

Lyman- α photons through rotating outflows

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ABSTRACT

Outflows and rotation are two ubiquitous kinematic features in the gas kinematics of galaxies. Here we perform Monte Carlo radiative transfer simulations of outflowing gas with additional solid body rotation to understand how these kinematic features impact the morphology of the Lyman- α emission line. We explore a range of Hydrogen optical depth of $10^5 \leq \tau_{\text{H}} \leq 10^7$, rotational velocity $0 \leq v_{\text{rot}}/\text{km s}^{-1} \leq 100$ and outflow velocity $0 \leq v_{\text{out}}/\text{km s}^{-1} \leq 50$. We find three important consequences of rotation. First, it introduces a dependency with viewing angle; second it produces a line broadening and third it increases the flux at the line’s center. We also develop a semi-analytic model that modifies the spectra of pure outflow simulations that manages to reproduce the line broadening and flux change at the line’s center within a 7% and 30% precision, respectively.

Key words: galaxies: dwarf — radiative transfer — Methods: numerical

1 INTRODUCTION

The interpretation of the Lyman- α emission in galaxies is key to understand their evolutionary processes, specially in star-forming, low-dust galaxies (Partridge & Peebles 1967). Recent improvements in instrumentation have revolutionized the kind of studies that can be performed on Lyman- α emitting galaxies (LAEs.) For instance, it is now possible to infer detailed kinematic maps for nearby galaxies. The study of these maps would allow us to build data-driven models to interpret the Ly α spectra of unresolved galaxies, helping us to constrain the physical conditions of the interstellar medium (ISM) processing the Ly α radiation.

For instances, dwarf galaxies show signs of coherent rotation (Swaters et al. 2009). Some of them are expected to have high neutral gas contents and thus show Ly α emission with rotation imprints (???) Some Compact Dwarf Galaxies actually show gas kinematics that range from pure rotation to high velocity dispersion without a clear rotation pattern. (Cairós et al. 2015; Cairós & González-Pérez 2017)

The case for outflows as traced in the Ly α line is much better established. In many cases the Ly α line profiles has a single peak redwards from the line’s center, in other cases there is a double peak but the peak on the red side is stronger (e.g. ???). These features been readily explained as the consequence of multiple Ly α photon scatterings through an homogeneous outflowing shell of neutral Hydrogen (?Orsi et al. 2012; ?; ?).

Here we present for the first time a study of the joint effects of galaxy outflows and rotation, two of the three major kinematic components expected in LAEs. We study a simplified geometrical configuration corresponding to a spherical gas cloud with symmetrical radial outflows and a rotation profile corresponding to a solid body. We base our modeling on a Monte-Carlo radiative transfer code called CLARA (Code for Lyman Alpha Radiation Analysis) presented for the first time by Forero-Romero et al. (2011).

Besides modeling the impact of joint rotation and outflows, we also check to what extent the analytical model presented by Garavito-Camargo et al. (2014) to explain the effects of rotation can also be applied in our case. We show how solid body rotation effects can be modelled by postprocessing the results of outflow only simulation.

in the results of other radiative transfer model in the case of large optical depths. In this case it is a good approximation to Doppler boost the results of the model without rotation.

The structure of the paper is the following. We introduce first our theoretical tools and assumptions in Section 2. We continue in Section 3 with the results from the Monte-Carlo simulation, the comparison against the semi-analytical approximation which we use to make a thorough exploration of the effect of rotation. In Section 4 we discuss our results and their possible implications for observational analysis to finally present our conclusions in Section 5.

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| τ_{H} | v_{rot} (km s ⁻¹) | v_{out} (km s ⁻¹) |
|--|--|--|
| {10 ⁵ , 10 ⁶ , 10 ⁷ } | {0, 50, 100} | {5, 25, 50} |

Table 1. Parameters' Values. List of values that were used to construct the radiative transfer models. Values in braces for a row indicate that all possible combinations in of τ_{H} , v_{rot} and v_{out} are used.

2 THEORETICAL MODELS

The Monte Carlo code we use (CLARA) follows the propagation of individual photons through a neutral Hydrogen medium characterized by its temperature, velocity field and global optical depth. The code assumes an homogeneous density throughout the simulated volume. In the current implementation we neglect the influence of dust. Our basic model is an spherical distribution of neutral hydrogen, an approximation commonly used in the literature, as it explains a wide variety of observational features (Ahn et al. 2003; Verhamme et al. 2006; Dijkstra et al. 2006).

The velocity field we use captures both outflows and rotation. Outflows are described by a Hubble-like radial velocity profile with the velocity magnitude increasing linearly with the radial coordinate; the outflows model is fully characterized by v_{out} , the velocity at the sphere's surface. Rotation follows a solid body rotation profile, which is fully characterized by V_{rot} , the linear velocity at the sphere's surface.

The total velocity field corresponds to the superposition of rotation and outflows. The cartesian components take the following form:

$$v_x = \frac{x}{R} V_{\text{out}} - \frac{y}{R} V_{\text{rot}}, \quad (1)$$

$$v_y = \frac{y}{R} V_{\text{out}} + \frac{x}{R} V_{\text{rot}}, \quad (2)$$

$$v_z = \frac{z}{R} V_{\text{out}}, \quad (3)$$

where x , y and z are the cartesian position coordinates with the origin at the sphere's center, R is the radius of the sphere and the direction of the angular velocity vector corresponds to the \hat{k} unit vector.

For each model setup we follow 10^5 individual photons generated at the center of the sphere at the Ly α line's center as they propagate through the volume and finally scape. We store the final frequency and propagation direction for each photon at its last scattering.

In Table 1 we list the combination of τ_{H} , v_{rot} and v_{out} values used in this paper. The range of values have some overlap with the expectations from a dwarf galaxy with a total neutral hydrogen mass of 10^8 - $10^9 M_{\odot}$. We run a total of 27 different models.

Garavito-Camargo et al. (2014) presented an analytical model that accounts for the effects of pure rotation on the Ly α line morphology. The basic assumption of their analytical model is that each differential surface element on the sphere Doppler shifts the photons that it emits. In this paper we introduce this ansatz by post-processing the results

of the outflows simulations without rotation. The frequency of each photon is Doppler shifted as follows

$$x' = x + \frac{\vec{V}_{\text{rot}} \cdot \hat{k}}{v_{\text{th}}} \quad (4)$$

where x' is the photon's new frequency, x is the photon's frequency after being processed by the outflow, v_{rot} is the rotational velocity at the point of escape of the photon, \hat{k} is the photon's direction of propagation and v_{th} is the thermal velocity of the sphere.

This allows us to produce new Ly α spectra and compare them with the full radiative transfer solution including both outflows and rotation.

3 RESULTS

3.1 Qualitative Trends

Figure 1 summarizes the most important trends. The six panels correspond to $\tau = 10^6$ and a viewing angle of $\theta = 90^\circ$, that is, perpendicular to the rotation axis of the galaxy. In every panel the thin black line corresponds to the pure outflow solution, i.e. without rotation. From top to bottom we see the effect of increasing the outflow velocity, which is the expected increasing asymmetry towards the red peak.

The thick black line corresponds to the solution that includes both outflows and rotation. Comparing the left and right columns (lower versus higher rotational velocity) we can see two immediate effects. First, the line broadens and second, the intensity at the line's center increases.

Finally, the thick gray line corresponds to the pure outflow solution with the Doppler boost added to model rotation's influence. At $\tau_{\text{H}} = 10^6$ the Doppler boost does a good job at capturing the broad morphological features introduced by rotation: the angle dependence, the broadening and the intensity increase at the line's center.

In Figure 2 we show the same results as in Figure 1 but for a viewing angle of $\theta = 90^\circ$, that is parallel to the rotation axis. In this case we confirm the result presented by Garavito-Camargo et al. (2014), namely that pure rotation introduces a strong dependence with viewing angle, a trend that we find also holds for rotation mixed with outflows.

The quality of the results from the Doppler boost improves for higher τ_{H} values. In the Appendix we show the same plots as Figures 1 and 2, there it is evident that for $\tau_{\text{H}} = 10^5$ the results are not as good as they are for $\tau_{\text{H}} = 10^6$, and that for $\tau_{\text{H}} = 10^7$ the Doppler boost provides a remarkable good approximation.

3.2 Quantitative trends

After finding the quantitative influence of the different parameters we move onto a qualitative study. To do this we summarize the line morphology by four different characteristics: standard deviation (STD), skewness (SKW), bimodality (BI) and valley/peak ratio. These quantities are defined by the following equations (Kokoska & Zwilling 1999):

$$\text{STD} = \sqrt{m_2}, \quad (5)$$

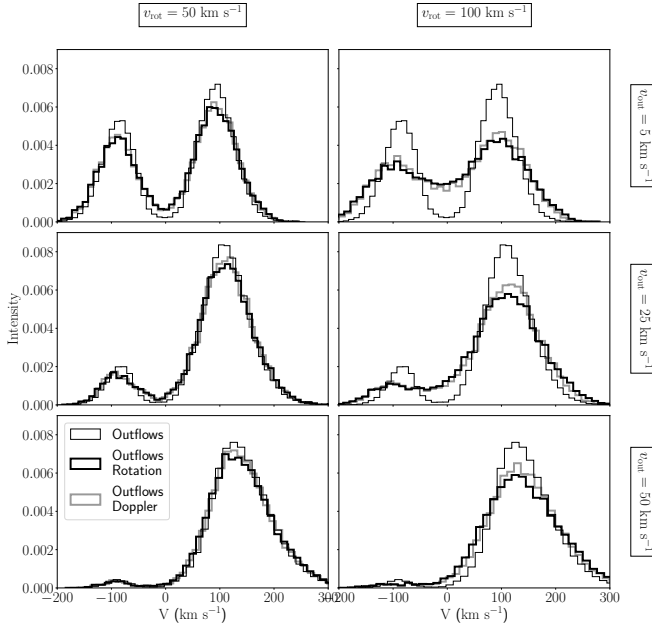


Figure 1. Qualitative trends of changing outflow and rotational velocity viewed perpendicular to the rotation axis. Here we fix $\tau_H = 10^6$ and $\theta = 90^\circ$. We vary v_{rot} increasing from left to right and v_{out} increasing from top to bottom. The thin black line corresponds to the Ly α line obtained with CLARA without any rotation and the indicated outflow velocity. The thick black line corresponds to the results including both outflows and rotation. The thick gray line shows the results of modifying the pure outflow solution by the Doppler shift presented in Equation 4 (in thin line), if there is a radiative transfer of rotation and outflows (thick and clear line), and if there is a radiative transfer of only outflows, but also a Doppler shift from the rotational velocity (thick and dark line).

$$\text{SKW} = \frac{m_3}{m_2^{3/2}}, \quad (6)$$

$$\text{BI} = \text{KURTOSIS} - \text{SKW}^2 = \frac{m_4}{m_2^2} - \frac{m_3^2}{m_2^3}, \quad (7)$$

where each m_i is the i -th moment about the mean. The STD has velocity units and quantifies the line's width. The SKW is adimensional and quantifies the peaks' asymmetry. In the case of a bimodal distribution, $\text{SKW} > 0$ means that the blue peak is taller and for $\text{SKW} < 0$ the red peak is taller. The BI is adimensional and quantifies whether the line has 1 or 2 peaks: it is always ≥ 1 (Pearson 1929) and the closer to 1, the more bimodal is the line (i.e. has 2 similar peaks). We found by visual inspection of our spectra that $\text{BI} = 2.5$ marks the transition between two peaks (however imbalanced) and a dominant single peak.

Figure 3 summarizes the standard deviation results for all our models. Each panel shows the STD as a function of v_{rot} . The black triangles correspond to the full RT solution and the line to the DS approximation. The optical depth increases from top to bottom and the outflow velocity from left to right. This quantitative plot confirms that the line width increases with rotational velocity, all else being equal. The DS successfully reproduces all trends with the optical

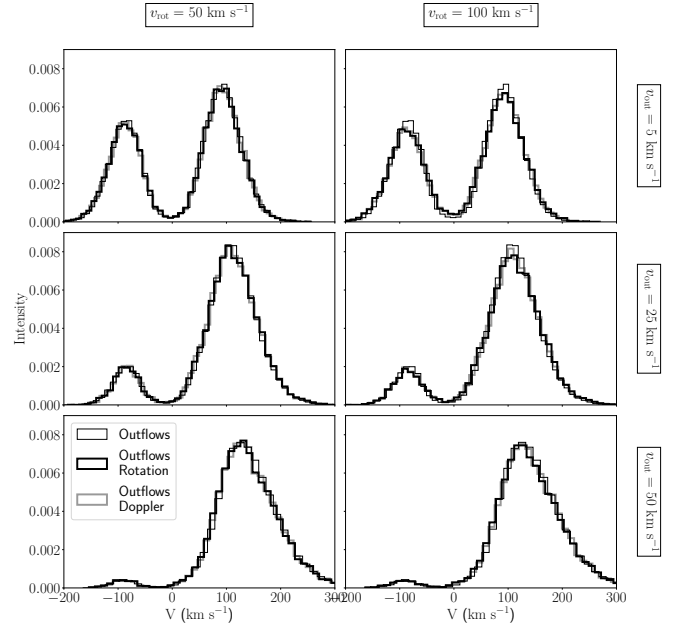


Figure 2. Qualitative trends of changing outflow and rotational velocity viewed parallel to the rotation axis. Same layout as Figure 1, this time the viewing angle corresponds to $\theta = 0^\circ$. The effects of rotation on the Ly α line morphology are not visible when viewed parallel to the rotation axis.

depth, rotational velocity and outflow velocity. However, the DS consistently underestimates the STD. The difference between the RT and DS increases with the outflow velocity and the rotational velocity, and decreases with increasing optical depth. In the range of parameter space explored, this difference has an upper bound of $\sim 7\%$, 3% and $\sim 2\%$ for $\tau_H = 10^5$, 10^6 and 10^7 , respectively.

This shows that the DS model can reproduce the main characteristics of the RT one. Because of this, we can introduce rotation effects in any spectra without running the radiative transfer simulations, that usually take a significant amount of time and computational resources.

In addition to this, we also evaluate the effects of the viewing angle for fixed rotational and outflows velocity. We measure the intensity of the valley between peaks, for each θ and τ_H . Figure 6 summarizes the information with all plots corresponding to the same outflow velocity of $v_{\text{out}} = 5 \text{ km s}^{-1}$ and rotation velocity of $v_{\text{rot}} = 100 \text{ km s}^{-1}$.

4 DISCUSSION

4.1 Theoretical Insights

Why Doppler Shift works. Talk about radiative transfer... In Fig. 7 we present the spectrum of a LAE taken from different sides of the galaxy. As the LAE is rotating, one side is being redshifted while the other is blueshifted. We see that the combined spectrum is a weighted line, in solid black, that combines these two. This shows that there is in fact a Doppler Shift and then it justifies our choice to apply it after the outflows spectrum is obtained.

A first approach to an analytical expression that returns

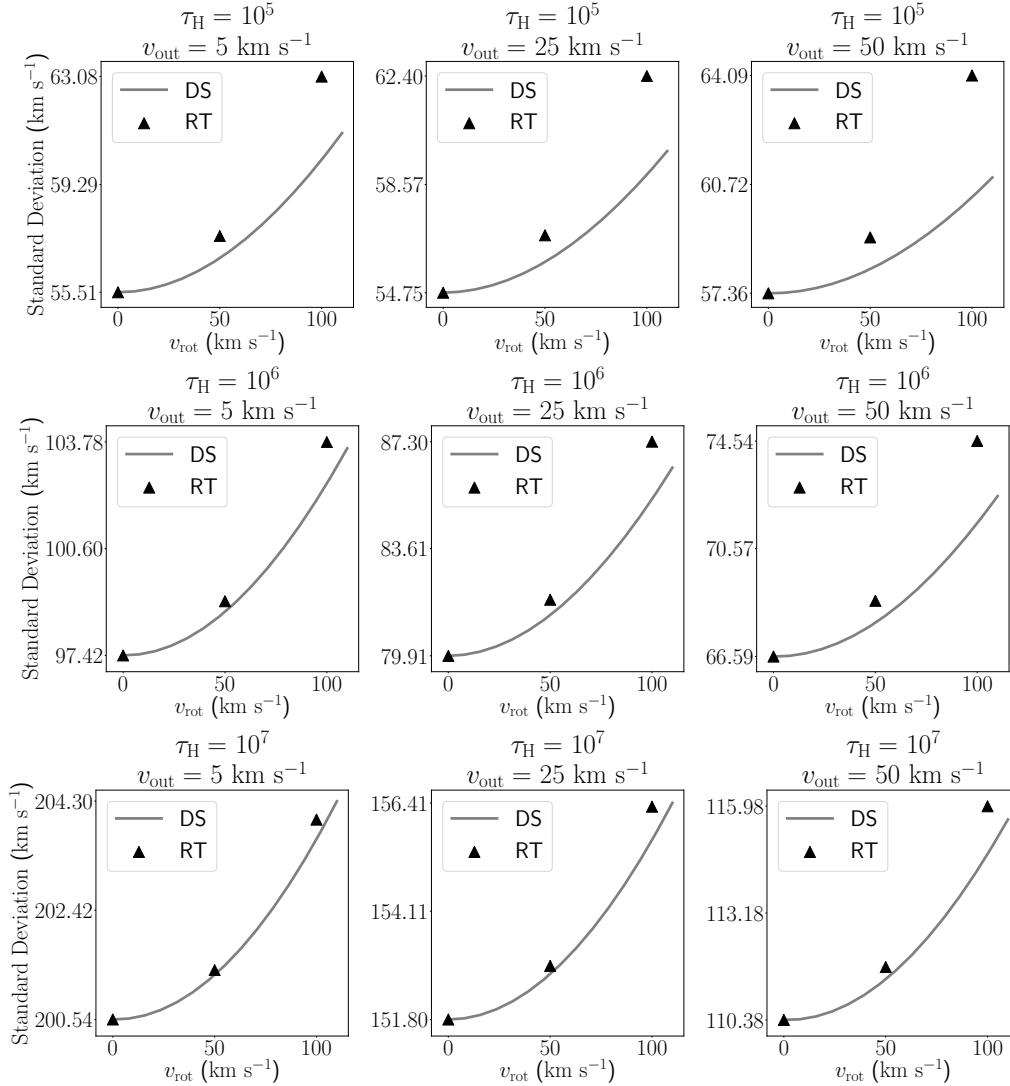


Figure 3. Standard Deviation trends. Results for all the Radiative Transfer simulations (in triangles) compares against the Doppler Shift model (lines).

the Ly α spectrum from a rotating galaxy is presented by Garavito-Camargo et al. (2014). This derivation is based on the assumption that the distribution of photons' propagation directions at the edge of the galaxy is anisotropic and depends of τ_H only. So this approximation becomes more accurate with higher optical depth and it is also the reason why the Doppler Shift technique to induce rotational effects to an outflow Ly α spectrum works.

On the other hand, regarding the parameters v_{rot} , v_{out} , and θ for which this model would work, we have the following. The effect of the outflows velocity is much more sensitive on the spectrum than the rotational one; meaning that for a high v_{out} , the v_{rot} value would have to be equal or greater in order to be able to glimpse the shift in frequency that rotation induces. Regarding θ , the introduction of rotation in the model implies that it will only affect galaxies with its viewing angle $\theta \neq 90^\circ$. This can be observed in the cartesian components of the velocity of the atoms (Eq. 1, 2, 3) where the only velocity factor affecting v_z is the outflows one.

4.2 Application to observational data

We find three different approaches how this model can have observational implications. Firstly, as the resolution of astronomical instruments is increasing, new images from LAEs can be spatially resolved in a way that rotation velocities of the galaxy can be determined. New spectrographs like MUSE should help obtain kinematic information from LAEs by using our model. As for now, previous works in the literatures have already found useful data to support this idea. Fig 7 of Prescott et al. Prescott et al. (2015) shows the presence of Doppler shift and Herenz et al. (2016) creates 2D line of sight velocity maps of several LARS (Lyman Alpha Reference Sample) galaxies.

Another application of this new model to the current interpretation of Ly α spectra, is that the central ($V = 0$) emission of the spectra seen in the Ly α line, is a consequence of the viewing angle of the galaxy and can be controlled by it. Several authors have suggested that this central emission is caused by radiation that escapes the galaxy without scat-

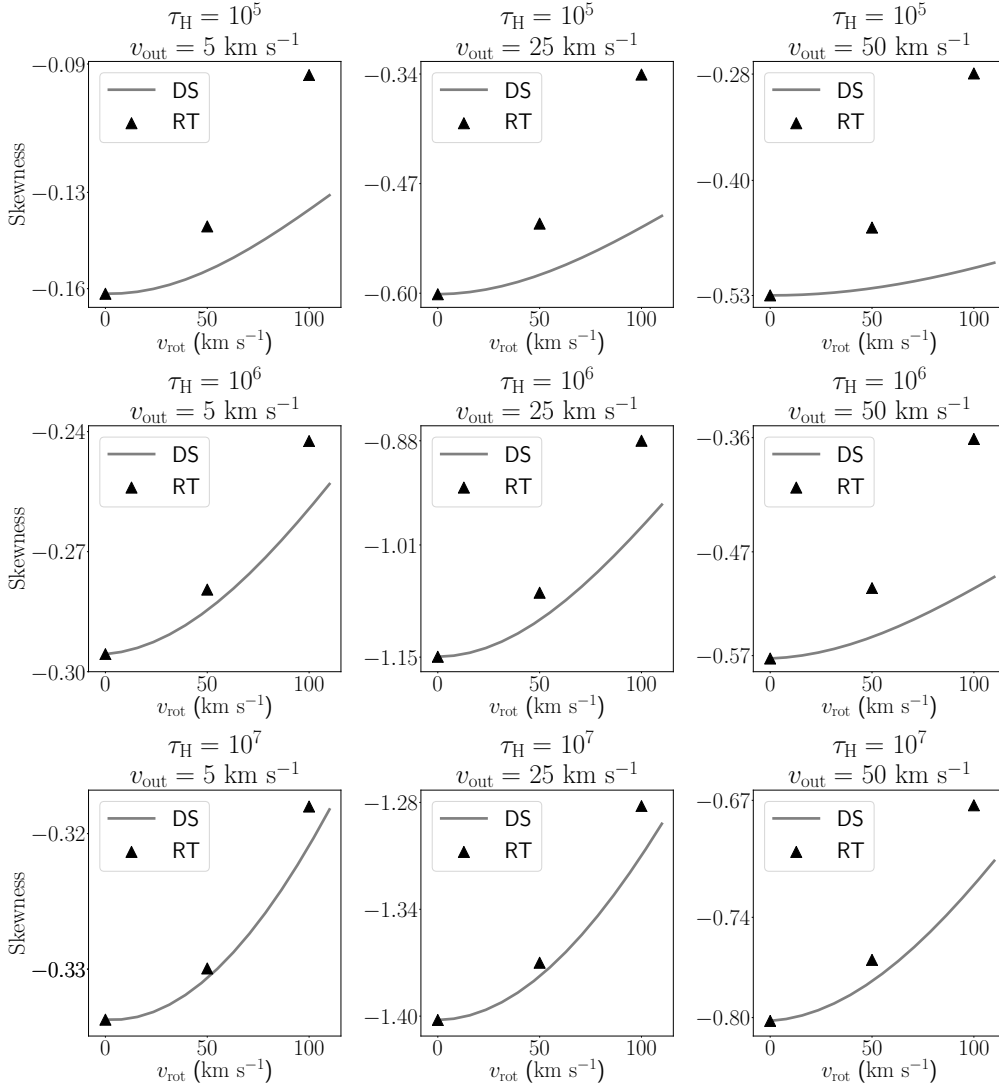


Figure 4. Skewness for RT and DS: The triangles represent the Radiative Transfer and the lines represent the Doppler Shift.

tering. So we present an alternative that solves this issue. In addition, the effect of outflows velocities v_{rot} in current models can modify the asymmetry of peaks present in the Ly α line. However the intensity of the valley and the width of the line were not easily reproduced. In this work we provide a tool to provide these effects with values of v_{out} and v_{rot} that do not exceed the typical LAEs' values found in the literature.

Kulas... Finally, we present a reconstruction of a selected Ly α spectrum presented by Kulas et al. (2012) and reproduced with the permission of the author. We create a fit of the Ly α line and predict its kinematic properties.

5 CONCLUSIONS

In this paper we explore, for the first time in the literature, the results of a model for the emergent Ly α line from rotating outflows. The main results for the model are computed from a Monte-Carlo radiative transfer simulation and

confronted with a simple semi-analytic ansatz that adds the effects of rotation onto results of pure outflow kinematics.

The main effects of rotation on the Ly α line morphology are:

- Broadening the line.
- Increasing the intensity at the line's center.
- Inducing a dependency on the viewing angle. The closer the observer is to the pole of the galaxy (defined by the rotation axis), the smaller are the effects from rotation.

We found that in the case of solid body rotation these effects can be quantitatively explained by a Doppler boost, where the Doppler factor can be computed as the product of quantities at the surface of last scattering, namely $\vec{v}_{\text{rot}} \cdot \hat{k}$, where \vec{v}_{rot} is the velocity due to rotation and \hat{k} is the direction of the photon's propagation. These conclusions, specially the confirmation of the Doppler boost as a good proxy for solid body rotation, strengthen the evidence reported by Garavito-Camargo et al. (2014) when they modeled the effect of pure rotation on Ly α spectra.

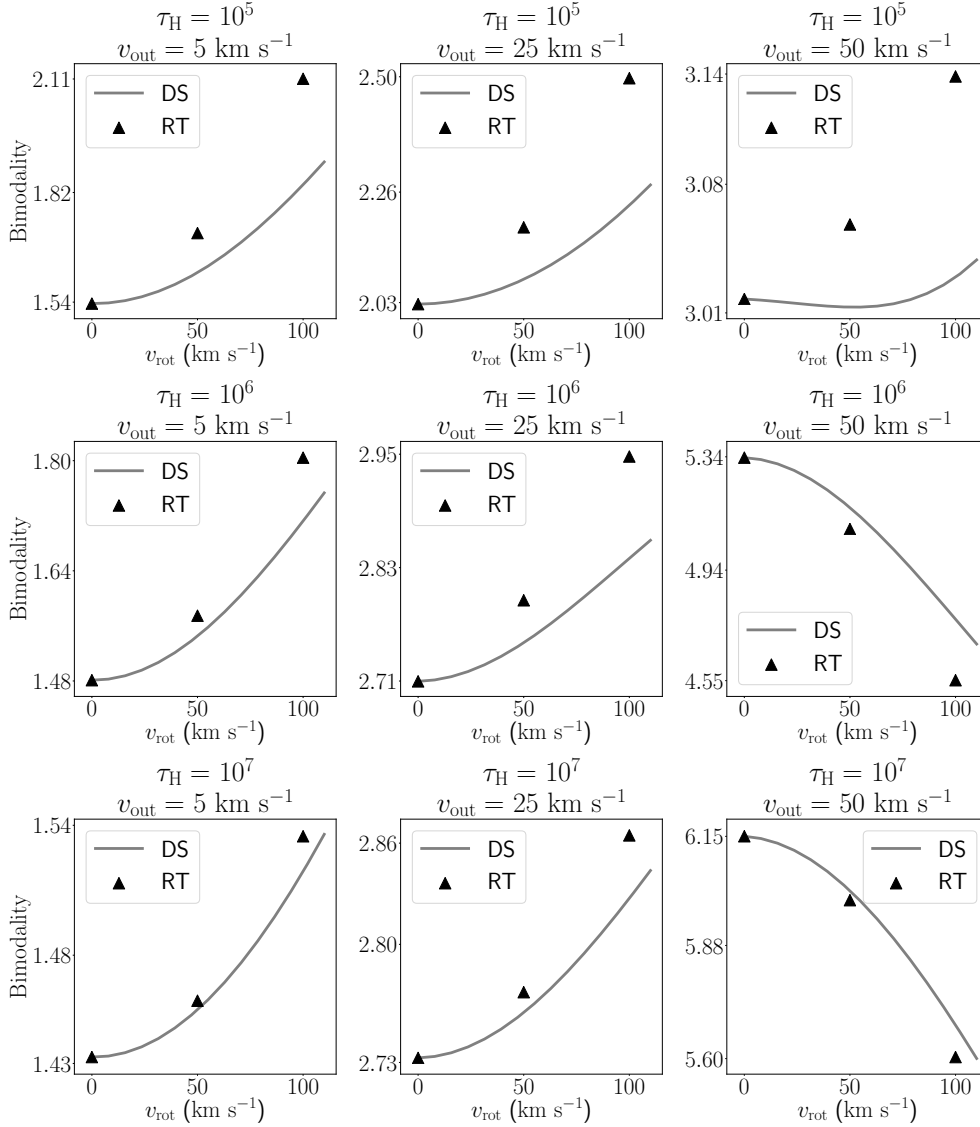


Figure 5. Bimodality for RT and DS: The triangles represent the Radiative Transfer and the lines represent the Doppler Shift.

As an application to observational data we find that recent results that take the spectra of two different sides of a galaxy can detect the effect of approaching/receding gas motions. However, the distances between the peaks of these two spectra correspond to $\approx v_{\text{rot}} \cos \theta$ due to the weights of the emitting regions.

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APPENDIX A: ADDITIONAL FIGURES

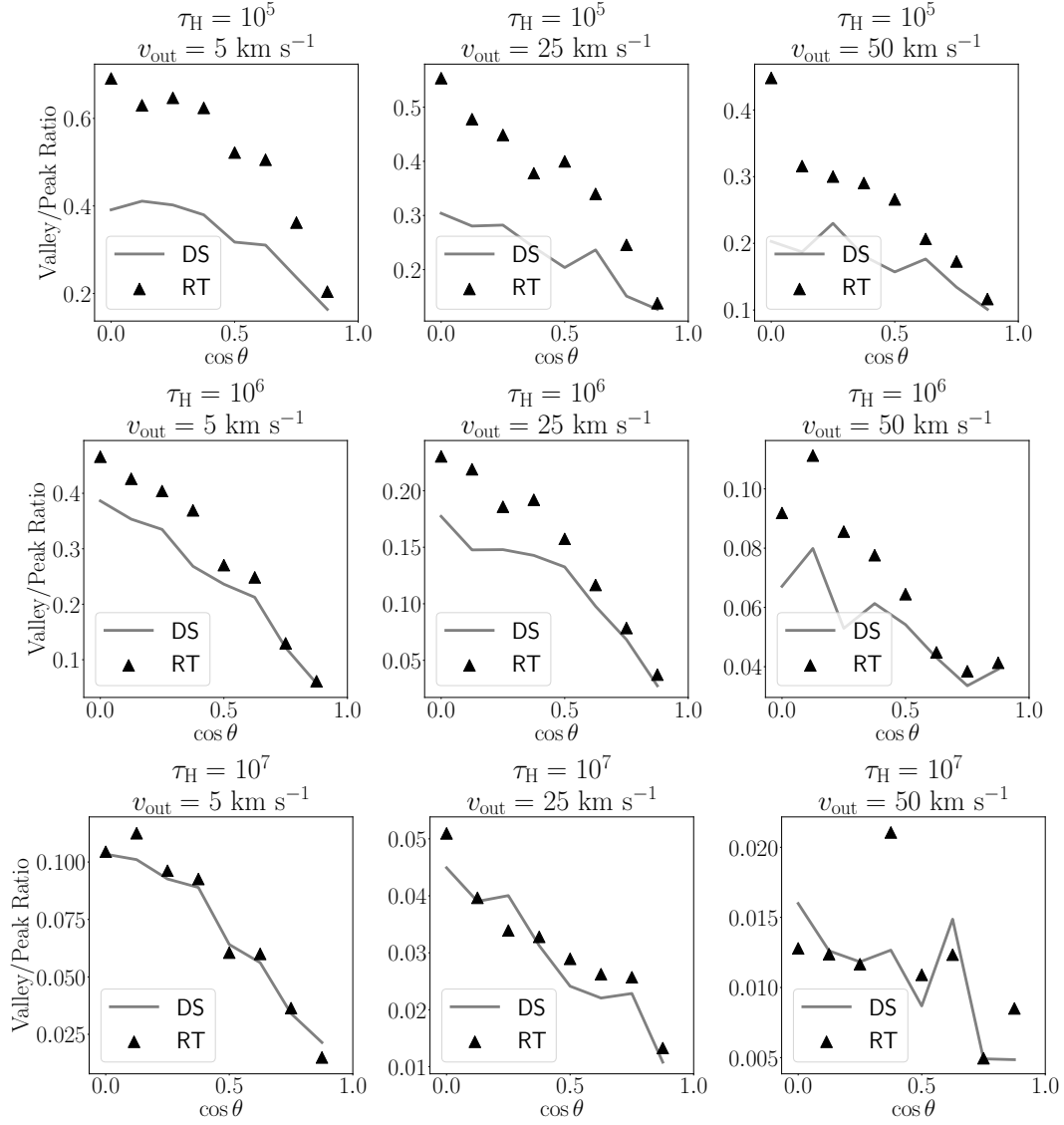


Figure 6. Valley Intensity: We show for each τ_H the dependency that the viewing angle θ has on the line's the valley intensity. The larger $\cos \theta$ the lower is the valley intensity, so the higher θ , the higher the valley intensity. Also, the higher τ_H , the better is the fit RT-DS. We fixed $v_{\text{rot}} = 100 \text{ km s}^{-1}$.

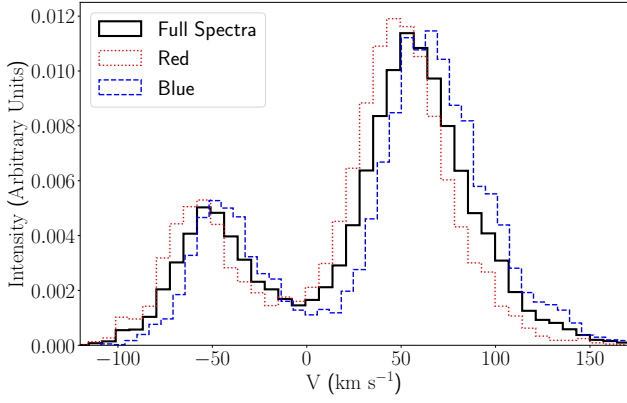


Figure 7. Doppler Shift: We fix $v_{\text{out}} = 25 \text{ km s}^{-1}$, $v_{\text{rot}} = 100 \text{ km s}^{-1}$, $\tau_{\text{H}} = 10^5$.

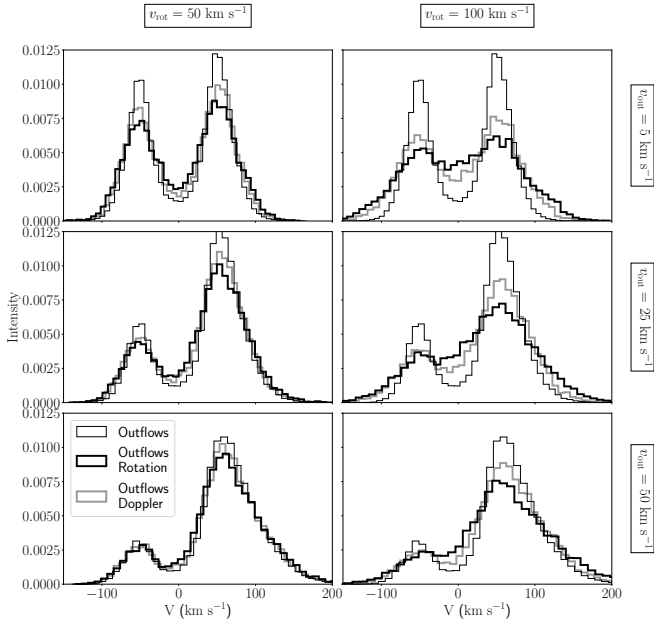


Figure A1. Qualitative trends of changing outflow and rotational velocity. Same layout as Figure 1, this time $\tau_{\text{H}} = 10^5$ and $\theta = 90^\circ$.

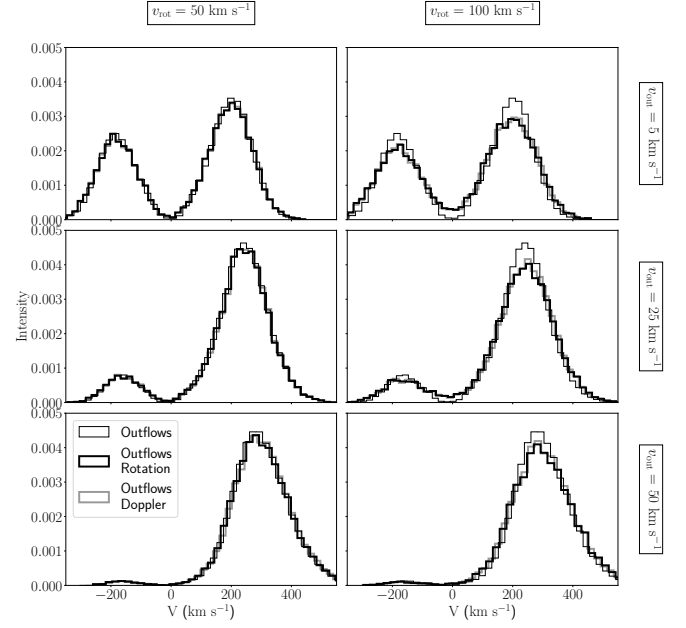


Figure A2. Qualitative trends of changing outflow and rotational velocity. Same layout as Figure 1, this time $\tau_{\text{H}} = 10^7$ and $\theta = 90^\circ$.