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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- α emission that had evaded theoretical interpretation so far. We explain these features by two different models: an homogeneous sphere undergoing gas bulk rotation and an interstellar medium composed by clumps with random motions. It is the first time that an observed Ly α spectrum can be explained assuming these physical conditions. We find that both models independently require high velocities that translate into a dynamical mass at least 10 times larger than the neutral mass hydrogen in the galaxy. We argue that a possibility to explain the high dynamical mass is the presence of a super-massive black hole. Ionization emission lines present in this galaxy support the idea that Tololo 1214-277 might have harbored an an Active Galactic Nucleus. The implications of our findings for the study of LAEs, including the first generation of galaxies are manifold. It demonstrates the importance of considering rotation and multiphase physics under the possible conditions shaping the Ly α spectra of the first galaxies. Additionally, if future kinematic maps of Tololo 1214-277 confirm the high velocities postulated in our model, it would provide new evidence for dwarf galaxies as hosts of active supermassive black holes.

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 [6] it was realized that young galaxies could be detected through a strong Lyman- α 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 tar-

geted in surveys. The presence of the Ly- α 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- α emission.

The Ly- α 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- α emission in nearby dwarf star forming galaxies [5]. 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- α observations is not straightforward. 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. 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- α 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- α 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 on the Lyman- α 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 close to the half-line width of the static line 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- α emission [9] with two puzzling features: it is symmetric and single peaked. Commonly, the Ly- α line has a single or asymmetric double peak. These two special features in Tololo 1214-277 had evaded a physical interpretation so far, because bulk rotation and a multiphase ISM can independently explain the Ly α 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 $v_{max} = 300_{-xx}^{+xx} \text{ km s}^{-1}$, an optical depth $\log \tau = 7_{-xx}^{+xx}$ and a temperature of $T = 1.5_{-xx}^{+xx} \times 10^4 \text{ K}$. This translates into a column density of $\log N_{HI}/\text{atoms cm}^{-2} = 20.5_{-xx}^{+xx}$. This model is also able to constrain the angle between the rotation axis and the observational line-of-sight to $\theta = 65_{-xx}^{+xx^\circ}$.

In the multiphase model the best constrained parameters are the clump velocity dispersion $\sigma_{cl} = 71_{-25}^{+17} \text{ km s}^{-1}$, the clumps outflowing velocity $v_{\infty,cl} = 79_{-60}^{+167} \text{ km s}^{-1}$ and the fraction of the Ly α emission that is coming from the cold clumps $P_{cl} = 0.72_{-0.32}^{+0.20}$. The multiphase model assumes that the clouds are distributed over a sphere of 5 kpc 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 σ_{cl} correspond to a dynamical mass of $3.0_{-1.8}^{+1.5} \times 10^9 \text{ M}_\odot$.

Radio surveys of the 21 cm line have put an upper limit to the neutral hydrogen mass in Tololo 1214-277 of $M < 2.65 \times 10^8 \text{ M}_\odot$ [7]. In the case of the rotation model, this information help us to constrain the diameter of the HI region where the Ly α emission and transfer takes place. We find this size to be in the range $0.11 < D/\text{kpc} < 0.34$, one order of magnitude smaller than Tololo 1214-277's size in the optical. That size and the rotational velocity of 300 km s^{-1} put a constraint on the dynamical mass of $4.5_{-2.4}^{+2.1} \times 10^9 \text{ M}_\odot$.

This is evidence for a dynamical mass at least 11 (multiphase case) to 17 (rotation case) times higher than the mass in neutral hydrogen. There are three main possibilities to explain the dynamical mass: stars, dark matter and a supermassive black hole. The stellar mass in old stars has been constrained by non-detections in the K-band to be $< XXX \text{ M}_\odot$. Considering a standard dark matter halo, it can only contribute to $xx \text{ M}_\odot$ in the region of interest. A super massive black hole remains an open possibility. Recent observations of ultra-compact dwarf galaxies [8] have confirmed the presence of super-massive black holes containing 15% of the total object mass, suggesting that there is a large population of undetected black holes in dwarf galaxies.

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 $0.5_{-0.4}^{+1.0}\%$.

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 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.

These findings demonstrate the importance of including rotation and mul-

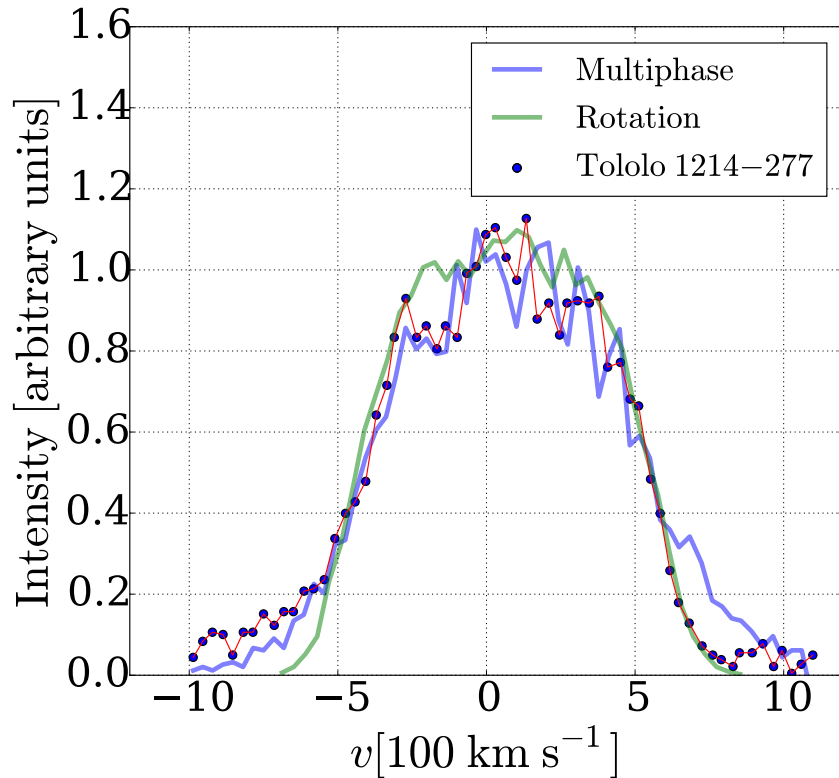


Figure 1: **Broadn, single peaked and symmetric Ly- α emission of Tololo 1214-277.** Dots correspond to the observational data. The line shows the results of our best model from a full radiative transfer simulation both for the rotation and multiphase models.

tiphase conditions as features to model the Ly α line in high redshift galaxies. Additionally, if the hypothesis of a supermassive black hole in Tololo 1214-277 proves to be consistent with future observational kinematic maps, it could correspond to a so far undetected black hole in a dwarf galaxy, providing a new way to test and probe theories on the co-evolution of galaxies and black holes in the first generation of galaxies.

References

- [1] Klaus J. Fricke, Yuri I. Izotov, Polychronis Papaderos, Natalia G. Guseva, and Trinh X. Thuan. An imaging and spectroscopic study of the very metal-deficient blue compact dwarf galaxy tol 1214-277. *The Astronomical Journal*, 121(1):169, 2001.
- [2] D. G. Hummer and P. J. Storey. Recombination-line intensities for hydrogenic ions. I - Case B calculations for H I and He II. *MNRAS*, 224:801–820, February 1987.

- [3] Y. I. Izotov, P. Papaderos, N. G. Guseva, K. J. Fricke, and T. X. Thuan. Deep VLT spectroscopy of the blue compact dwarf galaxies Tol 1214-277 and Tol 65. *A&A*, 421:539–554, July 2004.
- [4] J. M. Mas-Hesse, D. Kunth, G. Tenorio-Tagle, C. Leitherer, R. J. Terlevich, and E. Terlevich. Ly α Emission in Starbursts: Implications for Galaxies at High Redshift. *ApJ*, 598:858–877, December 2003.
- [5] G. Östlin, M. Hayes, F. Duval, A. Sandberg, T. Rivera-Thorsen, T. Marquart, I. Orlitová, A. Adamo, J. Melinder, L. Guaita, H. Atek, J. M. Cannon, P. Gruyters, E. C. Herenz, D. Kunth, P. Laursen, J. M. Mas-Hesse, G. Micheva, H. Otí-Floranes, S. A. Pardy, M. M. Roth, D. Schaerer, and A. Verhamme. The Ly α Reference Sample. I. Survey Outline and First Results for Markarian 259. *ApJ*, 797:11, December 2014.
- [6] R. B. Partridge and P. J. E. Peebles. Are Young Galaxies Visible? *ApJ*, 147:868, March 1967.
- [7] S. A. Pustilnik and J.-M. Martin. H I study of extremely metal-deficient dwarf galaxies. I. The Nançay radio telescope observations of twenty-two objects. *A&A*, 464:859–869, March 2007.
- [8] A. C. Seth, R. van den Bosch, S. Mieske, H. Baumgardt, M. D. Brok, J. Strader, N. Neumayer, I. Chilingarian, M. Hilker, R. McDermid, L. Spitler, J. Brodie, M. J. Frank, and J. L. Walsh. A supermassive black hole in an ultra-compact dwarf galaxy. *Nature*, 513:398–400, September 2014.
- [9] T. X. Thuan and Y. I. Izotov. Nearby Young Dwarf Galaxies: Primordial Gas and Ly α Emission. *ApJ*, 489:623–635, November 1997.

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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- α (erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$) | 8.1×10^{-14} |
| Ly- α EW | 70Å |
| H β (erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$) | 1.62×10^{-14} |
| 21cm (Jy km s $^{-1}$) | < 0.10 |

Table 1: Basic observational characteristics of TOL1214-277 [9]

Tololo 1214-277 characteristics

FIXME: Add non detection in 2MASS

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 $\sim Z_{\odot}/24$ [3] as derived from optical spectroscopy.

The observed flux for the Lyman alpha line is $\sim 8.1 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}$ [9] and a Equivalent Width of 70Å and its H β flux is $1.62 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Å}^{-1}$ [3] which gives a Ly α /H β flux ratio of 4.9 ± 0.1 . The Ly- α 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 [2] one can estimate an escape fraction of 20% for Ly α radiation.

The optical emission comes from a region with approximate diameter 4 kpc [1].

MCMC constraints

Physical Interpretation

Interpretation by [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 $M < 2.65 \times 10^8 \text{ M}_{\odot}$ [7]. From the optical depth of 10^7 and the non-detection in the HI line, we have an upper limit for the size where the Ly α emission comes of $D < 0.34 \text{ kpc}$.

For an homogeneous sphere the HI optical depth from its can be written as $\tau = \sigma_0 n D / 2$, where $\sigma_0 = 5.898 \times 10^{-14} \text{ cm}^{-2}$ is the Lyman α optical depth at the line's center, n is the number density and D is the sphere's diameter. From this we can impose additional constraints on D from the typical values

of the Hydrogen number density and our constrain on $\tau = 10^7$. Using a range of $1 < n/\text{atoms}/\text{cm}^{-3} < 10^{-3}$. This gives us a range of $0.11 < D/\text{kpc} < 100$. Together from the total HI mass we have thus that the HI region should have a diameter of $0.11 < D/\text{kpc} < 0.34$.

This can be rewritten in terms of the gas' temperature T and column density N_H as $\tau = 3.31 \times 10^{-14} (10^4 \text{K}/T)^{1/2} (N_H/\text{atoms cm}^{-2})$.

This allows us to approximate the total hydrogen mass as

$$M_H = m_H N_H D^2 = 226 \times \tau \left(\frac{T}{10^4 \text{K}} \right)^{1/2} \left(\frac{D}{\text{kpc}} \right)^2 M_\odot \quad (1)$$

On the other hand, we have an estimate for the dynamical mass from the galaxy size D and its rotational velocity V :

$$M_T = \frac{V^2 D}{G} = 2.16 \times 10^5 \left(\frac{V}{\text{km s}^{-1}} \right)^2 \left(\frac{D}{\text{kpc}} \right) M_\odot \quad (2)$$

From this limit and the rotational velocity of 300 km/s and the limit in the size D we have limits of for the dynamical mass of $2.1 \times 10^9 M_\odot < M_D < 6.6 \times 10^9 M_\odot$. which is at least 7 to 25 times larger than the HI mass. The mass to luminosity ratio is in turn between 2 to 7 times L_\odot/M_\odot considering the total luminosity in the V band.

Additional Information

The rotation model used was based on the one explored by [?]. Ly- α photons are propagated within a spherical and homogeneous cloud of HI gas undergoing solid body rotation. The sources of Ly- α photons are located in the center of the sphere of HI gas. Dust is not taking into account in our simulations since their effect doesn't affect the morphology of the Ly- α . The radiative transfer simulations were done using Monte Carlo simulations with the code [?].

In this model rotation increases the width of the line and the flux at the line center. Furthermore, observers at different line of sights (LOS) angles with respect to the rotation axis of the galaxy will observe different morphologies of the line. LOS parallel to the rotation axis will tend to observe a double peaked line, while an observer with a LOS perpendicular to the rotation axis will observed a single peaked broader line.

The idealized multiphase model consists of spherical, cold, dens 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 a observationally realistic range (based on the considerations of [?]) yielding a large variety of single-, double- and triple-peaked spectra. The full analysis of the the spectral features as well as more details on the radiative transfer are presented in [?].

MG: I don't know how much details you want – should we name all of the 14 (best fit) parameters? Just delete what is unnecessary.

For the current work, we computed the χ^2 for each of the 2500 parameters yielding the best fit parameters of (...). Here, the subscripts _{cl} and _{ICM} 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 σ_{cl} improved the fit significantly whereas others did not. This makes sense also 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.