

# Rotation effects on the Lyman- $\alpha$ line morphology in distant galaxies

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## ABSTRACT

Rotation is present in the gas kinematics of galaxies up to the highest redshifts. In this paper we present for the first time radiative transfer calculations that show the impact of rotation on the morphology of the Lyman  $\alpha$  line. To this end we construct simplified models where a galaxy is modeled as an homogeneous sphere composed as an homogeneous mixture of dust and hydrogen at a constant temperature. These spheres have a solid-body rotation with linear velocities at the surface in the range  $0 - 300 \text{ km s}^{-1}$ . We consider radiation sources both in the center of the rotating cloud and also homogeneously distributed around the sphere. We find that higher rotational velocities increase the width of each peak in the outgoing line profile while it also increases the amount of Lyman alpha photons escaping in the line center. This trends makes that for high rotational velocities and large Hydrogen optical depths the double peak of the line tends to be erased and be replaced by a single peak the lines center. This is more pronounced for radiation sources homogeneously distributed. Concerning the escape fraction we find that rotation does not have any effect, provided that all the sources are centrally emitted. However in the case of homogeneously emitted sources we measure an increase of about a factor of 2 in the escape fraction for higher rotational velocity values. Our work shows clearly that gas rotation has a non negligible impact on the shape of the Lyman  $\alpha$  line.

**Key words:** galaxies: high-redshift - galaxies: star formation - line: formation

## 1 INTRODUCTION

Due to the resonant nature of the Lyman alpha line, gas kinematics play an important role shaping its morphology...

There is an extensive literature studying the influence of outflow/inflow configurations in the shape of the outgoing Lyman-alpha line...

In this paper we study for the first time the impact of rotation on the morphology of the Lyman  $\alpha$  line. To isolate the effects of rotation we focus on a simple system: the gas distribution is spherical, with homogeneous density and the gas rotates as a solid body. We base our work on two independent Monte Carlo based radiative transfer codes CLARA (Forero-Romero et al. 2011) and XX (Dijkstra & Kramer 2012).

This paper is structured as follows...

In this paper we express a photon's frequency in terms of the dimensionless variable  $x \equiv (\nu - \nu_a)/\Delta\nu_\alpha$ , where  $\nu_\alpha = 2.46 \times 10^{15} \text{ Hz}$  is the Ly $\alpha$  resonance frequency,  $\Delta_\alpha \equiv \nu_\alpha \sqrt{2kT/m_p c^2} \equiv \nu_a v_{\text{th}}$  is the doppler broadening of the line which depends on the neutral gas temperature  $T$

scattering the radiation or equivalently the thermal velocity  $v_{\text{th}}$  of the atoms.

## 2 MODELING BULK GAS ROTATION

Describing the kinematics of gas rotation in all generality is a complex task. There is great variation in the shape of the rotation curve as observed in HI emission as a function of the distance to the galaxy center. However there are two features that are observed very often. First, in the central region the velocity increases proportional to the radius following the behaviour in a body with solid rotation. Second, beyond a certain radius the rotation curve tends to flatten. Furthermore, a thorough observational account of gas rotation in the redshifts of interest for the study of LAEs ( $z > 1.0$ ) is still missing.

An ab-initio description of realistic rotation curves in simulations depends on having access to the dynamic evolution the mass components in the galaxy: stars, gas and dark matter. Such level of realism is extremely complex to achieve,

Physical Parameter (units)	Symbol	Values
Velocity ( $\text{km s}^{-1}$ )	$V_{\text{max}}$	0, 50, 100, 200, 300
Hydrogen Optical Depth	$\tau_H$	$10^5, 10^6, 10^7$
Dust Optical Depth	$\tau_a$	0,1
Photons Distributions		Central, Homogeneous

**Table 1.** List of the physical parameters that define the spherical models we have simulated using Monte Carlo calculations. For each parameter we vary the values in the range listed in the last column. Taking into account all the possible combinations we end up with 60 different models.

specially of one wants to get a systematic description based on statistics of simulated objects.

Following the tradition of studies of Lyman $\alpha$  emitting systems, we implement a model with a simplified geometry and gas distribution. We assume that the gas is homogeneously distributed in a sphere that rotates as a solid body with constant angular velocity. This simple model will contain only one parameter: the linear velocity at the sphere's surface,  $V_{\text{max}}$ .

### 2.1 Detailed Implementation of Rotation

In the MonteCarlo code we define a cartesian coordinate system to define the position of each photon. The origin of this system coincides with the center of the sphere and the rotation axis is defined to be  $z$ -axis. With this choice, the components of the gas bulk velocity field,  $\vec{v} = v_x\hat{i} + v_y\hat{j} + v_z\hat{k}$ , can be written as

$$v_x = -\frac{y}{R}V_{\text{max}}, \quad (1a)$$

$$v_y = \frac{x}{R}V_{\text{max}}, \quad (1b)$$

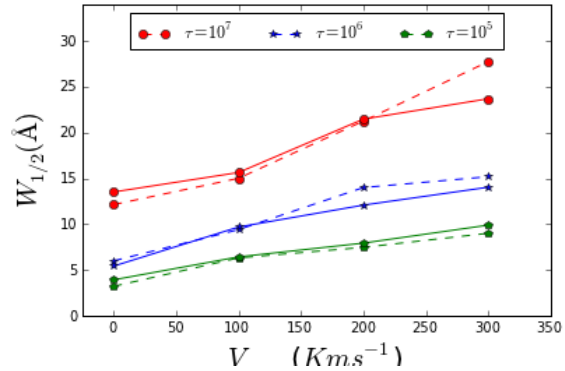
$$v_z = 0, \quad (1c)$$

where  $R$  is the radius of the sphere and  $V_{\text{max}}$  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. With these definitions we can write the angular velocity as  $\omega = V_{\text{max}}/R$ .

In contrast with spherically symmetric models (static, outflow, inflow) the rotation now defines a preferred direction in the problem. In Section 3 we quantify this difference by varying the line of sight of a mock observer with respect to the rotation axis. The results are parameterized by the polar angle  $\theta$  as defined by the dot product  $\cos\theta = \hat{u} \cdot \hat{k}$ .

### 2.2 Grid of Simulated Galaxies

In the Monte Carlo calculations we follow the propagation of  $N_\gamma = 10^5$  numerical photons through different spherical galaxies, each one varying in at least one of the following parameters: the maximum rotational velocity  $V_{\text{max}}$ , hydrogen optical depth  $\tau_H$ , dust optical depth  $\tau_a$  and the initial distribution of photons with respect to the gas. There are in total 60 models with the input parameters summarized in Table 1.



**Figure 2.** Half-width for the non-dusty models as a function of rotational velocity  $V_{\text{max}}$ . Continuous (dashed) lines correspond to homogeneous (central) source distributions.

## 3 RESULTS

The central result of this paper is summarized in Fig. 1 that shows clearly the considerable impact of rotation on the morphology of the emergent Ly $\alpha$  line. Both panels in the Figure focus on the results for  $\tau_H = 10^7$ , showing that the influence of rotation is present both when the photons are either homogeneously or centrally initialized over the gas volume.

In the following subsections we characterize the line morphology by the half-width at half intensity and the peak maxima. In order to interpret the morphological changes in the line we also report the median number of scatter for each Ly $\alpha$  photon in the simulation. Finally we measure the bulk escape fraction as a function of rotational velocity in the presence of dust.

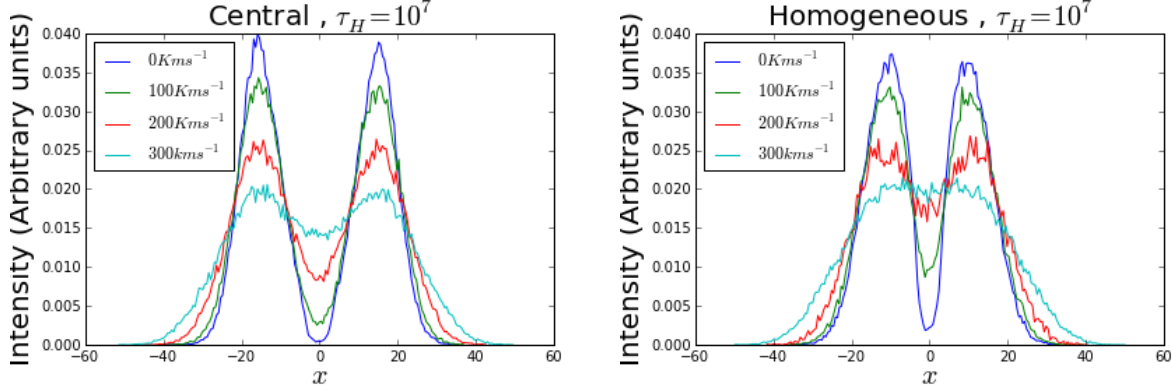
All the results in this section are constructed by taking into account all outgoing photons regardless of the direction of propagation. In the next section ?? we quantify the changes in the observed spectra for observers with different viewing angles.

### 3.1 Line width and peak maxima

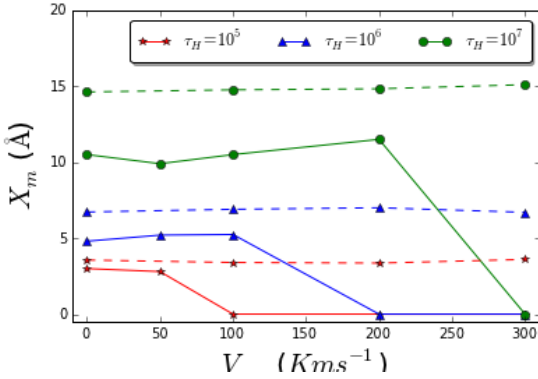
The first quantitative conclusion of the effect of rotation in the Ly $\alpha$  line is that double peaks broaden and reduce their intensity, while the line center rises. This produces the impression that, as the rotational velocity increases, the double peaks are merged into a single broad emission peak. This is most evident in the highest rotational velocities for the homogeneously distributed sources (right panel in Fig. 1).

To quantify the line broadening we measure a modified version of the full width at half maximum (FWHM). Instead we measure it only for half of the line,  $W_{1/2}$ . This definition allows us to quantify the line width both in the cases of double and single peak emission. In the case of double peaked emission  $W_{1/2}$  corresponds to the width of a single peak, while in the extreme case of high rotational velocities, when the double peak is erased, it simply corresponds to half FWHM.

Figure 2 shows how  $W_{1/2}$  increases with rotational velocity. Continuous (dashed) lines connect the results for homogeneous (central) source distribution. The line width in-



**Figure 1.** Shape of the Ly $\alpha$  line for different velocities rotational velocities for spherical distributions with  $\tau_H = 10^7$ . The left (right) panel shows the central (homogeneous) photon distribution. All photons were taken into account regardless of their propagation direction.

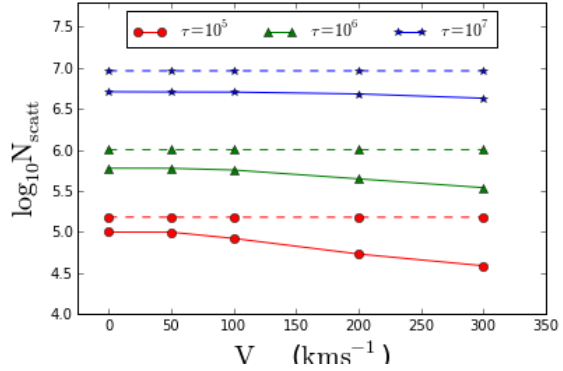


**Figure 3.** Position of the peak maxima as a function of rotational velocity  $V_{\max}$ . Continuous (dashed) lines correspond to homogeneous (central) source distributions. A value of  $x_{\max} = 0$  indicates that line becomes single peaked.

creases with rotational velocity up to factors of  $\sim 2$  at  $300 \text{ km s}^{-1}$  with respect to the static case. For the temperature  $T = 10^4 \text{ K}$  used in our radiative transfer calculations the thermal velocity is  $v_{th} = 12.8 \text{ km s}^{-1}$ . For a model with  $\tau_H$  it means that the half-width can increase up to  $350 \text{ km s}^{-1}$  (at  $V_{\max} = 300 \text{ km s}^{-1}$ ) compared to a half-width of  $150 \text{ km s}^{-1}$  in the static case.

Figure 3 shows the position for the peak maxima as a function of the rotational velocity  $V_{\max}$ . This figure shows us clearly that in the case of central distributed sources there is barely any change with rotational velocity in the range of explored parameters. However, in the case of homogeneously emitted sources the maxima position remain close to constant until beyond some velocity threshold the line becomes single peaked with  $x_{\max} = 0$ .

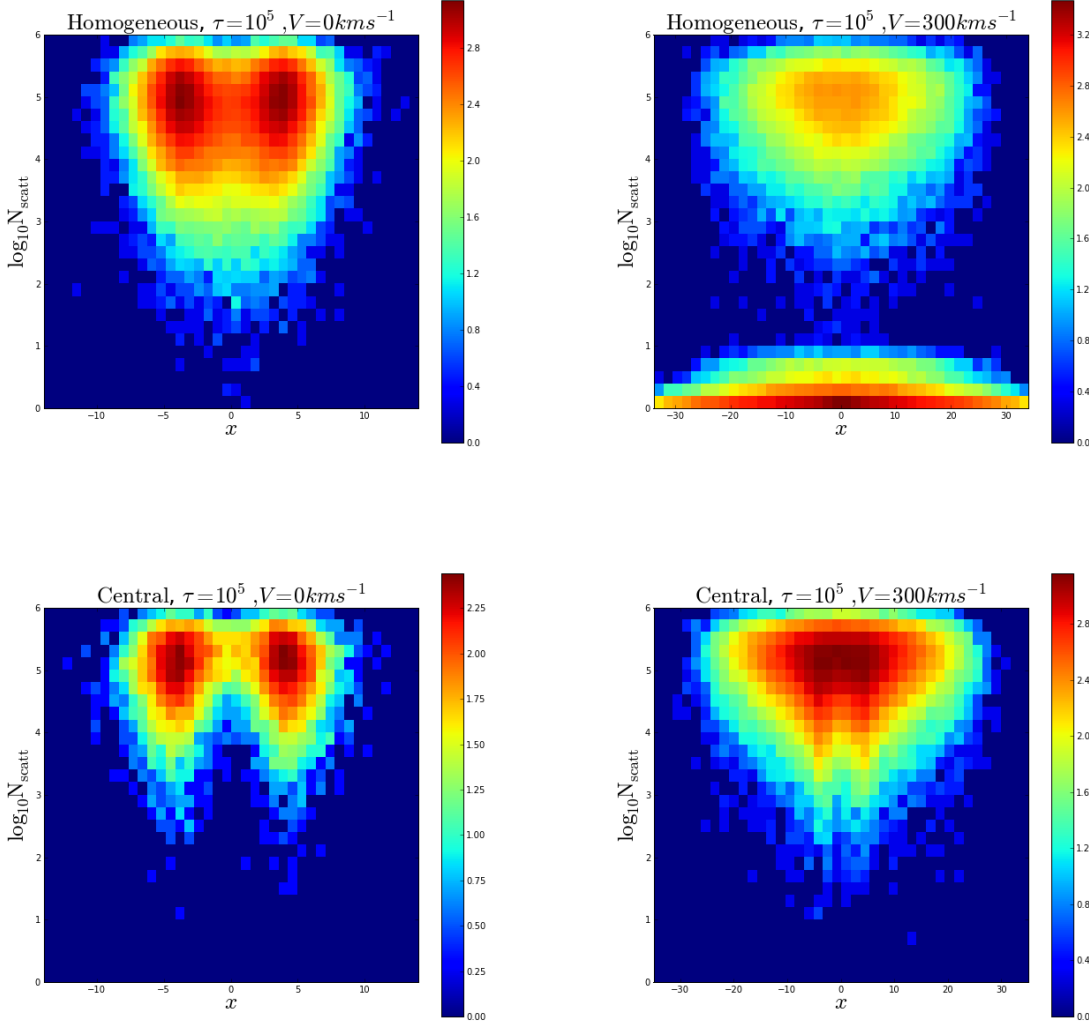
It is probable that the transition to a single peak line occurs for systems where it becomes easier for the bulk of the photons to escape with the lowest number of scatterings possible, allowing them not to move very far from the center of the line. This hypothesis can help to explain how the single peak stage is easily achieved in the homogeneous source distribution. In this case there is a fraction of the photons that are inside a photosphere region with  $\tau_{H,r} \ll \tau_H$



**Figure 4.** Logarithm of the average number of scatterings as function of the velocity.

where  $\tau_{H,r}$  is the optical depth from the radius of emission to the sphere's surface. This conditions allows the photons to escape with much less scatterings compared to the photons emitted at the very center of the sphere. In turn, it gives the photons less scatterings to be placed far from the line center. Increasing the rotational velocity  $V_{\max}$  reduces the optical depth making the photosphere region effectively larger, increasing the number of photons escaping close to the lines's center. For the central case the photosphere is not present, and other mechanisms must be at play in the steady reduction of the double peak.

For larger values of  $\tau_H$  the transitional velocity  $V_{\text{trans}}$  is also larger. In our models we find the following correspondance between the optical depth  $\tau_H = \{10^5, 10^6, 10^7\}$  and the transitional velocities  $V_{\text{trans}} = \{50 - 100 \text{ km s}^{-1}, 100 - 200 \text{ km s}^{-1}, 200 - 300 \text{ km s}^{-1}\}$  which can only be constrained to be in the range of velocities in the models that gave a  $x_{\max} \neq 0$  and  $x_{\max} = 0$ . In the next section explore the origin of this trends and consider to what extent the hypothesis of a low number of scatterings is correlated with the emergence of a single peak.



**Figure 5.** 2D histogram of  $N_{\text{scatt}}$  vs  $x$ . The upper (lower) pannels show the homogeneous (central) source distribution. Left corresponds to the static case and the right  $V_{\text{max}} = 300 \text{ km/s}$ . The colour scale is locarithmic

### 3.2 Average Number of Scatterings

The number of times that a Ly $\alpha$  photon is absorbed and re-emitted is connected to the final frequency that it can have after escaping the galaxy. In the case of static gas geometries, a large value of the optical depth is immediately followed by a high number of scatterings. In turn a large optical depth increases the probability that a Lyman $\alpha$  photon will be found far from the center of the line. The peak maxima shifting away from the line center as the amount of neutral hydrogen increases.

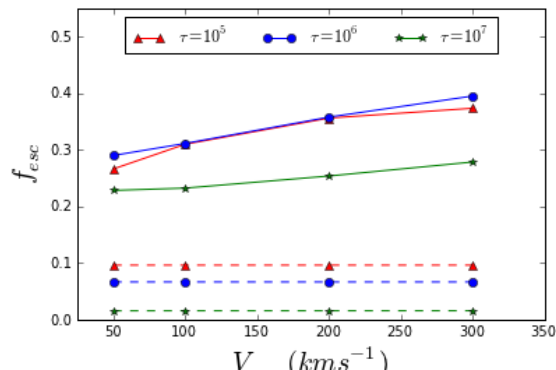
In Figure 4 we see the average number of scatterings  $\langle N_{\text{scatt}} \rangle$  as a function of the rotational velocity  $V_{\text{max}}$ . For the central distributions we find that there is not a significant change for increasing rotational velocities,  $\langle N_{\text{scatt}} \rangle$  changes less than 0.5% for different velocities. In this case we also find that the average number of scatterings is proportional to the optical depth, as expected in analogy from the analytic result for the homogeneous infinite-slab  $\langle N_{\text{scatt}} \rangle = 1.612\tau_{\text{H}}$

(Adams 1972; Harrington 1973). In our experiments we find  $\langle N_{\text{scatt}} \rangle = XXX\tau_{\text{H}}$ .

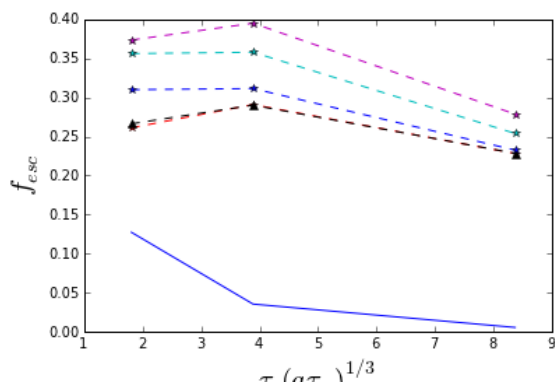
However, for the homogeneous distribution there is a clear decrease of  $\langle N_{\text{scatt}} \rangle$  as the  $V_{\text{max}}$  increases. This effect more pronounced for the lower values of the optical depth. For  $\tau_{\text{H}} = 10^5$  the average number of scatterings decreases by  $XX\%$  at  $V_{\text{max}} = 300 \text{ km s}^{-1}$  in comparison to the static case.

The analytic expectation for the slab with homogeneously emitted sources is  $\langle N_{\text{scatt}} \rangle = 1.16\tau_{\text{H}}$  (Harrington 1973), a factor of 0.72 lower than the case of the centrally emitted photons. In our case we find that for the static spheres this factor is  $xxx$ .

In order to gain a deeper understanding of these results we 2D histograms for the number of scatterings as a function of the outgoing dimensionless frequency  $x$ . In Figure 5 we show the results of such histogram in the case  $\tau_{\text{H}} = 10^5$  for the static case and  $V_{\text{max}} = 300 \text{ km s}^{-1}$ . The upper (lower)



**Figure 6.** Escape fraction as a function of rotational velocity. The continuous (dashed) lines correspond to homogeneous (central) models.



**Figure 7.** Escape fraction as a function of the product  $(a\tau_H)^{1/3}\tau_a$ . The analytic solution for the infinite slab is shown as a continuous line. Different dashed lines correspond to different rotational velocities.

panels show the results for the homogeneous (central) source distribution. The color scale is logarithmic in the number of photons at a certain value  $x - N_{\text{scatt}}$ . This Figure clearly support our hypothesis about the photosphere in the homogeneous distribution, in this case most of the photons that left with  $x \sim 0$  have escaped with less than 10 scatterings, clearly explaining the origin of a single central peak. However, for a central distribution the situation is different. In this case the number of scatterings remains high, on the order of the optical depth, but the two peaks do get closer to each other. In this situation each scattering leaves the photon closer to the center of the line than the static case.

### 3.3 Dusty Clouds: Escape Fraction

If there is a change in the number of scatterings with rotational velocity, there must be a change in the probability of being absorbed if dust is present. We study how rotation impacts the escape fraction of Ly $\alpha$  photons.

Taking into account the results in the previous section, we do not expect any change in the case of central distributions given that the average number of scatterings remain constant. On the other hand, in the homogeneous distribu-

tion there is a considerable drop in the number of scatterings as  $V_{\text{max}}$  increases, this preconditions the escape fraction to increase as well.

Figure 6 shows the dependence of the escape fraction as a function of rotational velocity. This Figure illustrates how our reasoning in the previous paragraph is correct. The escape fraction barely changes for the central source distribution, while it rises as the velocity  $V_{\text{max}}$  increases for the homogeneous case. The velocity has a higher relative impact in the models with low optical depth  $\tau_H = 10^5, 10^6$ , where it can raise from  $xxx$  in the static case up to  $xxx$  at  $V_{\text{rot}} = 300 \text{ km s}^{-1}$ .

In Figure 3.3 we put these results in the context of the analytical solution for the infinite slab (Neufeld 1990) shown by the continuous line. In this setup the analytic solution depends solely on the product  $(a\tau_H)^{1/3}\tau_a$ . This is valid only in the limits  $a\tau_H \gg 1$ . The dashed lines in Figure 3.3 correspond to the cases of different velocities. We observe that in all cases the escape fraction is higher than in the slab configuration. We also note that for  $\tau_H = 10^5$  the escape fraction does not increase as expected, This is due to the fact that the condition  $a\tau_h \gg 1$  does not hold.

### 3.4 Different line of sights

### 3.5 Off-Centered emission

## 4 DISCUSSION

... Comparison with Verhamme et al. results on the rotation

... Compare with Kulas et al (Figure 3), Rotation on the Lyman alpha line convert double peak profiles into a single one. comments about rotation with inflows and outflows.

... The results derived in this paper have consequences on the interpretation of galaxy observations in the Lyman alpha line.

..compare steidel et al (2011)

## 5 CONCLUSIONS

In this paper we have estimated the effects of gas bulk rotation on the emission of the Lyman  $\alpha$  line. We based the study on the study of a simplified configuration of an homogeneous sphere rotating as a solid body. We explored a range of models by varying the rotation speed, hydrogen optical depth, dust optical depth and initial distribution of Ly $\alpha$  photons with respect to the gas density. This was implemented in CLARA, a Monte-Carlo radiative transfer code already used to study the Lyman  $\alpha$  line.

As first we see how the width of the line changes using a modified FWHM explained in section 3.1, and we found that as gas bulk rotation increase also the width increase in a factor of 2 – 3 in comparison with the static case. We also take into account the influence of the observer viewing angle, we found that observers with a line of sight perpendicular to the axis of rotation measure a 15% larger line width than those aligned with the rotation axis.

As many observational spectra Ly $\alpha$  emission line (Kulas et al) is double peaked, these peaks provide important information concerning gas kinematics and geometry, which can be partially explained with inflows/outflows of gas content. We study the effect of rotation in the position of this

peaks, and we find that the position of the maxima does change with rotation for the homogeneous models when the double peak merged into a single peak as velocity increase. This effect is not seen for the central distribution when the double peak remains constant as the velocity increase. We also find that there is no dependency in the observer viewing angle with the maxima position.

Concerning the escape fraction under rotational effects on the Ly $\alpha$  emission line, we found that the escape fraction increase in about 20% – 30% for the homogeneous sphere model. While rotational effects are negligible for the central models and the escape fraction remains constant. Also the observer viewing angle have no effect in the escape fraction neither for the homogeneous and central models. Complementing this analysis we study the average number of scatterings  $\langle N_{scatt} \rangle$  that photons perform before escaping of the cloud taking into account rotational effects. The main result here is for the homogeneous models for which as velocity increase photons escape with about  $\sim 39\%$  less scatterings than in the static case.

As an application of these results we compute the integrated flux taking into account the narrow band filters used by (Steidel et al 2011), for our models we found an important decrease up to 40% for the homogeneous models, and up to 22% for the dusty homogeneous models in the flux as velocity increase. Also we calculate at what redshift should the filter be in order to get the maximum flux, and for the three filters we get values that rely in the filter redshift range. This effects would have a relevant implication at the time to find high redshift galaxies.

This paper illustrates for the first time the main effects of rotation in the morphology of the Ly $\alpha$  emission line, we estimate the range of this effects for simplified models.

## ACKNOWLEDGEMENTS

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## APPENDIX A: TABLES