

Modelling the gas kinematics of an atypical Lyman alpha emitting compact dwarf galaxy

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ABSTRACT

Star-forming Compact Dwarf Galaxies (CDGs) resemble the expected pristine conditions of the first galaxies in the Universe and are the best systems to test models on primordial galaxy formation and evolution. Here we report on one of such CDGs, Tololo 1214-277, which presents a broad, single peaked, highly symmetric Ly α emission line that had evaded theoretical interpretation so far. In this paper we explain these features by two different physically motivated kinematic models: an interstellar medium composed by outflowing clumps with random motions and an homogeneous gaseous sphere undergoing solid body rotation. It is the first time that an observed Ly α spectrum can be explained assuming either of these kinematic conditions. The multiphase model requires a clump velocity dispersion of at least 54.3 ± 0.6 km s⁻¹ with outflows of 54.3 ± 5.1 km s⁻¹ while the bulk rotation velocity is constrained to be 348^{+75}_{-48} km s⁻¹. We argue that the multiphase model has more chances to be correct. The clump velocity dispersion implies a dynamical mass of at least 2×10^9 M $_{\odot}$, ten times its baryonic mass, which can be explained if Tololo 1214-277 is hosted by a dark matter halo of at least 6×10^{11} M $_{\odot}$. If future kinematic maps of Tololo 1214-277 confirm the velocities suggested by the multiphase model, it would provide additional support to expect this condition to be present in primordial Ly α emitting galaxies.

Key words: galaxies: dwarf — galaxies: individual:Tololo 1214-277 — radiative transfer — Methods: numerical

1 INTRODUCTION

Primordial galaxies have not been detected yet. However, dwarf star forming galaxies with a low metallicity content are seen as templates to understand the early galaxy evolution process. Over fifty years ago it was realized that young galaxies could be detected through a strong Ly α line emission (Partridge & Peebles 1967).

This theoretical prediction was only confirmed thirty years later on distant, relatively young, not primordial, galaxies (Dey et al. 1998). Currently Lyman Alpha Emitting (LAE) galaxies are commonly targeted in surveys. The presence of the Ly α emission line gives confirmation of the distance to a galaxy and provides clues about the stellar population and inter-stellar medium conditions regulating the

Ly α emission. A careful clustering analysis of LAEs can also yield clues about their link to dark matter halos (Hayashino et al. 2004; Gawiser et al. 2007; Kovač et al. 2007; Orsi et al. 2008; Padilla et al. 2010; Greig et al. 2013; Mejía-Restrepo & Forero-Romero 2016).

The Ly α emission line is not exclusive of distant galaxies. There are local Universe surveys that target Ly α emission in nearby dwarf star forming galaxies. The study of nearby LAE samples has allowed the study of other indicators that might be more difficult to obtain for distant galaxies such as galaxy morphology, dust attenuation, neutral hydrogen contents and ionization state. See Hayes (2015) and references therein for a review.

However, the physical interpretation of Ly α observations is not straightforward (Östlin et al. 2014; Rivera-Thorsen et al. 2015). This is due to the resonant nature of the Ly α line. A Ly α photon follows a diffusion-like process before escaping the galaxy or being absorbed by dust.

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The resulting line profile becomes sensitive to the dynamical, chemical and thermal conditions in the interstellar medium. There are few analytical tools available to interpret the emerging Ly α line (Harrington 1973; Neufeld 1991; Loeb & Rybicki 1999; Tasitsiomi 2006). They are applicable only in cases of highly symmetrical conditions of the gaseous hydrogen distribution in the galaxy model, which are hardly met in real astrophysical systems. For these reasons the interpretation of Ly α observations requires state-of-the-art Monte Carlo radiative transfer simulations.

Observed Ly α line profiles usually present a single peak shifted redwards from the line's center. Sometimes a double peak is present but the asymmetry persists with the peak on the red side being stronger. This can be explained as the results of multiple Ly α photon scatterings through an outflowing shell of neutral Hydrogen (Verhamme et al. 2006; Orsi et al. 2012; Yamada et al. 2012; Gronke et al. 2015).

Tololo 1214-277 is a compact star forming dwarf galaxy that presents a strong Ly α emission with puzzling features: the line is highly symmetric, single peaked and broad (Thuan & Izotov 1997). This kind of profile also raises the question whether some high redshift LAEs have asymmetric lines because the blue half was truncated by the intergalactic medium (Dijkstra et al. 2007). In this case the Ly α radiation could emerge as a low surface brightness glow, which may be connected to Ly α halos, while also influencing the way LAEs can be used as a probe of reionization, see the review by Dijkstra (2014) and the references therein.

Attempts to explain the atypical Ly α features in Tololo 1214-277 with conventional models based on an expanding shell have not been successful so far (Mas-Hesse et al. 2003; Verhamme et al. 2015). This justifies a new study using two new physically motivated situations: a multiphase outflowing interstellar medium and bulk rotation for a galaxy without outflows.

The main motivation for the outflowing multiphase model (as presented in Gronke & Dijkstra (2016)) is that some dwarf galaxies are expected to present outflows. Observationally, outflows have been detected in few local dwarf galaxies (Martin 1998; Ott et al. 2005). Besides, clumpy multiphase outflows are capable to explain Ly α features around star-forming galaxies (Steidel et al. 2010; Dijkstra & Kramer 2012).

The motivation for the rotation without outflows (as presented in Garavito-Camargo et al. (2014)) is that dwarf galaxies show coherent rotation features (Swaters et al. 2009) and it is expected that some of them have high neutral gas contents with long quiescent phases without high gas outflows triggered by supernova activity (Begum et al. 2005; Tassis et al. 2008; Gavilán et al. 2013).

The models we use correspond to simplified geometrical configurations. This allows us to perform a deep exploration of parameter space and gain some physical insight into Tololo 1214-277's kinematic properties. In this paper we show, for the first time in the literature, that Tololo 1214-277's Ly α profile can be explicitly modeled by either of these two models.

We do not claim that our findings discard the existence of different undiscovered models that could reproduce the observed features in Tololo 1214-277. More involved models with multiple kinematic components can in principle also be successful. We focus on presenting two simple and successful

$\alpha(2000)$	12h17min17.1s
$\delta(2000)$	-28d02m32s
l, b (deg)	294, 34
m_V	17.5
M_V	-17.6
Redshift	0.026 ± 0.001

Table 1. Basic observational characteristics of Tololo 1214-277 (Thuan & Izotov 1997)

models that manage, for the first time, to account for Tololo 1214-277's Ly α line main features.

In the next section we review the observational characteristics of Tololo 1214-277, then we summarize the main features in the multiphase and rotation models to explain how we fit their free parameters to the Tololo 1214-277's Ly α line shape. We use the results to interpret them in terms of the galaxy's dynamical mass and argue why the multiphase model should be preferred over the rotation model. We close by discussing the additional observational information needed to clarify the kinematic nature of Tololo 1214-277.

2 OBSERVATIONS

Tololo 1214-277's basic observational characteristics are summarized in Table 1. Its receding velocity is $7785 \pm 50 \text{ km s}^{-1}$ translates into a distance of 106.6 Mpc, using a Hubble constant value of $H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Archival Chandra X-ray data¹ does not show any detection for Tololo 1214-277. This lack of detection motivates our assumption that Ly α emission is powered by star formation only.

The observed flux for the Ly α line is $\sim 8.1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ (Thuan & Izotov 1997). The Ly α Equivalent Width is 70 \AA and its H β flux is $1.62 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ \AA}^{-1}$ which gives a Ly α /H β flux ratio of 4.9 ± 0.1 (Izotov et al. 2004). Comparing the Ly α /H β ratio with the theoretical expectation from case B recombination of 23.3 (Hummer & Storey 1987) one can estimate an escape fraction of 20% for Ly α radiation.

The Ly α flux values correspond to a luminosity of $L_{Ly\alpha} = 2.2 \times 10^{42} \text{ erg s}^{-1}$, which in turn translates into a lower bound for the star formation rate of $2.0 \text{ M}_\odot \text{ yr}^{-1}$ after using a standard conversion factor between luminosity and star formation rate of $9.1 \times 10^{-43} L_{Ly\alpha} \text{ M}_\odot \text{ yr}^{-1}$ without any correction by extinction (Kennicutt 1998).

The bolometric UV luminosity is $9.43 \pm 1.94 \times 10^8 L_\odot$ as measured by GALEX. Without any correction by extinction and following the empirical relation by Kennicutt (1998), this corresponds to a star formation rate of $0.35 \pm 0.05 \text{ M}_\odot \text{ yr}^{-1}$. The absolute magnitude in the V band translates into a luminosity of $8.9 \times 10^8 L_\odot$. Its metallicity is $\sim Z_\odot/24$ as derived from optical spectroscopy (Izotov et al. 2004).

The near-infrared fluxes at $3.6 \mu\text{m}$ and $4.5 \mu\text{m}$ are $7.71 \pm 0.55 \times 10^{-5} \text{ Jy}$ and $7.98 \pm 0.71 \times 10^{-5} \text{ Jy}$ (Engelbracht et al. 2008). Using the conversion between fluxes and stellar mass, $M_\star = 10^{5.65} \times F_{3.6}^{2.85} \times F_{4.5}^{-1.85} \times (D/0.05)^2 \text{ M}_\odot$, calibrated on

¹ <http://cxc.harvard.edu/cda/>

Parameter	Description	Fiducial value	Allowed range	Units
$v_{\infty, \text{cl}}$	Radial cloud velocity	100.0	[0.0, 800.0]	km s $^{-1}$
σ_{cl}	Random cloud motion	40.0	[5.0, 100.0]	km s $^{-1}$
P_{cl}	Probability to be emitted in cloud	0.35	[0.0, 1.0]	
r_{cl}	Cloud radius	100.0	[30.0, 200.0]	pc
H_{em}	Emission scale radius	1000.0	[500.0, 3.0×10^3]	pc
f_{cl}	Cloud covering factor	3.5	[0.8, 8.0]	
T_{ICM}^{\dagger}	Temperature of ICM	10^6	$[3.0 \times 10^5, 5.0 \times 10^7]$	K
$n_{\text{HI, ICM}}^{\dagger}$	HI number density in ICM	5.0×10^{-8}	$[10^{-12}, 10^{-6}]$	cm $^{-3}$
σ_i	Width of emission profile	50.0	[5.0, 100.0]	km s $^{-1}$
T_{cl}^{\dagger}	Temperature in clouds	10^4	$[5.0 \times 10^3, 5.0 \times 10^4]$	K
β_{cl}	Steepness of the radial velocity profile	1.5	[1.1, 2.5]	
$\tilde{\sigma}_{\text{d, cl}}^{\dagger}$	Dust content in clumps	3.2×10^{-22}	$[4.7 \times 10^{-24}, 1.6 \times 10^{-21}]$	cm 2
$\zeta_{\text{d}}^{\dagger}$	Ratio of ICM to cloud dust abundance	0.01	$[10^{-4}, 0.1]$	
$n_{\text{HI, cl}}^{\dagger}$	HI number density in clouds	0.35	[0.03, 3.0]	cm $^{-3}$

Table 2. Overview of the parameters in the multiphase model and its fiducial values. Variables marked with † were drawn in log-space. Table reproduced from Gronke & Dijkstra (2016).

the Large Magellanic Cloud and where fluxes are in Jy and D is the luminosity distance to the source in Mpc, we find $M_{\star} = 1.45 \pm 0.45 \times 10^8 M_{\odot}$, with a 30% uncertainty coming from the calibration process (Eskew et al. 2012). There is an upper limit for the 21 cm line integrated flux of < 0.10 Jy km s $^{-1}$ which translates into a upper limit for the neutral Hydrogen mass of $M < 2.65 \times 10^8 M_{\odot}$ (Pustilnik & Martin 2007).

We compute the projected half-light radius to be $R_s = 1.5 \pm 0.1$ kpc from the surface brightness profiles reported by Noeske et al. (2003). Assuming spherical geometry, one can translate this value into a 3D half-light radius of $r_s = 3R_s/2 = 2.25$ kpc. Imaging observations by Fricke et al. (2001) show that Tololo 1214-277 is an isolated field galaxy not belonging to a group or cluster.

3 THEORETICAL MODELS AND PARAMETER ESTIMATION

3.1 Multiphase ISM

The idealized multiphase model consists of spherical, cold, dense clumps of neutral hydrogen (and dust) embedded in a hot, ionized medium (Gronke & Dijkstra 2016). The clumps also have a random and an outflowing velocity component which totals the number of parameters describing the model to be 14. We do not explore inflowing clumps given the slight line asymmetry redwards to the line center (see the dots in Figure 1) and thus set $v_{\infty, \text{cl}} > 0$. The parameter description list is in Table 2.

In order to map out this large parameter space, we randomly drew 2500 sets of parameters within a observationally realistic range, based on the considerations of Laursen et al. (2013), yielding a large variety of single-, double- and triple-peaked spectra. The full analysis of the spectral features as well as more details on the radiative transfer are presented by Gronke & Dijkstra (2016).

We compare each resulting spectra to the observational results from Tololo 1214-277 after normalizing the observed and simulated spectra to have a flux integral of one. We build a χ^2 on the normalized flux measurements for each one of the 2500 models as

$$\chi^2 = \sum_i \frac{(f_i - \hat{f}_i)^2}{\sigma_i^2}, \quad (1)$$

where i iterates over velocity bins, f_i is the observed flux, σ_i is the observed flux uncertainty and \hat{f}_i is the model estimated flux. As we do not have an analytic expression for \hat{f} ; we use the results of the Monte Carlo to build histograms that play the role of \hat{f} .

We select for further analysis the best 1% models according to the lowest χ^2 values. We note that the difference between the lowest and highest χ^2 values in those 25 models is close to $\Delta\chi^2 = 3000$, the lowest χ^2 being close to $\chi_{\text{min}}^2 = 1200$.

Using the total number of degrees of freedom, $d.o.f. = 104$ we divide the results in two classes: low $\chi^2/d.o.f. < 35$ and high $\chi^2/d.o.f. > 35$. We apply a random forest classification algorithm to find the more relevant parameters in splitting the results into these two classes. The algorithm uses 500 trees for the classification and a maximum of 3 depth levels. To check for stability we repeat the computation 10 times by randomly subsampling the input data to use 80% of the data as the training set.

We also perform a Kolmogorov-Smirnov (K-S) test to compare each parameter distribution in the best 25 models against the parent distribution of 2500 models. If we obtain a p-value < 0.05 for a given model parameter, we conclude that this parameter does influence the χ^2 result, as the distribution for the best χ^2 models is statistically different to the distribution from the global sample of 2500 models.

We finally compute the best values for the influential parameters as the values that produce the minimum χ^2 . We estimate the 1- σ uncertainty from a parabolic fit to the χ^2 as a function of the influential parameters around its corresponding minimum.

3.2 Bulk Rotation

The rotation model corresponds to the work presented in (Garavito-Camargo et al. 2014) based on the Monte Carlo code CLARA (Forero-Romero et al. 2011). In that model the

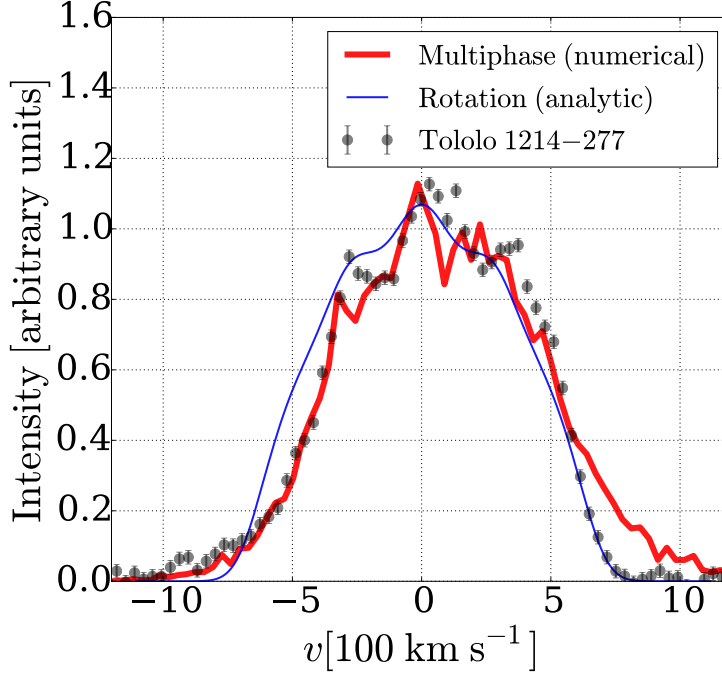


Figure 1. Broad, single peaked and highly symmetric Ly α emission of Tololo 1214-277. Dots correspond to the observational data (Mas-Hesse et al. 2003). The thick red and thin blue curves represent our best fit to the data using the full radiative transfer simulation with a rotation and multiphase model, respectively. These two different models are able to reproduce the main morphological features of Tololo 1214-277’s Ly α line emission.

Ly α photons are propagated within a spherical and homogeneous cloud of HI gas undergoing solid body rotation. The sphere is fully characterized by three parameters: the HI line’s center optical depth τ measured from the center to its surface, the HI temperature T , and the linear surface velocity V_{\max} . The observed line profile also depends on θ , the angle between the plane perpendicular to the rotation axis and the observational line-of-sight. In this model, dust only changes the overall line normalization and only weakly its shape, i.e. dust cannot change the line symmetry or induce a change in the number of line peaks, moreover it does not change the line width by more than 1% (5 km s^{-1} in the case of Tololo 1214-277), an effect too small to be observed at the resolution at which we have Tololo 1214-277’s line profile and also negligible compared to the influence of the other free parameters in the model. For these reasons we do not include any dust model.

We use an analytical approximation that captures the most important effects of rotation onto the Ly α line. We defer the reader to Garavito-Camargo et al. (2014) for complete details on the explicit form of this approximation. To fully explore the parameter space using a Markov Chain Monte Carlo (MCMC) calculation with the `emcee` Python library (Foreman-Mackey et al. 2013). `emcee` is an open source optimized implementation of the affine-invariant MCMC sampler (Goodman & Weare 2010). The algorithm creates a number of walkers that, during a sufficient number of steps, generate parameters’ combinations for a specific model. For each timestep, the code calculates the likelihood of the combination with respect to the observational data. The walkers explore the parameter space sampling the Gaussian likeli-

hood function built as $\propto \exp(-\chi^2/2)$, where the χ^2 follows the definition in Equation 1. We do not have a closed analytic expression for \hat{f} , we compute it by numerical integration of the analytical approximations found in Garavito-Camargo et al. (2014).

We explore flat priors on four parameters: $200 < V_{\max}/\text{km s}^{-1} < 600$, $6.0 < \log_{10} \tau < 9.0$, $4.0 < \log_{10} T/10^4 \text{K} < 4.5$ and $0 < \theta < 90$ using 500 steps with 24 walkers for a total of 12000 points in the chain. Previous exploratory work shows that it is impossible to fit the observed line outside these priors. Finally, we estimate the parameter values from the 16th, 50th and 84th percentiles.

4 RESULTS

Figure 1. Summarizes our main finding. Dots represent the observational data for Tololo 1214-277 with the overplot from our best fits from the analytical solution for the multiphase model (thick line) and the rotating homogeneous gas sphere (thin line).

The fit to the observations is not perfect. However, in spite of the simplicity of our models, this is the first time that the main Tololo 1214-277 features can be reproduced: a broad, highly symmetric, single-peaked Ly α line.

This result does not demonstrate that the kinematic features we include in our models are necessary to reproduce Tololo 1214-277’s features, but at least they show that they are a sufficient condition. This is a significant step forward to understand the influence that different kinematics have in producing the atypical line profile shown by Tololo 1214-277.

In what follows we summarize the values of the kine-

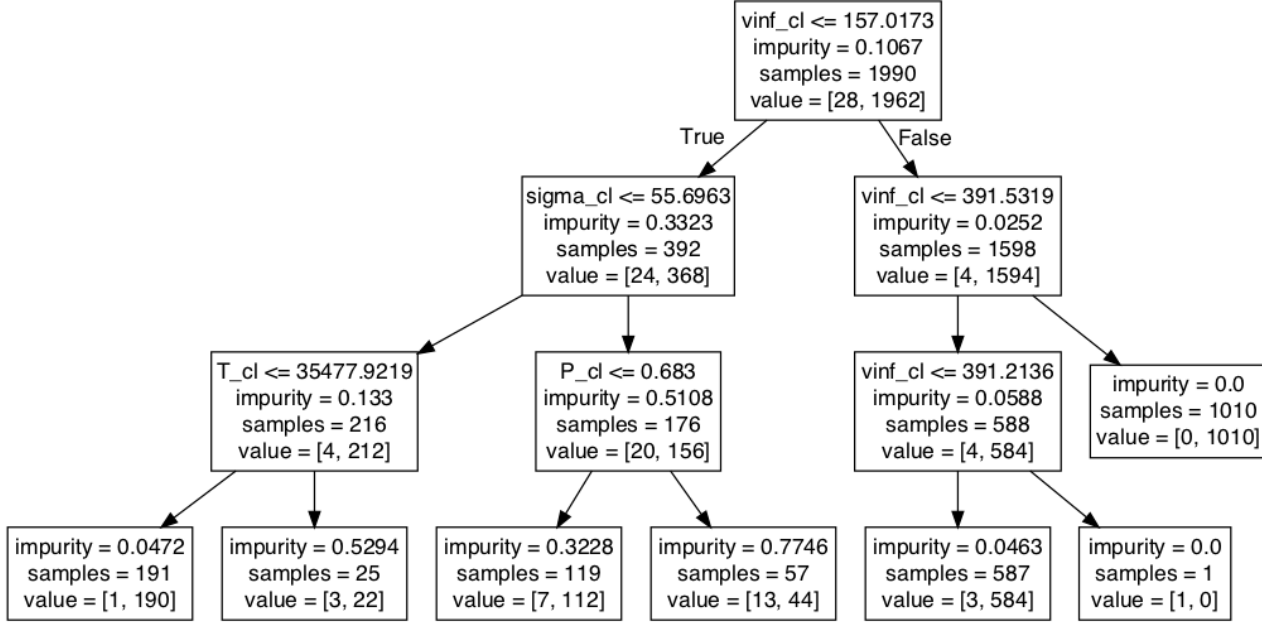


Figure 2. Classification tree example. The aim is to find the parameters that separate two classes: low $\chi^2/d.o.f.$ < 35 and high $\chi^2/d.o.f.$ > 35. Each box describes the condition over the parameter of interest, the level of sample impurity, the total number of samples and the value of the number of samples in each class. In this example we randomly sample 80% of the full data set of models to start with 28 models in the first class and 1962 models in the second class; the best way to increase the probability to find a result with low $\chi^2/d.o.f.$ (13 models, fourth bottom box, from left to the right) is having the clump radial velocity, $v_{\infty,cl} < 157.0$ km s $^{-1}$; the clump velocity dispersion, $\sigma_{cl} > 55.6$ km s $^{-1}$, and the probability to have a Ly α photon emitted in a clump, $P_{cl} > 0.683$. The final classification is not perfect, showing that all other parameters are also important but these three are the most relevant.

matic parameters that managed to explain Tololo 1214-277's Ly α profile.

4.1 Multiphase ISM

With 14 free parameters our first concern is discovering which are the most relevant in reproducing Tololo 1214-277's line shape. The results of the random forest classifier yield that the clump outflow velocity $v_{\infty,cl}$, the clump velocity dispersion σ_{cl} and the probability that the Ly α emission comes from the clumps P_{cl} , are the most influential parameters in finding a model with low $\chi^2/d.o.f.$.

Figure 2 shows as an illustration the results for a single classification tree. The tree starts with 28 and 1962 models in the low and high $\chi^2/d.o.f.$ classes, respectively. We find that the best classification yields 13 and 44 models in the low and high $\chi^2/d.o.f.$ classes, respectively, after selecting for $v_{\infty,cl} < 157.0$ km s $^{-1}$, $\sigma_{cl} > 55.6$ km s $^{-1}$ and $P_{cl} > 0.683$. The split in two classes is not perfect. This means that the 3 parameters in the model are the most influential in finding models with low $\chi^2/d.o.f.$, but that some combinations of the other 11 parameters are also relevant to find a good fit.

From the K-S tests we confirm that the same 3 parameters are the only ones that can be constrained by observations; $v_{\infty,cl}$ (p-value 10^{-18}), σ_{cl} (p-value 10^{-4}) P_{cl} (p-value 10^{-4}). Once again, this test does not mean the other parameters do not influence the resulting spectra at all; it means that they cannot be constrained from Tololo 1214-277's observations.

The best models are shown in Figure 3. Left column shows the difference between the integrated distributions

of the full sample (2500 input models) and the models with the lowest $\chi^2/d.o.f.$. The right column shows the actual $\chi^2/d.o.f.$ and its corresponding parameter value. Under these conditions we find $\sigma_{cl} = 54.3 \pm 0.6$ km s $^{-1}$, $v_{\infty,cl} = 54.3 \pm 5.1$ km s $^{-1}$ and $P_{cl} = 0.96 \pm 0.01$.

Qualitatively this result can be understood as follows. The broad Ly α line is the result of subsequent Ly α photon scatterings due to (relatively) fast moving clumps while the multi-phase nature (i.e., the existence of low-density inter-clump regions where Ly α photons can freely propagate) ensures the high flux at line center as observed. In turn, a lower velocity dispersion would produce a thinner line than it is observed. From the lower right panel in Figure 3 we find that it is unlikely that the clump velocity dispersion is lower than 50 km s $^{-1}$. This is also supported by the classification tree example in Figure 2.

As a test, we also run a small set of 100 additional radiative transfer simulations with random values for all parameters, except for σ_{cl} , $v_{\infty,cl}$, P_{cl} which are within the derived constraints. Consistent with the results from the random forest algorithm, illustrated by the classification tree of Figure 2, we find that 30 models show $\chi^2/d.o.f. < 35$.

Having constrained only 3 parameters, one might wonder why the other 11 parameters do not seem to matter. However, this view is misleading. Even if for clumpy models the line profile is most sensitive to only a few parameters (Gronke & Dijkstra 2016), there are the rest of parameters which affect the line profile at a level that cannot be neglected, i.e. we cannot randomly pick 11 random, reasonable values for these parameters, and expect to fit the line

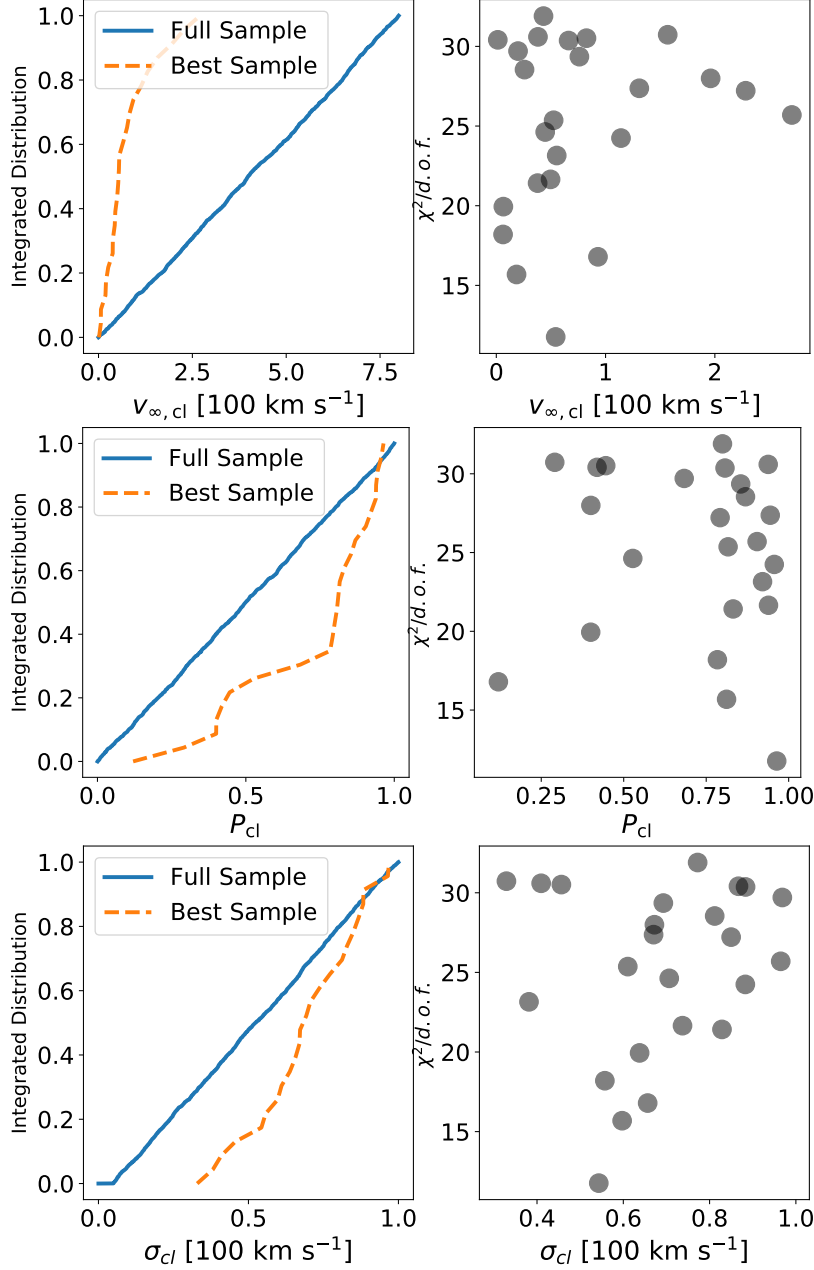


Figure 3. Results from the multiphase model. We only show results for the three parameters with a significant statistical difference between the models with the lowest $\chi^2/d.o.f.$ values and its prior distribution. These three parameters are the clump radial velocity at infinity $v_{\infty,cl}$; the probability that the Ly α photons were emitted in the clumps, P_{cl} ; the clump velocity dispersion, σ_{cl} . The left column corresponds to the parameter's integrated distributions for models with the lowest $\chi^2/d.o.f.$ values (dotted line) compared against the parameter's prior integrated distributions (continuous line). The right column shows a scatter plot of $\chi^2/d.o.f.$ and its corresponding physical parameters. The clump kinematic state is the key ingredient to reproduce Tololo 1214-277's Ly α line morphology.

profile while only varying the other 3, as the results for the classification tree example in Figure 2 shows.

We cannot discard that another region of parameter space could also work. It might be interesting to explore in the future with a higher sampling of the parameter space once new observations clarify the kinematic nature of Tololo 1214-277². Furthermore, considering the sparse sampling of

parameter space and the results from the random forest classifier, it is safer to consider that the best values for σ_{cl} , $v_{\infty,cl}$, P_{cl} are actually lower/upper/lower bounds, respectively.

² In Section §6 we describe in more detail what kind of obser-

vations could be performed in the near future to improve our understanding of Tololo 1214-277's kinematics.

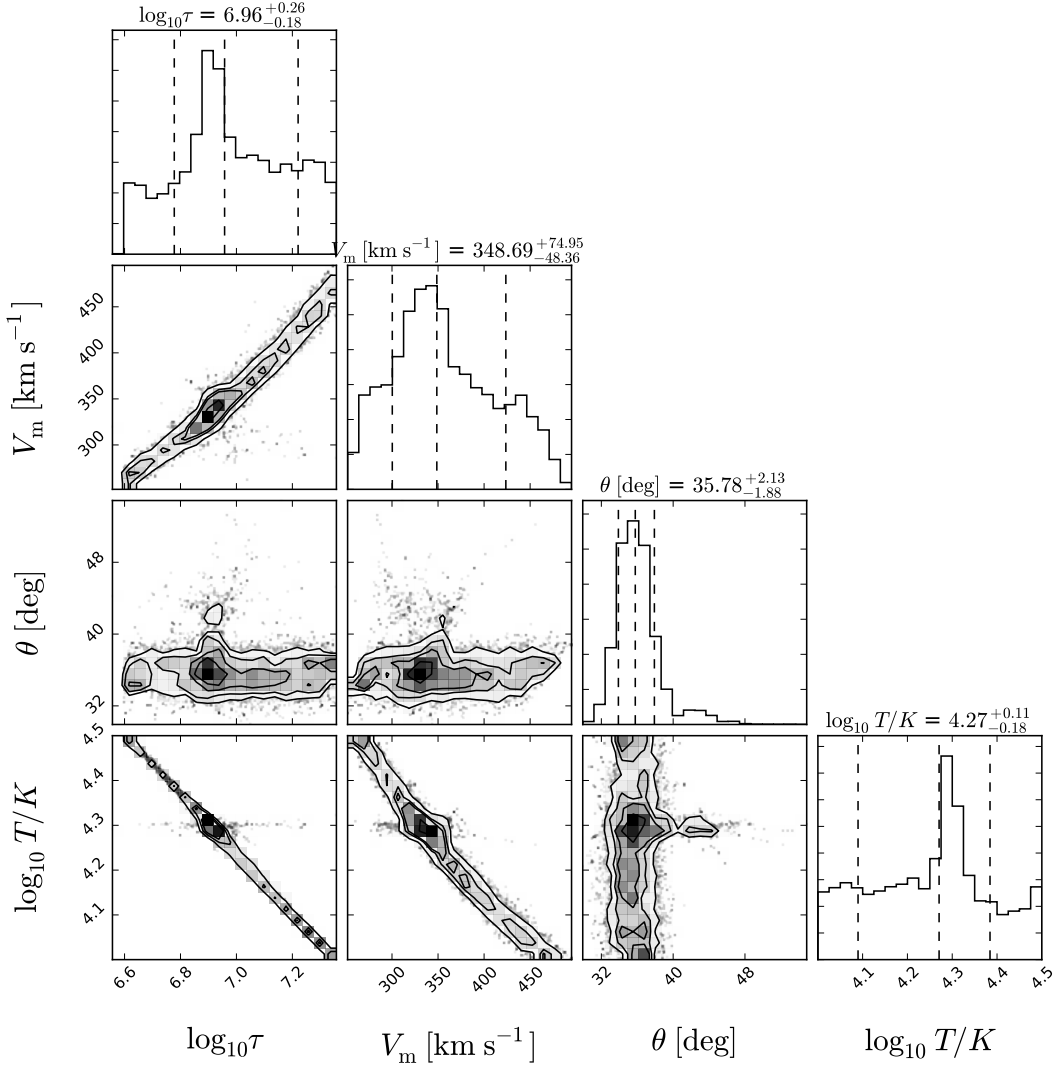


Figure 4. Results from the Markov Chain Monte Carlo computation for the rotation model. The gray scale indicates the point density in parameter space. The dotted vertical lines in the histograms in the diagonal panels represent the 16th, 50th and 84th percentiles. All parameters in the rotation model can be successfully constrained by Tololo 1214-277’s Ly α line morphology to the values written in the top region of the diagonal panels.

4.2 Bulk Rotation

The results for this model are easier to interpret due to the fewer number of free parameters and its explicit influence on the semi-analytic solution. The results are summarized in Figure 4. From this analysis we find that the best parameters in the rotation model are a rotational velocity of $V_{\text{max}} = 348^{+75}_{-48}$ km s $^{-1}$, a neutral Hydrogen optical depth of $\log_{10} \tau = 6.96^{+0.26}_{-0.18}$, and an inter-stellar medium temperature of $\log_{10} T/K = 4.27^{+0.11}_{-0.18}$. We are also able to constrain the angle between the plane perpendicular to the rotation axis and the observational line-of-sight to $\theta = 35.78^{+2.13}_{-1.88}$ degrees. This model cannot reproduce the slight asymmetry present in Tololo 1214-277’s Ly α line; most probably this would require a small amount of outflows, a feature that is not present in the model provided by Garavito-Camargo et al. (2014).

The preferred value for the rotational velocity can be

explained as follows. Lower rotational velocities than the favored value would produce a double peaked line as the different doppler shifts produced on different regions of the rotating sphere would not be large enough to smear the double peaks into a single peak (Garavito-Camargo et al. 2014). For the same reason, higher rotation velocities could produce a single peak but the line would be broader than it is observed. The fact that the velocity and optical depth priors were wide enough, allows us to suggest that the current values for the spherical model found by the MCMC are robust given the observational constraints.

5 DISCUSSION

Tololo 1214-277 presents one of the most atypical Ly α spectra observed so far. Its flux at the line’s center is high compared to other LAEs at low redshift and the broad, highly

symmetrical peak is virtually absent from other LAEs at low and high redshift (Yamada et al. 2012; Östlin et al. 2014; Erb et al. 2014; Trainor et al. 2016). Simple shell models fail to reproduce such a spectrum as reported by Verhamme et al. (2015). In the previous sections we show how these characteristics can be explained by two different kinematic models: multiphase ISM and solid body rotation.

Which model has more chances to be correct? We discard the rotation model by considering that the rotational velocity of $\sim 350 \text{ km s}^{-1}$ is too high for such a low mass system. Tololo 1214-277's inferred rotational velocity is larger than the Milky Way's ($\sim 200 \text{ km s}^{-1}$) while its baryonic mass is one order of magnitude smaller. Furthermore, Tololo 1214-277's structural properties seem to be similar to known dwarf elliptical galaxies. The sample of 7 dwarf ellipticals (dE) observed by Geha et al. (2003) show similar properties as Tololo 1214-277. For instance, the dE galaxies IC 3344 and IC 794 have similar absolute M_V magnitudes (-17.10 and -17.19) and sizes (0.90 kpc and 0.82 kpc) as Tololo 1214-277. These dE galaxies have velocity dispersions of 31.1 km s^{-1} and 44.6 km s^{-1} , respectively, and their rotational velocities are lower than 1 km s^{-1} . This leads us to prefer the multiphase model as it provides a broad consistency with kinematic properties of dE galaxies.

Following the results of Tollerud et al. (2011), who made a detailed analysis for all kind of elliptical galaxies including dE galaxies, we estimate a value for the dynamical mass using the constraints for the velocity dispersion, σ , in a spherical system localized in a region of size r

$$M_{\text{dyn}} = 3 \frac{\sigma^2 r}{G} = 3.48 \times 10^9 \left(\frac{\sigma}{100 \text{ km s}^{-1}} \right)^2 \left(\frac{r}{\text{kpc}} \right) M_{\odot}, \quad (2)$$

Assuming that the Ly α emission is entirely powered by star formation we use the 3D half-light radius $r_s = 2.25 \text{ kpc}$ as the typical size for the HI region, in the multiphase model the clump velocity dispersion $\sigma_{\text{cl}} = 54.3 \pm 0.6 \text{ km s}^{-1}$ thus corresponds to a dynamical mass of $M_{\text{dyn}} = 2.31 \pm 0.04 \times 10^9 M_{\odot}$, which is ten times the estimated baryonic mass in Tololo 1214-277. Considering that the results for σ_{cl} are most probably a lower bound, the results for the dynamical mass should also be considered as a lower bound.

Figure 5 illustrates how such dynamical mass can be explained if Tololo 1214-277 is hosted by a dark matter halo of at least $6 \times 10^{11} M_{\odot}$ in virial mass. This estimate is based on computing the integrated mass profile of a spherical dark matter halo with a Navarro-Frenk-White profile with its concentration following the median mass-concentration relationship found in the Bolshoi simulation (Prada et al. 2012; Poveda-Ruiz et al. 2016).

These results would imply that Tololo 1214-277 is part of the dE class. However, this hypothesis opens up two puzzles. First, dE galaxies are found either in clusters or groups of galaxies; while Tololo 1214-277 does not belong either to a group or a cluster (Fricke et al. 2001). The second issue is that, unlike a dE, Tololo 1214-277 hosts a bright and compact starburst; imaging and spectroscopy studies suggest that the starburst started less than 4 Myr ago, while the low surface brightness regions are consistent with an age below one Gyr (Fricke et al. 2001).

We suggest that new observational tests are needed to clarify the kinematic nature of Tololo 1214-277. Integral field

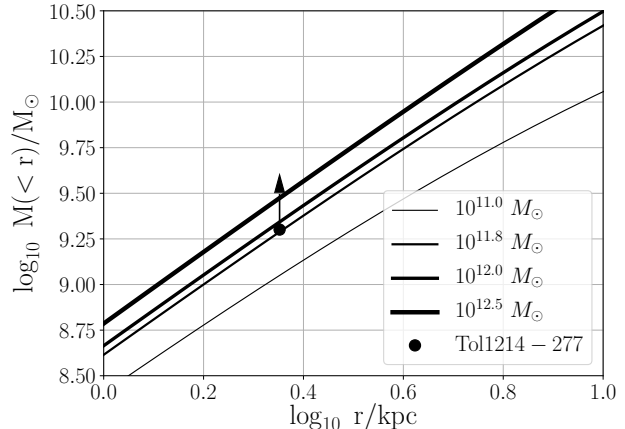


Figure 5. Enclosed mass in a spherical system as a function of radius. Lines correspond to the expectation for dark matter halos with different virial masses as shown in the legend, the arrow corresponds to the dynamical mass lower bounds for Tololo 1214-277. The dynamical mass estimates for Tololo 1214-277 are consistent with the galaxy being hosted by a dark matter halo of at least $6 \times 10^{11} M_{\odot}$ in mass.

unit measurements resolving its spatial extent are up to the task. Tololo 1214-277 spans a region of 4 arcseconds, an instrument such as the Multi Unit Spectroscopic Explorer (MUSE) (Bacon et al. 2014) with its nominal 0.2 arcseconds spatial sampling over a 1.0 arcminute field in wide-field mode could provide a coarse mapping of different ionization lines to infer a kinematic map in the H α line, following the kind of work presented by Herenz et al. (2016) done with the Potsdam Multi-Aperture Spectrometer (PMAS) (Roth et al. 2005) on nearby Ly α emitting galaxies.

Another observational hint to clarify Tololo 1214-277's state could be the measurement of the Ly α ionizing continuum escape fraction. The multiphase model predicts that averaging over all sightlines it should be around $0.5^{+1.0}_{-0.4}\%$, with the possibility of strong variations depending on viewing angle, i.e. some sightlines can have an escape fraction close to 100%, (Gronke & Dijkstra 2016).

6 CONCLUSIONS

In this paper we presented two kinematic models that independently reproduce the so far unexplained observational features of Tololo 1214-277's Ly α emission line. One model is based on a multiphase ISM with random clump motions and the other on gas bulk solid body rotation. It is the first time that an observed Ly α profile can be fully reproduced by either of these two kinematic conditions. Our findings highlight the importance of including multiphase and/or rotation conditions as kinematic features to model the Ly α line.

In this particular case, we prefer the multiphase model because it has kinematic conditions similar to those in dwarf ellipticals, while the rotational model produces rotational velocities too high for a dwarf galaxy.

However, Tololo 1214-277's environment and star forming activity are radically different from those of dwarf ellip-

ticals. We suggest that additional integral field unit observations are the only way to be certain about the detailed kinematic structure in Tololo 1214-277.

All in all, the mere existence of a strong LAE galaxy with a broad, highly symmetric line is interesting. Tololo 1214-277's line shape is different to others and seems to reveal an unexpected kinematic structure. A confirmation of our results by new observations would support the multi-phase model as an element to be included in the study of primordial Ly α emitting galaxies.

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