Lyα RESONANT SCATTERING IN YOUNG GALAXIES: PREDICTIONS FROM COSMOLOGICAL SIMULATIONS

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ABSTRACT

We present results obtained with a three-dimensional, Lyα radiative transfer code applied to a fully cosmological galaxy formation simulation. The developed Monte Carlo code is capable of treating an arbitrary distribution of source Lyα emission, neutral hydrogen density, temperature, and peculiar velocity of the interstellar medium. We investigate the influence of resonant scattering on the appearance and properties of young galaxies by applying the code to a simulated “Lyman break galaxy” at redshift $z = 3.6$, star formation rate $22 M_\odot$ yr$^{-1}$, and total Lyα luminosity $2.0 \times 10^{43}$ ergs s$^{-1}$. It is found that resonant scattering of Lyα radiation can explain that young galaxies are frequently observed to be more extended on the sky in Lyα than in the optical. Moreover, it is shown that, for the system investigated, due to the anisotropic escape of the photons, the observed maximum surface brightness can differ by more than an order of magnitude, and the total derived luminosity by a factor of $\sim 4$, depending on the orientation of the system relative to the observer.

Subject headings: galaxies: formation — line: formation — line: profiles — radiative transfer — scattering

1. INTRODUCTION

The Lyα line is a very important diagnostic in a wide range of fields of astrophysics, not the least of which is galaxy formation, providing us with extensive information on redshift, dynamics, kinematics, morphology, etc. Three distinct physical processes result in Lyα source emission in the context of galaxies: First, Lyα emission due to photoionization of hydrogen atoms by UV radiation from nearby, massive stars and subsequent recombinations may contribute as much as 10% of the total luminosity of the galaxy (Partridge & Peebles 1967). Second, part of the potential energy gained by gas falling into galactic potential wells is converted into cooling radiation. Fardal et al. (2001) find that, at high redshifts, most of this radiation is emitted by gas with $T < 20,000$ K, and consequently $\sim 50\%$ in Lyα alone. Finally, the external, metagalactic UV field, penetrating some (in case of damped Lyα systems) or all (in case of Lyman limit systems) of the outer parts of galactic hydrogen “envelopes” will also produce some Lyα radiation through case B recombination. Moreover, this UV field can also photoheat non–self-shielded gas, which subsequently cools, radiating Lyα (Furlanetto et al. 2005).

Over the past years it has become possible to actually resolve observationally these young, Lyα-emitting galaxies. In several cases, the galaxies have been found to be significantly more extended on the sky when observed in Lyα as opposed to optical bands (e.g., Møller & Warren 1998; Fynbo et al. 2001, 2003). Due to the complexity and diversity of the systems, in order to correctly interpret observations and make predictions about the properties of young galaxies, it is desirable to develop realistic theoretical and numerical models.

For a number of idealized cases analytical solution are obtainable. Harrington (1973) investigated the emergent spectrum of resonantly scattered radiation in the case of a highly optically thick slab of finite thickness but infinite extension, and uniform temperature and density. Neufeld (1990) extended this solution to include the possibility of the photons being destroyed (as by dust) and injected with arbitrary initial frequency. Dijkstra et al. (2006) derived a similar analytical expression for spherical symmetry, allowing for isotropic expansion or collapse of the gas, and Loeb & Rybicki (1999) examined the spectrum for an isotropically expanding or contracting medium with no thermal motion.

However idealized these configurations may seem, they provide valuable and at least qualitative insight into the characteristics of young galaxies. Moreover, they offer direct means of testing numerical methods.

The Monte Carlo (MC) method has been used for solving radiative transfer (RT) problems since the beginning of the 1960s. Nevertheless, although conceptually simple, the demand for strong computer power until quite recently restricted this technique to deal with more or less the same idealized configurations that had already been dealt with analytically. Thus, the majority of previous attempts to model RT in astrophysical situations have been based on strongly simplified configurations of the physical parameters. Only a few authors (Cantalupo et al. 2005; Tasitsiomi 2006; Verhamme et al. 2006) considered more general cases.

With the aim of predicting the appearance and properties of Lyα-emitting galaxies, we developed an MC code capable of treating an arbitrary distribution of source Lyα emission, neutral hydrogen density, temperature, and peculiar velocity of the medium and subsequently applied it to a simulated Lyman break galaxy (LBG) from a fully cosmological simulation.

2. SIMULATIONS

2.1. The Cosmological Simulation and Monte Carlo Code

The cosmological simulation of the formation and evolution of an individual galaxy was performed using the N-body/hydrodynamical TreeSPH code of Sommer-Larsen et al. (2003); see also Sommer-Larsen (2006). The system becomes a Milky Way/M31–like disk galaxy at $z = 0$ and is simulated using $\sim 2.2 \times 10^8$ particles in total, comprising only smoothed particle hydrodynamic (SPH) and dark matter (DM) particles at the initial redshift $z_i = 39$. The masses and gravity softening lengths of SPH and star particles are $9.9 \times 10^4 h^{-1} M_\odot$ and 200 $h^{-1}$ pc, respectively ($h = 0.65$). For the DM particles the corresponding values are $5.7 \times 10^5 h^{-1} M_\odot$ and 370 $h^{-1}$ pc. The minimum SPH smoothing length in the simulation is about 62.2 $h^{-1}$ pc. For the DM particles the corresponding values are $5.7 \times 10^5 h^{-1} M_\odot$ and 370 $h^{-1}$ pc.

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The MC code, used to propagate the photons through the medium, by and large resembles those recently developed by other authors (e.g., Cantalupo et al. 2005; Tasitsiomi 2006). Since it is grid-based—the number of cells typically being 512—the physical parameters of interest are first interpolated from the SPH particles to the cells of the computational box. These parameters are the Lyα emissivity, the temperature \( T \), the density \( n_H \), of neutral hydrogen, and the three-dimensional velocity field \( \mathbf{v}_{\text{inh}} \) of the gas.

### 2.2. Determination of Source Lyα Emission

The emission cell of a given Lyα photon is found by setting the probability of being emitted from a given cell equal to the ratio of the luminosity in that cell to the total luminosity \( L_{\text{tot}} \). The photon is then injected in the line center (in the reference frame of the fluid element) from a random point \( x \) in the cell. The frequency \( \nu \) of the photon is parameterized through \( x = (\nu - \nu_0)\Delta \nu_0 \), where \( \nu_0 = 2.466 \times 10^{13} \text{ Hz} \) is the line-center frequency and \( \Delta \nu_0 = (\nu_0/c)v_\text{D} \) is the Doppler frequency, with \( v_\text{D} = (2\pi n_H m_H/c)^{1/2} \) being the thermal atom velocity dispersion (times \( \sqrt{2} \)) and the rest of the variables having their usual meanings. In terms of this variable, the injected photon obviously has a frequency of \( x = 0 \). The initial direction \( \mathbf{n}_\text{i} \) of the photon follows an isotropic probability distribution.

### 2.3. Propagation of the Radiation

The optical depth \( \tau \) covered by the photon before it is scattered is drawn randomly from the probability distribution \( e^{-\tau} \) and subsequently converted into a physical distance \( r = \tau n_L a_\tau \), where the physical parameters are given by the present cell. The cross section \( a_\tau \) is given by a Voigt profile, i.e.,

\[
s_\tau = f_{12} \frac{\pi \nu e^2}{m_e c \Delta \nu_0} H(a, x),
\]

where \( f_{12} = 0.4162 \) is the Lyα oscillator strength, and

\[
H(a, x) = \frac{a}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2}}{(x-y)^2 + a^2} dy \quad (2)
\]

is the Voigt function with \( a = \Delta \nu_0/2\Delta \nu_0 \) the ratio between the natural line width \( \Delta \nu_0 = 9.936 \times 10^7 \text{ Hz} \) and the Doppler width. Since equation (2) is not analytically integrable, we use the analytic fit given by Tasitsiomi (2006).

If the final position \( x_f \) of the photon is outside the original cell, the photon is placed at the point \( x_{af} \) of intersection with the face of the cell, and the above calculation is redone with the parameters of the new cell, an optical depth \( \tau' = \tau - |x_{af} - x_i|/(n_H a_\tau)_{\text{prev. cell}} \), and a frequency Lorentz-transformed to the bulk velocity of the new cell. This procedure is repeated until either the originally assigned value of \( \tau \) is spent, and the photon is scattered, or it leaves the computational box.

### 2.4. Scattering

Except for a small recoil effect, the scattering is coherent in the reference frame of the atom. However, to an external observer, the nonzero velocity \( \mathbf{u} = \mathbf{v}_{\text{atom}}/\mathbf{v}_{\text{inh}} \) of the atom will shift the frequency of the photon. In the directions perpendicular to \( \mathbf{n}_i \), the velocities \( u_{1,2} \) will follow a Gaussian distribution. When \( x \sim 0 \), the photon barely diffuses spatially. Only when it has diffused sufficiently far in frequency space will it be able to make a large journey in real space. To skip these nonimportant core scatterings and thus accelerate the code, if \( |x| \) is less than some critical value \( x_{\text{crit}} \), following Dijkstra et al. (2006) \( u_{1,2} \) is drawn from a truncated Gaussian so as to favor fast moving atoms and artificially push the photon back in the wing. \( x_{\text{crit}} \) is determined according to \( a_{\text{esc}} \) in the given cell. If \( a_{\text{esc}} \leq 1 \), a proper Gaussian is used; otherwise we find that \( x_{\text{crit}} = 0.02 e^{1/12} a_{\text{esc}} \), where \( (\xi, x) = (0.6, 1.2) \) or \( (1.4, 0.6) \) for \( a_{\text{esc}} < 60 \) or \( a_{\text{esc}} \geq 60 \), respectively, can be used without affecting the final result. The effect of this acceleration scheme is a speed-up of several orders of magnitude.

Due to the resonance nature of the scattering event, the velocity \( u_{ij} \), parallel to \( \mathbf{n}_i \) depends on \( x \) and is generated following Zheng & Miralda-Escude (2002).

The final frequency \( \nu' \) of the scattered photon (in the reference frame of the fluid element) depends on the direction in which the photon is scattered. For scattering in the line center, transitions to the \( 2P_{1/2} \) state results in isotropic scattering, while the \( 2P_{3/2} \) transition causes some polarization, resulting in a probability distribution \( W(\theta) \propto 1 + \cos^2 \theta \), where \( \theta \) is the angle between \( \mathbf{n}_i \) and the outgoing direction \( \mathbf{n}_f \) (Hamilton 1940). Since the spin multiplicity is \( 2J+1 \), the probability of being excited to the \( 2P_{3/2} \) state is twice as large as being excited to the \( 2P_{1/2} \) state. For scatterings in the wing, polarization for \( \pi/2 \) scattering is maximal, resulting in a dipole probability \( W(\theta) \propto 1 + \cos^2 \theta \) (Stenflo 1980). The transition from core to wing scattering is given by the value of \( x \), where the Lorentzian starts dominating the Gaussian profile, i.e., where \( x/a \pi x^2 \sim \sqrt{x} e^{-x^2} \), or \( x \sim 3 \) (the exact value is not crucial). In all cases, the scattering is isotropic in the azimuthal angle \( \phi \). In the observers frame, the final frequency is then given by \( x' = x - u_{ij} \cdot \mathbf{n}_f + g(1 - \mathbf{n}_f \cdot \mathbf{n}_i) \), where the factor \( g = h_p n_L/c v_{\text{inh}} \) (Field 1959) accounts for the recoil effect.

### 2.5. Observable Surface Brightness Maps

Following the above scheme, the photons are propagated through the medium, one by one, until they escape the computational box. For each scattering (as well as the emission) of a photon, the probability that the photon will escape in the direction of six virtual observers situated in the negative and positive directions of the three principal axes is calculated. This probability is added as a weight to a three-dimensional array (the two spatial dimensions of the projected image of the galaxy, plus a spectral dimension for each pixel). The array is finally collapsed along the spectral dimension and along the spatial dimensions to yield the image and spectrum, respectively, that an external observer would see. The contribution of each pixel element to the surface brightness (SB) is then

\[
\text{SB}_{\text{pix}} = \frac{L_{\text{tot}}}{n_{\text{ph}} d_l^2 \Omega_{\text{pix}}} \sum e^{-\tau_{\text{esc}}} W(\theta), \quad (3)
\]

where \( n_{\text{ph}} \) is the number of photons, \( d_l \) is the luminosity distance to the observer, \( \Omega_{\text{pix}} \) is the solid angle subtended by the pixel, and \( \tau_{\text{esc}} \) is the optical depth of the gas lying between the scattering event and the edge of the computational box in the direction of the observer.

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1. For the environments produced here, transitions to the \( 2S \) state and subsequent destruction of the photon can be neglected.
of the system is 22 $M_{\odot}$ yr$^{-1}$. Observed LBGs have SFRs in the range 10–1000 $M_{\odot}$ yr$^{-1}$ (e.g., Rigopoulou et al. 2006), so the simulated galaxy corresponds to a small LBG. The Ly$\alpha$ emissivity is produced according to the three different scenarios described in § 1. Specifically, the luminosity originating from the H II in the vicinity of massive stars (accounting for approximately 90% of $L_{tot}$) is determined following Fardal et al. (2001) using the code Starburst99 (Leitherer et al. 1999) to yield the Lyman continuum and assuming a Miller-Scalo initial mass function, a mean Lyman continuum photon energy of 1.4 ryd, and that 0.68 Ly$\alpha$ photons are emitted per photon-ionization. The length of the box used for the MC calculations is 50 kpc (physical), and $d_{L} \sim$ 34 Gpc. Figure 1 shows the results obtained (all with a resolution of 512$^3$ cells), viewed from two different directions—from the negative x- and z-direction, corresponding to an edge-on and a face-on view of the sheetlike structure, respectively. Upper panels assume that the gas is optically thin to the Ly$\alpha$ line; the lower panels show the corresponding results with resonant scattering included. The effect of the scattering is incontestable: Although the original constellation of the principal emitters is still visible, the surface brightness distribution is clearly much more extended. Moreover, we note the effect of the viewing angle. Qualitatively, we expect the photons to escape more easily from the face of the sheet than from the edge and hence that the system should have a higher surface brightness than when viewed edge-on. Here this anticipation is quantified: Figure 2 shows the azimuthally averaged SB profiles. To allow for direct comparison with observations, the profiles are also shown not including the luminosity of the emitter lying in the outskirts of the image and smoothed with a point-spread function corresponding to a seeing of 0.8″. The maximum SB of the $x$-$y$ plane is found to be $6.1 \times 10^{-2}$ ergs s$^{-1}$ cm$^{-2}$, or $\sim$14 times higher than that of the $y$-$z$ plane. The average SB, from which the total luminosity is usually derived assuming isotropic emission, is 3.8 times higher.

Finally, we show the emergent spectrum. Although not as clear for the edge-on view, both profiles exhibit the characteristic double humpback profile (see, e.g., Venemans et al. 2005). Obviously, this is the result of the high opacity for photons near the line center; diffusing to either side of $\lambda_{Ly\alpha}$, the photons quickly decrease $\tau$ so as to make escape more probable. Furthermore, both profiles imply a net inward velocity of the gas; for infalling gas, red photons are shifted into resonance, while blue photons

3. RESULTS

The MC code was applied to a protogalaxy at $z = 3.6$, consisting of two small, star-forming “disks” separated by approximately 2 kpc, on one of which the computational box is centered, and a third more extended disk of lower star formation rate (SFR), located about 15 kpc from the center. The star-forming regions are embedded in a significant amount of more diffuse, non–star-forming H I gas in a 10–15 kpc thick, sheetlike structure, taken to constitute the $x$-$y$ plane. The total SFR
escape even more easily, thus enhancing the blue peak and diminishing the red.

Fitting a “Neufeld profile” to the observed spectra can give us an idea of the intrinsic characteristics of the system. Unfortunately, there is a degeneracy in that the profile is dependent only on the parameter \( \alpha \). Assuming some temperature, e.g., \( 10^4 \) K, representative of most of the \( \text{Ly}\alpha \)-emitting gas, one could in principle deduce the equivalent column density \( N_{\text{HI}} \). Alternatively, if \( N_{\text{HI}} \) is obtainable due to, e.g., the presence of a background quasar, constraints can be put on the temperature.

A bulk rotational motion of the gas will also alter the profile. Since, in fact, a full spectrum is obtained for every pixel element, this effect can be studied through long-slit spectroscopy.

### 4. DISCUSSION AND CONCLUSION

The present MC calculations do not include the effect of dust. Effectively, dust will act as a photon sink and an extra scattering possibility. Since, on average, each photon scatter ∼4 \( \times 10^8 \) times and travel a distance of ∼40 kpc before escaping, \(^4\) approximately half of which is in the high-density \( (n_{\text{H}} \gtrsim 0.1 \text{ cm}^{-3}) \), cooler \( (T \sim 10^4 \text{ K}) \) regions, even a small amount of dust may be expected to be capable of causing a significant decrease in the observed intensity. However, it is not clear to which extend the dust will affect the observations. If the medium is clumpy, the ratio of \( \text{Ly}\alpha \) to continuum radiation may, in fact, be increased (Neufeld 1991; Hansen & Oh 2006). Moreover, Tasitsiomi (2006) argues that dust acting as a catalyst for hydrogen molecules will lower \( n_{\text{H}} \), making the medium more transparent. We will study these effects in future work, implementing a realistic model of the dust based on the eight different metal species kept track of by the cosmological simulation.

As a very recent improvement of the cosmological simulation, a post-processed RT scheme of UV radiation from star-forming regions was developed by Razoumov & Sommer-Larsen (2006). They find that up to 5%–10% of the ionizing photons escape these regions at \( z \approx 3.6 \). However, a very preliminary analysis indicates that the results presented in this work are not significantly changed by the inclusion of H-ionizing photon RT. The quantitative effects of this on \( \text{Ly}\alpha \) RT will also be discussed in a forthcoming paper.

The developed Monte Carlo code has reproduced qualitatively and quantitatively the observation that young galaxies often appear significantly more extended on the sky in \( \text{Ly}\alpha \) than in the optical. Furthermore, we investigated the impact of the viewing angle on the observed surface brightness. Future simulations of a large statistical sample of galaxies, taking properly into account dust and H-ionizing UV photon radiative transfer, will allow us to learn more about the enigmatic \( \text{Ly}\alpha \) emitters.

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