SINGLY PEAKED ASYMMETRIC Lyα FROM STARBURST GALAXIES

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ABSTRACT

We present results of Monte Carlo calculations for the Lyα line transfer in an expanding dusty supershell, surrounding Lyα sources in a starburst galaxy. The Lyα photons escape the system by a number of backscatterings, which results in a series of emission peaks redward of the systemic redshift, in contrary to observed singly peaked asymmetric profiles. We find that in order to form a singly peaked asymmetric Lyα emission, dust should be distributed in the ionized bubble, as well as within the supershell of neutral hydrogen. We also find that the overall escape probability of Lyα photons is determined by H i column density, Doppler width, and expansion velocity of the supershell, as well. The kinematic information of the expanding supershell is preserved in the profile of Lyα emission even when the supershell is dusty. Our results are potentially useful to fit the P Cygni–type Lyα line profiles from starburst galaxies, either nearby galaxies or high-z Lyman break galaxies.

Subject headings: galaxies: starburst — line: profiles — methods: numerical — radiative transfer

1. INTRODUCTION

Lyα is the most prominent line feature in the rest-frame ultraviolet (UV) spectra of starburst galaxies, and so Lyα is often used as a redshift indicator. Recently a large number of star-forming galaxies have been spectroscopically observed by using the Lyman break method (Steidel et al. 1996, 1999; Shapley et al. 2003). A detailed review was given by Taniguchi et al. (2003). The rest-frame UV spectra of those galaxies often show unique emission. In these cases, we usually identify this emission as Lyα and use it as a redshift indicator.

Lyα profiles of starburst galaxies can be classified into three types: P Cygni–type asymmetric emission, broad absorption, and symmetric emission. The P Cygni–type emission consists of absorption in the blue part and asymmetric emission in the red part. However, the rest-frame UV continua of high-z galaxies are often too weak to be detected, and so we can see only the asymmetric emission lines.

Kunth et al. (1998) showed that the kinematics of ambient material is crucial in determining whether emergent Lyα has either broad absorption or P Cygni–type emission in local starbursts. P Cygni–type Lyα emission can be seen only in those galaxies whose interstellar absorption lines are blueshifted with respect to either Lyα emission or stellar photospheric lines. There seems to be a general consensus that the outflowing motion is caused by either a galactic superwind or a galactic supershell (Lee & Ahn 1998; Heckman et al. 1998; Taniguchi & Shioya 2001; Ahn & Lee 2002; Ahn, Lee, & Lee 2003a, 2003b; Silich et al. 2003; Spinrad 2003). According to Shapley et al. (2003), in contrast to local starbursts, the Lyα emission equivalent width (EW) increases as the velocity offset between Lyα and the interstellar absorption lines decreases. Although there exists evidence that the Lyman break galaxies (LBGs) are different from local starburst galaxies (Shapley et al. 2003), this difference may be due to evolution of ambient media around starbursts in high-z LBGs. Hence, a simple supershell model in this study can be helpful to describe a certain evolutionary stage of LBGs.

The formation of asymmetric Lyα by outflows was discussed qualitatively by Tenorio-Tagle et al. (1999). Lyα radiative transfer is achieved mainly by backscattering processes in outflowing media. We have studied the role of backscattering processes in the formation of the Lyα line profile (Ahn et al. 2003a, 2003b). For the case of a dust-free supershell, we found that a series of peaks appear in the red part of Lyα. However, the majority of the observed Lyα emission lines are singly peaked. Possibly we can attribute this discrepancy to previously neglected dust extinction in the radiative transfer. We study quantitatively in this Letter the Lyα line formation mechanism through the interplay among the Lyα resonance scattering in an optically thick supershell of neutral hydrogen, the spatial extension of dust in the H i bubble, and the kinematics of the supershell with respect to Lyα sources at the center of the supershell.

2. MODEL

Galactic supershells are very well-known structures in nearby starburst galaxies (Marlowe et al. 1995; Martin 1998; Kothes & Kerton 2002). Their origin is known to be multiple explosions of supernovae in active star-forming regions. In this Letter we adopt a model of high-z starburst galaxies in which Lyα sources are presumed to be surrounded by a dusty galactic supershell. The supershell is assumed to be made of a uniform medium of neutral hydrogen and is expanding in a bulk manner. We assume that the interior of the supershell is fully ionized, which is a vacuum in the sense of Lyα scattering. Although the model in this study is very simple, the main purpose of this Letter is to emphasize the role of the spatial distribution of dust in destroying the secondary and higher peaks. We itemize and clarify the assumptions in this study as follows:

1. In optical and near-IR images, LBGs have typical half-light radii of 1.6 h−1 kpc (Giavalisco, Steidel, & Macchetto 1996). About half of them show the amorphous shape, while the other half show the kiloparsec-scale nuclear starburst (Calzetti & Giavalisco 2001). There exists a strong correlation between widths of interstellar absorption lines and color excess E(B−V) (Shapley et al. 2003). In addition, a major fraction of the observed Lyα emission lines is asymmetric. Thus, we assume that the star-forming regions for the cases with asymmetric Lyα are totally covered by galactic-scale outflowing absorbing media.

2. The partially ionized inner part of the supershell can also be a source of Lyα photons. However, the fraction of photons generated in the ionized part of the supershell, is smaller than that of the stellar Lyα photons (Tenorio-Tagle et al. 1999). Moreover, there is no kinematic difference between the photons
backscattered by the neutral supershell and the photons emitted by the ionized supershell. Hence we neglect photons emitted from the ionized inner part of the supershell.

3. Pettini et al. (2001) found that the projected velocity dispersions of nebular lines from LBGs are between 50 and 116 km s$^{-1}$. We simply choose $\sigma_{v,\text{sys}} = 50$ km s$^{-1}$ as the input width of Ly$\alpha$. We note that width of the H$\alpha$ emission with a high signal-to-noise ratio from a nearby H II galaxy Haro 2 is also $\sigma_{H\alpha} = 50$ km s$^{-1}$ (Legrand 1997).

4. The continuum is neglected in this Letter. According to Shapley et al. (2003), the Ly$\alpha$ profiles for 38% of their sample of LBGs consist of a combination of both emission and absorption. The EW of the broad absorption component is 10–20 Å, which will be dumped in the primary and the secondary peaks by backscatterings. However, those photons must be partially destroyed by dust extinction. Moreover, dust-free galaxies would have Ly$\alpha$ EWs of 50–200 Å (Charlot & Fall 1993), which is much larger than the absorption EW of the continuum. Hence we assume that the continuum will give a minor contribution.

5. We assume that $R_{\text{min}} = 0.9 R_{\text{max}}$. Here $R_{\text{max}}$ is the outer radius of the supershell and $R_{\text{min}}$ is the inner radius of the supershell. We also assume that the H I column density outside the supershell is negligible, because the supershell is assumed to have already grown to a galactic scale. We adopt the column density of neutral hydrogen $N_{H_1} = 10^{19}$–$10^{20}$ cm$^{-2}$ seen in both high-$z$ galaxies and nearby starburst galaxies. This column density corresponds to the line-center optical depth by $\tau_0 = 2.27 (b/80$ km s$^{-1})^{-1} (N_{H_1}/10^{14}$ cm$^{-2}$). Here $b$ is the Doppler parameter corresponding to turbulence. We adopt a typical value of 80 km s$^{-1}$ by referring results of both unsaturated low-ionization absorption lines in a lensed galaxy MS 1512−cB58 (Pettini et al. 2002) and nearby H II galaxies (Kunth et al. 1998). Hence, the Voigt parameter is given by $a = 7.60 \times 10^{-3} (80$ km s$^{-1}/b)$.

6. We assumed for simplicity that the neutral hydrogen in the supershell is uniformly distributed. In fact, the supershell can either be clumpy or have a density gradient, which is also important for escape of Lyman limit photons. The geometry of the supershell is assumed to be spherical for simplicity. The supershell evolves more rapidly toward the steepest density gradient (Silich & Tenorio-Tagle 1998). However, when it evolves to be of galactic scale, we can assume its sphericity.

7. We assume that the supershell is bulk expanding spherically. Here the bulk expansion also implies that dust and gas are strongly coupled. It is known that the interstellar absorption lines in the spectra of LBGs have velocity widths of several hundred km s$^{-1}$ (Pettini et al. 2001; Shapley et al. 2003). In order to describe a more realistic outflow, the satisfactory model is probably a superwind model rather than a supershell model. However, the supershell model can be helpful to understand the basic processes of Ly$\alpha$ transfer in outflowing media.

8. In the composite spectrum of high-$z$ galaxies, Shapley et al. (2003) measured an average blueshift for the low-ionization interstellar features of $\Delta v = -150 \pm 60$ km s$^{-1}$ with respect to the stellar systemic redshift. In addition, the neutral gas in nearby starburst galaxies 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$^{-1}$ (Kunth et al. 1998). Hence, we adopt $V_{\text{exp}} = 200$ km s$^{-1}$ as a typical expansion velocity of the outflowing supershell.

9. We assume that dust is uniformly distributed in the ionized bubble as well as within the supershell. When $R_d$ is the inner radius of the dust shell, $R_d$ can be less than $R_{\text{min}}$. The outer radius of the dust shell is assumed to be equal to $R_{\text{max}}$. Jones et al. (1994) investigated grain destruction in supernova blast waves and found that for carbonaceous grains the fractional destruction is $\leq 0.29$, for silicate it is $\leq 0.45$, and for shock velocities $\leq 200$ km s$^{-1}$. Even in photoionized warm media, mantles of dust grains can be evaporated, but both silicate and graphite can survive (Draine & Salpeter 1979; Osterbrock 1989, p. 227). Although the temperature of the star-forming regions in local starbursts reaches 10$^5$ K (Heckman, Armus, & Miley 1990), the typical temperature in the outer part of the ionized bubble can be of the order of 10$^4$ K (Ott, Martin, & Walter 2003; Griffiths et al. 2000). In these cases, large silicate and graphite grains can survive at least during the lifetime of starbursts as long as plasma density is not too high (Draine & Salpeter 1979). We also assume that dust size distribution is the same both in the ionized bubble and within the supershell. However, a more realistic model should describe the changes of size distribution and number density of dust by shock waves.

10. We defined a radial dust opacity through the dust shell $\tau_d$ in order to reconcile with the usual way of estimating dust opacity by analyzing the extinction of the UV continuum from the stars in the central region of an H II region. The dust-to-gas ratio is also useful to consider the absorbing probability of Ly$\alpha$ photons during a large number of core and wing scatterings within the supershell. We define the dust-to-H I ratio in the supershell by $\beta = \int N_{H_1}/(R_{\text{max}} - R_{\text{min}})$ m$_d$/m$_{H_1}$. Here the typical mass of grains is given by $m_d = 4\pi/3\alpha_d\rho_d$, $\alpha_d$ is the absorption cross section of dust grains, $\rho_d$ is the mass of the hydrogen atom, and $\alpha_d$ is the radius of dust grains effective at 1216 Å. We adopt the mass density of dust grains $\rho_d = 1$ g cm$^{-3}$ and the size of a typical dust grain $\alpha_d = 1.9 \times 10^{-6}$ cm. We adopt the typical albedo $A = 0.5$ in accordance with Draine & Lee (1984).

We use the Monte Carlo method, whose detailed description was presented in our previous papers (Ahn, Lee, & Lee 2000, 2001, 2002, 2003a). In the Monte Carlo code, we integrate the path lengths between all the scattering events of a Ly$\alpha$ photon before its escape only if the photon is passing through the dust shell. Thus the integrated dust opacity experienced by the photon is given by $\tau' = \tau_d/\tau_0 \Sigma S$. Here $S$ is a path length in units of $\tau_0$, along which a Ly$\alpha$ photon propagates between the $(i-1)$th scattering and the $i$th scattering within the dust shell in $R_i < r < R_{\text{max}}$. A more detailed description of the Monte Carlo code for dust-free supershells was given in Ahn, Lee, & Lee (2003b).

3. RESULTS

We present the emergent profiles that are calculated using the Monte Carlo method in Figures 1 and 2. We can see that there are two or three peaks for each case, which is similar to our previous study (Ahn et al. 2003a, 2003b). We call the peaks at $V = V_{\text{exp}}$ the primary peaks and the peaks at $V = 3V_{\text{exp}}$ the secondary peaks. Figure 1 shows the emergent profiles for $N_{H_1} = 10^{19}$ and $10^{20}$ cm$^{-2}$. When we compare the left panels with $R_d = 0.4 R_{\text{max}}$ to the right panels with $R_d = 0.9 R_{\text{max}}$, we can see that the secondary peaks are destroyed efficiently when the dust shell extends into the ionized bubble.

This fact means that if the dust is distributed only within the supershell, the emergent Ly$\alpha$ photons have experienced almost the same amount of dust extinction. This can be explained as follows. Backscatterings cause redshift of Ly$\alpha$ photons. Since the supershell is optically very thick, Ly$\alpha$ photons are backscattered at the shallow inner part of the supershell.
Fig. 1.—Lyα profiles calculated by the Monte Carlo method. Top panels: Cases with \( N_{\text{HI}} = 10^{19} \ \text{cm}^{-2} \); bottom panels: cases with \( N_{\text{HI}} = 10^{20} \ \text{cm}^{-2} \). The inner radii of the cases in the left panels are 0.4\( R_{\max} \), and those of the right panels are 0.9\( R_{\max} \). The expansion velocity of the supershell is \( V_{\exp} = 200 \ \text{km s}^{-1} \), and the Doppler parameter is \( b = 80 \ \text{km s}^{-1} \). In order to show the relative flux ratio between the primary and the secondary peaks, fluxes of all the profiles are rescaled to have the same value at the primary peaks. The survival fraction for the cases with \( b = 20 \ \text{km s}^{-1} \) is shown by dotted lines in Fig. 3. We can see in Fig. 2 that the secondary peak decreases more sensitively with \( \tau_d \) as \( b \) decreases.

Hence, the dust opacity contributed by path length within the supershell is relatively small, while the dust opacity contributed during the final escape after backscattering is dominant. Hence, the dust opacity suffered by most of the Lyα photons escaping after backscattering becomes similar, which results in the inefficient decrease of any secondary peaks.

The situation becomes quite different when the dust shell extends into the ionized bubble, \( R_C < R_{\min} \). While they are scattered back and forth in the bubble by backscatterings, the Lyα photons are redshifted and eventually escape to form the secondary and the tertiary peaks. Thus, backscattered Lyα photons have a large path length within the dust shell in the ionized bubble. The dust opacity contributed by the dust shell within the ionized bubble is roughly proportional to the number of backscatterings. Hence the secondary and the tertiary peaks are more severely reduced than the primary peak.

In moderately thick media with \( \alpha r_e < 10^3 \), a Lyα photon experiences a large number of resonance core scatterings followed by a single longest flight (Adams 1972; Harrington 1973; Neufeld 1990; Ahn et al. 2002). In extremely thick media, Lyα photons experience excursions. Lyα photons can either escape the supershell after a single longest flight or be scattered backward into the ionized bubble during excursions. These backscattered photons are redshifted and form peaks, which are much reduced by dust extinction during the scatterings within the supershell. Therefore, the survival fraction of Lyα photons is also affected by two factors: one is the dust abundance (dust-to-gas ratio) within the supershell, and the other is the integrated path length within the supershell.

First, the dust opacity within the supershell is \( \tau_d (R_{\max} - R_p) \). Thus, although both the H\, i column density and the total dust opacity are fixed, the dust opacity within the supershell increases as \( R_p \) approaches to \( R_{\min} \). As a result, in Figure 3, the survival fraction curves for \( R_p = 0.9 R_{\max} \) are steeper than those for \( R_p = 0.4 R_{\max} \) for fixed \( N_{\text{HI}} \) and \( b \). Second, as \( \alpha r_e \) increases, both the number of wing scatterings per excursion and the number of excursions within the supershell increase, just because the average frequency shift per
scattering is $b$. The path length within the supershell is an increasing function of $\alpha_{rb}$. In Figure 3, for cases with the same Doppler parameter $b = 80 \text{ km s}^{-1}$, we can see that the curve with $N_{HI} = 10^{20} \text{ cm}^{-2}$ is decreased much faster than that with $N_{HI} = 10^{19} \text{ cm}^{-2}$.

Third, we know in §2 that $a \propto b^{-1}$ and $\tau_0 \propto b^{-1}$. Thus, $\alpha_{rb} \propto b^{-2}$. Because of the same reason mentioned above, we can expect that the destruction of the secondary and higher peaks is enhanced for small $b$. We show in Figure 2 the changes of profiles for different Doppler widths, where both the column density of neutral hydrogen $N_{HI}$ and the dust configuration (or $R_0$ and $\tau_0$) are fixed. The secondary peak is decreased more rapidly as $b$ is decreased. In addition, the widths of the primary peaks decrease for small $b$. The red part of the primary peak is formed from the photons that are scattered backward. Because of the dust extinction both within the supershell and in the dust shell, the Ly$\alpha$ photons can be easily destroyed, and so the primary peaks become narrow. We show in Figure 3 the variation of survival fraction of Ly$\alpha$ photons for the cases of different Doppler parameters, while $N_{HI}$, $\tau_0$, and $R_0$ are fixed. When we compare the solid line with filled circles with the dotted line with filled circles, we can see that the curve for small $b$ decreases rapidly.

On the other hand, we can see in Figures 1 and 2 that both the widths of the peaks and the velocity difference between the peaks are relatively insensitive to dust opacity, except for small dust optical depths. In dust-poor cases, the primary peak and the secondary peaks are partly overlapped, as seen in the top panels of Figure 1. We showed that the kinematics of outflowing material is imprinted on both the velocity width of the peaks and the velocity differences between peaks (Ahn et al. 2003a, 2003b). Therefore, those characteristics can be used potentially to estimate the expansion velocity of the supershell even in dusty interstellar media.

4. SUMMARY

In this Letter we have shown that the spatial distribution of dust grains in the supershell is as important in forming the singly peaked asymmetric Ly$\alpha$ emission profiles as the kinematics of the supershell. When the supershell is expanding with respect to the central Ly$\alpha$ sources, the Ly$\alpha$ resonance scattering is off-centered. The Ly$\alpha$ photons are scattered backward by the expanding supershell with the high H$i$ column density. As the number of backscatterings increases, Ly$\alpha$ photons are redshifted more and more, which enhances the escape probability. Therefore, in the cases of dust-free supershells, these back-scattering processes result in a series of peaks redward of Ly$\alpha$. However, the majority of observed Ly$\alpha$ emission profiles show no such peaks. In this Letter, we have found that the single peak can be formed only when dust extends in the ionized bubble as well as within the supershell. In this case, the integrated path length in the dust shell increases as the Ly$\alpha$ photons are scattered back and forth by the shallow part of the inner wall of the supershell. Thus, the integrated dust opacities increase as the inner radius of the dust shell decreases. Moreover, when Ly$\alpha$ photons suffer a large number of resonance and wing scatterings within the supershell, their path lengths become large. Thus, the dust abundance within the supershell is also another of the decisive factors that determine the overall escape probability of Ly$\alpha$ photons. Furthermore, both the optical depth and the Doppler parameter of the supershell are another crucial cooperating factor to determine the survival fraction of Ly$\alpha$ photons. We found that the kinematic information about the outflowing media surrounding Ly$\alpha$ sources is imprinted on the Ly$\alpha$ profiles, and it is conserved even when the media are dusty. However, our model is a very simplified one. In order to explain various types of observed Ly$\alpha$ profiles, we have to consider more realistic models, in which we consider either multiple shells or outflowing media with gradients in density and velocity. Then the realistic models may describe a galactic superwind rather than a galactic supershell. Our work can be applied to a certain period in the full evolutionary phases of outflowing materials of starburst galaxies.

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REFERENCES

Adams, T. 1972, ApJ, 174, 439
Ahn, S.-H., & Lee, H.-W. 2002, J. Korean Astron. Soc., 35, 175
Ahn, S.-H., Lee, H.-W., & Lee, H. M. 2000, J. Korean Astron. Soc., 33, 29
———. 2001, ApJ, 554, 604
———. 2002, ApJ, 567, 922
———. 2003a, in ASP Conf. Ser. 289, Proc. IAU 8th Asian-Pacific Regional Meeting, Vol. II, ed. S. Ikeuchi, J. Hearshaw, & T. Hanawa (San Francisco: ASP), 243
———. 2003b, MNRAS, 340, 863
Calzetti, D., & Giavalisco, M. 2001, Ap&SS, 277, 609
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Draine, B. T., & Lee, H. M. 1984, ApJ, 285, 89
Draine, B. T., & Salpeter, E. E. 1979, ApJ, 231, 77
Giavalisco, M., Steidel, C. C., & Macchetto, F. D. 1996, ApJ, 470, 189
Griffiths, R. E., Ptak, A., Feigelson, E. D., Garmire, G., Townsley, L., Brandt, W. N., Sunbruna, R., & Bregman, J. N. 2000, Science, 290, 1325
Harrington, J. P. 1973, MNRAS, 162, 43
Heckman, T. M., Armus, L., & Miley, G. K. 1990, ApJS, 74, 833
Heckman, T. M., Robert, C., Leitherer, C., Garnett, D., & van der Rydt, F. 1998, ApJ, 503, 646
Jones, A. P., Tielens, A. G. M., Hollenbach, D. J., & McKee, C. F. 1994, ApJ, 433, 797
Kothes, C., & Kerton, C. R. 2002, A&A, 390, 337
Kunth, D., Mas-Hesse, J. M., Terlevich, E., Terlevich, R., Lequeux, J., & Fall, S. M. 1998, A&A, 334, 11
Lee, H.-W., & Ahn, S.-H. 1998, ApJ, 504, L61
Legrand, F., Kunth, D., Mas-Hesse, J. M., & Lequeux, J. 1997, A&A, 326, 929
Marlowe, A. T., Heckman, T. M., Wyse, R. F. G., & Schommer, R. 1995, ApJ, 438, 563
Martin, C. 1998, ApJ, 506, 222
Neufeld, D. A. 1990, ApJ, 350, 216
Osterbrock, D. E. 1989, Astrophysics of Gaseous Nebulae and Active Nuclei (Mill Valley: University Science Books)
Ott, J., Martin, C. L., & Walter, F. 2003, ApJ, 594, 776
Pettini, M., Rix, S. A., Steidel, C. C., Adelberger, K. L., Hunt, M. P., & Shapley, A. E. 2002, ApJ, 569, 742
Pettini, M., Shapley, A. E., Steidel, C. C., Cuby, J., Dickinson, M., Moorwood, A. F. M., Adelberger, K. L., & Giavalisco, M. 2001, ApJ, 554, 981
Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
Silich, S. A., & Tenorio-Tagle, G. 1998, MNRAS, 299, 249
Silich, S. A., Tenorio-Tagle, G., & Muñoz-Tuñón, C. 2003, ApJ, 590, 791
Spinrad, H. 2003, Astrophysics Update, ed. J. Mason (Berlin: Springer), in press (astro-ph/0308411)
Steidel, C. C., Adelberger, K. L., Giavalisco, M., Dickinson, M., & Pettini, M. 1999, ApJ, 519, 1
Steidel, C. C., Giavalisco, M., Pettini, M., Dickinson, M., & Adelberger, K. L. 1996, ApJ, 462, L17
Taniguchi, Y., & Shioya, Y. 2001, ApJ, 547, 146
Taniguchi, Y., Shioya, Y., Akiji, M., Fujita, S., Nagao, T., & Murayama, T. 2003, AJ, 126, 1167
Tenorio-Tagle, G., Silich, S. A., Kunth, D., Terlevich, E., & Terlevich, R. 1999, MNRAS, 309, 332
Whittet, D. C. B. 1992, Dust in the Galactic Environment (Bristol: IOP)