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HST study of Lyman-alpha emission in star-forming galaxies: the effect of neutral gas flows*

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Abstract. We present high dispersion HST GHRS UV spectroscopic observations of 8 H II galaxies covering a wide range of metallicities and physical properties. We have found Lyα emission in 4 galaxies with blueshifted absorption features, leading to P Cygni like profiles in 3 of them. In all these objects the O I and Si II absorption lines are also blueshifted with respect to the ionized gas, indicating that the neutral gas is outflowing in these galaxies with velocities up to 200 km s^{-1} or more. The rest of the sample shows broad damped Lyα absorption profiles centered at the wavelength corresponding to the redshift of the H II emitting gas. We therefore find that the velocity structure of the neutral gas in these galaxies is the driving factor that determines the detectability of Lyα in emission. Relatively small column densities of neutral gas with even very small dust content would destroy the Lyα emission if this gas is static with respect to the ionized region where Lyα photons originate. The situation changes dramatically when most of the neutral gas is velocity-shifted with respect to the ionized regions because resonant scattering by neutral hydrogen will be most efficient at wavelengths shorter than the Lyα emission, allowing the Lyα photons to escape (at least partially). This mechanism complements the effect of porosity in the neutral interstellar medium discussed by other authors, which allows to explain the escape of Lyα photons in regions surrounded by static neutral gas, but with only partial covering factors. The anisotropy of these gas flows and their dependence on the intrinsic properties of the violent star-forming episodes taking place in these objects (age, strength, gas geometry,...) might explain (in part) the apparent lack of correlation between other properties (like metallicity) and the frequency of occurence and strength of Lyα emission in star-forming galaxies. Attempts to derive the comoving star-formation rate at high redshifts from Lyα emission searches are highly questionable.

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1. Introduction

The detection of galaxies at large redshifts that are forming stars for the first time, the so-called primeval galaxies, remains a very important astrophysical challenge. Bearing in mind that galaxy formation may not be assigned to any preferential cosmological epoch but instead is probably a continuous process, one might find left-over pristine gas pockets that are forming young galaxies at the present epoch. For this reason there may be star-forming galaxies in our local universe that look very much like distant primeval ones. Hopes have been that Lyα emission could be a signature of star formation that would be recognized up to very large redshifts; hence there have been numerous studies of the Lyα emission from distant and local starbursts. Early IUE observations were performed on more than a dozen nearby starburst galaxies in its SWP low resolution mode (Meier & Terlevich 1981; Hartmann et al. 1984; Deharveng et al. 1986; Hartmann et al. 1988 and Terlevich et al. 1993). Galaxies with redshifts large enough that their Lyα emission is separated from the geocoronal line were selected. It was realized from the very beginning that the Lyα/Hβ ratio and the Lyα equivalent width are much smaller, by at least an order of magnitude, than expected from the recombination theory. These early works have also shown a possible anticorrelation between the Lyα/Hβ ratio and the H II galaxy metallicity (actually the O/H abundance, as measured in the ionized gas).

These results, the lack of "primeval galaxies" at large redshift in blank sky searches for redshifted Lyα emission and the few tentative detections of Lyα emission from the damped Lyα systems have been attributed to the effects of dust absorption that preferentially destroys Lyα photons (Charlot & Fall 1993, and references therein). The process behind this is that the transfer of Lyα radiation is strongly affected by resonant scattering from

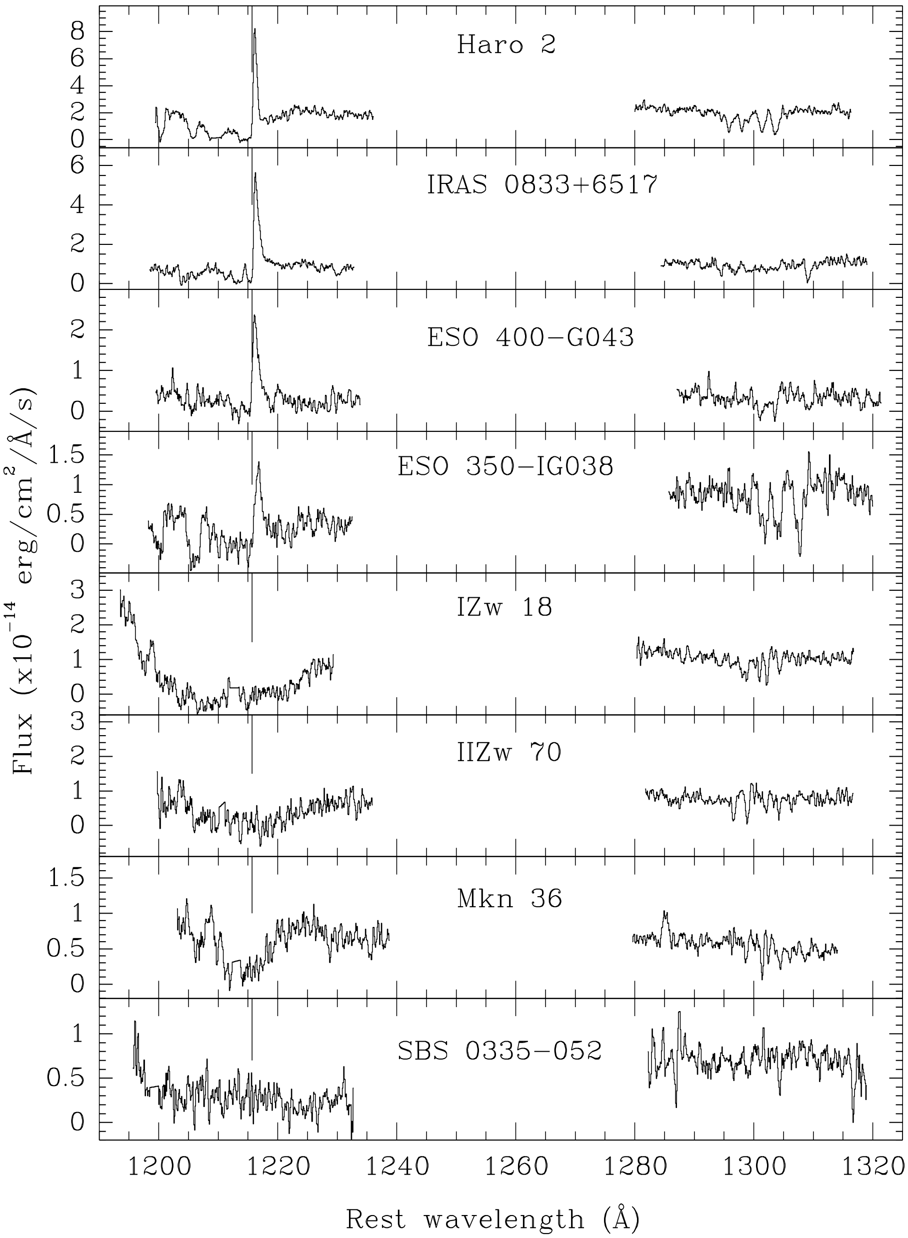

Fig. 1. GHRS spectra of all the galaxies in the sample. The spectra have been shifted to rest velocity assuming the redshift derived from optical emission lines. Vertical bars indicate the wavelength at which the Lyα emission line should be located. The geocoronal emission profile has been truncated for the sake of clarity. The spectra have been plotted after rebinning to 0.1 Å per pixel and smoothed by a 3 pixel box filter.

neutral interstellar hydrogen atoms. By increasing enormously their optical path length, Lyα photons become more vulnerable to dust absorption, even in small amounts (Neufeld 1991; Charlot & Fall 1991; Chen & Neufeld 1994). This process was believed (even in the early paper of Meier & Terlevich 1981) to account for the anticorrelation between the Lyα emission line visibility and the dust abundance in these galaxies, as parameterized by the metallicity. Alternatively such an anticorrelation has been attributed to a metallicity-dependent extinction law at the wavelength of Lyα (Calzetti & Kinney 1992, Valls-Gabaud 1993). However this conclusion seems very unlikely in view of the anticorrelation between the Lyα equivalent width and the gas-phase abundance of oxygen O/H. Charlot & Fall (1993) have emphasized the advantages of using the Lyα equivalent widths rather than the Lyα/Hβ ratios, because the former do not depend on the extinction curve of the dust and can be measured with a single observational device. Their discussion of the anticorrelation between the Lyα line equivalent widths and the O/H abundances in a sample of nearby star-forming galaxies has examined several factors that will affect the observed Lyα emission from galaxies, among which contributions from supernova remnants and active galactic nuclei, the orientation of the galaxy and the absorption by dust. They finally suggest that the structure of the interstellar medium (porosity and multi-phase structure of the medium) is most probably the dominant one.

Our new HST observations indicate that velocity structure in the interstellar medium plays a key role in the transfer and escape of Lyα photons. At first place, Lyα was observed only in absorption in the starburst dwarf galaxy IZw 18 by Kunth et al. (1994). Since IZw 18 at $Z = 1/50\ Z_{\odot}$ is the most metal-poor starburst galaxy known at present, it was considered previously

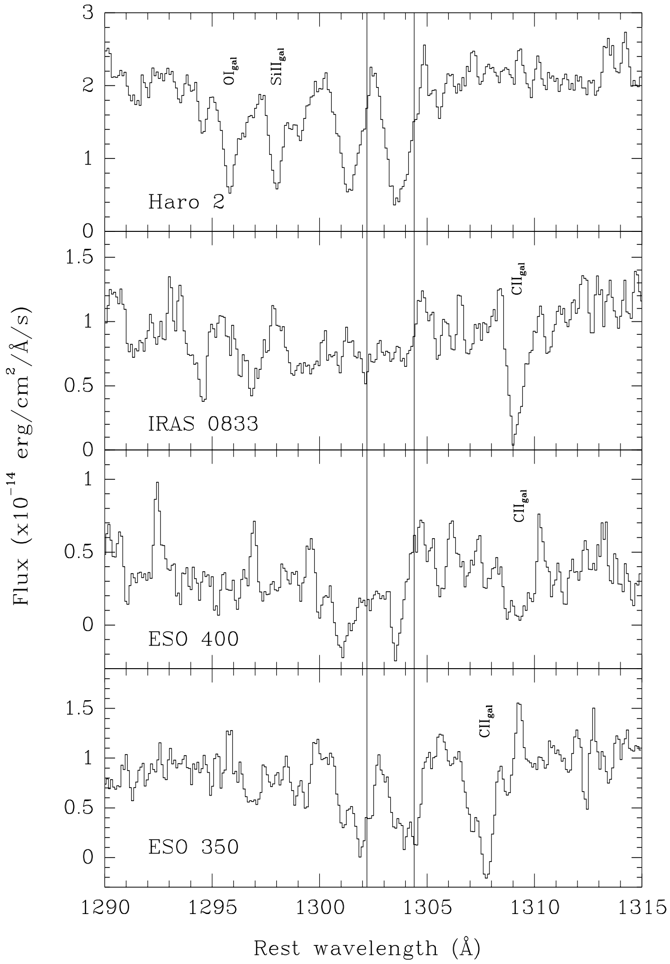

Fig. 2. Detail on the O I and Si II region for the galaxies showing Lyα emission. The vertical bars indicate the wavelength at which the O I and Si II absorption lines should be located, according to the redshift derived from optical emission lines. Some Galactic absorption lines have been marked. Note that the metallic lines appear systematically blueshifted in these galaxies with respect to the systemic velocity. In some cases there is no significant absorption at all at zero velocity.

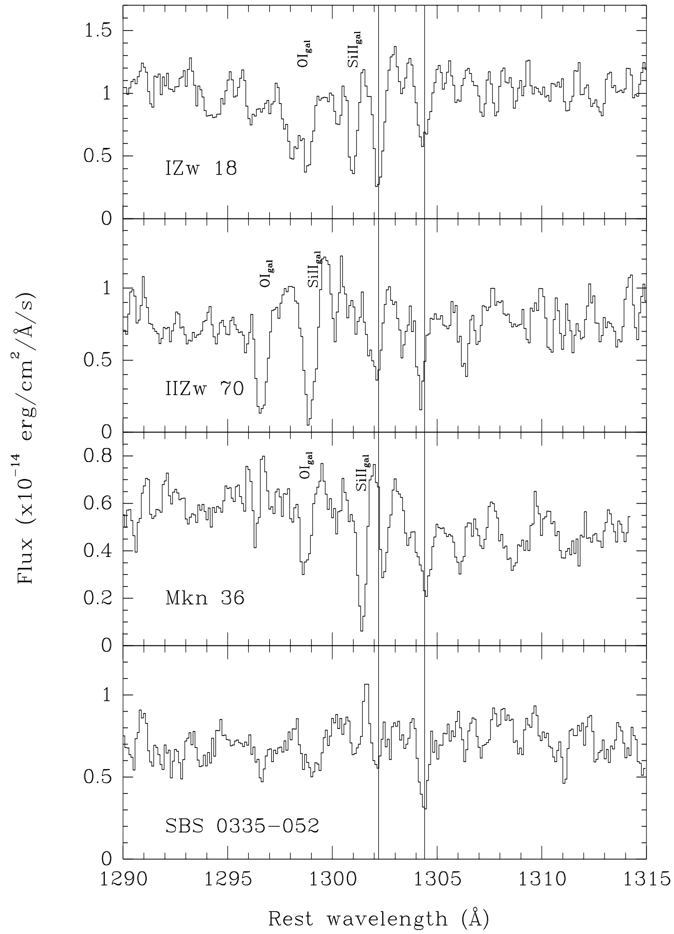

Fig. 3. O I and Si II region for the galaxies showing damped Lyα absorptions. Details as in Fig. 2. Note that in these galaxies the metallic lines are essentially at the same redshift than the ionized gas, indicating the presence of static clouds of neutral gas, as discussed in the text.

Table 1. Adopted properties of observed H II galaxies. Systemic velocities have been taken from the NASA Extragalactic Database, except for Haro 2 (Legrand et al. 1997).

Galaxies	m(V or B)	v(km s^{-1})	12+log(O/H)	E(B-V)
ESO 350-IG038	14.27V	6156	??	0.16
SBS0335-052	16.65V	4043	7.36	0.18
IRAS 08339+6517	14.16V	5730	??	0.55
IZw 18	15.6B	740	7.17	<0.10
Haro 2	13.4V	1465	8.40	0.12
Mkn 36	15.5V	646	7.86	<0.10
IIZw 70	14.83V	1215	8.33	0.15
ESO 400-G043	14.22B	5900	8.0	0.20

a good candidate to show Lyα in emission. To add to the confusion, a Lyα emission line showing a complicated profile, but a clear P Cygni component, has been detected in Haro 2, a rather dusty star-forming galaxy at $Z = 1/3\,Z_{\odot}$ (Lequeux et al. 1995). Giavalisco et al. (1996) have strengthened the suggestion that the transport of the Lyα photons is primarily controlled by the ISM geometry rather than by the amount of dust, so that the Lyα emission line would be detected only if there are holes (regions with low column density of neutral gas) along the line of sight, a factor which in principle is independent on dust and metal content of the gas. As we show hereafter, other factors can be more important in accounting for variations in the Lyα emission strength, at least in some cases. The detection of a P Cygni profile in the Lyα emission line of Haro 2 led us to postulate that the line was visible because the absorbing neutral gas was velocity-shifted with respect to the ionized gas. This was confirmed by the analysis of the UV O I and Si II absorption lines, which were blue-shifted by 200 km s^{-1} with respect to the optical emission lines, and also of the profile of the Hα line (Legrand et al. 1997).

These new facts and the capability of the HST to analyze in detail for the first time Lyα line profiles in nearby galaxies led us to embark on a longer-term project using the GHRS to study the processes controlling the detectability of the Lyα emission line in star-forming galaxies. These studies also aim at the measurement of abundances in the neutral gas of gas-rich dwarf galaxies with spectra dominated by recent star formation episodes. Indeed, in objects such as these, the H I clouds largely extend beyond the optical images suggesting that a substantial fraction of this gas might still be chemically unevolved or even pristine (Roy & Kunth 1995). At a spectral resolution of 20 000 it became possible to disentangle nebular from stellar absorption lines and to give crude estimates of the metal abundances in the interstellar medium. The study of the IZw 18 data by Kunth et al. (1994) and the preliminary analysis of the rest of the sample (Kunth et al. 1997) have yielded extremely low values of the O I/H I ratios (log N(O I)/N(H I) $<$ -7) in some galaxies of the sample. The complete analysis of the interstellar abundances will be presented in a forthcoming paper.

In Sect. 2 we present new HST data on a sample of 8 H II galaxies. Spectra are described in Sect. 3 and the results are discussed in Sect. 4. The conclusions are finally summarized in Sect. 5.

2. The HST observations

Eight galaxies have been observed so far, and their properties are listed in Table 1. They were selected by the following procedure:

- The H II galaxies IZw 18, Mkn 36, IIZw 70 and Haro 2 were first chosen (Cycle 1 and Cycle 4) because they span a wide range of metallicity. The original aim was to investigate a possible relationship between the composition of their H II regions and that of the H I gas using the O I and Si II lines.
- Results obtained with IZw 18 and Haro 2 prompted us to investigate the Lyα emission profiles per se. Therefore three starburst galaxies were selected in the IUE-ULDA from the a-priori knowledge that they were Lyα emitters; they include: IRAS 08339+651, ESO 350-IG038 and ESO 400-G043. Their redshifts are necessarily larger than those of the above galaxies because their Lyα emission on IUE spectra had to be separated from the geocoronal line.
- In addition the SBS 0335-052 spectra, observed by Thuan et al. (1997) with the same setup, were retrieved from the HST archives.

Observations were made using the same settings as in Kunth et al. (1994) and Lequeux et al. (1995) using the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST). The journal of observations is given in Table 2. The Large Science Aperture (LSA) ($2''.0\times 2''.0$) was chosen to ensure a sufficient flux level. The grating angle was selected according to the redshift of the objects, so as to cover the Lyα and the O I 1302.2 Å and Si II 1304.4 Å regions respectively. The spectral resolution achieved with this setup at around 1300 Å is close to 0.08 Å. The Lyα range was chosen to investigate both emission and absorption features so that the H I column density could be estimated. The O I 1302 Å and Si II 1304 Å region was selected to crudely estimate the chemical composition of the gas and to measure with reasonable accuracy the mean velocity at which the absorbing material lies with respect to the star-forming region of a given galaxy. The spectrum and internal background were moved on the diode array by steps of one fourth of a diode (GHRS substep pattern 5). In most cases, the photocathode granularity was averaged out using the GHRS FP-SPLIT = 4 procedure breaking each exposure into four parts between which the grating is moved by about 5 diodes. We have subsequently extracted those scans to align and combine them using the standard STSDAS software and form final spectra with four samples per diode. Wavelength calibrations were achieved using the platinum-neon lamp onboard the spacecraft resulting in an expected accuracy of the wavelength scale of about 0.08 Å. However after correcting from heliocentric orbital motion of the earth, we noticed on the IZw 18 spectrum a systematic shift of about 0.24 Å between tabulated vacuum wavelengths and measured ones. We thus have applied a further shift so as to match the geocoronal Lyα line and the observed O I and Si II lines originating from Galactic clouds. We later were informed that the reduction package had introduced a wrong sign to the heliocentric correction. The centroid of the Galactic H I profile in the direction of Haro 2 is at -27.5 km s^{-1} LSR, or -23.3 km s^{-1} heliocentric (Hartmann & Burton 1995). Therefore we have checked the scale on the Galactic O I 1302 Å and Si II 1304.4 Å absorption lines, for which we measured heliocentric radial velocities of -27 and -23 km s^{-1} respectively. Similar checks with Galactic lines have been performed with the other galaxies in the sample. Thus the wavelength scale we used should be correct to a few km s^{-1}.

3. Description of individual spectra

The individual spectra of all the galaxies in our sample are shown in Fig. 1.

3.1. Galaxies with damped Lyα absorption

- IZw 18: The HST spectrum shows a damped Lyα absorption with no sign of emission at the redshift of the galaxy (740 km s^{-1}). This absorption is a blend of the intrinsic IZw 18 and the Galactic components. A multi-component fit yields an H I column density in front of the northwest (NW) emission patch of log N(H I) = 21.06 cm^{-2}, with a Galactic component of log N(H I) = 20.3 cm^{-2}. The multi-component fit requires a third contribution blueshifted with respect to the Galactic absorption. This component seems to be an observational artifact due to the poor signal to noise in the region. Absorption lines due to O I λ1302 Å and Si II λ1304 Å were also detected at the redshift of the NW H II region. Unfortunately the O I line is saturated casting some doubts on any attempts to derive a reliable O/H abundance for the H I region (see discussion). O I and Si II absorptions at a velocity of -160 km s^{-1} due to a Galactic high velocity cloud (No. 117 of Hulsbosch & Wakker 1988) were detected indicating that the high velocity clouds are not composed of primordial material.
- Mkn 36: A broad Lyα is observed in absorption. The observed profile can be reproduced by assuming two compo-

Table 2. Journal of observations. All spectra obtained through the GHRS Large Science Aperture, using the G160M grating, and a 5-fold substep pattern.

Name	Slit position (2000) RA	Dec	Mode	Date	λ-range (Å)	Exposure time (s)
ESO 350-IG038	00 36 52.3	-33 33 18.2	FP-SPLIT = NO	16/01/96	1222 - 1258	7018
				16/01/96	1312 - 1347	4678
SBS 0335-052	03 37 44.0	-05 02 39.0	FP-SPLIT = DS 4	03/01/95	1211 - 1247	7181
				04/01/95	1299 - 1335	7181
IRAS 08339+6517	08 38 23.2	65 07 15.0	FP-SPLIT = NO	24/02/96	1221 - 1257	7997
				25/02/96	1309 - 1344	4787
IZw 18	09 34 02.0	55 14 27.4	FP-SPLIT = DS 4	23/04/92	1195 - 1231	9216
				22/04/92	1283 - 1319	10137
Haro 2	10 32 31.8	54 24 03.5	FP-SPLIT = 4	29/04/94	1205 - 1241	7181
				30/04/94	1286 - 1321	5222
Mkn 36	11 04 58.4	29 08 15.2	FP-SPLIT = 4	19/04/95	1205 - 1241	5984
				20/04/95	1281 - 1317	5984
IIZw 70	14 50 56.5	35 34 17.8	FP-SPLIT = 4	08/04/95	1204 - 1240	3590
				08/04/95	1286 - 1321	7181
ESO 400-G043	20 37 41.9	-35 29 06.4	FP-SPLIT = NO	16/04/96	1221 - 1258	7181
				16/04/96	1312 - 1347	4787

nents: one is due to neutral gas in Mkn 36 with H I column density of log N(H I) = 20.07 cm^{-2} and the second is a Galactic component with log N(H I) = 19.7. The O I region clearly shows O I and Si II absorptions that are in good agreement with the systemic velocity of the galaxy. An unidentified emission line or glitch is seen at 1287.92 Å. We note that the standard photometric calibration of the Lyα region spectrum had to be corrected by an offset of +2.5$\cdot 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}, apparently due to poor background subtraction.

- IIZw 70: From the damped Lyα absorption line we derive log N(H I) = 20.8 cm^{-2}, together with a Galactic component with log N(H I) = 19.3 cm^{-2}. Both the Galactic and the intrinsic O I and Si II lines are well detected, with the later at the systemic velocity of the galaxy. We had to offset the Lyα region spectrum as well by -5.0$\cdot 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1} in order to have the core of the absorption profile at zero level.
- SBS 0335-052: The GHRS spectrum of this galaxy has been discussed by Thuan et al. (1997). A broad absorption is observed but the intensity of the central part of the Lyα profile does not go to zero. Thuan et al. (1997a) attribute this broad residual emission to resonant scattering of the Lyman photons that would be re-directed into the line of sight. We disagree with this interpretation for the following reason: we noticed that the continuum level is weak (i.e. $< 2.0\cdot 10^{-15}$ erg s^{-1} cm^{-2} Å^{-1}) hence the GHRS extraction procedure corrects for an instrumental background level that is a least 10 times higher than the signal. The signal on this object being the lowest of the sample, the result is consequently very sensitive to this difficult subtraction and we suspect the Lyα region to be spoiled by the extraction procedure. Similar effects have been discussed above for Mkn 36 (zero level below zero) and IIZw 70 (zero level above zero), on profiles which otherwise are very well reproduced by theoretical ones. In this respect it is interesting to note that the blue wing of the line, which should be dominated by the Galactic absorption profile, does not reach the zero level either, although the H I column density along this line of sight is around log N(H I) = 20.68 cm^{-2} (Dickey & Lockman 1990). This supports our interpretation about an instrumental artifact due to low signal to noise ratio. A more recent lower resolution GHRS spectrum obtained by Thuan & Izotov (1997) shows indeed no significant contamination at the core of the absorption line.
In any case, the red wing of the profile can be extended using the available IUE spectrum. By combining both spectra, we have fitted the whole profile up to 1300 Å, obtaining log N(H I) = 21.5 (± 0.2) cm^{-2}, as shown in Fig. 4. Thuan & Izotov (1997) obtain log N(H I) = 21.8 cm^{-2} from their lower resolution spectra.Weak O I at 1319.66 Å (v = 4041 km s^{-1}) and Si II at 1321.94 Å are also detected.

3.2. *Galaxies with Lyα emission*

- Haro 2: For a full discussion of this GHRS spectrum we refer the reader to Lequeux et al. (1995). The spectrum around Lyα is complex. We find a deep absorption line at the blue edge, below 1207 Å that is probably the redshifted NI triplet (1199.6 - 1200.7 Å) from the interstellar medium in front of the H II region of Haro 2. A deep, broad line at 1211.7 Å is the Si III line at 1206.51 Å from Haro 2, probably interstellar and redshifted by 1260 km s^{-1} (heliocentric). Some Galactic Lyα interstellar absorption is detected at zero velocity, with log N(H I) = 19.9 cm^{-2}. A broad absorption around 1221 Å, produced by the gas in front of the star cluster of Haro 2, is attributed to Lyα absorption. A strong asymmetric emission line around 1222.1 Å is Ly α red-

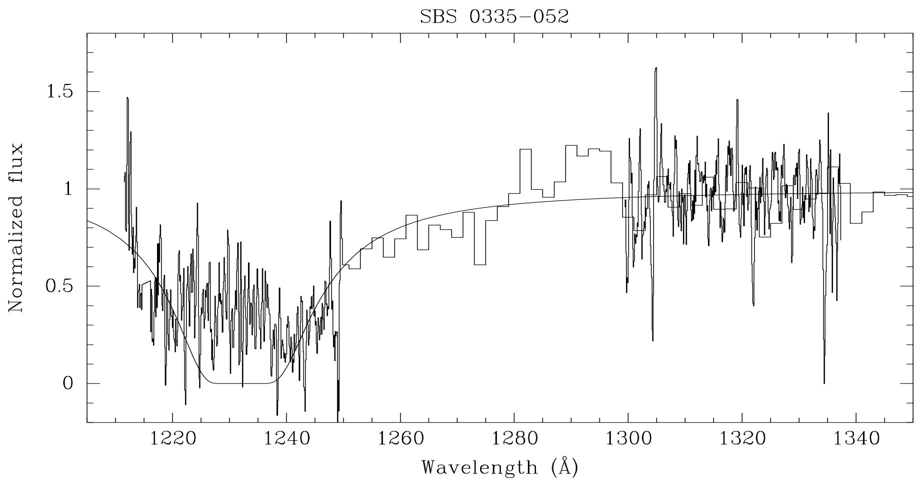

Fig. 4. IUE spectrum of SBS 0035-052 superposed on the GHRS one. Although the GHRS Lyα absorption profile is very noisy, its red wing extends clearly into the IUE range. The Lyα absorption profile fitted to this red wing is also shown.

shifted by 1580 km s^{-1}. The existence of this line came as a surprise. The spectrum around 1305 Å shows several absorption lines. Most of the fainter absorption lines are presumably produced in the stars of Haro 2. The four strong lines are the Galactic interstellar lines of O I at 1302.2 Å and Si II at 1304.4 Å, and the same lines from Haro 2 redshifted by about 1260 km s^{-1}. Hence the heliocentric velocities of the absorption lines are about 200 km s^{-1} lower than the velocity of the H II region as measured from the Hα emission (Legrand et al. 1997). Lequeux et al. (1995) interpreted these profiles as being produced by a neutral (partially ionized) medium outflowing from the central star cluster at a projected velocity around 200 km s^{-1}, as we will discuss later.

– IRAS 0833+6517: This galaxy has a redshift of 5730 km s^{-1}. The Lyα emission measured at 1339.5 Å (flux of 5.6 $\cdot 10^{-14}$ erg s^{-1} cm^{-2} and EW of 34 Å) is narrow and exhibits a clear P Cygni profile. Remarkable enough is a clear secondary emission situated at 1237.76 Å (at -200 km s^{-1} from the main line component). The intensity of this secondary peak is 10 times smaller than that of the main component (with $5 \cdot 10^{-14}$ erg s^{-1} cm^{-2}). The absorption component extents over 1500 km s^{-1} on the blue side of the line emission. The presence of a secondary emission peak reveals the chaotic structure of the interstellar medium in this case. Unfortunately no O I and/or Si II absorption is detected that could provide more detailed information about the kinematics of the absorbing gas.

– ESO-B400-G043: This galaxy is at a redshift of 5900 km s^{-1}. An asymmetric Lyα emission is measured at 1339.5 Å with a flux of $3.1 \cdot 10^{-14}$ erg s^{-1} cm^{-2} and EW of 20 Å, showing a P Cygni shape. Metallic lines are blueshifted by around -225 km s^{-1}, with the O I line at 1326.68 Å (-252 km s^{-1}) and the Si II at 1329.18 Å (-194 km s^{-1}). The absorption profile is best fitted assuming an absorption with log N(H I) of 19.7 cm^{-2}, slightly shifted with respect to the metallic lines by -70 km s^{-1}. There might be an additional secondary emission peak at around -300 km s^{-1}, with a flux of $1.1 \cdot 10^{-15}$ erg s^{-1} cm^{-2}, but the low signal to noise of this spectrum does not allow us to make any firm conclusion.

– ESO 350-IG038: This galaxy has a redshift of 6156 km s^{-1}. At this redshift the O I region falls close to the C II 1334 Å Galactic line which can be used as a reference for the wavelength scale. We find indeed that the O I 1302.2 Å and Si II 1304.4 Å lines are at 1328.63 Å and 1330.89 Å respectively, corresponding to a mean velocity of 6097 km s^{-1} or -58 km s^{-1} from the recession velocity of the ionized regions. In fact both interstellar lines are very broad, indicative of multicomponents on the line of sight spanning roughly 200 km s^{-1} in velocity range. A careful inspection of the underlying Lyα absorption shows that it extends over more than 1500 km s^{-1} to the blue side of the emission. The Lyα emission peaks at 1241.79 Å (its flux is $1.8 \cdot 10^{-14}$ erg s^{-1} cm^{-2} and EW is 37 Å) but does not exhibit a clear P Cygni profile. On the contrary, the blue wing of the line does not sharply drop at zero velocity and moreover the underlying absorption extends beyond to the red. This agrees with the finding that the metallic lines are shift by -58 km s^{-1} with respect to Lyα but extend to 100 km s^{-1} on both sides. The Lyα absorption is best with three components at -26, -197 and -330 km s^{-1} and log N(H I) of 18.81, 19.93 and 20.26 cm^{-2}, respectively. The gas coverage is contributed therefore by numerous components.

We have fitted all absorption profiles interactively by using the Xvoigt code (Xvoigt, Copyright 1994, David Mar). In case of damped Lyα lines blended with the Galactic line, special weight has been given to the red wing. On the other hand, when there is an emission feature on the red, the blue side of the profile and its terminal velocity have allowed to determine precisely the required H I column density. In most cases the Lyα fitting procedure is insensitive to the b value due to the strong saturation of the profile, so that only upper limits have been estimated. The line measurements are listed in Table 3 (metallic lines) and Table 4 (Lyα line). We have also included the absorption lines attributed to Galactic clouds. We have checked that the centroid of the Galactic 21 cm line is in good agreement with the velocity derived from these lines, supporting our velocity calibration. In

Table 3. Measured values for the metallic absorption lines. For each object the first line gives the centroid wavelength of the different lines. The second line gives the systemic velocity, measured from the optical emission lines, and the corresponding mean velocity offset of the metallic lines δv. All wavelengths are given in Angströms and all velocities in km s^{-1}.

Name v(H II) km s^{-1}	O I 1302 v(O I)	Si II 1304 v(Si II)	 δv	Galactic O I	Galactic Si II	Galactic C II
ESO 350-IG038	1328.63	1330.89		-	-	1334.46
6156±31	6096.0	6099.0	-58			
SBS 0335-052	1319.7	nd		-	1304.29	-
4043±10	4030.0	-	-13			
IRAS 08339+6517	nd	nd		-	-	1334.15
5730±80	-	-	-			
IZw 18	1305.3	1307.45		1301.88	1304.06	-
740±5	721.4	708.3	-25			
Haro 2	1307.76	1310.02		1302.15	1304.34	-
1465±10	1288.2	1299.4	-171			
Mkn 36	1305.3	1307.25		1301.50	1304.20	-
646±5	714.5	662.3	+40			
IIZw 70	1307.3	1309.5		1301.88	1304.17	-
1215±23	1182.2	1184.4	-32			
ESO 400-G043	1326.7	1329.2		-	-	1334.97
5900±8	5647.0	5706.0	-225			

Table 4 we have included the measured logN(H I) as well as the flux of the emission component and its peak wavelength, if any. In Fig. 5 we show the Lyα region at rest wavelength with the fitted H I absorption profiles superposed to the observed spectra.

4. Interpretation

Lyα photons are produced by recombinations in H II regions at about 2/3 of the ionization rate (the exact yield depends weakly on the density and temperature of the gas). They are subsequently absorbed and reemitted by H atoms, both in the H II regions in which they were produced and in the surrounding H I regions, if present. This process - resonant scattering - changes both the frequency and direction of the Lyα photons but not their produced within a galaxy would eventually escape from it, in one direction or another. This scattering process increases enormously the mean free path of the trapped photons, so that if some dust is present, the probability of absorption around the Lyα wavelength increases also by a significant factor with respect to the standard UV extinction. As a consequence, absorption is potentially important whenever the dust-to-gas ratio exceeds about one percent of the Galactic value (see, e.g., Eq. (3) of Charlot & Fall 1993).

If the neutral gas surrounding the star-forming regions is not static with respect to the ionized gas, but is outflowing from these regions towards the observer, the resonant scattering would affect photons at shorter wavelengths than the Lyα emission line, i.e., the photons resonantly trapped, and potentially destroyed by dust, would be mostly stellar continuum photons emitted at wavelengths below 1216 Å. For a galaxy in which the source of ionizing radiation is a stellar population with a normal initial mass function, the angle-averaged equivalent width of the Lyα emission line is about 100 Å in the dust-free case (Charlot & Fall 1993). This depends only weakly on the star formation rate in the galaxy provided it is reasonably continuous (and nonzero over the past few $\times 10^7$ yr). This value can be somewhat higher if instead the star formation episode is "instantaneous", i.e. lasts less than a few $\times 10^6$ yr, as it seems to be the case in most compact star-forming galaxies. Nevertheless, since the Lyα photons would diffuse (in the dust-free case) through the external surface of the neutral clouds (which are rather large in these compact star-forming galaxies, extending far beyond the optical regions), its surface brightness would be very small. Therefore, even in a dust-free case, we would expect to detect an absorption line around the Lyα wavelength if the aperture sustended by the slit is small compared to the spatial extension of the neutral cloud. This absorption will be centered at the wavelength corresponding to the mean velocity of this neutral gas, i.e., it will be blueshifted with respect to the Lyα emission line if the neutral gas is moving towards the observer.

This scenario allows to explain in a natural way most of the observational properties in our sample. Among the eight galaxies observed with the GHRS four show no Lyα emission at all. Instead, a strong damped Lyα absorption at the systemic ve-

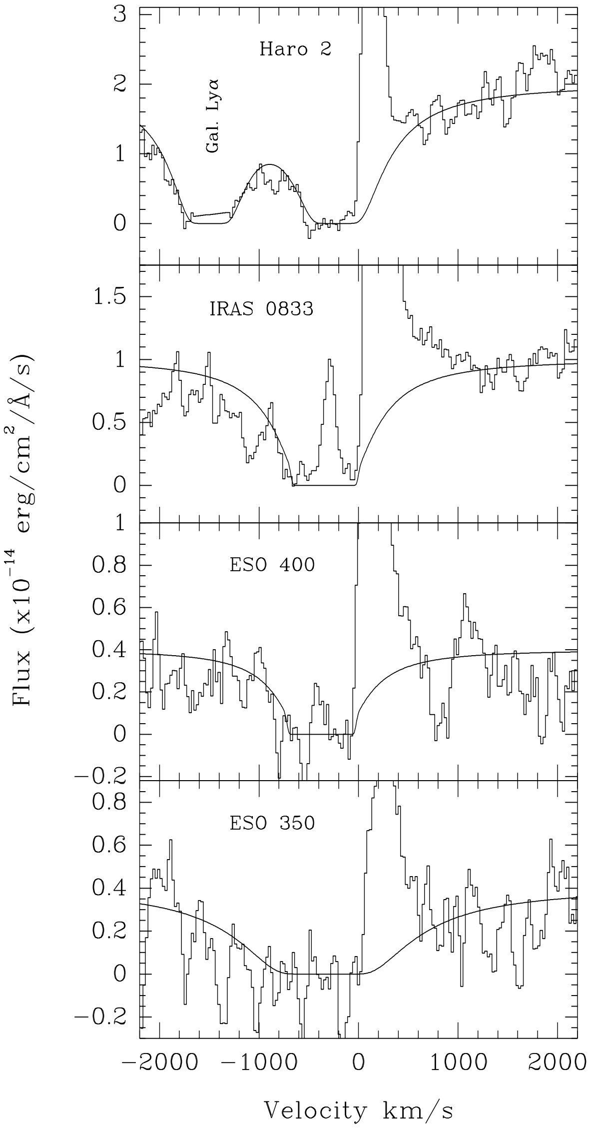

Fig. 5. Lyα line profiles plotted in velocity scale. The zero point corresponds to the systemic velocity as derived from the optical emission lines. The Galactic Lyα absorption profile has been also included in Haro 2. The geocoronal Lyα profile has been truncated in this case. The sharp edge on the blue side of the emission profile is evident in most cases. Note the secondary Lyα emission peak in IRAS 0833+6517, and possibly also in ESO 400-G043.

locity (as derived from the optical emission lines) is observed with O I and Si II appearing in absorption. We can infer from Table 3 and from the above description that these lines occur without any significant velocity shift with respect to the H II regions. This indicates that the neutral gas in which they mostly originate is static with respect to the star-forming region. Therefore, since these galaxies have a low dust content (see Table 1; IZw 18 shows weak signs of reddening and its dust-to-gas ratio is at least 50 times smaller than the Galactic value - Kunth et al. 1994), this suggests that it remains possible to observationally weaken Lyα by simple multiple resonant scattering from the neutral gas, and even to produce an absorption feature. If this is the case, the H I cloud surrounding these galaxies should be leaking Lyα photons through its external surface. The Lyα line would then become very hard to detect because of its low surface brightness. This extended emission could be detected with deep, large area observations around these galaxies. Nevertheless, it might be that even the small amounts of dust present in these galaxies is enough to efficiently destroy a significant fraction of Lyα photons, especially if the clouds extension is very large. In fact this may be the most inescapable explanation from the lack of extended Lyα emission seen at large redshift in blank searches, since high-z galaxies are expected to have much smaller angular size.

On the other hand, the Lyα emission in Haro 2 is accompanied by a broad absorption in the blue wing of that line, with the general appearance of a typical P Cygni profile. The amount of neutral gas that produces the blue absorption trough at Lyα is rather modest and of the order of N (H I) = $7.7{\cdot}10^{19}$ atom cm^{-2}. The crucial point here is that the neutral gas responsible for the absorption in this galaxy is not at the velocity at which the Lyα photons were emitted. Moreover, it seems that all the neutral gas along the line of sight is being pushed by an expanding envelope around the H II region, outflowing at velocities close to 200 km s^{-1}. This interpretation is of course strengthened by the presence of other detected absorptions of O I, Si II and Si SC III due to outflowing gas in front of the ionizing hot stars of the central H II region. The heliocentric velocities of all these absorptions are lower by about 200 km s^{-1} than that of the bulk of the galaxy as measured in the 21-cm line and of the optical emission lines. To confirm this hypothesis, Legrand et al. (1997) have obtained high resolution spectroscopic observations of Hα with the William Herschel telescope at La Palma, finding evidences of an expanding shell not participating in the rotation of the galaxy. Comparison of the Lyα with the Hα profiles shows that the Lyα line is significantly broader than Hα, suggesting also scattering of photons from the back side of the expanding neutral cloud.

The data on the other three H II galaxies with detected Lyα emission confirm that Haro 2 is not an isolated case. All spectra show Lyα emission with a broad absorption on their blue side except for ESO 350-IG038 in which the emission is seen atop of a broad structure requiring several filaments. When the metallic lines are detected, they are always blueshifted with respect to the ionized gas, further supporting the interpretation. In the case of ESO 350-IG038 the velocity structure seems to be more complicated and several components at different velocities are identified on the metallic lines.

The Lyα absorption profile fitting requires one or several components (in addition with a Galactic component if the redshift is small). We find relatively little scatter in the derived column densities (see Table 4). Most clouds have a column density log N(H I) of nearly 19.7 to 21.1. The static clouds tend to have larger column densities than the moving ones that are also splitted into several components as expected in a dynamical medium.

The main conclusions that are drawn from this set of data is that complex velocity structures are determining the Lyα emis-

Table 4. Measured values in the Lyα spectral region. The second line gives the estimated error bars for logN(H I), except for ESO 350-IG038 for which the column density of the three main absorbing components have been indicated.

Name	λ(abs) Å	logN(H I) cm^{-2}	b km s^{-1}	λ(em.peak) Å	Flux erg s^{-1} cm^{-2}	EW Å	logN(H I) Galactic
ESO 350-IG038	1240.37	20.4	<140	1241.9	1.8(-14)	37	-
		18.8-19.9-20.3					
SBS 0335-052	1232.4	21.5	-	no em.	-	-	-
		21.4-21.7					
IRAS 08339+6517	1237.7	19.9	90	1239.5	5.6(-14)	34	-
		19.7-20.0					
IZw 18	1218.6	21.1	-	no em.	-	-	20.3
		21.0-21.5					
Haro 2	1220.9	19.9	-	1222.1	6.0(-14)	13	19.8
		19.6-20.5					
Mkn 36	1218.4	20.1	-	no em.	-	-	19.7
		19.9-20.3					
IIZw 70	1220.46	20.8	<200	no em.	-	-	19.3
		20.6-21.0					
ESO 400-G043	1238.6	19.7	70	1240.0	3.1(-14)	20	-
		19.6-19.8					

sion line detectability, showing the strong energetic impact of the star-forming regions onto their surrounding ISM. This velocity structure is indeed the driving factor for the Lyα line visibility in the objects of our sample. We want to stress again that if the absorbing gas is not static with respect to the ionized region, the Lyα emission line would be detected, almost independently on the dust and metal abundance of the gas. It would be affected of course by the same extinction than the UV continuum but this extinction would not be enhanced by resonant scattering effects.

If the neutral gas is static with respect to the H II region, the covering factor by these neutral clouds would probably become the key factor determining the visibility of the line. Thuan & Izotov (1997) have indeed detected strong Lyα emission in T1214-277, with no evidences of blueshifted Lyα absorption. In this case the detection of the line requires that a significant fraction of the area covered by the slit along the line of sight is essentially free from neutral gas, suggesting a patchy or filamentary structure of the neutral clouds. Such a geometry would be possible only in galaxies not surrounded by enormous H I clouds, as it seems to be the case in IZw 18 and similar objects.

The effect of neutral gas flows helps to understand why luminous high-redshift objects have only been found up to now with linewidths larger than 1000 km s^{-1}. High-redshift galaxies with very strong (EWs $>$ 500 Å) extended Lyα emission are characterized by strong velocity shears and turbulence (v $>$ 1000 km s^{-1}); this suggests an AGN activity, in the sense that other ISM energising mechanism than photoionization by young stars may be operating. However Steidel et al. (1996) have recently discovered a substantial population of star-forming galaxies at $3.0<z<3.5$ that were selected not from their emission-line properties but from the presence of a very blue far-UV continuum and a break below 912 Å in the rest frame. Similarly to our local starbursts they find that 50% of their objects show no Lyα emission whereas the rest does, but with weak EWs no larger than 20 Å at rest. The Lyα profiles of this population look indeed very similar to those of our local starburst galaxies (Franx et al. 1997 ; Pettini et al. 1997). We can conclude from the preceeding discussion that the use of Lyα as a star formation indicator underestimates the comoving star formation density at high redshift (e.g. Cowie & Hu, 1998).

5. Conclusions

We have analyzed HST UV spectroscopical data of eight H II galaxies aiming to characterize the detectability of the Lyα emission line in this kind of objects. We obtain the following results:

– Lyα emission has been observed in four out of the eight H II galaxies. In all these four galaxies we have found a clear evidence of a wide velocity field by the presence of deep absorption troughs at the blue side of the Lyα profiles. Moreover, absorption lines of metallic elements (O I, Si II) are also significantly blueshifted with respect to the H II gas velocity.
– The determining factor for the detectability of the Lyα emission line in these galaxies is therefore the velocity structure of the neutral gas along the line of sight, rather than the abundance of dust particles alone. If most of the neutral gas is outflowing from the ionized region, the Lyα emission line would escape (partially) unaffected, independently on the metal abundance and dust content of this neutral gas.
This outflowing material apparently powered by massive stars winds and/or SN may eventually leave the galaxy. We thus may be witnessing galactic winds resulting from intense star formation activity. In the case of Haro 2, Lequeux et al. (1995) suggested that 10^7 $M_\odot$ are expanding at 200 km s^{-1}.

– Broad Lyα absorption is detected in all H II galaxies. The derived N(H I) column densities lie unexpectedly inside a relatively small range with 6 of the 8 H II galaxies having logarithmic column densities logN(H I) between 19.9 and 21.1 cm^{-2} (extreme values are 19.7 and 21.5). We stress again that the Lyα photons emitted by the H II region are absorbed or redistributed by the H I gas only if its velocity is the same as that of the H II region. Otherwise, the photons that are resonantly trapped were emitted in the stellar continuum close to Lyα.
– The dependence of Lyα emission detectability on the presence/absence of neutral static/outflowing gas along the line of sight (and within the field of view covered by the slit), helps to explain the apparently contradictory detection of Lyα emission in metal and dust-rich galaxies (like Haro 2), while it may be absent in metal and dust deficient objects, of which IZw 18 is the prototype.
– A partial covering factor of the H II region by neutral gas, with low H I column densities, would be required to allow the detection of the Lyα emission line if the neutral gas is static with respect to the ionized regions.
– The generally weak or absent Lyα emission from "primeval" and other galaxies at high redshifts can only be explained by velocity-structure effects combined with absorption of the Lyα photons by dust grains. The relatively small angular extent of these sources implies that if photons were leaking through the neutral gas clouds surface after multiple scattering without being destroyed, the equivalent widths of the lines measured from Earth should be significantly higher than observed.
– The present study invalidates attempts to measure the comoving star-formation rate density at high redshift on the basis of Lyα emission surveys.

Future work should address the several effects discussed in this work to understand the reasons that govern the presence/absence of the Lyα line emission and absorption: the strength and age of the burst, the metallicity of the gas (controlling the cooling, hence the wind evolution), the gravitational potential of the parent galaxy and its morphology and the H I and the dust distributions will all play a role. The challenge is to determine their relative importance in affecting the Lyα emission and absorption processes. Clearly the way forward is to realistically model the hydrodynamical evolution of the ISM in gas rich dwarf galaxies under the influence of starburst of different fractional masses. Particular attention should be paid to the time evolution of neutral gas kinematical and structural parameters.

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