

## Lyman- $\alpha$ emission reveals a dispersion-supported dwarf

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Star-forming Compact Dwarf Galaxies (CDGs) resemble the expected pristine conditions of the first galaxies in the Universe. Before the observational detection of the first galaxies becomes reality, CDGs are the best systems to test our ideas on primordial galaxy formation and evolution. Here we report on one of such CDGs, Tololo 1214-277, which presents a broad symmetric Lyman- $\alpha$  emission that had evaded theoretical interpretation so far. In this letter we explain these features by two different models: an homogeneous gaseous sphere undergoing bulk rotation and an interstellar medium composed by outflowing clumps with additional random motions. It is the first time that an observed Ly $\alpha$  spectrum can be explained assuming either of these physical conditions. We find that both models independently require high velocities (either a bulk rotation of  $348^{+75}_{-48}$  km s<sup>-1</sup> or a clump velocity dispersion of  $69^{+17}_{-15}$  km s<sup>-1</sup> with outflows of  $79^{+73}_{-42}$  km s<sup>-1</sup>) consistent with a dynamical mass at least 10 times larger than its baryonic mass. We argue that the most plausible explanation is provided by the multiphase model as it is a close match to the galaxy scaling relationship for a dark matter dominated dwarf elliptical supported by its velocity dispersion. This work demonstrates the importance of considering multiphase physics among the possible conditions shaping the Ly $\alpha$  spectra of the first galaxies. Additionally, if future kinematic maps of Tololo 1214-277 confirm the high velocities postulated in our model, it would help to establish the Ly $\alpha$  line morphology as an observational tracer to study the co-evolution of the first generation of galaxies and its host dark matter halos.

The first generation of galaxies trace our cosmic origins. They were the first steps in the evolution of galaxies such as the Milky Way. In the standard Big Bang cosmology the only chemical elements that were created in the nucleosynthesis process were Hydrogen, Helium and Lithium. Heavier elements must have been created in stellar evolution process. Therefore, we expect the first generation of galaxies to be metal free and rich in Hydrogen. This kind of 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.

Almost fifty years ago [12] it was realized that young galaxies could be de-

tected through a strong Lyman- $\alpha$  line emission. This theoretical prediction was only confirmed thirty year later on distant, relatively young, not primordial, galaxies. Currently Lyman Alpha Emitting (LAE) galaxies are commonly targeted in surveys. The presence of the Ly- $\alpha$  emission line provides confirmation of the distance of a galaxy while provides clues about the stellar population and inter-stellar medium conditions regulating the Ly- $\alpha$  emission.

The Ly- $\alpha$  emission line is not exclusive of distant galaxies. Any galaxy with low dust content and ongoing star formation has the right conditions to show this line. There are, for instance, local Universe surveys that target Ly- $\alpha$  emission in nearby dwarf star forming galaxies [11]. 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 morphology, dust attenuation, neutral hydrogen contents and ionization state.

However, the physical interpretation of Ly- $\alpha$  observations is not straightforward. This is due to the resonant nature of the Ly- $\alpha$  line. A Ly- $\alpha$  photon follows a diffusion-like process before escaping the galaxy or being absorbed by dust. The resulting line profile becomes sensitive to the dynamical, chemical and thermal conditions in the interstellar medium. There are very few analytically tools available to interpret the Ly- $\alpha$  line. They are applicable only in very few cases of highly symmetrical conditions, which are hardly met in real astrophysical systems. For these reasons the interpretation of Ly- $\alpha$  observations require state-of-the-art Monte Carlo radiative transfer simulations. Recent advances in these computational models have explored the effects that bulk rotation and a multiphase state in the interstellar medium should have on the Lyman- $\alpha$  line.

The most important consequence of bulk rotation is that, even for a spherical gas distribution, the line morphology now depends on the viewing angle respect to the rotation axis. For a line of sight perpendicular to the rotation axis the intensity and the line center and the line width increase with rotational velocity. When the rotational velocity is high enough, the line becomes single peaked and symmetric, a unique feature that other theoretical models find difficult to reproduce without introducing more complexity into the gas distribution.

This is the case of a multiphase interstellar medium. The model is more complex as it must take into account the behavior of neutral dense hydrogen clumps dispersed in a tenuous intraclump medium. Corresponding to the elaborate physical conditions in the model, there are a wide variety of possible emerging spectra. This variety includes single, double and triple peaked spectra with different degrees of symmetry around the line's center.

Tololo 1214-277 is a compact star forming dwarf galaxy that presents a strong Ly- $\alpha$  emission [14] with two puzzling features: it is symmetric and single peaked. Commonly, the Ly- $\alpha$  line has a single or asymmetric double peak. These two special features in Tololo 1214-277 had evaded a physical interpretation so far. Including the effects of either bulk rotation or a multiphase ISM, we manage to explain the Ly $\alpha$  line in Tololo 1214-277.

Figure 1. summarizes our findings. Dots represent the observational data

for Tololo 1214-277 with the overplot from our best fit models from the full radiative transfer simulations for a rotating sphere (continuous line) and a clumpy ISM (dashed line).

The best parameters in the rotation model are a rotational velocity of  $V_{\max} = 348^{+75}_{-48} \text{ km s}^{-1}$ , an optical depth  $\log_{10} \tau = 6.96^{+0.26}_{-0.18}$ , and a temperature of  $\log_{10} T/\text{K} = 4.27^{+0.11}_{-0.18}$ . This model is 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.

In the multiphase model the best constrained parameters are the clump velocity dispersion  $\sigma_{\text{cl}} = 69^{+17}_{-15} \text{ km s}^{-1}$ , the clumps outflowing velocity  $v_{\infty, \text{cl}} = 79^{+73}_{-42} \text{ km s}^{-1}$  and the fraction of the Ly $\alpha$  emission that is coming from the cold clumps  $P_{\text{cl}} = 0.78^{+0.16}_{-0.43}$ . The multiphase model assumes that the clouds are distributed over a sphere of 5kpc in radius, close to the  $\approx 4\text{kpc}$  physical size of Tololo 1214-277 as determined by optical imaging. The assumed physical size and the velocity dispersion  $\sigma_{\text{cl}}$  correspond to a dynamical mass of  $M_{\text{dyn}} = 2.8^{+1.3}_{-1.2} \times 10^9 M_{\odot}$ . In the rotation model assuming reasonable bounds for the number density of neutral Hydrogen atoms ( $0.01 < n/\text{atoms cm}^{-3} < 0.1$ ) and using  $\tau = 10^7$  the radius of the emission region can be bracketed to be in  $0.55 < r_s/\text{kpc} < 5.5$ . Using  $V_{\max} = 300 \text{ km s}^{-1}$ , we find a dynamical mass range of  $5.45 \times 10^9 M_{\odot} < M_{\text{dyn}} < 5.45 \times 10^{10} M_{\odot}$ .

Which solution is more plausible? If Tololo 1214-277 followed the fundamental plane relationship between its mean surface brightness  $I_e$ , the projected half-light radius  $R_e$  and the velocity dispersion  $\sigma$ , described by  $\log I_e = 1.6 \log \sigma - 1.21 \log R_e + 0.55$  [6, 15], the expected velocity dispersion would be on the order of  $47 \pm 3 \text{ km s}^{-1}$ , which only presents a small tension with the multiphase model. The solution of a high rotational velocity pushes Tololo 1214-277 outside the scaling relationship for dwarfs. One could account for the high velocities if the galaxy had a supermassive black hole accounting for the mass that cannot be explained by baryonic or dark mass. The economy of assumptions makes it more reasonable to expect that the multiphase model could be a better match to reality.

A future observational test to clarify the physical nature of Tololo 1214-277 would require integral field unit measurements spatially resolving its spatial extent. Tololo 1214-277 spans a region of 4 arcseconds, an instrument such as the Multi Unit Spectroscopic Explorer 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. Another observational test includes the measurement of the escape fraction of Ly continuum ionizing radiation. In the rotational model this fraction should be zero, while the multiphase model predicts that in this case it should be around  $0.5^{+1.0}_{-0.4}\%$ .

All in all, the mere existence of a strong LAE galaxy with a broad, symmetric line is interesting. It raises the question whether some high redshift LAEs have asymmetric lines because the blue half was truncated by the intergalactic medium. In this case the Ly $\alpha$  radiation could emerge as a low surface brightness glow, which may be connected to Ly $\alpha$  halos, while also influencing the way LAEs can be used as a probe of reionization.

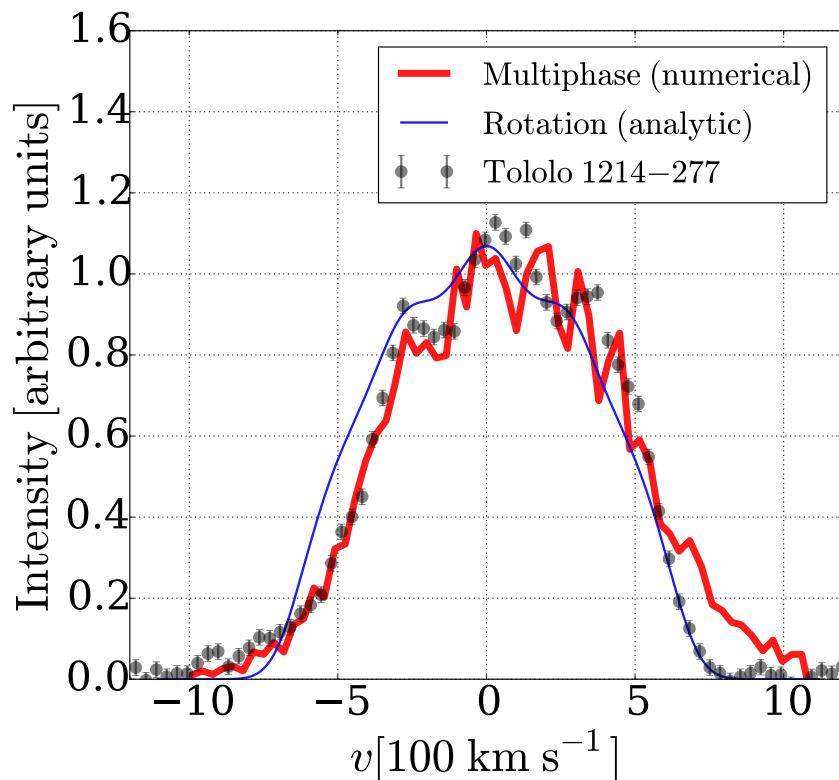


Figure 1: **Broad, single peaked and symmetric Ly- $\alpha$  emission of Tololo 1214-277.** Dots correspond to the observational data. The line shows the results of our best model from a full radiative transfer simulation both for the rotation and multiphase models.

These findings demonstrate the importance of including multiphase conditions as a feature to model the Ly $\alpha$  line in high redshift galaxies. If the estimated velocity dispersion proves to be consistent with future observational kinematic maps, it could provide a new way to study velocity dispersions in distant gas rich starbursting galaxies, opening the possibility to study the dynamical co-evolution of galaxies and dark matter halos in the first generation of galaxies.

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$\alpha(2000)^a$	12h17min17.1s
$\delta(2000)^b$	-28d02m32s
$l, b$ (deg)	294, 34
$m_V$	17.5
$M_V$	-17.6
$v(\text{km s}^{-1})$	7795
Ly- $\alpha$ (erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$ )	$8.1 \times 10^{-14}$
Ly- $\alpha$ EW	70Å
H $\beta$ (erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$ )	$1.62 \times 10^{-14}$
21cm (Jy km s $^{-1}$ )	< 0.10

Table 1: Basic observational characteristics of TOL1214-277 [14]

## Tololo 1214-277 characteristics

Tololo 1214-277 receding velocity is  $7785 \pm 50 \text{ km s}^{-1}$ , which translates into a distance of 106.6 Mpc (Hubble constant  $73 \text{ Mpc km}^{-1} \text{ s}^{-1}$ ) Its metallicity is  $\sim Z_{\odot}/24$  [9] as derived from optical spectroscopy.

The observed flux for the Lyman alpha line is  $\sim 8.1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$  [14] and a Equivalent Width of 70Å and its H $\beta$  flux is  $1.62 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$  [9] which gives a Ly $\alpha$ /H $\beta$  flux ratio of  $4.9 \pm 0.1$ . The Ly- $\alpha$  flux values correspond to luminosities of  $L_{Ly\alpha} = 2.2 \times 10^{42} \text{ erg s}^{-1}$  over a 20Å bandwidth, which in turns translates into a star formation rate of  $2.0 \text{ M}_{\odot} \text{ yr}^{-1}$  using a standard conversion factor between luminosity and star formation rate of  $9.1 \times 10^{-43} L_{Ly\alpha} \text{ M}_{\odot} \text{ yr}^{-1}$ . The absolute magnitude in the V band translates into a luminosity of  $8.9 \times 10^8 L_{\odot}$ . Comparing this ratio with the theoretical expectation from case B recombination of 23.3 [8] one can estimate an escape fraction of 20% for Ly $\alpha$  radiation. The bolometric UV luminosity is  $9.43 \pm 1.94 \times 10^8 L_{\odot}$  as measured by GALEX.

The optical emission comes from a region with approximate diameter 4 kpc [4].

There is an upper limit for the integrated flux of  $< 0.10 \text{ Jy km s}^{-1}$ , which translates into a upper limit for the HI mass of  $M < 2.65 \times 10^8 \text{ M}_{\odot}$  [13].

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  $7.98 \pm 0.71 \times 10^{-5} \text{ Jy}$  [1]. Using a conversion between fluxes and stellar mass calibrated on the Large Magellanic Cloud  $M_{\star} = 10^{5.65} \times F_{3.6}^{2.85} \times F_{4.5}^{-1.85} \times (D/0.05)^2 \text{ M}_{\odot}$ , where fluxes are in Jy and  $D$  is the luminosity distance to the source in Mpc, we find  $M_{\star} = 1.45 \pm 0.45 \times 10^8 \text{ M}_{\odot}$ , with a 30% uncertainty coming from the calibration process [2].

## The Rotation Model

The rotation model corresponds to the work presented in [5]. In that model the Ly- $\alpha$  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 optical depth  $\tau$  measured from the center to its surface, the HI temperature  $T$ , and the linear surface velocity  $V_{\max}$ . Photons are emitted at their natural frequency from the center of the sphere. Including the effect of dust only changes the overall line normalization but not its shape. The results we report in the main body of the paper do not include any dust model. In the current work, the radiative transfer simulations were done using Monte Carlo simulations with the code **CLARA** [3].

The first important effect of rotation is that it breaks the spherical symmetry of the static case. Now the line's observed morphology depends on the angle  $\theta$  between the line-of-sight (LOS) and the rotation axis. LOS parallel to the rotation axis tend to observe the line without any modification from rotation, while the perpendicular LOS will observe a maximal change in the line's morphology due to rotation.

The main change in the line's morphology is that it broadens and the intensity at the center increases. For high enough rotational velocities the intensity at the peak's center increases so much that the line goes from double to single peaked, sometimes slightly triple peaked. This is the feature that allows this model to fit the observational features of Tololo 1214-277.

There is a concise analytical description for those features. This description takes into account how different parts of the sphere's surface shift in frequency the Ly $\alpha$  photons. Different shifts in frequency come from different values for the projected velocity along the LOS. As presented in [3], using the analytical solution for the Ly $\alpha$  spectra of a static sphere plus the right frequency shifts computed from geometrical considerations, one is able to produce an analytical solution for the rotating sphere that reproduces the main features found using the full numerical simulation.

The analytical solution for the rotation sphere was the base to perform the Markov Chain Monte Carlo Calculation using the **emcee** implementation. We explore flat priors on  $V_{\max}$ ,  $\log_{10} \tau$ ,  $\log_{10} T$  and  $\theta$  using  $XX$  steps. The results are summarized in Figure  $XX$ . From this model we find that the fiducial parameters that could explain the broad features in Tololo 1214-277 are  $V_{\max} = 348_{-48}^{+75}$  km s $^{-1}$ ,  $\log \tau = 6.96_{-0.18}^{+0.26}$ ,  $\log_{10} T/\text{K} = 4.27_{-0.18}^{+0.11}$  and  $\theta = 35.78_{-1.88}^{+2.13}$  degrees.

## The Multiphase Model

The idealized multiphase model consists of spherical, cold, dense clumps of neutral hydrogen (and dust) embedded in a hot, ionized medium. The clumps also have a random and an outflowing velocity component which totals the number of parameters describing the model to be 14. In order to map out this large parameter space, we randomly drew 2500 sets of parameters within an observationally realistic range (based on the considerations of [10]) 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 in [7].

For the current work, we computed the  $\chi^2$  for each of the 2500 parameters



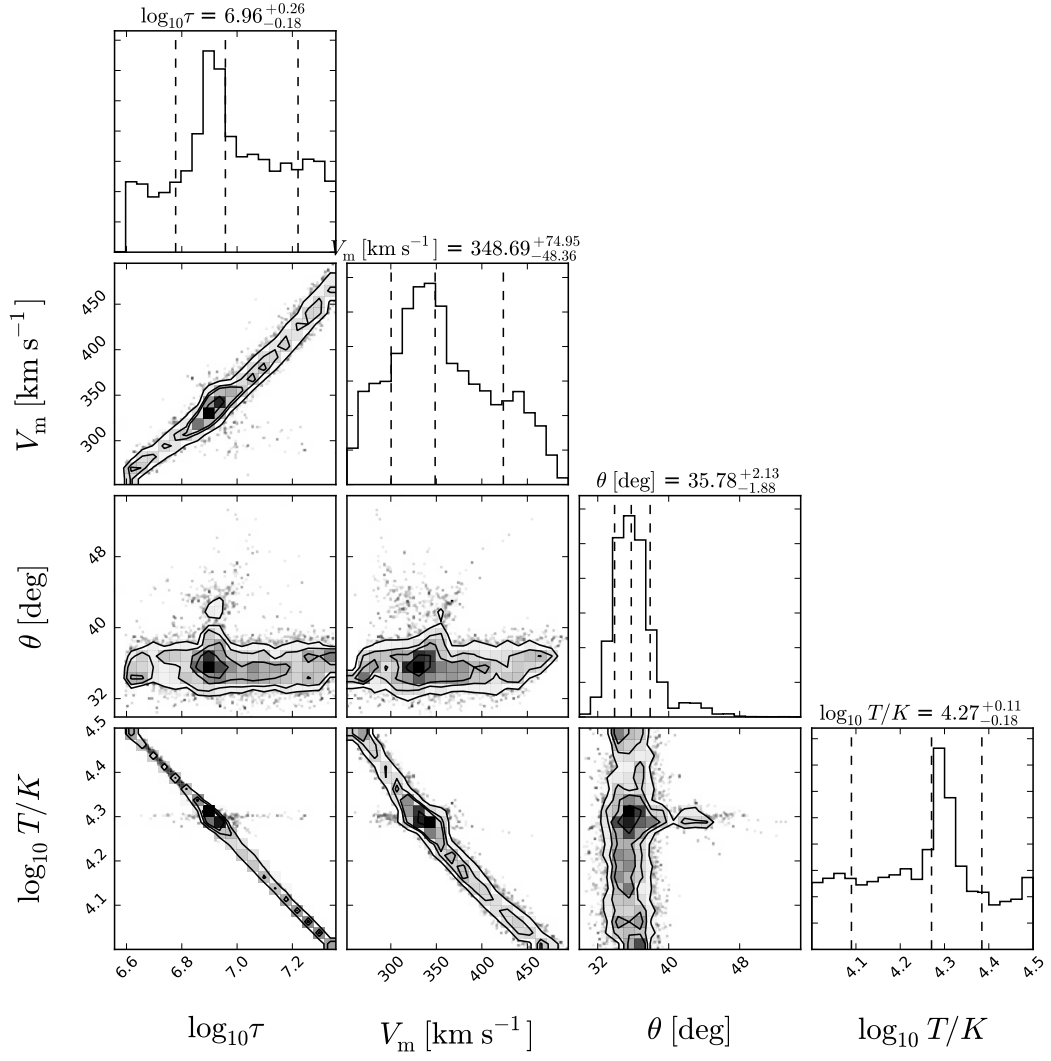


Figure 2: Results from the Markov Chain Monte Carlo computation for the rotation model.

yielding the best fit parameters of (...). Here, the subscripts <sub>cl</sub> and <sub>ICM</sub> stand for the quantities filling the clumps and the medium between the clumps, respectively. Furthermore, we found that some parameters such as the magnitude of the random clump motion  $\sigma_{\text{cl}}$  improved the fit significantly whereas others did not.

Qualitatively as Tololo 1214-277 possesses a very wide spectrum which can be achieved by subsequent scatterings off (relatively) fast moving clumps while the multi-phase nature (i.e., the existence of low-density channels) ensures the high flux at line center as observed.

## Physical Interpretation

Both the rotation and the multiphase model constrain the typical velocity  $v$  of the HI gas, with and additional constrain on the typical size for the emission region  $r$  on could estimate a dynamical mass with

$$M_{\text{dyn}} = \frac{v^2 r}{G} = 1.16 \times 10^9 \left( \frac{v}{100 \text{ km s}^{-1}} \right)^2 \left( \frac{r}{\text{kpc}} \right) M_{\odot} \quad (1)$$

From the multiphase model we obtained  $v = 69_{-15}^{+17} \text{ km s}^{-1}$  and  $r = 5 \text{ kpc}$ . This corresponds to a dynamical mass of  $M_{\text{dyn}} = 2.8_{-1.2}^{+1.3} \times 10^9 M_{\odot}$  which is at least 5 times the HI mass plus the stellar mass estimated from observations.

In the rotation model the size of the spherical region,  $r_s$ , can be inferred from the relationship  $\tau = \sigma_0 n r_s$ , where  $\sigma_0 = 5.898 \times 10^{-14} \text{ cm}^{-2}$  is the Lyman $\alpha$  cross section at the line's center,  $n$  is the number density. This expression can be rewritten as

$$r_s = 0.055 \left( \frac{\tau}{10^7} \right) \left( \frac{\text{atoms cm}^{-3}}{n} \right) \text{ kpc}. \quad (2)$$

Using this result and assuming a bound for the number density of  $0.01 < n/\text{atoms cm}^{-3} < 0.1$  we have  $0.55 < r_s/\text{kpc} < 5.5$ .

This is consistent with the constraint on the total HI mass and the optical depth  $\tau_0$  as we show next. The total HI mass can be approximated as  $M_H = \frac{4\pi}{3} m_H n r_s^3$ , where  $m_H = 1.67 \times 10^{-24} \text{ gr}$  is the mass of a single Hydrogen atom. This allows us to write the total hydrogen mass as

$$M_H = 5.70 \times 10^6 \left( \frac{\tau}{10^7} \right) \left( \frac{r_s}{\text{kpc}} \right)^2 M_{\odot} \quad (3)$$

The upper limit from the HI mass non-detection imposes  $r_s < 6.81 \text{ kpc}$ , which is consistent with the bound we found in the first place, as we wanted to show.

Using those size bounds for the spherical model we find a constrain for the dynamical mass of  $5.45 \times 10^9 M_{\odot} < M_{\text{dyn}} < 5.45 \times 10^{10} M_{\odot}$ .