The Lyman-alpha emission in local Star-Forming Galaxies: Scenario and Connection with Primeval Galaxies

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Abstract

We review the Lyα emission in local star-forming galaxies. In most cases as already shown by the IUE, the emission is absent or much weaker than expected. This occurs because Lyα photons can be resonantly scattered by the neutral gas and destroyed by even very low amounts of dust. However new Hubble Space Telescope observations (HST) indicate that other factors such as the velocity structure of the gas play a crucial role. Gas flows are likely to occur as powered by the kinetic energy released via stellar winds and supernova. We propose a scenario based on the hydrodynamics of superbubbles powered by massive bursts of star formation that naturally accounts for the variety of Lyα line detections in star-forming galaxies. We caution with the attempts to derive the co-moving star formation rate at high redshift from Lyα emission searches.

1 Introduction

The search for high-redshift galaxies have progressed rapidly over the last ten years using color techniques which basically select galaxies with massive ongoing star formation and little extinction while more evolved objects that could be heavily dust-reddened are picked out at millimeter wavelengths (see [14] for references). It has been conjectured that primeval galaxies at their very early stage would be nearly dust-free hence easily detected from their Lyα emission ([26]; [24]). For this reason it is reasonable to speculate that local star-forming galaxies producing Lyα emission would resemble distant primeval ones.
Early ultraviolet observations of nearby starburst galaxies however, have revealed in most starburst galaxies a much weaker Lyα emission than predicted by simple models of galaxy formation. In some other galaxies Lyα was non-existent or even appeared as a broad absorption profile ([25], [12], [13]; [7]; [32], [17], [18]). The reason for the weakness of the Lyα emission has been the subject of debates. For young star-forming galaxies without so much dust as to suppress Lyα large equivalent widths should be observed in the range of 100-200 (1+z) Å [4]. However it was early realized that pure extinction by dust would be unable to explain the low observed Lyα/Hβ, although Calzetti and Kinney [2] tentatively proposed that proper extinction laws would correctly match the predicted recombination value. Valls-Gabaud [34] on the other hand suggested that ageing starbursts could reduce Lyα equivalent widths because they are affected by strong underlying stellar atmospheric absorptions. Early IUE data have provided evidence for an anticorrelation between the Lyα/Hβ ratio and the HII galaxy metallicity. These results were attributed to the effect of resonant scattering of Lyα photons and their subsequently increased absorption by dust ([24]; [4] and references therein). Indeed, the enormous increase in optical path length experienced by the Lyα photons implies that small amounts of dust are able to completely destroy the emission line, even originating a broad, damped absorption profile [3]. Finally Charlot and Fall [4] advocated that the structure of the interstellar medium (porosity and multi-phase structure) is most probably an important factor for the visibility of the Lyα line.

2 HST observations

New observations performed with the HST bring additional insight into this picture. They indicate that the velocity structure in the interstellar medium plays a key role in the transfer and escape of Lyα photons. Kunth et al. [16] and Lequeux et al. [21] have used the Goddard High Resolution Spectrograph (GHRS) onboard the Hubble Space Telescope (HST). The Large Science Aperture was chosen to ensure a sufficient flux level and grating angles were 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. The Lyα range was chosen to investigate both emission and absorption features so that the HI 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. In a first attempt, Lyα was observed only in absorption in the starburst dwarf galaxy IZw 18 [16]. Since IZw 18 at Z = 1/50 Z⊙ is the most metal–poor starburst galaxy known at present, it was considered previously 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 dustier star-forming galaxy with a Z = 1/3 Z⊙ ([21]). The detection of such a profile in the Lyα emission line of Haro 2 led 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 (blue–shifted by 200 km s⁻¹ with respect to the optical emission lines) and that of the profile of the Hα line ([19]). Observations were subsequently made on additional galaxies by Kunth et al. [18] while Thuan and Isotov [33] have obtained GHRS spectra of two more starburst galaxies, namely Tol65 and T1214-277 with the G140L grating allowing a larger spectral region around Lyα. Tol65 reveals a broad damped Lyα absorption while T1214-277 shows a pure Lyα emission profile with an equivalent width of 70 Å and with no blue absorption. The individual spectra of galaxies observed in [18] are shown in Fig. [4]
Figure 1: GHRS spectra of all the galaxies in [18]. 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.
Figure 2: Detail of the O I and Si II region for the galaxies with Ly$\alpha$ 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.

3 Results of HST observations and interpretation

3.1 The Local Star-Forming Galaxies

Three types of observed lines have been identified so far: pure Ly$\alpha$ emission; broad damped Ly$\alpha$ absorption centered at the wavelength corresponding to the redshift of the HII emitting gas and Ly$\alpha$ emission with blue shifted absorption features, leading in some cases to P Cygni profiles.

As noted by [18], Ly$\alpha$ emission with deep blueward absorption troughs evidence a wide velocity field. The equivalent widths of the Ly$\alpha$ emission range between 10 and 37 Å hence much below the value predicted by Charlot and Fall, [4] for a dust free starburst model. In all cases interstellar absorption lines (OI, SiII) are significantly blueshifted with respect to the HII gas (see Fig. 2). On the other hand, if the HI is static with respect to HII, the destroyed Ly$\alpha$ photons are those emitted by the HII region and the interstellar lines are not displaced (see Fig. 3).
The details of the processes are as follows. Ly$\alpha$ photons are produced by recombinations in H II regions at about 2/3 of the ionization rate. They are subsequently absorbed and reemitted by H atoms, both in the H II regions in which they were produced and in the surrounding HI regions, if present. This process – resonant scattering – changes both the frequency and direction of the Ly$\alpha$ photons. Therefore those 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 Ly$\alpha$ 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 [4]).

A further complication arises if the neutral gas surrounding the star-forming regions is not static with respect to the ionized gas, but outflows from these regions towards the observer. The resonant scattering would affect photons at shorter wavelengths than the Ly$\alpha$ emission line, i.e., 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 Ly$\alpha$ emission line is about 100 Å in the dust-free case ([4]). 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. if it 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 Ly\(\alpha\) 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 Ly\(\alpha\) wavelength if the aperture sustained 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 Ly\(\alpha\) emission line if the neutral gas is moving towards the observer.

Among the galaxies showing a strong damped Ly\(\alpha\) absorption at the systemic velocity, the O I and Si II appear in absorption 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 - IZw 18 shows weak signs of reddening and its dust-to-gas ratio is at least 50 times smaller than the Galactic value, [16] -, this shows that it remains possible to weaken observationally Ly\(\alpha\) by simple multiple resonant scattering from the neutral gas, and even to produce an absorption feature. The HI cloud surrounding these galaxies might be leaking Ly\(\alpha\) photons through its external surface. The Ly\(\alpha\) 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 amount of dust present in these galaxies efficiently destroys a significant fraction of Ly\(\alpha\) photons, especially if the clouds extension is very large.

On the other hand, the Ly\(\alpha\) emission in Haro 2 is accompanied by a broad absorption in the blue wing of the line, with the general appearance of a typical P Cygni profile. The amount of neutral gas that produces the blue absorption trough at Ly\(\alpha\) is rather modest and of the order of $N(\text{HI}) = 7.7 \times 10^{19}$ atoms cm$^{-2}$. The crucial point here is that the neutral gas responsible for the absorption is not at the velocity at which the Ly\(\alpha\) 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 III due to outflowing gas in front of the ionizing hot stars of the central H II region. Legrand et al., [19] have obtained high resolution spectroscopic observations of Haro 2 in H\(\alpha\) with the WHT at La Palma, finding evidence for an expanding shell. Comparison of the Ly\(\alpha\) and the H\(\alpha\) profiles shows that the Ly\(\alpha\) line is significantly broader than H\(\alpha\), suggesting also scattering of photons from the back side of the expanding neutral cloud.

Data on other H II galaxies with detected Ly\(\alpha\) emission confirm that Haro 2 is not an isolated case. Most spectra show Ly\(\alpha\) 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 and T1214-277 that shows pure emission. When 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. Note that there might be a secondary peak emission in the blue side of the main line in the spectrum of ESO-B400-G043.

Ly\(\alpha\) absorption profile fitting requires one or several components (in addition to a Galactic component if the redshift is small) with relatively little scatter in the derived column densities. Most clouds have a column density $\log N(\text{HI})$ of nearly 19.7 to 21.5. The static clouds tend to have larger column densities than the moving ones that are also split into several components
as expected in a dynamical medium.

The main conclusion drawn from this set of data is that complex velocity structures are determining the Lyα emission line detectability, showing the strong energetic impact of the star-forming regions onto their surrounding ISM. This velocity structure is therefore the driving factor for the Lyα line visibility in the objects of our sample. We want to stress that this effect seems to be almost independent of the dust and metal abundance of the gas.

If the neutral gas is static with respect to the HII region, the covering factor by these neutral clouds would probably become the key factor determining the visibility of the line. Thuan and Isotov [33] have detected strong Lyα emission in T1214-277, with no evidence 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 unlikely in galaxies surrounded by enormous HI clouds, as in IZw 18 and similar objects.

3.2 The Galaxies at High-Redshift

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. [29] 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 ([10]; [27]; see also [8] for the z=5.34 galaxy). 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 ([14]).

4 The evolution of superbubbles in extended HI halos

To account naturally for the variety of Lyα line detections in star-forming galaxies Tenorio-Tagle et al. [31], have proposed a scenario based on the hydrodynamics of superbubbles powered by massive starbursts. This scenario is visually depicted in Fig. 4. The overpowering mechanical luminosity (\(E_0 \geq 10^{41}\)erg s\(^{-1}\)) from massive starbursts (\(M_{\text{stars}} = 10^5 - 10^6\) M\(_{\odot}\)) is known to lead to a rapidly evolving superbubble able to blowout the gaseous central disk configuration into their extended HI haloes, as \(E_0\) exceeds the energy input rate required for the remnant to reach a disk scale-height with supersonic velocity. As shown by [15] if \(E_0\) exceeds the threshold luminosity \(L_0 = 7.2 \times 10^{36} P_4 H_{100}^2 a_{s,10}\) erg s\(^{-1}\) (where \(P_4 =\) disk pressure in units of \((10^4 k)\) cm\(^{-3}\) K, \(H_{100}\) is the disk scale height in units of 100 pc and \(a_{s,10}\) is the disk sound speed in units of 10 km s\(^{-1}\)), the superbubble will blowout and thus massive starbursts will lead to superbubble blowout phenomena even in massive galaxies such as the Milky Way. One can then predict the venting of the hot superbubble interior gas through the Rayleigh-Taylor fragmented shell, into the extended HI halo where it would push once again the outer shock allowing it to build a new shell of swept up halo matter (see Fig. 4b). Blowout occurs quite early in the evolution of the starburst (\(T_{\text{blowout}} \leq 2\)Myr).
supershell

Galaxy edge

starburst

fragments from original shell

new fast expanding shell

conical HII region

HI halo

HI halo (a)

HI halo (f)

HI halo (e)

HI halo (d)

HI halo (c)

HI halo (b)

ionization front

recombining shell

outer shock recombination front

expanding shell

trapped ionization front

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo

HI halo
A coeval starburst with a total mass larger than several $10^5 M_\odot$, also produces an almost constant ionizing photon flux ($F_{uv} \geq 10^{52}$ photons s$^{-1}$) during the first few (3-4) Myr and then abruptly, after $t = t_{\text{ms}}$, it begins to decrease as $t^{-5}$ (see [3], [23]) as the most massive stars begin to evolve away from the main sequence to eventually end up as supernovae. But then blowout or the fragmentation of the shell that allows the expansion of the hot interior gas into the extended low density HI halo, also allows the leakage of the $uv$ photons emitted by the starburst. These photons establish an ionized conical HII region with its apex at the starburst. The density of the halo steadily decreases with radius, but even if one regards it as a constant density medium with an $n_{\text{halo}} \sim 10^{-2}\text{cm}^{-3}$, one can show that the conical sector of the HII region will extend all the way to the galaxy outer edge, i.e. several kpc. This is because the isotropic stellar radiation manages to support along the plane of the galaxy an ionized central region of say, typically, 100 pc in radius, at the very core of the giant HII region where the density is the largest ($n_{\text{core}} \sim 1 - 10 \text{ cm}^{-3}$). Thus, along the breakout direction it could support the ionization of a region of length $l = 100\text{pc} \left(n_{\text{core}}/n_{\text{halo}}\right)^2$, several kpc long. Furthermore, the low halo density implies a long recombination time ($t_{\text{rec}} = 1/(\beta n_{\text{halo}}) \geq 10^7 \text{ yr}$), with the implication that the ionized conical sector of the galaxy halo becomes, and remains, transparent to the ionizing flux produced during the ensuing lifetime of the ionizing massive stars ($\leq 10$ Myr). Then clearly, the Ly$\alpha$ photons produced at the central HII region will also be able to travel freely in such directions. The escape of $uv$ photons from the galaxy would be particularly important during the early stages after blowout and until the new shell of swept up halo matter condenses enough material as to allow its recombination. This will be favoured if the shock progresses with speeds of a few hundred ($\leq 400$) km s$^{-1}$, (i.e. with a Mach number $M \leq 40$) leading to temperatures: $T_{\text{shock}} = 1.4 \times 10^7 (v_{\text{shock}}/1000 \text{ km s}^{-1})^2$, near the top of the interstellar cooling curve. This fact will promote the rapid cooling of the shocked gas in a time $t_{\text{cool}} = 3kT_{\text{shock}}/(4\Lambda n_{\text{halo}})$, where $\Lambda$ is the interstellar cooling rate. Given the values of $\Lambda$ ($\sim$ a few times $10^{-22}$ erg cm$^3$ s$^{-1}$) and of $n_{\text{halo}}$, $t_{\text{cool}}$ is of the order of one Myr; but note that lower density haloes (with an $n_{\text{halo}} \sim 10^{-3}$) will not have time to cool within the life-time of the massive stars. Rapid cooling implies that the shocked gas will cool down to the HII region temperature making the shock isothermal, and thus causing compression factors of several hundreds (as the shocked gas density $n_{\text{shock}} = n_{\text{halo}}M^2$). Compression leads then to recombination in time-scales ($t_{\text{rec}} = 1/\beta n_{\text{shock}}$) of less than $10^5$ yr, and this immediately and steadily will reduce the number of stellar $uv$ photons leaking out of the galaxy. At the same time recombination in the fast expanding shell will lead to a correspondingly blueshifted Ly$\alpha$ emission, as depicted in Fig. [3c]. Once the shell presents a large column density ($\sim 10^{19}$ atoms cm$^{-2}$), as it grows to dimensions of a few kpc, it will trap the ionization front. This is promoted by the large shell densities and the geometrical dilution of the ionizing radiation. Note that from then onwards, recombinations in the shell will inhibit the further escape of ionizing photons from the galaxy (compare Fig. [3b, c, and d). The trapping of the ionization front, makes the shell, acquire a multiple structure with a photoionized inner edge, a steadily growing central zone of HI, and an outer ionized sector where the recently shocked ionized halo gas is steadily incorporated. The growth of the central layer eventually will cause sufficient scattering and absorption of the Ly$\alpha$ photons emitted by the central HII region, leading to a blueshifted Ly$\alpha$ absorption. Note also that for as long as recombinations continue to occur at the leading edge of the shell, a blueshifted Ly$\alpha$ in emission will appear superposed to the blueshifted absorption feature (see Fig. [3d]). Recombination at the leading edge of the shell will become steadily less frequent, depleting the blueshifted Ly$\alpha$ in emission. This is due when the shell and its leading shock move into the outer less dense regions of the halo, and the shell recombination time, despite the compression at the shock, becomes larger than the dynamical time. At this stage, an observer looking along the conical sector of the HII region will detect a
P-Cygni-like Lyα line profile as shown in Fig. 4e.

Geometrical dilution of the uv flux will begin to make an impact as the superbubble grows large. This and the drop in the uv photon production rate, caused by the death of the most massive stars after $t = t_{ms}$, will enhance the column density of neutral material in the central zone of the recombined shell to eventually cause the full saturated absorption of the Lyα line (see Fig. 4f). Full saturated absorption has usually been accounted for by the large column density of the extended HI envelope of these galaxies and thus, as in all models, many different orientations will suit the observations. In our scenario however, also when observing within the solid angle defined by the conical HII region formed after blowout, such broad absorptions could arise well after blowout, once a large column density of shocked neutral material ($N \geq 10^{20}$ atoms cm$^{-2}$) has formed ahead of the trapped ionization front.

The solid angle subtended by the ionized cone will be a rapidly changing function of time, particularly during the early stages of evolution, immediately after blowout. However, numerical experiments and observations (see [28], and [30] and references therein) restrict this to a maximum value of about 70°, with the walls of the superbubble near the galaxy plane inhibiting its further growth.

5 Discussion

The main implication of the evolution depicted in Fig. 4 is that it is the feedback from the massive stars what – through ionization and the evolution of superbubbles – leads to the large variety of Lyα emission profiles. The escape of Lyα photons depends sensitively on the column density of the neutral gas and dust following the suggestion that the attenuation by dust is enhanced by scattering with hydrogen atoms. Note that apart from the observed profiles: Lyα in emission, P-Cygni-like profiles and full saturated absorption (as in Fig. 4a, b, e and f) the scenario predicts also secondary blueshifted Lyα emission profiles emanating from the rapidly expanding and recombining shell (see Fig. 4c and d). If massive star formation leads also to networks of shells such as those observed in 30 Dor ([6]) one should also expect a forest of Lyα in emission arising from recombinations in the various expanding shells in the network. P-Cygni Lyα profiles are predicted when observing along the angle subtended by the conical HII region but only once the ionization front is trapped by the sector of the superbubble shell evolving into the extended halo. This will produce the fast moving layer of HI at the superbubble shell, here thought to be responsible for the partial absorption observed in sources such as Haro 2, ESO B400-G043 (which probably exhibits a secondary blueshifted Lyα emission) and ESO 350-IG038 ([18]). In the latter case however, the profile is not typical of a clear P Cygni one. Instead the underlying damped Lyα absorption extends beyond the red of the line emission.

Damped Lyα absorption is seen in several galaxies. We note that these objects are all gas rich dwarf galaxies whereas in most cases but Haro 2, the galaxies that exhibit Lyα in emission or with a P-Cygni profile, are on the higher luminosity side of the distribution ($M \leq -18$).

Pure Lyα emission is observed in C0840+1201 and T1247-232 ([32]; IUE) or T1214-277 ([33]; HST). Such a line implies no absorption and thus no HI gas between the starburst HII region and the observer, as when observing the central HII region after the superbubble blowout, within the conical HII region carved in the extended HI halo. It is not a straightforward issue to estimate what is the fraction of Lyman continuum radiation that leaks out from galaxies. Direct observations from nearby star-forming galaxies indicate that less than 3% of the intrinsic Lyman continuum photons escape into the intergalactic medium ([20]) while a more restrictive value of less than 1% has been obtained using the Hα luminosity density of nearby galaxies ([1]). Our scenario however predicts a short but significant evolutionary phase (between blowout and...
the trapping of the ionization front by the fast expanding shell) during which a large amount of \textit{uv} radiation could leak out of a galaxy into the intergalactic medium. Detailed numerical calculations of the scenario proposed here are currently underway. Our results and further implications of the model will be reported in a forthcoming communication.

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