). When [O III] λ4363 is detected too, then the [O/H] is determined using proper estimates of the electron temperature from this line (Terlevich et al. 1993).

In the case of I Zw 18, the value of the metallicity is debated. Kunth et al. (1994) have proposed a value of 1/1000 $[O/H]_\odot$ for this galaxy, based on the equivalent widths of the far-UV interstellar absorption lines. However, Pettini & Lipman (1995) have shown that these lines are saturated and that their equivalent widths are proportional to the velocity spread of the unresolved individual clouds, rather than to the total column density of the gas. Under these conditions, any value of metallicity between $\approx 1/1000[O/H]_\odot$ and $\sim [O/H]_\odot$ is compatible with the observed UV line strengths. However, given the extremely blue spectrum of the galaxy, we have adopted the value $1/50[O/H]_\odot$ measured from the optical oxygen nebular lines by Dufour, Garnett, & Shields (1988).

Overall, the galaxies in the sample are characterized by intense and narrow optical nebular lines, while the UV portion of the spectra shows a relatively strong and blue featureless continuum with a Lyα line often weak or observed in absorption, although the sample includes a couple of galaxies with relatively large equivalent widths. The strong UV continuum is indicative of radiation dominated by O and B stars, implying either ongoing star formation or a recent burst, probably within the last 10^7 yr. In both cases, the unobscured Lyα equivalent width is expected to be $W_\alpha \sim 150$ Å (Charlot & Fall 1993) or, equivalently, Lyα/H$\beta_C \approx 33$, while none of the observed galaxies have such an intense emission line.

3. ESTIMATORS OF OBSCURATION

Traditionally, the obscuration of Lyα has been empirically studied by analyzing only the correlation between the ratio Lyα/Hβ and the oxygen abundance [O/H] of the galaxy used as an estimator of the dust content (see, for instance, Hartmann et al. 1988 or Terlevich et al. 1993). However, as exemplified by the case of I Zw 18, where no Lyα is observed, even if the galaxy is one of the bluest and, probably, the most metal-poor known, the dust content is not the only relevant parameter, and the ISM geometry must be taken into account as well. The aim of the present study is to empirically estimate, on average, the effectiveness of the ISM geometry in determining the intensity of the emerging Lyα, and in what follows we will discuss the observable quantities used to measure the obscuration of continuum and Lyα photons and how these can provide the information on the ISM geometry.

There are three main estimators of the "mean dust layer" placed between the emitting regions and the observer. The two most direct are the deviation of the Balmer decrement Hα/Hβ/Hγ from the case B recombination value (Osterbrock 1989) and the UV spectral slope, β, which defines the extinction of the UV stellar continuum. The third dust estimator—the most frequently used—is the metallicity index [O/H].

Measures of reddening derived from the Balmer decrement, and expressed in the form of the color excess $E(B-V)$, are direct estimates of the mean amount of dust foreground to the ionized gas, because the Balmer lines are produced by the same mechanism that produces the Lyα but are not affected by the resonant scattering.

The UV spectral index β—namely, the slope of the UV continuum—is similar in character. It is typically measured in the wavelength range 1250–2000 Å, a region dominated by the emission of O and B stars—the same stars that photoionize the gas to produce the nebular lines. For a dust-free star formation, either instantaneous or continuous, β is expected to be in the range $[-2.3, -2.6]$, with a dispersion of ~ 0.15 (Leitherer & Heckman 1995). Calzetti et al. (1994) showed that the observed β is primarily affected by the dust obscuration of the UV continuum and only very marginally by differences in the composition of the hot stellar population. Aging of the massive stars reduces the number of ionizing photons and attenuates the nebular lines before a significant change in β can be detected. In addition, β is only weakly dependent on differences in the geometry of the dust distribution. As shown by CKS94, for a fixed amount of dust, the observed β scatters around the appropriate average value by only $\lesssim 0.4$ because of geometry effects. Thus, although the final intrinsic uncertainty, ~ 0.43, is larger than the typical measurement error, it is quite smaller than the observed range of β values (see Figs. 2*a* and 3*a* below), showing that the total amount of dust is the dominant effect.

While $E(B-V)$ and β are direct measures of dust obscuration, the [O/H] ratio is more properly an estimator of the metal content of the galaxy, and it can be used to derive the dust content only if the gas depletion onto dust and the dust properties are independent of the galaxy environment, which is not true in general. Furthermore, while both the Balmer lines and the UV continuum are extincted by the dust layers foreground to the emitting regions, the oxygen abundance does not account for the distribution of the Lyα-emitting sources relative to the galaxy dust distribution. Finally, from a practical point of view, although dependent on the assumptions on the extinction curves, measures of the Balmer decrement and β are characterized by relatively small errors, typically $\lesssim 0.1$ dex. Using β also has the further advantage of not requiring aperture-matched optical and UV observations, eliminating this additional source of error. By contrast, measures of the [O/H] ratio are characterized by relatively large uncertainties, of the order of ~ 0.2 dex, particularly when measures of the electron temperature are not available (see Edmunds & Pagel 1984).

Assuming case B recombination, the unobscured Lyα line from star-forming galaxies is expected to have an equivalent width of ≈ 150 Å (Charlot & Fall 1993) and flux ratio Lyα/Hβ ≈ 33. The obscuration suffered by the Lyα radiation can be measured by the deviations of either the observed equivalent width W_α or the Lyα/Hβ flux ratio from the expected theoretical values. The equivalent width has the advantage of being unaffected by the selective extinction (though the resonant scattering is still effective). However, it is affected by variations of the ionization conditions. These can differ from galaxy to galaxy because of variations in the initial mass function or in the age of the newly formed stellar population. The observed Lyα/Hβ ratio is independent of the ionization conditions but depends on the differential extinction between 1216 and 4861 Å, which is, in general, different from galaxy to galaxy. We have also used the dereddened Lyα/Hβ_C ratios as measures of Lyα extinction to account for this effect.

In general, none of the above three dust estimators are as sensitive to the details of the geometrical distribution of dust and gas as is the Lyα. Thus, by correlating W_α or Lyα/Hβ with the amount of dust extinction, we probe the difference of obscuration suffered by resonant and nonresonant radiation. We should expect to see a large scatter around the mean trends, if the Lyα is strongly dependent on the geometry of dust and gas.

4. THE ATTENUATION OF THE Lyα PHOTONS

Figure 1shows a plot of the observed Lyα fluxes as a function of the Hβ fluxes. As mentioned above, if no obscuration were present, the fluxes of the two nebular emission lines would have been found strictly correlated. However, the data clearly show the lack of such a correlation, reflecting the combined effects of the regular differential extinction plus that due to the resonant scattering. Figures 2*a*–2*c* show the scatter plots of the Lyα equivalent width W_α versus the UV spectral index β, the intrinsic reddening $E(B-V)$, and the metal content [O/H], respectively. In Figure 3 we have replaced the equivalent width with the flux ratio Lyα/Hβ, while in Figure 4 we use the dereddened flux ratio Lyα/Hβ_C for the case of emissions only. Filled circles represent galaxies for which the $E(B-V)$ and the [O/H] have been measured from the data by CKS94, while open circles mark galaxies for which these data have been taken from other works.

We have analyzed the correlation between the Lyα strength and the dust extinction or abundance indicators using the nonparametric generalized Kendall's τ and Spearman's ρ statistics, and reported the results of the analysis in Table 2 for each pair of variables considered. It can be noticed that the results of the two statistics are in agreement. Overall, the data are rather scattered, and the analysis does not show any well-detected correlation in any of the cases, although some interesting trends are noticeable.

First, the data are clearly less scattered and show the presence of a possible correlation, albeit at very low significance, when the Lyα intensity, either in the form of W_α or

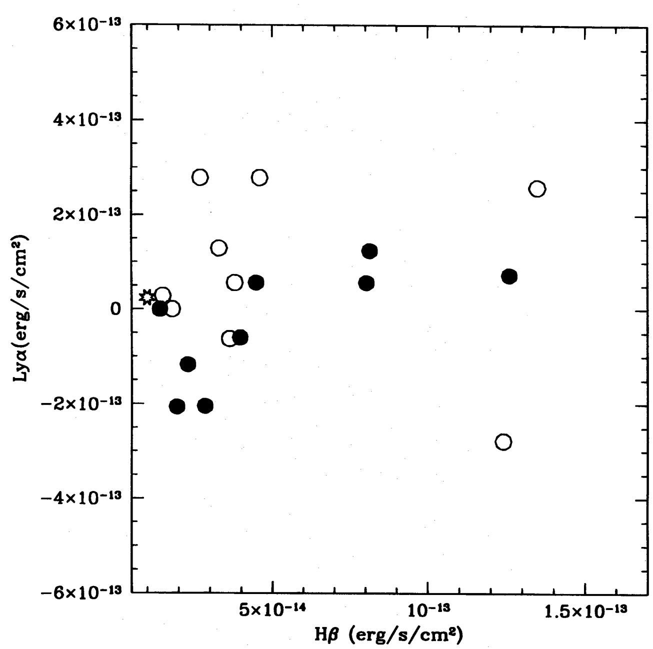

FIG. 1.—Scatter plot of the Lyα flux vs. the Hβ flux for the sample galaxies. Filled circled show galaxies for which the Hβ flux has been measured from the data of CKS94. Open circles show galaxies for which the data are from literature. The data point for galaxy I Zw 18, marked as a star, is an upper limit.

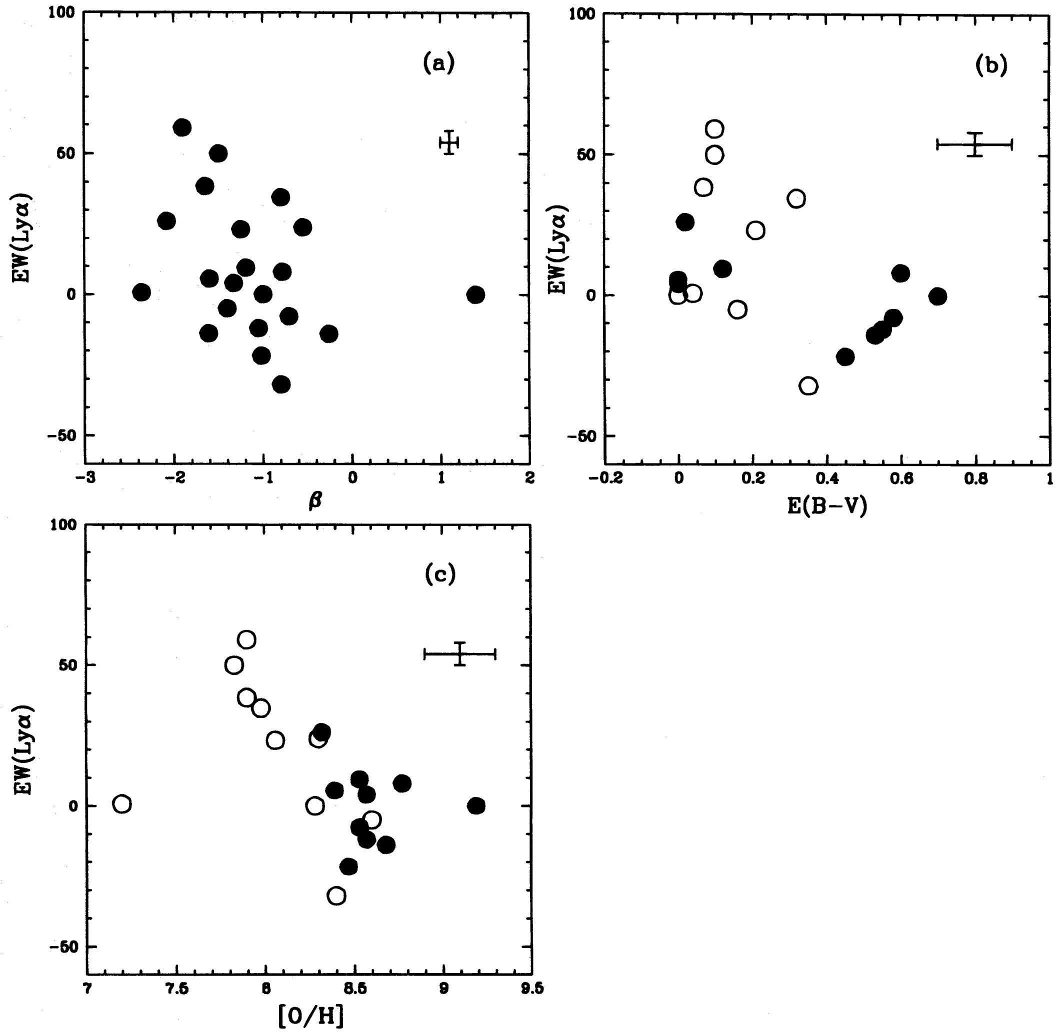

FIG. 2.—Scatter plot of the Lyα equivalent width W_α vs. (*a*) the UV spectral index β, (*b*) the color excess $E(B-V)$, and (*c*) the oxygen abundance [O/H]. The 1 σ error bars are also plotted. Open circles show galaxies for which optical data are from literature, as detailed in Table 1.

Lyα/Hβ, is compared to [O/H] rather than to β or $E(B-V)$. Second, the correlations between the Lyα strength and β or $E(B-V)$ are characterized by about the same amount of scatter, confirming that these two reddening indicators are indeed similar in character.

When we have used Lyα/Hβ_C to quantify the Lyα obscuration, we have limited the sample only to galaxies with Lyα in emission, because while the ratio Lyα/Hβ has an upper limit, it does not have a lower limit (i.e., the absorption can be arbitrarily large), and this would artificially skew the

TABLE 2

THE CORRELATION ANALYSIS

Data Set	Independent Variable	Dependent Variable	Data Points	τ[a]	$1-p_\tau$[b]	σ_τ[c]	ρ[d]	$1-p_\rho$[e]
1	β	W_α	21	−0.429	0.833	1.38	−0.300	0.820
2	$E(B-V)$	W_α	19	−0.316	0.667	0.97	−0.336	0.846
3	[O/H]	W_α	20	−0.779	0.985	2.44	−0.506	0.973
4	β	Lyα/Hβ	20	−0.579	0.929	1.81	−0.388	0.909
5	$E(B-V)$	Lyα/Hβ	19	−0.468	0.847	1.43	−0.373	0.886
6	[O/H]	Lyα/Hβ	20	−0.832	0.991	2.60	−0.533	0.980
7	β	Lyα/Hβ_C	19	−0.140	0.330	0.43	−0.128	0.412
8	$E(B-V)$	Lyα/Hβ_C	19	0.023	0.057	0.07	−0.092	0.303
9	[O/H]	Lyα/Hβ_C	19	−0.561	0.912	1.71	−0.317	0.821

[a] Generalized Kendall's τ correlation test.
[b] Probability that the correlation is detected.
[c] Deviations from the null hypothesis in variance unity.
[d] Spearman's ρ correlation test.
[e] Probability that the correlation is detected.

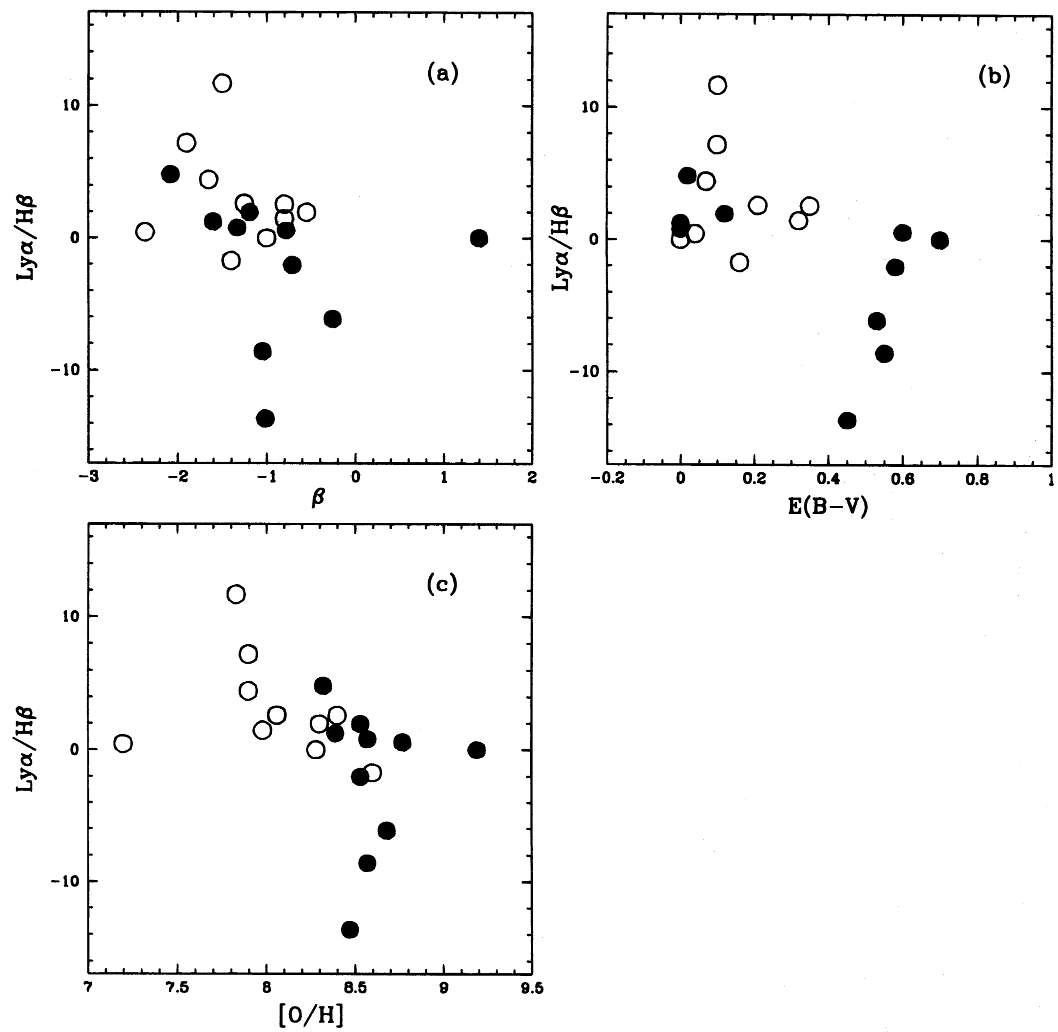

FIG. 3.—Scatter plot of the ratio Lyα/Hβ vs. (*a*) the UV spectral index β, (*b*) the color excess $E(B-V)$, and (*c*) the oxygen abundance [O/H]. The 1 σ error bars are also plotted. Open circles show galaxies for which optical data are from literature, as detailed in Table 1.

distribution toward negative values and largely increase the scatter. Interestingly, the correlation nevertheless seems characterized by a larger amount of scatter than in the previous cases. Given that the dereddening multiplicative factor in equation (1) is derived using the same extinction curve for all the galaxies of the sample, either random variations in the extinction curve from galaxy to galaxy are rather large, or the measures of $E(B-V)$ are affected by large random errors. The latter case seems excluded by the less noisy correlation between Lyα/Hβ and $E(B-V)$. In this respect, we note that an artificial correlation between Lyα/Hβ and β, $E(B-V)$, and [O/H] could, in principle, be present because for a given galaxy all these quantities depend on the same extinction curve. However, this cannot be an important effect, because the scatter between β and W_α is essentially identical to that between β and Lyα/Hβ, even if data set 1 is more homogeneous than data set 4.

Thus, the observed scatter does not seem to be dominated by observational random errors. As we will discuss in the next section, the presence of such a large scatter is direct evidence of the action of resonant scattering in a largely inhomogeneous ISM.

Data set 1 is the largest and most homogeneous of the sample, and in this sense of more statistical significance. The statistical tests applied to it show absence of correlation between the Lyα intensity, measured by W_α, and the dust extinction, measured by β. Thus, the obscuration of the Lyα photons seems to be largely uncorrelated with that of the nonresonant radiation. The same conclusion is reached when either the Lyα/Hβ or Lyα/$H\beta_C$ ratios are used instead of W_α (data sets 4 and 7).

Systematic differences between measures derived from the CKS94 data and those from other sources do not seem to significantly affect the results of the analysis. Figures 2*b*, 2*c*, and 3 show that, although on average characterized by a higher metallicity, the CKS94 galaxies (*filled circles*) also have a less intense Lyα, and their distribution relative to the literature data (*open circles*) does not show evidence of systematic deviations. As discussed above, this seems confirmed by the fact that the results of the analysis of data sets 1 and 4 are essentially identical. Finally, there are no appreciable differences in the results when either β or $E(B-V)$ is used to quantify dust extinction, and the two indicators are substantially equivalent (see Figs. 2*a*, 2*b*, 3*a*, and 3*b*, and data sets 1, 2, 4, and 5). Thus, our analysis agrees with the conclusions by CKS94 that the spectral index β is a robust (and convenient) measure of the obscuration of the UV continuum.

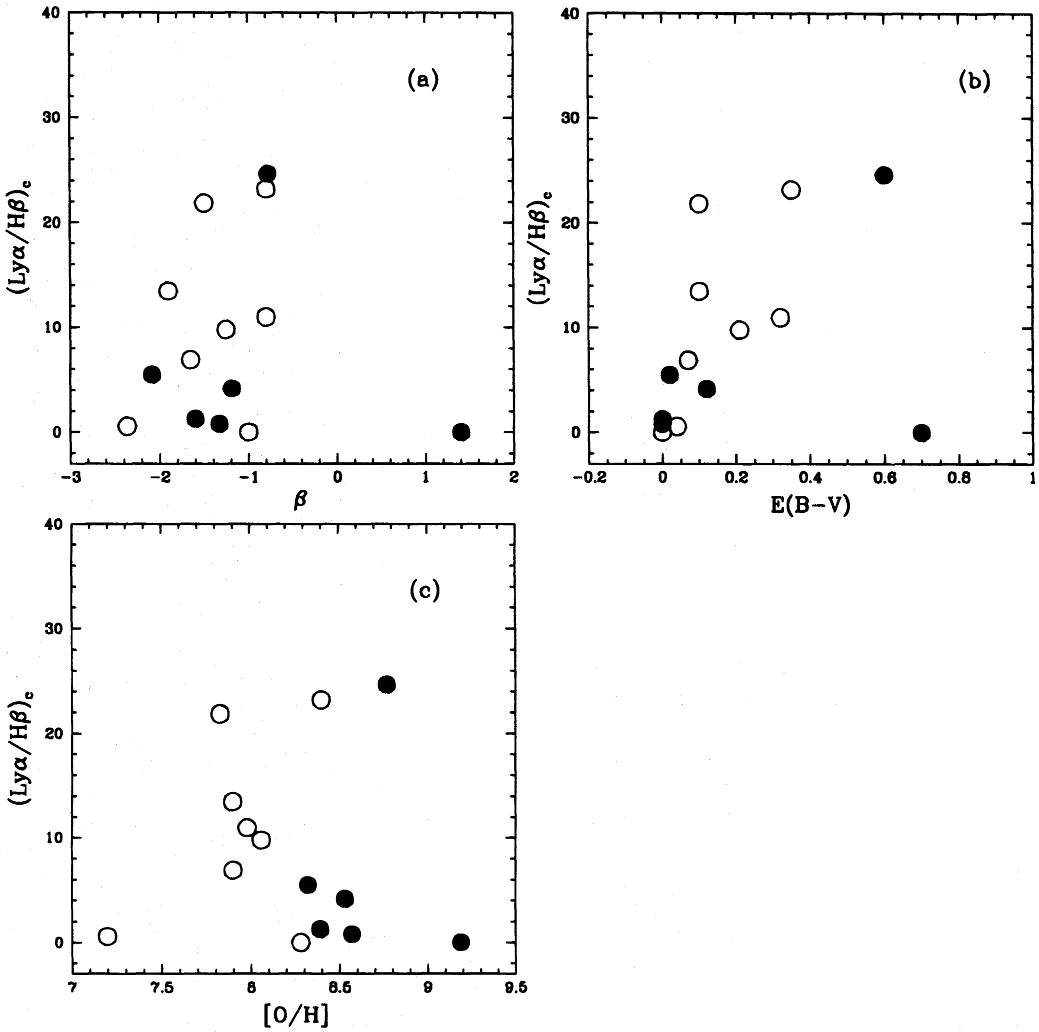

FIG. 4.—Scatter plot of the flux ratio Lyα/Hβ_C, namely, corrected for the differential extinction between the rest frame wavelengths of the Lyα and Hβ lines, vs. (*a*) the UV spectral index β, (*b*) the color excess $E(B-V)$, and (*c*) the oxygen abundance [O/H]. The 1 σ error bars are also plotted. Open circles show galaxies for which optical data are from literature, as detailed in Table 1.

Variations in the ionization conditions across the galaxies of the sample, which would increase the scatter of the W_α values, seem to be rather small, as can be seen by comparing the results from data sets 1, 2, and 3 with those from data sets 4, 5, and 6, respectively, which show essentially identical results.

Figures 2*c*, 3*c*, and 4*c*, where the metallicity index [O/H] is used to estimate the dust content, show the deviant point due to galaxy I Zw 18. However, this galaxy is not deviant at all when either β or $E(B-V)$ is used to quantify dust extinction. To test the stability of the results, we have also repeated the analysis excluding this galaxy, finding no significant variations in the correlation between the Lyα strength and either β or $E(B-V)$. However, neglecting galaxy I Zw 18 in the correlation between W_α and [O/H] and between Lyα/Hβ and [O/H], we found that the probabilities that the correlation is detected are $p_\tau = 0.997$ ($p_\rho = 0.996$) and $p_\tau = 0.999$ ($p_\rho = 0.998$), respectively, corresponding to ∼3.0 σ and ∼3.2 σ detections.

In conclusion, no correlation is found between the Lyα intensity and the obscuration of the nonresonant radiation, and only a marginal correlation seems to be detected between the Lyα and the metal content.

5. DISCUSSION AND CONCLUSIONS

The obscuration of UV nonresonant radiation along a given line of sight is primarily regulated by the amount of dust in the optical path and, to a minor extent, by the geometry of the dust distribution. The Lyα photons, in addition, are subject to resonant scattering, which increases their mean path across the ISM over that of the nonresonant radiation, effectively increasing the cross section for dust destruction and making them very sensitive to the details of the geometry of the ISM distribution. Because of the large cross section for scattering, the observed intensity of the Lyα radiation is a direct probe of the additional extinction over the nonresonant radiation due to the increased optical path by the scatter and, consequently, of the geometrical distribution of neutral gas and dust. For instance, mirror reflections by denser gas clouds can significantly subtract (or add) flux along the line of sight, and the net amount of observable Lyα radiation is expected to be rather unpredictable (Charlot & Fall 1993).

Three important conclusions can be derived from the above analysis: (1) the observed amount of Lyα radiation is systematically smaller than the value expected from recombination theory in the case of no obscuration, namely, $W_\alpha \sim 150$ Å, on average by a factor of ≈ 5; (2) the Lyα obscuration is uncorrelated with the obscuration of the nonresonant radiation and is weakly correlated with the metal content; (3) using the ratio Lyα/Hβ instead of W_α in the analysis does not change the conclusions, implying that variations of the ionizing conditions of the nebular gas do not significantly affect our sample.

Point (1) clearly shows that obscuration mechanisms largely dominated by resonant scattering strongly affect the amount of observable Lyα radiation. As pointed out by Calzetti & Kinney (1992), it is interesting that there are galaxies, namely, Mrk 496, Mrk 702, and Pox 120, that have Lyα/Hβ_C close to the theoretical recombination value, indicating that the regular extinction is mostly responsible for the observed obscuration, with little effect from resonant scattering. Point (2) is direct evidence that the continuum and Lyα radiations have been strongly decoupled in their propagation through the ISM of the galaxy and have followed totally different obscuration vicissitudes. The continuum radiation has propagated through all the various phases of the ISM along the line of sight, and its obscuration reflects the integral column density of dust along this path. The Lyα photons have followed, in general, different optical paths, mirrored into or away from the line of sight by multiple scattering, and those that survived and are detected have propagated into regions of the ISM whose total dust column density is much smaller than and largely independent of the average one.

It is not particularly surprising that W_α correlates (albeit weakly) with [O/H]. Ultimately, dust is what destroyed the Lyα photons, and although in general [O/H] does not accurately map the *local* amount of dust, on average, extinction and metal content are correlated (CKS94). Thus, galaxies that are more metal rich tend, on average, to have weaker (or more absorbed) Lyα. Such a correlation is weak, though, because it is diluted by the randomness of the Lyα propagation through the ISM. We explicitly note that the correlation between W_α and [O/H] that we measure seems weaker than that found in previous works (see, for instance, Charlot & Fall 1993).

Point (3) shows that differences in the stellar population composition (due mostly to aging of the burst) do not seem to be present in appreciable measure in our sample. Only a minor decrease in the scatter among the data is observed when Lyα/Hβ is replaced by W_α, but overall, the details of the correlation between the Lyα strength and β, $E(B-V)$, or [O/H] are very similar and do not depend on whether W_α or Lyα/Hβ is used as an estimator of the intensity of the line. This also shows that the values of the ratio Lyα/Hβ (and, correspondingly, the other quantities derived from the optical data) are very mildly affected by random errors due to aperture mismatches or different techniques of reduction and analysis. Thus, either the majority of the galaxies in the sample are characterized by a continuous star formation rate, an interpretation that we favor, or the current bursts are rather young, probably $\lesssim 10^7$ yr for all of them.

The above phenomenology is rather difficult to explain if the topology of the ISM is that of a homogeneous mixture of gas and dust surrounding the H II regions with a covering factor of unity. A more satisfactory model that naturally explains the lack of correlation between W_α and β or $E(B-V)$ is one where denser clouds of dust and gas are distributed in a more tenuous, relatively dust-free ISM surrounding the H II regions. In this way, the effective τ responsible for the continuum reddening will be given by the integral path through the clouds, weighted by the covering factor. Conversely, the Lyα radiation, due to resonant scattering, will be mirrored by the clouds without penetrating through them. The net amount of Lyα observable in a given direction will be mostly determined by the distribution and covering factor of the clouds, and only marginally by the overall dust and metallicity content of the ISM. For instance, two out of the three reddest galaxies in our sample, Mrk 309, Mrk 347, and BSO 234, show Lyα in emission, the latter with a relatively large equivalent width, $W_\alpha = 24$ Å. On the other hand, I Zw 18, which is the most metal-poor galaxy known, shows no Lyα at all. As mentioned above, there also are galaxies that show very little Lyα obscuration due to resonant scattering.

Thus, the prediction by Neufeld (1991) and Charlot & Fall (1991, 1993) that, because of the resonant character of the Lyα line and the complex structure of the ISM, the net amount of Lyα radiation leaving a given galaxy is highly unpredictable, is confirmed by the observations. The interesting point that has emerged from our analysis is that, at least in the limiting case of small metallicity, this behavior is rather independent of the metallicity itself, and therefore of the dust content. This seems to suggest that dust is depleted in the intercloud gas, probably because of sputtering by UV photons, whereas it survives in the denser clouds, where the most energetic, ionizing photons have very small optical depth.

If present in large numbers at high redshifts, a population of star-forming galaxies with star formation rates like those in our sample, i.e., a few $M_\odot$ yr^{-1}, would have been substantially unnoticed in the deep, optical narrowband surveys that have attempted to detect Lyα emission from primeval galaxies at $2 \lesssim z \lesssim 7$. For instance, if placed at $z = 3.5$, Tol 1924−416, the brightest UV galaxy in the sample, would have $V \sim 28$ and a Lyα narrowband magnitude $N_\alpha \sim 27$, where we have used $H_0 = 75$ km s^{-1} Mpc^{-1}, $q_0 = 0.25$, a FWHM of the narrowband filter of 25 Å, and included intervening Lyα forest absorption as in Madau (1995). However, the median value of W_α in emission in our sample (11 galaxies, excluding I Zw 18) is 24.0 Å, with a standard deviation of 18.5 Å, while that of the absorption cases (10 galaxies, including I Zw 18) is −9.9 Å, with a standard deviation of 10.4 Å. At $z = 3.5$, the two medians would be 108 and −45 Å, respectively, and although they can be reduced by intervening Lyα forest absorption in the wings of the line (at the chosen redshift an upper limit to this attenuation should be about a factor of 2), the emission value is large enough that reliable detections are presently possible for a galaxy population about an order of magnitude brighter than those in our sample (e.g., $L \gtrsim L^*$ in the B-band rest frame, assuming an Im spectral type), because of higher star formation rates.

Thus, if the Lyα properties of our sample are representative of those of primeval galaxies of relatively bright luminosity—for instance, this could be the case if the structure of the ISM is primarily determined by the release of energy from supernova explosions—then the narrowband surveys have shown that (1) either the redshift ranges searched do not correspond to the epoch during which the presumably violent bursts of star formation took place, (2) primeval galaxies were characterized by star formation efficiencies low enough to elude massive detections at the current sensitivity, or (3) the hydrogen line recombinations were inhibited by a massive ionization of the ISM due to supernovae (Bithell 1991). Finally, we observe that the intensity of the Lyα feature (either in absorption or in emission) is, in general, strong enough that at the sensitivity of the modern 10 m class telescopes, optical spectroscopy can be efficiently exploited to measure redshifts of distant ($z > 2$) star-forming galaxies.

We would like to thank Harry Ferguson and Mike Fall for many interesting discussions. We also wish to thank the referee, George Djorgovski, for his very useful comments and careful review of the manuscript.

REFERENCES

Bithell, M. 1991, MNRAS, 253, 344
Calzetti, D., & Kinney, A. L. 1992, ApJ, 399, L39
Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582 (CKS94)
Caplan, J., & Deharveng, L. 1986, A&A, 155, 297
Charlot, S., & Fall, S. M. 1991, ApJ, 378, 471
———. 1993, ApJ, 415, 580
Chen, W. L., & Neufeld, D. A. 1994, ApJ, 432, 567
Cowie, L. L., Hu, E. M., & Songaila, A. 1995, Nature, 377, 603
Deharveng, J. M., Joubert, M., & Kunth, D. 1986, in First IAP Workshop: Star Forming Dwarf Galaxies and Related Objects, ed. D. Kunth & T. X. Thuan (Gif-sur-Yvette: Editions Frontieres), 431
Dufour, R. J., Garnett, D. R., & Shields, J. A. 1988, ApJ, 332, 752
Edmunds, M. G., & Pagel, B. E. J. 1984, MNRAS, 211, 507
Harrington, J. P. 1973 MNRAS, 162, 43
Hartmann, L. W., Huchra, J. P., & Geller, M. J. 1984, ApJ, 287, 487
Hartmann, L. W., Huchra, J. P., Geller, M. J., O'Brien, P., & Wilson, R. 1988, ApJ, 326, 101
Kinney, A. L., Bohlin, R. C., Calzetti, D., Panagia, N., & Wyse, R. 1993, ApJS, 86, 5
Kinney, A. L., Bohlin, R. C., & Neill, J. D. 1991, PASP, 103, 694
Kunth, D., Lequeux, J., Sargent, W. L. W., & Viallefond, F. 1994, A&A, 282, 709
Leitherer, C., & Heckman, T. 1995, ApJS, 96, 9
Madau, P. 1995, ApJ, 411, 18
Meier, D., & Terlevich, R. 1981, ApJ, 246, L109
Neufeld, D. A. 1990, ApJ, 350, 216
———. 1991, ApJ, 370, L85
Nichols, J. S., Garhard, M. P., De La Pena, M. D., & Levay, K. L. 1994, *IUE*-NASA Newslettters, 53
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (Mill Valley: Univ. Science Books)
Partridge, R. B., & Peebles, P. J. E. 1967, ApJ, 147, 868
Pettini, M., & Lipman, K. 1995, A&A, 297, L63
Steidel, C. C., & Hamilton, D. 1993, AJ, 105, 2017
Terlevich, E., Díaz, A. I., Terlevich, R., & García, M. L. 1993, MNRAS, 260, 3