Þú ert jörðin

JEFR[1], MCRG[1], JNGC[2], MG[3], MD[3]

[1] Bogota

[2] Tucson

[3] Oslo

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 features in its Lyman-α emission that had evaded theoretical interpretation so far. We show that these special features, a symmetric triple peaked emission line, can be explained by gas bulk rotation. We find that the Lyman-α emission region in Tololo 1214-277 should have a rotational velocity of $V_r = 300$ km s^{-1} and a neutral Hydrogen column density of $\log N_{HI}/\text{atoms cm}^{-2} = 20.5$. Using archival observational information about Tololo 1214-277 we find that the diameter for that emission region diameter should be in the range of 110 pc $< D <$ 340 pc and its total dynamical mass should be between $2.1 \times 10^{9}\text{M}_{\odot} < M_D < 6.6 \times 10^{9}\text{M}_{\odot}$. This dynamical mass is at least 16 ± 9 times larger than the neutral mass hydrogen. We argue that a possibility to explain the excess in dynamical mass is the presence of a super-massive black hole.

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 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 [7] 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 targeted 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. [6]. 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 [2] have shown that galaxy rotation imprints an effect on the Lyman-α line. The most important consequence of 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, as it is observed in Tololo 1214-277, a unique feature that other theoretical models find difficult to reproduce without invoking complex gas distributions.

Tololo 1214-277 is a compact star forming dwarf galaxy that presents a strong Ly-α emission [10] with two important features. First, it has symmetric profile without any systemic displacement from the expected line-center. Second, it shows a triple peaked profile. Commonly, the Ly-α line features a single or asymmetric double peak. These two special features in Tololo 1214-277 had evaded a natural physical interpretation so far.

We find that a rotating spherical gas distribution provides a satisfactory explanation of Tololo 1214-277's puzzling features. Figure 1. summarizes our findings. Dots represent the observational data for Tololo 1214-277with the overplot from our best fit model from the full radiative transfer simulation. The parameters for the best fit are a rotational velocity of $v_{max} = 300$km s^{-1}, an optical depth $\tau = 1 \times 10^7$ and temperature of $T = 1.5 \times 10^4$K. The optical depth and temperature can be translated into a column density of $\log N_{HI}/\text{atoms cm}^{-2} = 20.5$. Our model is also able to constrain the angle between the rotation axis and the observational line-of-sight to $\theta = 65°\pm$. To determine the uncertainties we perform a Markov Chain Monte Carlo calculation using an approximate analytic solution for the Ly-α spectrum including rotational effects.

Radio surveys of the 21cm line have put an upper limit to the neutral hydrogen mass in Tololo 1214-277 of $M < 2.65 \times 10^8$ M$_\odot$. Together with our velocity and column density results we constrain the total dynamical mass of the HI region to be in the range $2.1 \times 10^9\text{M}_\odot < M_D < 6.6 \times 10^9\text{M}_\odot$ and the diameter of HI region should have a diameter of $0.11 < D/\text{kpc} < 0.34$. This makes the dynamical mass at least 7 to 25 times larger than the neutral

Hydrogen mass.

We consider three possibilities to explain the dynamical mass: stars, dark matter and a supermassive black hole. The stellar mass can be constrained by measurements of the stellar continuum, this can only represent xxM$_{\odot}$ of the total contribution. Considering a standard dark matter halo, it can only contribute to xx M$_{\odot}$ in the region of interest. A super massive black hole remains an open possibility. Recent observations of ultra-compact dwarf galaxies [9] 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 of this possibility in Tololo 1214-277 would require integral field unit measurements spatially resolving its spatial extent. Tololo 1214-277 spans a region of 4 arcminutes. 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 detailed mapping of different ionization lines to infer a kinematic map.

Why is triple peaked emission not common in Lyman-alpha emitting gaalaxies? The ubiquity of galaxy outflows overimposed to the rotation transforms the line into the common double or single peaked line. Therefore, the absence of HI outflows in Tololo 1214-277 is another special feature that permitted a symmetric triple peaked lya line to emerge.

The implications of our finding for the study of LAEs, including the first generation of galaxies are manifold. First of all, it demonstrates the importance of including rotation as theoretical feature to interpret observed spectra. Secondly, it provides a motivation to explore under what conditions rotation dominated dynamics dominate over outflow dominated dynamics. Finally, if the hypothesis of a supermassive black hole in Tololo 1214-277 proves to be consistent with future observational kinematic maps, it would provide a new information 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] J. N. Garavito-Camargo, J. E. Forero-Romero, and M. Dijkstra. The Impact of Gas Bulk Rotation on the Lyα Line. *ApJ*, 795:120, November 2014.

[3] 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.

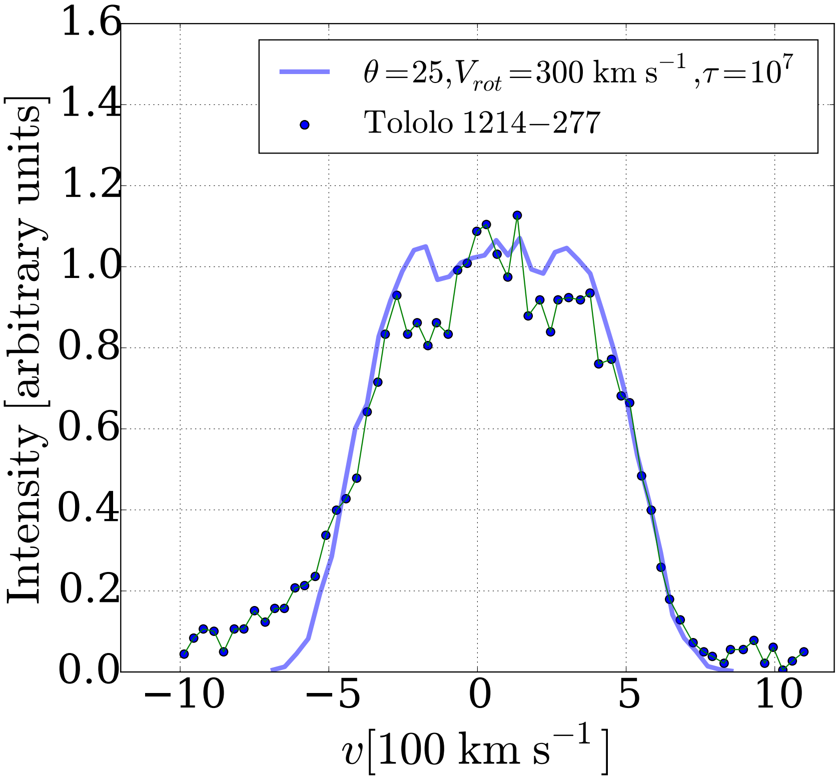

Figure 1: **Symmetric triple peaked Ly-α emission of Tololo 1214-277.** Dots correspond to the observational data. The line shows the result of our best model from a full radiative transfer simulation. The best parameters correspond to a rotational velocity of 300km s^{-1}, neutral Hydrogen optical depth of 10^7 and a viewing angle of 65° measured from the rotation axis.

[4] 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.

[5] J. M. Mas-Hesse, D. Kunth, G. Tenorio-Tagle, C. Leitherer, R. J. Terlevich, and E. Terlevich. Lyα Emission in Starbursts: Implications for Galaxies at High Redshift. *ApJ*, 598:858–877, December 2003.

[6] 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 Lyα Reference Sample. I. Survey Outline and First Results for Markarian 259. *ApJ*, 797:11, December 2014.

[7] R. B. Partridge and P. J. E. Peebles. Are Young Galaxies Visible? *ApJ*, 147:868, March 1967.

[8] 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.

[9] 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.

[10] T. X. Thuan and Y. I. Izotov. Nearby Young Dwarf Galaxies: Primordial Gas and Lyα Emission. *ApJ*, 489:623–635, November 1997.

$\alpha(2000)^a$	12h17min17.1s
$\delta(2000)^b$	-28d02m32s
l, b (deg)	294, 34
m_V	17.5
M_V	-17.6
v(km s^{-1})	7795
Ly-α (erg cm^{-2} s^{-1} Å^{-1})	8.1×10^{-14}
Ly-α EW	70Å
Hβ (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 [10]

Tololo 1214-277 characteristics

Tololo 1214-277receding velocity is 7785 ± 50km s^{-1}, which translates into a distance of 106.6 Mpc (Hubble constant 73 Mpc km^{-1} s^{1}) Its metallicity is $\sim Z_{\odot}/24$ [4] as derived from optical spectroscopy.

The observed flux for the Lyman alpha line is $\sim 8.1\times10^{-14}$ erg cm^{-2} s^{-1} [10] and a Equivalent Width of 70Åand its Hβ flux is 1.62×10^{-14} erg cm^{-2} s^{-1} Å-1 [4] which gives a Lyα/Hβ flux ratio of 4.9$\pm$0.1. The Ly-α flux values correspond to luminosities of $L_{Ly\alpha} = 2.2 \times 10^{42}$ erg s^{-1} over a 20Åbandwidth, which in turns translates into a star formation rate of 2.0 M$_{\odot}$ yr^{-1} using a standard conversion factor between luminosity and star formation rate of 9.1×10^{-43} $L_{Ly\alpha}$ M$_{\odot}$ yr^{-1}. The absolute magnitude in the V band translates into a luminosity of 8.9×10^{8} L$_{\odot}$. Comparing this ratio with the theoretical expectation from case B recombination of 23.3 [3] one can estimate an escape fraction of 20% for Lyα radiation.

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

MCMC constraints

Physical Interpretation

Interpretation by [5].

There is an upper limit for the integrated flux of < 0.10 Jy km s^{-1}, which translates into a upper limit for the HI mass of $M < 2.65 \times 10^{8}$ M$_{\odot}$ [8]. 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 Lya emission comes of $D < 0.34$kpc.

For an homogeneous sphere the HI optical depth from its can be written as $\tau = \sigma_0 n D/2$, where $\sigma_0 = 5.898 \times 10^{-14}$cm^{-2} is the Lyman$\alpha$ 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 constrains on D from the tipical values of the Hydrogen number density and our constrain on $\tau = 10^{7}$. Using a range of $1 < n/\mathrm{atoms/cm}^{-3} < 10^{-3}$. This gives us a range of $0.11 < D/\mathrm{kpc} < 100$.

Together from the total HI mass we have thus that the HI region should have a diameter of $0.11 < D/\mathrm{kpc} < 0.34$.

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

This allows us to approximate the total hydrogen mass as

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

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

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

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 $2.1 \times 10^9 \mathrm{M}_\odot < M_D < 6.6 \times 10^9 \mathrm{M}_\odot$. 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.

Joint Effect of Rotation and Outflow

The almost complete absence of outflows is a central requirement for reproducing the lyman alpha line in Tololo 1214-277. In this section we present some results on the exploration of the presence of outflows join with the bulk rotation. We defer a detailed exploration of this effects for another publication.

Figure XX shows the results of four different models. a) pure rotation ($V_{\mathrm{rot}} = 100$ km s^{-1}), b) pure outflow ($V_{\mathrm{out}} = 100$ km s^{-1}), c) mixed outflow with rotation ($V_{\mathrm{rot}} = 100$ km s^{-1})($V_{\mathrm{rot}} = 25$ km s^{-1}).