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Effects of bulk gas rotation on the emergent Lyman-α line in distant galaxies

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ABSTRACT

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 in the shape of this line. In particular we study the case in which this gas is spherically symmetric and its rotating.

2 IMPLEMENTATION OF BULK GAS ROTATION

We implement into CLARA the simplest model whereby a sphere rotates with homogeneous angular velocity. We define a cartesian coordinate system with its origin at the center of the sphere and the rotation axis to be the z-axis, the components in the bulk velocity field, $\vec{v} = v_x\hat{\imath} + v_y\hat{\jmath} + v_z\hat{k}$. in the gas can be written as

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

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

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

where R is the radius of the sphere and $V_{\max}$ is the linear velocity at the sphere's surface. The minus sign in the x-component of the velocity is due to the direction of rotation, in this case we assume that the angular velocity vector goes in the $\hat{k}$ direction.

3 GRID OF SIMULATED MODELS

We compute the emergent Lyman-α line for several models with differents values for the maximal rotational velocity, hydrogend optical depth, dust optical depth and initial distributions of the photons with respect to the gas. There are in total 60 models with the input parameters summarized in Table 1.

Additionaly in the postprocessing process we will take into account different observer positions with respect to the cloud rotation axis.

Velocity (km s^{-1})	$V_{\max}$	0, 50, 100, 200, 300
Hydrogen Optical Depth	τ_H	10^5, 10^6, 10^7
Dust Optical Depth	τ_A	XXX
Photons Distributions		Central, Homogeneous

Table 1. Values for the varying input parameters in CLARA. Taking into account all the possible combinations for these models

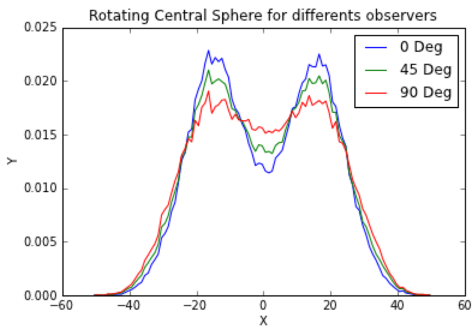

Figure 2. Spectra for different observers. Model:$V = 300km/s$, Optical Depth $\tau = 10^7$ and Central Distribution without dust.

Now if we take into account the position of the observer and compute this for differents angles of observation θ the outcoming spectra is modified as is shown in Figure 2. The main feature here is that as the angle increases the line height decreases. It means that a observer in the poles will observe a higher double peak than a observer in the ecuator. We will understand this in more detail when we present the results of the scape fraction in section 4.3.

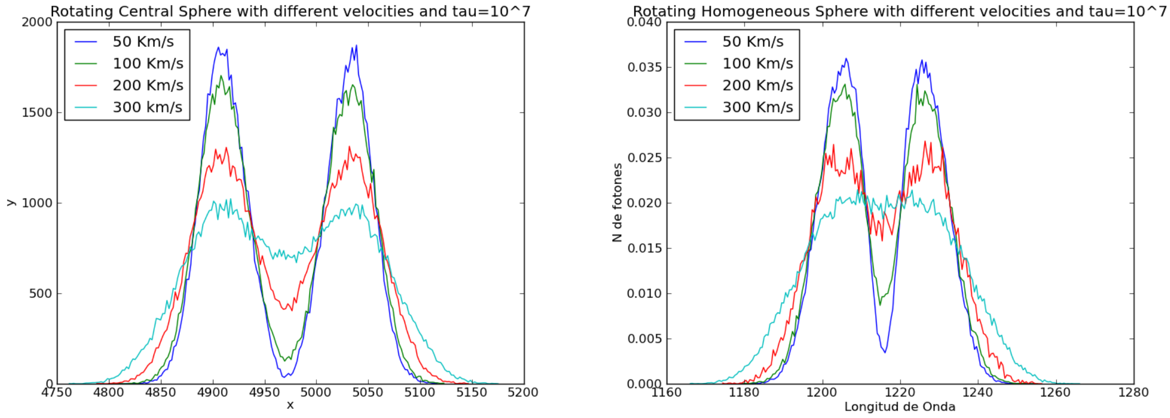

Figure 1. Shape of the lyman alpha line for differents velocities. The left panel show the central distribution while the right panel show the homogeneous distribution.

4 RESULTS

In the previous section we describe the models that we use to study the effect of rotation in the Lyman alpha line for this we saw the outcoming specrtums including rotation. Now we show the main results that we obtain, in particual we pay spetial attention to the position of the maximums, the width of the line and the escape fraction in function of the rotational velocity and the angle of observation θ.

In Figure 3 the effect that rotation have in the spectra is shown, for both distributions central (Left) and homogeneous (right). This is a general case in the sense that is independent of the position of an external observer.

4.1 Maxima Positions

The maximums position gives information about the wave lenght of the mayority of the outcoming photons after they interact with the gas, in addition as a photon have more scatterings its wave lenght would be larger than the initial which is 1216 Å. As we can see in Figure 4.1 the position of the maximums does not change with rotational velocity for the central dsitribution. On the other hand for the homogeneous distriution the maxima position X_m change for $Log_{10}\tau = 5$, this is because at higher rotational velocities photons escape with less scatterings, for $v = 100\frac{km}{s}$ the majority of the photons still escape with scatterings but for $v = 200\frac{km}{s}$ the number of photons that escape with a few or any scatterings is higher, this is why the maxima change to the center of the spectra.

If we now study the effect of the optical depth τ in the maxima position X_m Figure 4.1, we found that as the optical depth increase (include reference of previous articles) the maxima position increase and this is a well known result, but when rotation is included the dependence is not linear.

4.2 Line Equivalent Width

The width of the line provide information of how many photons scape with a particular wave lenght, in the ideal case in which all the photons scape with the same wave lenght the outcoming spectrum would be narrower.

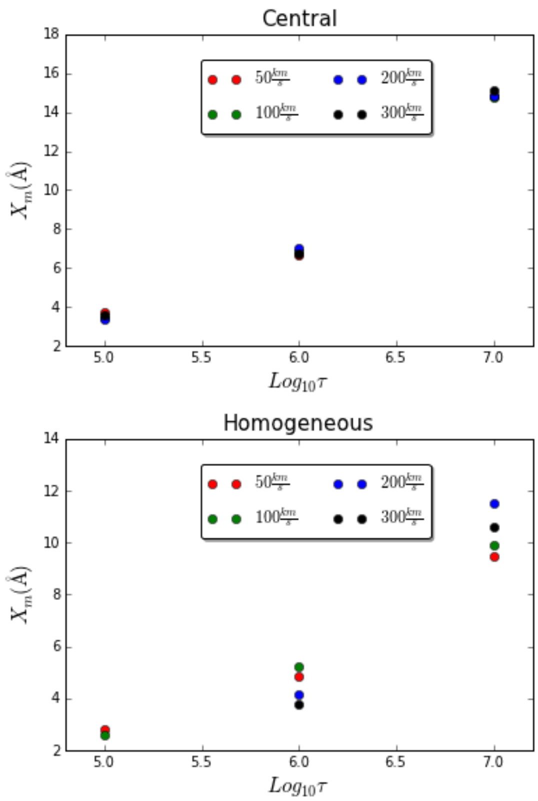

Figure 3. Position of the maxima in the outgoing spectra for differents Optical Depths, (up)Central Distriution, (Down) Homogeneous Distribution.

We found a dependency of the equivalent width with the rotation of the gas cloud for all the models we study, this is shown in Figure 4.2. As velocity increase also the equivalent width increase, it means that some photons escape with fewer scatterings than the static case but at the same time some photons escape with more scatterings.

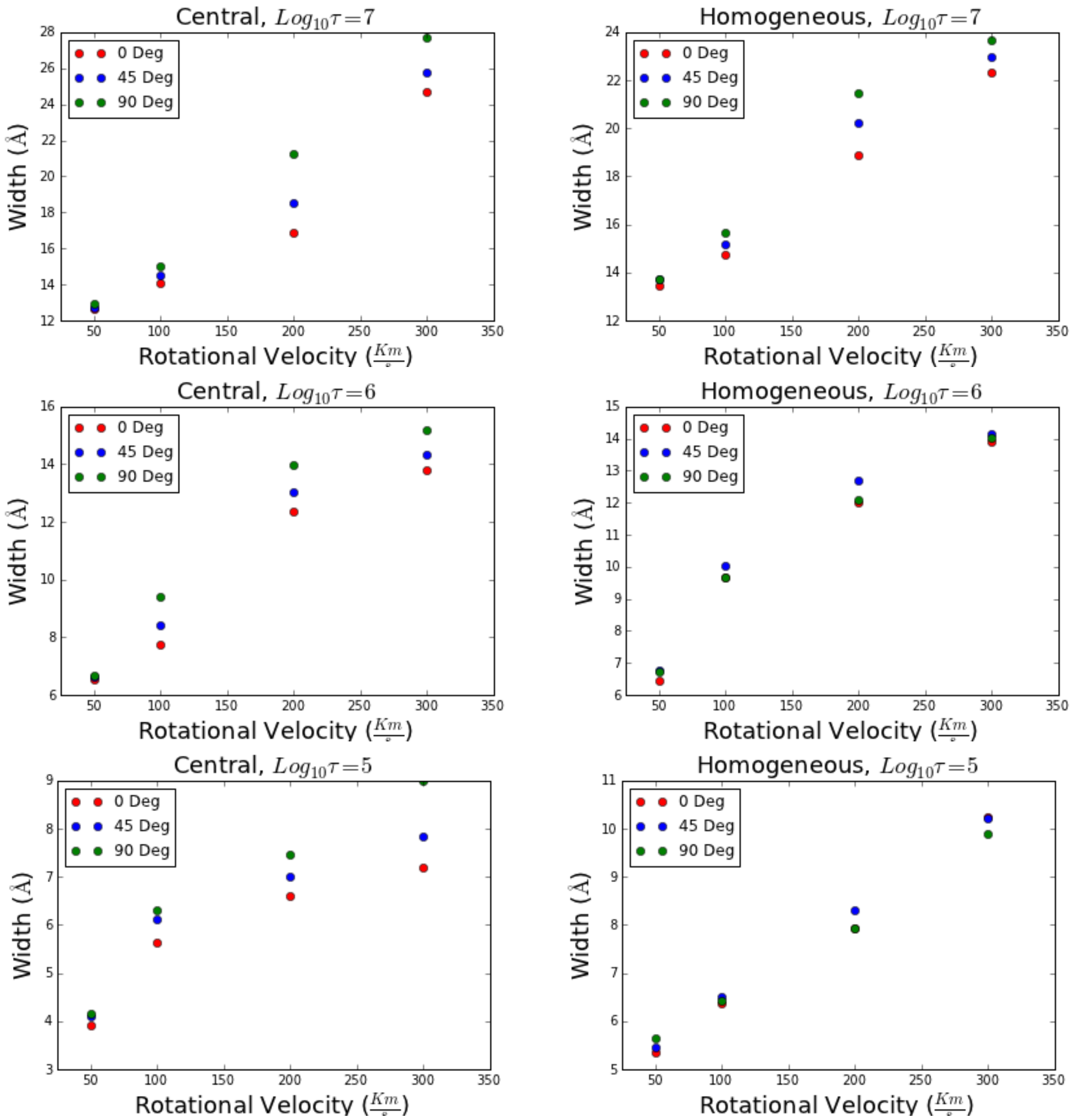

Figure 5. Width of the lyman-alpha line for all the models.

We also found that the equivalent width is not the same for differents angles of observation in particular as the angle increase the width also increase Figure **??**, this is related with the fact that photons escape easily (with less scatterings) in the $\hat{k}$ direction
Following the convention of Verhamme et al 2012 we define $\mu = cos(\theta)$, we can make a polynomial fit the $EW(\mu)$ for our models, this is resumed in Table 2

Model	Fit
Central, $\tau = 10^5, V = 200\frac{km}{s}$	$EW(\mu) = -59 - 1677\mu - 17864\mu^2 +$
Central, $\tau = 10^6, V = 200\frac{km}{s}$	$EW(\mu) = -1 + 53.8\mu - 1080\mu^2 +$
Central, $\tau = 10^7, V = 200\frac{km}{s}$	$EW(\mu) = 0.011 + 0.9\mu - 27\mu^2 +$
Hom, $\tau = 10^5, V = 200\frac{km}{s}$	$EW(\mu) = 11.66 - 187.22\mu - 54.58\mu^2 +$
Hom, $\tau = 10^6, V = 200\frac{km}{s}$	$EW(\mu) = -361.64 + 17158.92\mu - 305268.4\mu$
Hom, $\tau = 10^7, V = 200\frac{km}{s}$	$EW(\mu) = -0.28 + 23.29\mu - 721\mu^2$ -

Table 2. Fits for EW models

4.3 Escape Fraction

The fraction of photons that escape from the cloud of gas and dust is defined as:

$$F_e = \frac{\Sigma_{NI}\vec{k}\cdot\vec{o}}{\Sigma_{NF}\vec{k}\cdot\vec{o}} \tag{2}$$

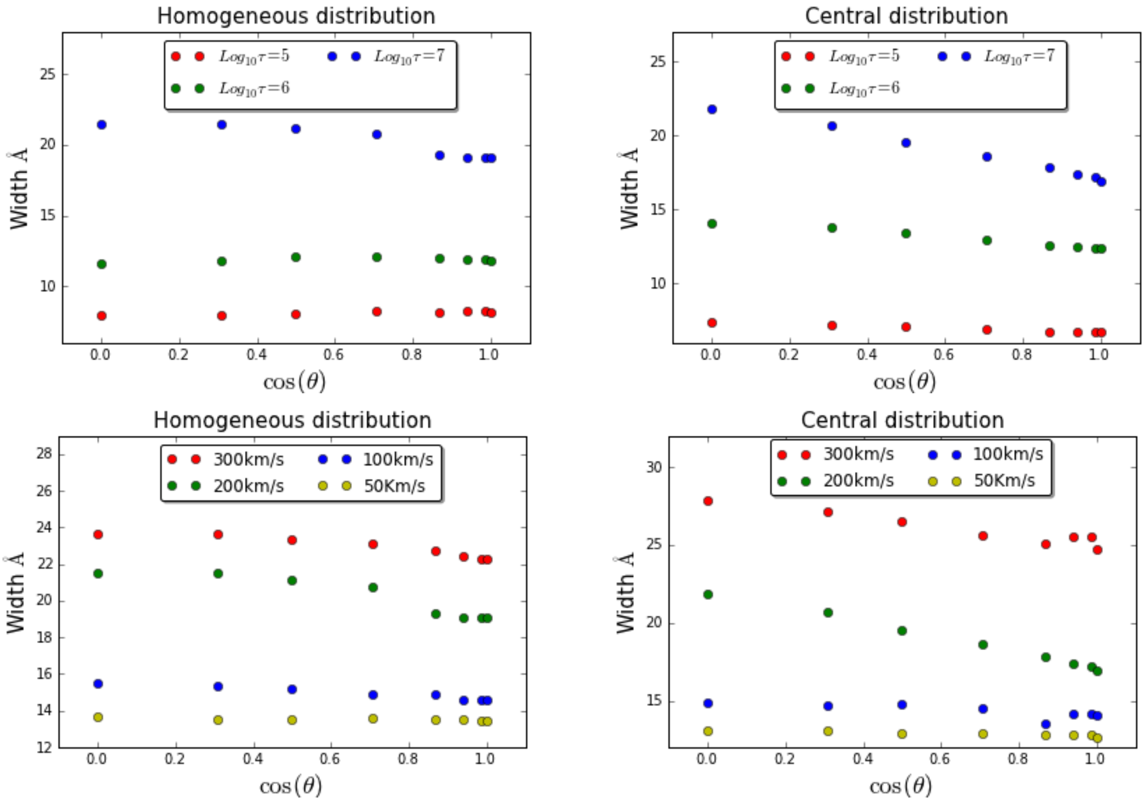

Figure 6. Width of the lyman-alpha line for all the models.

Velocity (Km/s)	Maximum 1 position	Maximum 2 position
50	-16.2695	16.23705
100	-15.66496	15.33504
200	-16.93149	14.56851
300	-13.40048	16.09952

Table 3. Optical Depth $\tau = 10^7$, Central Distribution

Where NI is the initial number of photons and NF is the final. This escape fraction is computed for all the models which results are shown in Fig.[6]

When the distribution is homogeneous the effect of velocity in the escape fraction is clear while in the central model the effect is not notorious. The main effect is that the escape fraction increase as the velocity increase.

5 DISCUSSION

6 OBSERVATIONAL IMPLICATIONS

7 CONCLUSIONS

ACKNOWLEDGEMENTS

APPENDIX A: TABLES

Line width

Velocity (km/s)	Maximum 1 position	Maximum 2 position
50	-7.46286	6.53714
100	-7.53357	6.96643
200	-8.17453	7.32547
300	-6.81487	6.18513

Table 4. Optical Depth $\tau = 10^6$, Central Distribution

Velocity(Km/s)	Maximum 1 position	Maximum 2 position
50	-4.33708	3.66292
100	-4.27326	3.72674
200	-3.7737	3.7263
300	-3.84903	4.15097

Table 5. Optical Depth $\tau = 10^5$, Central distribution

Escape fraction

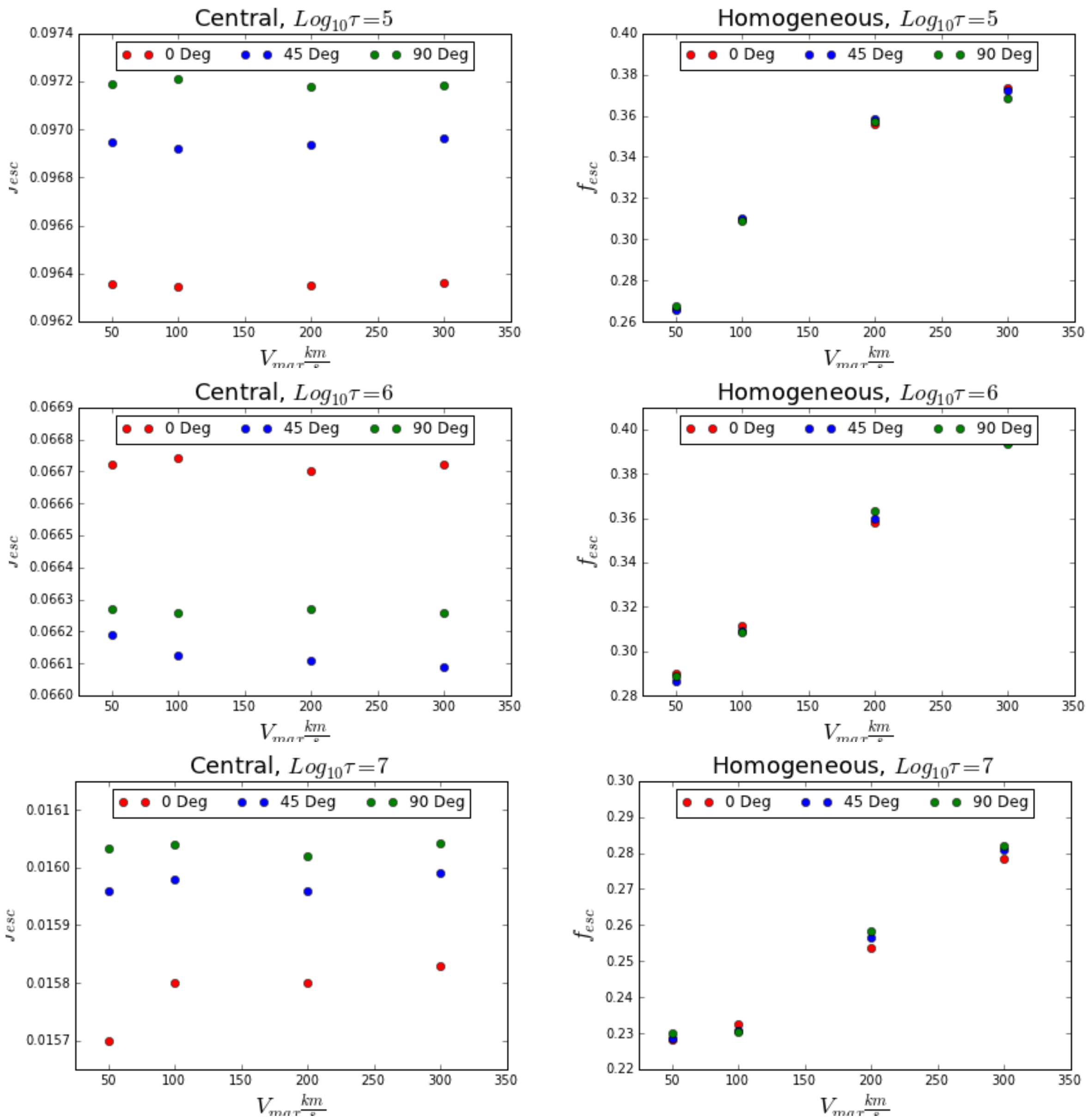

Figure 7. Escape fraction for all the models. Left panels show the central distribution, while right panels show the homogeneous distribution

Velocity(Km/s)	FWHM	θ
50	12.62	0^o
50	12.72	45^o
50	12.93	90^o
100	14.07	0^o
100	14.48	45^o
100	15.00	90^o
200	16.90	0^o
200	18.51	45^o
200	21.24	90^o
300	24.69*	0^o
300	25.79*	45^o
300	27.73*	90^o

Table 6. Lines Widhts for a Central Distribution and $\tau = 10^7$

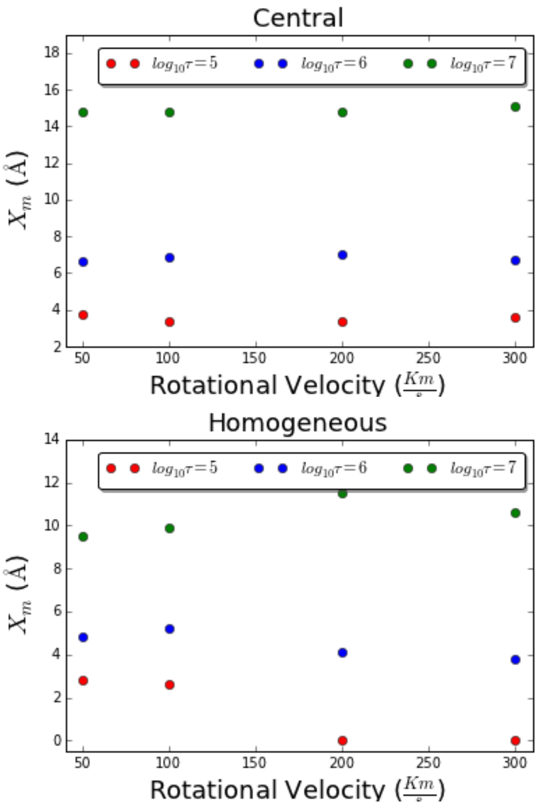

Figure 4. Position of the maxima in the outgoing spectra for differents Rotational velocities, (up)Central Distriution, (Down) Homogeneous Distribution.

[H]

Model	Velocity (km/s)	θ	Dust $\sum(s)$	$\sum(s)$
Homogeneous	50	0^o	13293.06	49939.53
Homogeneous	50	45^o	13291.04	50001.59
Homogeneous	50	90^o	13348.76	49922.73
Homogeneous	100	0^o	15527.69	50114.11
Homogeneous	100	45^o	15511.56	49967.17
Homogeneous	100	90^o	15401.71	49833.65
Homogeneous	200	0^o	17830.85	50078.69
Homogeneous	200	45^o	17932.87	50064.42
Homogeneous	200	90^o	17830.85	49931.748
Homogeneous	300	0^o	18687.33	50048.33
Homogeneous	300	45^o	18572.12	49922.67
Homogeneous	300	90^o	18421.79	49979.37

Table 7. Escape fraction for a Homogeneous Distribution and optical depth 10^5.

Model	Velocity (km/s)	θ	Dust $\sum(s)$	$\sum(s)$
Central	50	0^o	4809.881	49917.069
Central	50	45^o	4829.21	49811.79
Central	50	90^o	4845.108	49853.039
Central	100	0^o	4809.665	49921.30
Central	100	45^o	4828.65	49820.13
Central	100	90^o	4846.45	49854.0
Central	200	0^o	4809.63	49917.64
Central	200	45^o	4829.25	49818.49
Central	200	90^o	4844.89	49856.66
Central	300	0^o	4810.56	49922.98
Central	300	45^o	4831.16	49823.33
Central	300	90^o	4845.33	49858.48

Table 8. Escape fraction for the central Distribution and optical depth 10^5.