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LYMAN-ALPHA EMISSION IN STAR-FORMING GALAXIES: LOW-REDSHIFT COUNTERPARTS OF PRIMEVAL GALAXIES?

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ABSTRACT

We present UV plus optical spectra of three galaxies, Mrk 496, Mrk 357, Tol 1924−416, obtained by matching the size of the optical aperture with that of *IUE*. From the Hα/Hβ ratios, we estimate values of $E(B-V)$—extinction due to dust—for the two Markarian galaxies which are higher than those derived in previous works. We have used the new values of $E(B-V)$ to deredden the Lyα fluxes, although this technique can be considered an approximation of the detailed extinction process, since it is unlikely that the dust is homogeneously distributed within a galaxy. An important aspect of our approach is the application of different extinction curves according to the different metallicity of the three galaxies, using the extinctions laws of our Galaxy, the Large Magellanic Cloud, and the Small Magellanic Cloud. The resulting Lyα/Hβ ratios are consistent with case B recombination (within the observational uncertainties) without invoking absorption of multiple scattered Lyα photons by dust. Since multiple scattering must be present because of the large H I column densities in our galaxies, we interpret our findings as an effect of the geometrical distribution of gas and dust inside the galaxies. The decreasing trend of *observed* Lyα/Hβ with metallicity reported in previous works result directly from extinction rather than multiple scattering. Our results suggest that the search for primeval galaxies using the Lyα line emission can be still considered a valid strategy.

Subject headings: galaxies: evolution — galaxies: general — galaxies: starburst

1. INTRODUCTION

In this *Letter* we analyze the Lyα flux and the Lyα/Hβ line ratio of three metal-poor blue galaxies, Mrk 496, Mrk 357, Tol 1924−416, using the archival *IUE* spectra together with new optical spectra obtained in an aperture which matches the size of the *IUE* aperture. These observations are part of a larger project aimed at obtaining full wavelength coverage from 1200 to ~8000 Å in matched apertures of the galaxies contained in the Atlas of Ultraviolet Spectra of Star-forming Galaxies (Kinney et al. 1992). The three galaxies analyzed here are the first galaxies observed in the optical of a sample of 30 Atlas galaxies with high enough redshift to allow observations of Lyα.

The use of matched apertures in the UV and optical wavelengths is important because of the possible presence of inhomogeneously distributed dust. In addition, these star-forming galaxies are extended by 6″–10″ in the UV (see Table 1, col. [5]), so that including comparable regions of the galaxy within the optical aperture is essential.

The three galaxies show Lyα emission in the UV spectra. Using matched apertures in the optical and obtaining the extinction parameter $E(B-V)$ from the observed Hα/Hβ ratio, we have derived dereddened Lyα/Hβ ratios roughly constant over the range of metallicities. Although we analyze only three galaxies here, the lack of correlation between the dereddened Lyα/Hβ and metallicity is interesting, since it implies that the effects of pure dust extinction are *not* negligible, in contrast with the conclusions reached by previous works (see Hartmann et al. 1988 and references therein), and play an important role in determining the observed Lyα/Hβ ratio. In addition, we find that the dereddened Lyα/Hβ ratio are consistent within the uncertainties with the theoretical case B recombination value for nebular emission, if we take into account the possible contribution of the underlying stellar absorption in the Lyα line emission. The selective absorption by dust of the Lyα photons in the presence of multiple scattering within extended uniform H I regions, as predicted by Neufeld (1990), seems to be ruled out by our results.

The derived star formation rates (SFRs) of the two Markarian galaxies show that they are experiencing an intense burst of star formation (see the discussion). This fact and the large H I column densities make Mrk 496 and Mrk 357 good candidates for comparison with primeval galaxies (PGs; see Hartmann, Huchra, & Geller 1984).

Although Djorgovski (1992) remarks that the analogy between low-redshift metal-poor blue compacts and high-redshift PGs is not clear, nevertheless much effort has been devoted to the study of low-redshift metal-poor star-forming galaxies in order to aid in the design of strategies for finding PGs (Meier & Terlevich 1981; Hartmann et al. 1984; Deharveng, Joubert, & Kunth 1985; Hartmann et al. 1988). The main results of previous works are (1) the Lyα/Hβ ratios are reported to be a factor ~20–30 lower than expected for case B recombination; (2) an inverse correlation is reported between the Lyα/Hβ line ratio and the metallicity of the galaxy (Hartmann et al. 1988). Both results are in agreement with the expectation of a substantial reduction of the Lyα flux for absorption of multiply scattered Lyα photons by dust when crossing extended H I regions (see Hartmann et al. 1984; Neufeld 1990). As Hartmann et al. remark, even a small amount of dust mixed with neutral hydrogen can strongly reduce the Lyα flux. The same process limits our ability to search for PGs using Lyα emission, since the expected extended H I regions in PGs easily increase the optical depth for Lyα and trigger the absorption of Lyα photons by any dust present (Hartmann et al. 1988).

The results reported in the present *Letter* do not support the previous findings, since we find that the theoretical Lyα/Hβ ratio is almost completely recovered by applying the standard

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TABLE 1

EMMISSION-LINE FLUXES

Galaxy Name (1)	z (2)	D(Mpc) $H_0 = 50$ (3)	M_B (4)	UV Width (5)	Lyα[a] 1216 Å (6)	E.W.(Lyα) (Å) (7)	[O II][a] 3727 Å (8)	Hβ[a] 4861 Å (9)	[O III][a] (4959+5007) Å (10)	Hα[a] 6563 Å (11)	[N II][a] 6584 Å (12)
Mrk 496	0.030	174	−21.3	10″.0	7.90 (−14)	~5	1.73 (−13)	1.27 (−13)	1.25 (−13)	6.85 (−13)	3.00 (−13)
Mrk 357	0.053	303	−21.8	8.5	1.23 (−13)	~9	1.45 (−13)	8.17 (−14)	3.27 (−13)	3.42 (−13)	6.20 (−14)
Tol 1924−416	0.011	55	−20.8	6.5	11.48 (−13)	≃22	9.59 (−13)	4.55 (−13)	3.16 (−12)	1.48 (−12)	5.56 (−14)

[a] Fluxes are given in ergs cm^{-2} s^{-1}.

dereddening procedure. This is, indeed, unexpected, since in all cases the H I column density in front of the galaxy is enough to substantially scatter the Lyα photons, increasing their chances to be absorbed by dust. This effect can possibly be explained by the uneven distributions of gas and dust inside the galaxy. If the same conclusion is reached by the investigation of other similar galaxies in our sample, these results suggest that the search for PGs through the detection of their Lyα emission can be still considered a valid technique, since PGs are likely to have very low dust content, and gas and dust can be inhomogeneously distributed as well.

2. THE OPTICAL DATA

Mark 496 and Mrk 357 were observed in 1991 October at the KPNO 0.9 m + IRS, using a circular aperture of 13″.5 diameter. The difference in flux due to the difference in size between the KPNO and the *IUE* apertures is negligible in the case of Mrk 357, since the galaxy has dimensions of 14″ × 14″ (Hartmann et al. 1984). The analogous difference in flux for Mrk 496 is estimated to be between 10%–20%, (dimension of the galaxy: 22″ × 17″) and is well within the measurement uncertainties.

Tol 1924−416 was observed in 1991 October with the CTIO 1 m + 2D FRUTTI, using a rectangular aperture of 20″ × 10″, matching exactly the *IUE* aperture (Storchi-Bergmann et al. 1992). Among the three galaxies here analyzed, Tol 1924−416 is the only one with complete UV coverage (1200–3200 Å).

The data were flat-fielded, wavelength-calibrated, flux-calibrated, and extinction-corrected using standard IRAF packages. In all cases the spectral resolution is ~10 Å and the optical spectral range covered is ~3300–7700 Å. Evidence that the apertures have been well matched is that the UV and optical spectra are plotted together with *no normalization* in Figure 1, where the entire range from 1200 Å to 7700 Å, is shown.

Table 1 lists the redshift, the adopted distance, the absolute blue magnitude, the rms width (in arcseconds) of the light profile measured in the *IUE* spectrum, the Lyα line flux, the Lyα equivalent width (EW) and the flux of some of the optical emission lines for the three galaxies. The width of the detected UV point spread function from the *IUE* spectrum demonstrates the importance of our choice of a large optical aperture in order to perform meaningful comparisons between optical and UV spectra of these galaxies. Fluxes for both the UV and the optical emission lines and the Lyα EW were measured using standard IRAF packages. The typical uncertainty of the Lyα flux is ~30%. The optical lines in Tol 1924−416 are known within 5%, except [N II] 6584 Å, which has an uncertainty of ~15%, because of blending with Hα. The optical lines of Mrk 496 and Mrk 357 reported in the Table have been corrected for the extinction induced by the eruption from Mount Pinatubo (NOAO Newsletter, 1991 December). Because of this additional uncertainty, the optical lines of the two Markarian galaxies are known with an accuracy of ~10% (25% for [N II]).

The Hα and Hβ lines have been subsequently corrected for the underlying stellar absorption, according to Keel (1983). The corrections are a few percent for both lines. The value of the dust extinction $E(B-V)$ has been calculated from the ratio

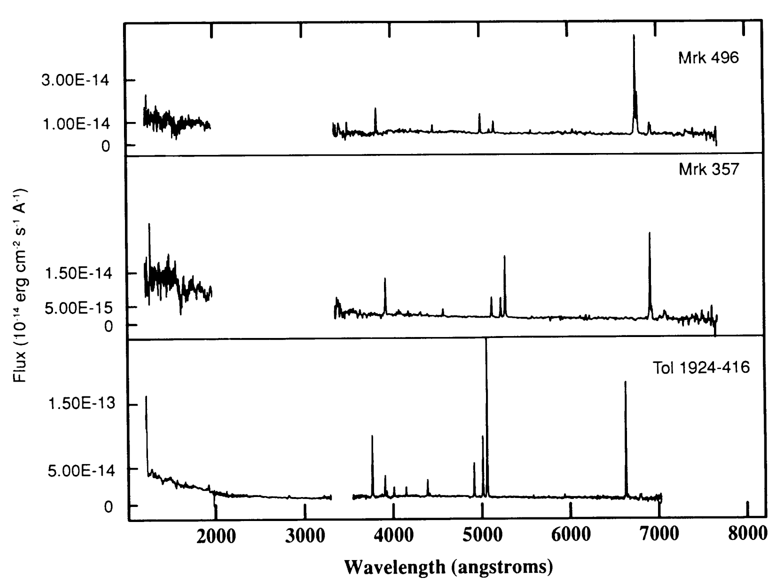

FIG. 1.—The UV plus optical spectra of Mrk 357, Mrk 496, Tol 1924−416 are plotted in the rest-frame of the galaxies. No normalization has been applied between the optical and the UV spectra.

TABLE 2

DERIVED PHYSICAL PROPERTIES

Galaxy Name	$E(B-V)$[a] Galactic	$E(B-V)$ Intrinsic	Hα/Hβ	Lyα/Hβ Undereddened	Lyα/Hβ[b] Galactic Extinction	Lyα/Hβ[b] LMC Extinction	Lyα/Hβ[b] SMC Extinction	[O/H][c] ±0.20	$10^{21} N_{\rm H\,I}$ ($\rm cm^{-2}$)	SFR(Hα) ($M_\odot$ yr^{-1})	SFR(L_B) ($M_\odot$ yr^{-1})
Mrk 496	0.00	0.52 ± 0.15	5.28	0.60	$12.4^{+7.5}_{-7.2}$	...	...	−0.05	3.7[d]	70–80	5–10
Mrk 357	0.04	0.26 ± 0.15	4.08	1.45	$8.3^{+11.3}_{-4.8}$	$20.0^{+0.0}_{-14.9}$	...	−0.5	3.3[e]	70–80	5–10
Tol 1924−416	0.07	0.05 ± 0.10	3.25	2.40	$4.8^{+3.8}_{-1.2}$	$5.7^{+8.9}_{-2.1}$	$7.0^{+19.8}_{-3.5}$	−0.8	0.2–4[f]	6	2–3

[a] From Burstein & Heiles 1982.

[b] 1 σ error bars are quoted for the uncertainties in Lyα/Hβ as obtained from the uncertainties in $E(B-V)$. However, this procedure has been not applied for the positive error bars in Lyα/Hβ of Mrk 496 and Mrk 357. In this cases the positive error bar comes from the maximum ratio allowed between the 1216 Å continuum and the 4861 Å continuum. We have assumed that this ratio is that obtainable from O stars. Theoretical models (Auer & Mihalas 1972) indicate $c(1216)/c(4861) \simeq 80$, which corresponds for both Mrk 496 and Mrk 357 to a maximum value Lyα/Hβ ≃ 20. No correction for possible underlying stellar absorption of the observed Lyα has been introduced in this estimation.

[c] Solar units, i.e., $[{\rm O/H}] = \log [({\rm O/H})_{\rm obj}/({\rm O/H})_\odot]$. Metallicities have been evaluated from the ratios [O III]/Hβ and ([O II] + [O III])/Hβ using the calibration diagrams by Edmunds & Pagel 1984.

[d] Martin et al. 1991.

[e] Bothun et al. 1984.

[f] There are no direct measurements of the H I content of Tol 1924−416, so the value reported is an estimate obtained using the well-known relation $N_{\rm H\,I}/E(B-V)$ (Bohlin, Savage, & Drake 1978) and a gas/dust ratio appropriate to the metallicity of the galaxy (Koornneef 1984).

Hα/Hβ, assuming a theoretical value 2.87 (Ferland & Osterbrock 1985). Both $E(B-V)$ and Hα/Hβ are reported in Table 2. The relatively large values of the ratio Hα/Hβ we find for Mrk 496 and Mrk 357 are in disagreement with the negligible extinction values quoted by Hartmann et al. (1984) using an aperture slit of 3″.2 × 6″.4, but are comparable with similar values found by other authors using larger apertures (Balzano 1983; Dahari 1985).

3. DISCUSSION

3.1. *Extinction versus Metallicity*

The Lyα/Hβ ratio is critically dependent on the extinction parameter and on the adopted extinction law. Table 2 shows the Lyα/Hβ ratio adopting four different corrections: (1) negligible extinction (Hartmann et al. 1984); (2) Galactic extinction law (Seaton 1979), with $E(B-V)$ as given in columns (2) and (3) of Table 2; (3) LMC extinction law (Koornneef & Code 1981); (4) SMC extinction law (Bouchet et al. 1985). Since our galaxies span a range in metallicity (see Table 2), the three extinction curves are from galaxies with approximately the same range in metallicity. Mrk 496, which has [O/H] ∼ −0.05 (in solar units) can be reasonably dereddened using the Galactic extinction law. Mrk 357, which has [O/H] ∼ −0.5, can be reasonably dereddened with a LMC extinction law ($[{\rm O/H}]_{\rm LMC} \simeq -0.4$) and Tol 1924−416, which has a metallicity [O/H] ∼ −0.8, can be reasonably dereddened using a SMC extinction law ($[{\rm O/H}]_{\rm SMC} \simeq -0.9$, Lequeux et al. 1979). Although the correspondence between metallicity and the shape of the extinction is not known in detail (see, however, the discussion in Lequeux 1988), this seems like the most plausible approach to deredden our galaxies.

A caveat must be nevertheless raised about these considerations. The dereddening of the UV continuum is a problematic topic since it is not clear which parameters enter in determining the reddening law. The average metal content of the galaxy is one parameter, but others may be equally important. For instance, Kinney et al. (1992) have noticed that, despite the large range of metallicities covered in their UV spectra of 143 star-forming galaxies, the 2200 Å dust signature is hardly present. This represents an important constraint on any theoretical consideration about the distribution and composition of dust and, obviously, affects any conclusion after applying the standard dereddening procedure. Thus, the methodology we apply in this *Letter* can be considered a first-order approximation to the problem of the dust extinction.

From the values of $E(B-V)$ and [O/H] in Table 2 we can conclude that the intrinsic extinction parameter $E(B-V)$ increases with metallicity. This relation is predicted by Deharveng et al. (1985), although they do not find this result in their data. Indeed, it seems reasonable that higher metallicities imply higher amounts of dust and, thus, higher extinction (Lequeux 1988).

Once the Lyα line ratio is dereddened according to the above criteria, the absolute value of the ratio is, within the uncertainties, in the expected range for the nebular emission ($[{\rm Ly}\alpha/{\rm H}\beta]_{\rm theor} = 23-34$, increasing from low to high electron densities; Ferland & Osterbrock 1985), and not 20–30 times smaller as previously found (see Hartmann et al. 1984 for Mrk 496 and Mrk 357). The mean values of Lyα/Hβ lie in the range 0.3–0.8 times the theoretical expectation. However, the Lyα emission has not been corrected for the underlying stellar absorption, which would contribute with an EW of ∼10 Å (Sunyaev, Tinsley, & Meier 1978). With such a correction, the disagreement is marginal and the line ratios in the three galaxies are consistent with case B recombination.

3.2. *The* Lyα/Hβ *Ratio*

The anticorrelation of the Lyα/Hβ ratio with metallicity reported for a sample of 13 objects by Hartmann et al. (1988) is not confirmed by the dereddened Lyα/Hβ ratios in our three galaxies, which span a relatively large range in metallicity. However, the anticorrelation of the *observed* (undereddened) Lyα/Hβ with metallicity is perfectly evident from our data (col. [5] of Table 2) and it can be mostly attributed to dust extinction rather than mutiple scattering. In addition, the decrease in Lyα/Hβ with decreasing metallicity seen in column (6) of Table 2 when dereddening with the Galactic extinction law is probably artificial and can likely be attributed to the fact that the Galactic extinction law is not appropriate for metal-poor galaxies. Indeed, comparing the dereddened values of Lyα/Hβ derived by using extinction curves suitable for the metallicity of the galaxies, the trend of decreasing Lyα/Hβ for decreasing metallicity disappears.

Although the small values of the observed Lyα/Hβ ratios can be mostly attributed to extinction, the presence of absorption of multiply scattered Lyα photons by dust is expected, since the three galaxies have enough H I (see Table 2) to drastically increase the path length of the Lyα photons through dust regions. Indeed, the large uncertainties on the dereddened Lyα/Hβ value allows the presence of dust absorption by multiple scattering. However, this is not at the expected level. The measured H I column densities (see Table 2) imply a mean Lyα optical depth of $\approx 10^7$–10^8 and, for a uniform slab of gas with a dust opacity $\sim$0.1–1 the galactic value, a fraction of escaping Lyα photons $\lesssim 10^{-5}$ (see Fig. 18 in Neufeld 1990). This result must be compared with the values of $(2\text{–}8) \times 10^{-2}$ of the observed Lyα/Hβ obtained for our three galaxies. A possible explanation for the low amount of absorption of Lyα by dust in this case may be the particular geometric distribution of gas and dust, so that an approximation assuming a uniform slab geometry is probably an oversimplification.

3.3. *Comparison with Primeval Galaxies*

From the dereddened optical line of Hα we can estimate the present SFR in the galaxies (Kennicutt 1983, 1992), while the optical blue luminosity L_B gives a measure of the steady state SFR in the past $\sim 10^9$ yr (Gallagher, Hunter, & Tutukov 1984). The comparison between the two numbers gives an estimate of the variations in the SFR in the last billion years, and an estimate of the strength of the present burst. From Table 2, it is clear that Tol 1924−416 is experiencing a mild burst of star formation, because its present SFR is only a factor of 2 above the average over the last billion of years. Conversely, the two Markarian galaxies are undergoing a strong burst of star formation ($SFR_{pres} \simeq 10\ SFR_{av}$), also confirmed by the fact that at the present level of gas depletion, they would consume their total H I content in less than 10^9 yr.

If the two Markarian galaxies or Tol 1924−416 are representative of PGs is not clear. From the above results, Mrk 496 and Mrk 357 have large H I content and are experiencing an intense burst of star formation. Nevertheless, the metal content of the two galaxies reveals that they are quite evolved, so the Lyα fluxes and equivalent widths can be easily affected by strong underlying stellar absorption (Valls-Gabaud 1992). Tol 1924−416 meets the requirement of low metallicity, low dust content, and relatively large Lyα equivalent width [EW(Lyα) $\sim$ 22] better than the other two, although the burst it is experiencing is not very strong. Any attempt to draw conclusions about PGs from these three examples of blue galaxies must account for the similarities as well as the dissimilarities. A larger, more statistically significative sample is necessary to form a reasonable comparison.

4. CONCLUSIONS

The dereddening of the Lyα/Hβ ratio is problematic since many processes contribute to the emission line fluxes: inhomogeneity of the dust and gas distribution within the galaxy, choice of the extinction law (probably dependent on the metallicity of the galaxy), enhanced absorption due to multiple scattering in the case of Lyα, different optical depths of the emitting regions for different wavelengths, albedo, etc. Although all these various effects are difficult to model, it is possible to take into account at least the first two by (1) performing the observations in different wavelength regions using apertures of similar sizes; (2) applying an extinction correction appropriate to the metallicity content of the galaxy.

By simply applying the two criteria above, we have seen that the three galaxies analyzed in this *Letter* show a dereddened average Lyα/Hβ ratio, which is $\sim$6–20 times higher than previously determined (Hartmann et al. 1984). If the underlying stellar Lyα absorption is also taken into account, the Lyα/Hβ ratio is consistent, within the uncertainties, with the theoretical value expected for nebular emission in case B recombination. However, the uncertainties are large enough to allow the presence of absorption of multiply scattered photons, although *not* at the expected level.

This result has interesting consequences for the problem of strategies for the search of PGs (see Djorgovski 1992; Djorgovski & Thompson 1992), since the conclusions reached for the three cases studied here can be tentatively extrapolated to PGs, which possibly can be represented as metal-poor, low dust content, starbursting galaxies. In fact, the large values for dereddened Lyα/Hβ ratios found here, together with the fact that PGs should have less dust and less underlying stellar absorption than our three galaxies, suggest that the search for PGs using the Lyα emission is more reasonable than predicted by previous works (see, e.g., Hartmann et al. 1988).

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