Draft version January 16, 2015
Preprint typeset using LaTeX style emulateapj v. 12/16/11

TITULO

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Draft version January 16, 2015

ABSTRACT

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Subject headings: Lyman Alpha Emission, Galaxy Rotation, Galaxy Outflows ....MISSING....

1. INTRODUCTION

The Lyman-Alpha emission line is the spectral line produced when an electron goes from the second energy level to the first, loosing energy and emitting it as light. When this energy decays are seen in Hydrogen atoms, the wavelength of the Ly-α line is 121.567 nm. The detection of this emission line is a main tecnique in extragalactic astronomy because galaxies with a strong emission of this (called Lyman Alpha Emitters - LAEs) are used to study the evolution of the universe in big scale.

LAEs are young and far away galaxies with most of its matter composed by Hydrogen atoms, being the rest heavier elements, like Iron, produced by growing stars burning their material. Then, this spectral line tells very important information about the galaxy, most of it actually, which creates a motivation to find a way to model the Ly-α line according to certain free parameters that vary from a galaxy to another and that can be obtained from observations.

Our purpose in this paper is then to make a theoretical model, based on radiative transfer simulations, that use MonteCarlo computational methods to emulate how the line profile is going to come out of the galaxy if it is rotating and has a surrounding outflow, both of this phenomena characterized by key parameters that are going to be described further on the paper.

MISSING: What has been done related to this?

As it has been described, the main purpose of this project is to mix a rotating galaxy with an external outflow surrounding it and analyze the resulting spectrum. The rotation model for the LAE consists on a sphere with an homogeneous mixture of dust and hydrogen at a constant temperature undergoing a solid-body rotation. The spectrum then depends on the maximum velocity of the sphere, the neutral hydrogen optical depths and the viewing angle. What happens is that photons are emitted from a central distribution of gas and escape the sphere after a radiative transfer process that ends at the border.

In this model, rotation does not induce any spatial anisotropy in the integrated line flux, the escape fraction or the average number of scatterings, which led to the creation of an analytic approximation for the galaxy spectrum. This mathematical expression helps to minimize the computational costs and lets try with several parameters without spending great amounts of time running the code.

After this photons escape the galaxy to empty space, they encounter a thin spherical shell of matter at a certain radius from the center. That material is the outflow of the LAE, created mainly by starbursts which composition is characterized with the parameters of Hydrogen column density and metallicity. Besides its components, the galactic outflow is also defined by an expanding constant velocity that affects the redshift of the photons.

As there is a lot of empty space inside the shell, it acts as a reflector of photons. This means, that when one wants to comes out it is most likely to bounce inside the sphere several times before finally escaping. However it is not likely that the photon comes back again inside the galaxy, which helps that the first process does not have to be repeated, and both stages can be treated as consecutive, not simultaneous.

2. THEORETICAL BACKGROUND

In this section we describe the two different models that together are used to reproduce a real and consistent Ly-α profile. The first one is a rotation model for the galaxy and the second is a thin shell model for the outflow.

2.1. *Rotation Model*

We use the simplified rotation model developed by (Garavito-Camargo et al. 2014) in which a rotating galaxy is modeled as a solid rotating sphere, with a homogeneous mixture of hydrogen and dust. Photons can be initially at the center or can be homogeneously dis-

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tributed inside the sphere. The equations governing this solid-body rotation sphere in which the axis of rotation is defined to be align with the z-axis are:

$$v_x = -\frac{y}{R} V_{\max}, \tag{1}$$

$$v_y = \frac{x}{R} V_{\max}, \tag{2}$$

$$v_z = 0, \tag{3}$$

Where R is the radius of the sphere and $V_{\max}$ is the linear velocity at the sphere's surface. The minus/plus sign in the x/y-component of the velocity indicates the direction of rotation. In this case we take the angular velocity in the same direction as the $\hat{k}$ unit vector.

In this work we use the analytical expression for rotation derived in (Garavito-Camargo et al. 2014) where a rotating sphere can be seen as a static sphere in the laboratory frame with a bulk velocity difference in each surface element with respect to a distant observer. With the previous analysis the outcoming spectra can be expressed as:

$$J(x, i) \approx 2\pi \int_0^R db\, b \int_0^{2\pi} d\phi\; J(x, b, \phi, i), \tag{4}$$

Where $J(x, b, \phi, i)$ is the spectrum of the flux emerging from the surface at point (b, ϕ) and is expressed as:

$$J(x, b, \phi, i) = \frac{\sqrt{\pi}}{\sqrt{24} a\tau_0} \left(\frac{(x - x_{\rm b})^2}{1 + \cosh\left[\sqrt{\frac{2\pi^3}{27}} \frac{|(x-x_{\rm b})^3|}{a\tau_0}\right]} \right) \tag{5}$$

2.2. *Outflow Model: ThinShell*

We use the outflow model stated in (Orsi et al. 2012) in which the outflow consists of a homogeneous, expanding, isothermal spherical shell surrounding a central galaxy. The inner radius R_{in} is related to the outer radius R_{out} by the expression $R_{in} = f_{th} R_{out}$, where $f_{th} = 0.9$. The temperature of the medium is assumed constant and equal to $T = 10^4 K$ and it is expanding at a constant velocity v_{out} . This outflow is composed by dust and gas uniformly mixed described by the column density n_H and the metallicity Z as follows:

$$n_H = \frac{X_H M_{shell}}{4\pi m_H {R^2}_{out}} \tag{6}$$

Where M_{shell} is the mass of the outflow, m_H is the mass of the hydrogen atom and $X_H = 0.74$ is the fraction of hydrogen in the cold gas.

$$Z = f_Z \langle Z_{cold} \rangle \tag{7}$$

Where $\langle Z_{cold} \rangle$ is the average metallicity of the cold gas and it is weighted by the product of the mass of cold gas and the Ly-α luminosity of the disc and bulge f_Z.

We decided to choose this model for two main reasons. First, when we analyze observed spectra we can se that the line is spread around the place where line should be when already taking into account the redshift due to the distance to the LAE. This implies that the photons before escaping the composed system suffer a change in frequency themselves, which we explain by making them rebound over the inner surface of the shell such as some of them suffer blueshift and other redshift, that even small, is significant and observed.

The second reason is because as the space between the shell and the galaxy is said to be void, the photons that escape from it suffer the scattering process at a far distance from the center, in a way such as if they rebound the chances that it happens in the normal direction to the surface are lower than in any other model. This implies that the photons are less likely to re-enter the galaxy so there is no need to start the diffusion inside again, allowing us to divide the spectrum creation process into 2 independent events, saving computational time and simplifying the model to its best.

2.3. *Joint Model*

The joint model consists of combining the two models that were just explained. A rotating spherical galaxy is placed at the center with a thin shell outflow surrounding it. What happens is that the photons that escaped the galaxy enter now into the outflow with the same radial direction that they came out with. At the end only a fraction of those manage to get out of the outflow and their wavelengths are measured to find the final spectrum.

In order to simulate all the possible cases we set some key parameters for the program to vary, and some others fixed which are defined by the characteristics of LAEs. This are chosen as follows.

2.3.1. *Fixed Parameters*

For the first stage there are two fixed parameters: the optical depth $\tau = 10^8$ and the galaxy rotation velocity $v_{gal} = 100$ km s^{-1}. For the second stage there is one fixed parameter: the metallicity of the outflow $Z = -4.0$. This 3 fixed values are selected because the characteristics of observed LAEs, especially their low mass and their highest star formation rate of all.

2.3.2. *Free Parameters*

We have then 3 parameters left that are going to vary along a wide range. These are: the galaxy viewing angle θ_{gal} , the hydrogen column density n_H and the outflow expanding velocity v_{out} .

θ_{gal} covers 3 different angles: 0°, 45° and 90°. $\log n_H$ takes 41 different values from 20.0 to 22.5. And v_{out} covers 5 equidistant velocities from 100 km s^{-1}to 500 km s^{-1}. The permutations of these three are analyzed in section 3.

3. RESULTS

Here goes the results....

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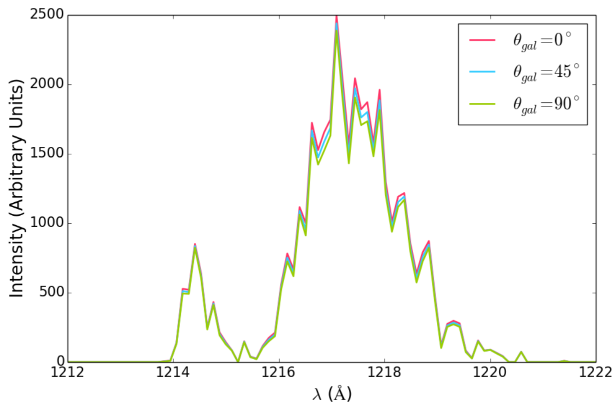

FIG. 1.— **Influence of Galaxy Viewing Angle:** The values of the fixed parameters are $v_{out} = 100$ km s^{-1}and $\log n_H = 21.3125$. The 3 possible angles are shown in the plot with different colors. The increase is visible as well as its small enlargement factor.

- What are the compact results.
- Some plots.
- Not a physical analysis yet.
- Write better (prettier)

3.1. *Influences of the Free Parameters*

In order to study the influence of each of the three free parameters, we fix two of them and see how the final spectrum varies along the other one left. In each case we will state these changes.

3.1.1. *Influence of the Galaxy Viewing Angle: θ_{gal}*

If one sets fixed outflow v_{out} and $\log n_H$ in each case the viewing angle has the same effect: it increases proportionally the intensity. However this change is not that significant. The resulting spectra are completely the same, but enlarged vertically by a small factor. Fig. 1 helps visualize this effect in a better way.

3.1.2. *Influence of the Outflow Hydrogen Column Density: $\log n_H$*

The effect of the $\log n_H$ is the creation of 2 peaks: the left one very thin, tall and pronounced, and the right one very wide, small and soften. When the $lognH$ is increased, the left peak starts to decrease while mixing with the right one, decreasing their height ratio until the left peak completely disappears. The resulting spectrum, with high column density, is a wide single mountain with intensity significantly less than at the beginning. Fig. 2 helps visualize this effect in a better way.

3.1.3. *Influence of the Outflow Expanding Velocity: v_{out}*

MISSING:
- Influence Outflow Velocity.

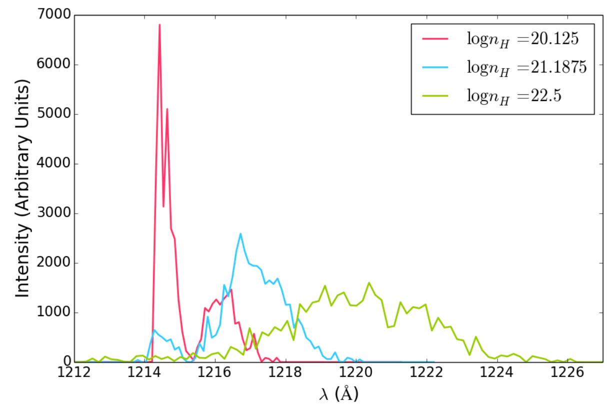

FIG. 2.— **Influence of Outflow Hydrogen Column Density:** The values of the fixed parameters are $v_{out} = 100$ km s^{-1}and $\theta_{gal} = 90°$. There are three stages of the $\log n_H$ value shown: initial, intermediate and final, with the values shown on the plot.

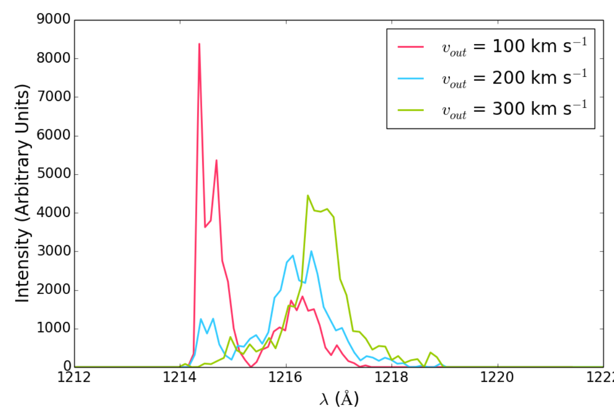

FIG. 3.— **Influence of Outflow Expanding Velocity:** The values of the fixed parameters are $\log n_H = 20.0625$ and $\theta_{gal} = 90°$. MISSIIIIIIING.

4. DISCUSSION

MISSING:
- Comparison with some other result (probably observations).
- Why is this result useful?
- What possible implications can this model have?

Ideas:

The decrease of the intensity while increasing the column density is caused because the second is proportional to the absorption of light in the gas. The more $lognH$, the less photons get out of the outflow.

5. CONCLUSIONS

Here goes the conclusions....

ACKNOWLEDGMENTS

To ...

The data, source code and instructions to replicate the results of this paper can be found here https://github.com/mariacamilaremolinagutierrez/LymanAlpha/. Most of our code benefits from the work of the IPython and Matplotlib communities (Pérez & Granger 2007; Hunter 2007).

MISSING:
- Help from Alvaro and Julian: data, explanations, advice and collaboration.
- Soooo many more acknowledgments.

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