BAAA, Vol. 61B, 2020
A.M. Vásquez, P. Benaglia, F.A. Iglesias & M.A. Sgró, eds.

Asociación Argentina de Astronomía
Boletín de artículos científicos

Emission line galaxies around protoclusters in a galaxy formation model

T. Hough[1], S. Gurung-López[2,3], Á. Orsi[2] & S.A. Cora[1]

[1] *Instituto de Astrofísica de La Plata, CONICET–UNLP, Argentina*
[2] *Centro de Estudios de Física del Cosmos de Aragón, Teruel, España*
[3] *Department of Physics, Missouri University of Science and Technology, Rolla, EE.UU.*

Contact / tomas@fcaglp.unlp.edu.ar

Resumen / Las galaxias que presentan líneas de emisión Hα (HAEs) y Lyα (LAEs) son muy útiles para trazar la distribución de materia con alto corrimiento al rojo (*redshift*). En general, son utilizadas para encontrar regiones de alta densidad, llamados protocúmulos, que son objetos que luego formarán los cúmulos de galaxias más masivos ($\mathrm{M}_\star > 10^{14}\ \mathrm{M}_\odot$) en el presente. Estudiar las galaxias que presentan líneas de emisión en estos ambientes es muy importante para entender aspectos de la formación y evolución de galaxias en épocas tempranas del Universo. Además, los protocúmulos están embebidos en el medio intergaláctico, el cual puede dispersar los fotones Lyα. En este trabajo utilizamos el modelo semi-analítico de formación y evolución de galaxias GALFORM para estudiar el efecto de transferencia radiativa del medio interestelar e intergaláctico en la distribución espacial de las galaxias con líneas de emisión. Encontramos que las LAEs no evitan las regiones densas a $z = 2.2$, y que pueden trazar la misma densidad que las HAEs. Además, la presencia del medio intergaláctico disminuye levemente la correlación espacial de las LAEs a $z > 2$.

Abstract /
Galaxies exhibiting Hα (HAEs) and Lyα (LAEs) emission lines are one of the most important tracers of the high redshift Universe in modern astrophysics. They often probe high density environments, as protoclusters, which are the seeds of the most massive clusters of galaxies ($\mathrm{M}_\star > 10^{14}\ \mathrm{M}_\odot$) at the present epoch. Studying the properties of emission-line galaxies in these environments is key to understand aspects of the formation and evolution of galaxies. Protoclusters are also embedded in the intergalactic medium (IGM), which can scatter the Lyα photons. In the present work we use the GALFORM semi-analytic model of galaxy formation and evolution to analize how he radiative transfer of Lyα photons inside the inter-stellar medium (ISM) and IGM shapes the spatial distribution of emission-line galaxies at high redshift. We found that LAEs do not avoid dense regions at $z = 2.2$, and can trace same densities as HAEs. We also found that the presence of the inter-galactic medium slightly diminish the clustering of LAEs at $z > 2$.

Keywords / galaxies: clusters: general — galaxies: high-redshift — intergalactic medium

1. Introduction

The large-scale environment in which protoclusters are embedded is crucial to determine how they will evolve into the massive clusters of galaxies ($\mathrm{M}_\star > 10^{14}\ \mathrm{M}_\odot$) at the present time. At high redshift ($z \geq 2$), protoclusters are composed by an overdense distribution of galaxies and gas, and are usually located around radio galaxies (e.g. Le Fevre et al., 1996; Pentericci et al., 1997; Venemans et al., 2002; Venemans et al., 2007; Hayashi et al., 2012; Orsi et al., 2016) or quasars (e.g. Kashikawa et al., 2007; Overzier et al., 2009; Adams et al., 2015).

Emission-line galaxies (ELG) are often used to detect matter overdensities at high redshift, as narrow band filters help to detect galaxies with high emission lines and constrain their spatial distributions over a small slice of cosmic volume.

Among ELG, the nebular emission lines of Hα emitters (HAEs) and Lyα emitters (LAEs) have the same astrophysical origin, i.e., the emission of young and massive stars embedded in HII regions (Orsi, Lacey & Baugh, 2012; Dijkstra, 2017). Lyα photons are absorbed and scattered by the inter-stellar medium (ISM) and the inter-galactic medium (IGM) through complex radiative transfer processes that affect the observed properties of LAEs (Orsi et al., 2014; Gurung-López et al., 2019a). On the other hand, HAEs are not subject to these effects, making these galaxies excellent tracers of instantaneous SFR (Kennicutt, 1998; Calzetti, 2013).

In this work we use the GALFORM semi-analytic model of galaxy formation (Baugh et al., 2019) to explore the spatial distribution of LAEs and HAEs around protoclusters, at $z = 2.2$, $z = 3.0$, and $z = 5.7$, and evaluate the impact of the IGM on the LAEs.

2. Theoretical approach

We use the P-Millennium dark matter only simulation (Baugh et al., 2019), which is a state-of-the-art N-body simulation ruled by the Plank cosmology: $\mathrm{H}_0 = 67.77\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\Lambda = 0.693$, $\Omega_\mathrm{M} = 0.307$, $\sigma_8 = 0.8288$ (Planck Collaboration et al., 2016). The box size is $542.16\ \mathrm{cMpc}\,h^{-1}$ and the particle mass resolution is $M_\mathrm{p} = 1.061 \times 10^8\ \mathrm{M}_\odot\,h^{-1}$. The dark matter only simu-

Poster contribution

lation is combined with the GALFORM semi-analytic model of galaxy formation and evolution, detailed in Lacey et al. (2016) and Baugh et al. (2019).

For every galaxy, we model the ISM transmission of the Lyα photons using the Fast Lyman-Alpha Radiative transfEr trough Outflowing Neutral gas code (FLaREON, Gurung-López & et. al. 2019). The radiative transfer of Lyα photons in the IGM is described in Gurung-López et al. (2019a).

3. Searching for LAE depletion at high densities

In this section we study the spatial segregation of LAEs relative to HAEs in a wide sample of simulated protoclusters. We follow Shimakawa et al. (2017) approach, who studied the relation between the spatial distribution of galaxies and local density of galaxies that exhibit Hα and Lyα emission simultaneously (HAEs+LAEs) on a protocluster located at $z = 2.53$.

We create mock catalogues of protoclusters at $z = 2.2$ with the same spatial constraints as the one observed by Shimakawa et al. (2017). From all our central galaxies, we select every protocluster centre using the halo mass function of radio galaxies (Orsi et al., 2016). At $z = 2.2$ we have 1048 protoclusters with $M_{\rm halo} > 10^{13.2}$ M$_{\odot}$. The density of galaxies around 2 cMpc of these objects spans between 10 and 400 times the mean density of objects in our simulation.

The distance to the Nth neighbour is used as a proxy for local density, and has the advantage of not assuming an underlying geometry. In the case of Shimakawa et al. (2017), they use $< {\rm a} >_{\rm 5th} = 2 \times (\pi \sum_{\rm Nth})^{-0.5}$, where $\sum_{\rm Nth} (= {\rm N}/\pi {\rm r}^2_{\rm Nth})$ is the number density of galaxies within the radius $r_{\rm Nth}$, which is the distance to the $({\rm N}-1)$th neighbour from each galaxy. To build our ELG sample we impose luminosity cuts that allow us to match the observed surface density of HAEs and HAEs+LAEs. In our sample, HAEs have Hα luminosities $L_{{\rm H}\alpha} > 10^{41}$ erg s^{-1} and line emission equivalent widths (EW) EW > 18.6 Å, while HAEs+LAEs are imposed to have also $L_{{\rm Ly}\alpha} > 1.5 \times 10^{42}$ erg s^{-1} with EW > 15 Å.

Fig. 1 shows the projected $< {\rm a}_{\rm 5th} >$ for every HAE, and the cumulative number of HAEs and HAEs+LAEs as a function of $< {\rm a}_{\rm 5th} >$. We find that the depletion of HAEs+LAEs is not reproduced by our sample of protoclusters: while some follow the observational trend, others present the opposite behaviour, giving place to a statistically negligible depletion. Although there are less HAEs+LAEs than pure HAEs, the former do not avoid specifically the dense cores of protoclusters as infered from observations.

4. IGM impact on clustering at low scales

In the ΛCDM paradigm, the overdensity of dark matter haloes at high redshift are traced by overdensity of galaxies. The density of the IGM is higher around these structures, increasing the probability of scatter of Lyα photons that escape star-forming galaxies (Gurung-López et al., 2019b).

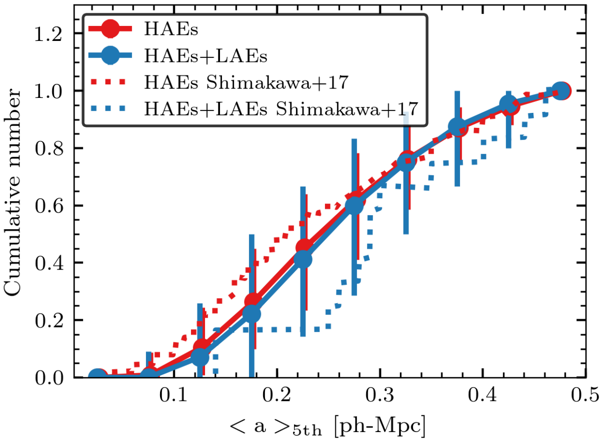

Figure 1: Cumulative number of HAE and HAEs+LAE in terms of the local density proxy $< {\rm a} >_{\rm 5th}$. Solid lines represent the median and error bars denote the $10 - 90th$ percentiles of HAEs (red) and HAEs+LAEs (blue) for 1048 protoclusters selected at $z = 2.2$. Dotted lines represent the behaviour of the USS-1558 protocluster, located at $z = 2.53$ (Shimakawa et al., 2017).

We explore the impact of the IGM model on the HAEs+LAEs sample, studying the clustering at small scales (< 10 cMpc h^{-1}) around protoclusters, where we expect a noticeable effect.

Our fiducial model consider both the ISM and IGM radiative transfer, and we compare with a model with only ISM radiative transfer included.

We quantify the clustering as the cross-correlation function between halo mass selected central objects and ELGs, ξ_{cc}. This is estimated as:

In Fig. 2 we show the clustering of HAEs and HAEs+LAEs for $z = 2.2$, $z = 3.0$ and $z = 5.7$ for the models with and without IGM effect. We find that HAEs+LAEs are $\sim$75 % less clustered in the cores ($\leq$ 0.5 cMpc h^{-1}), and $\sim$30 % up to 1 cMpc h^{-1} for $z = 2.2$ and $z = 3.3$, independently of the presence of the scattering effect of the IGM. This may arise because HAEs+LAEs tend to have lower SFRs, metallicities and inhabit less massive DM haloes than HAEs (Gurung-López et al., 2019b). Therefore, they are not a representative subsample of the HAEs, and have lower clustering than HAEs. We also notice that the impact of the IGM on the clustering is negligible at small scales, as expected, because the hydrogen present in the IGM at these redshifts is mainly ionized.

On the other hand, at $z = 5.7$ the IGM is partially neutral, and therefore the transmission of the Lyα photons is highly diminished for $\lambda < 1216$ Å (Gurung-López et al., 2019b). In the lower panel of Fig. 2 we show that the impact of the IGM on the HAEs+LAEs population is less than 10 % inside 1 cMpc h^{-1} with respect to the HAEs, indicating that the protoclusters may be surrounded by a self-produced bubble of ionized hydrogen

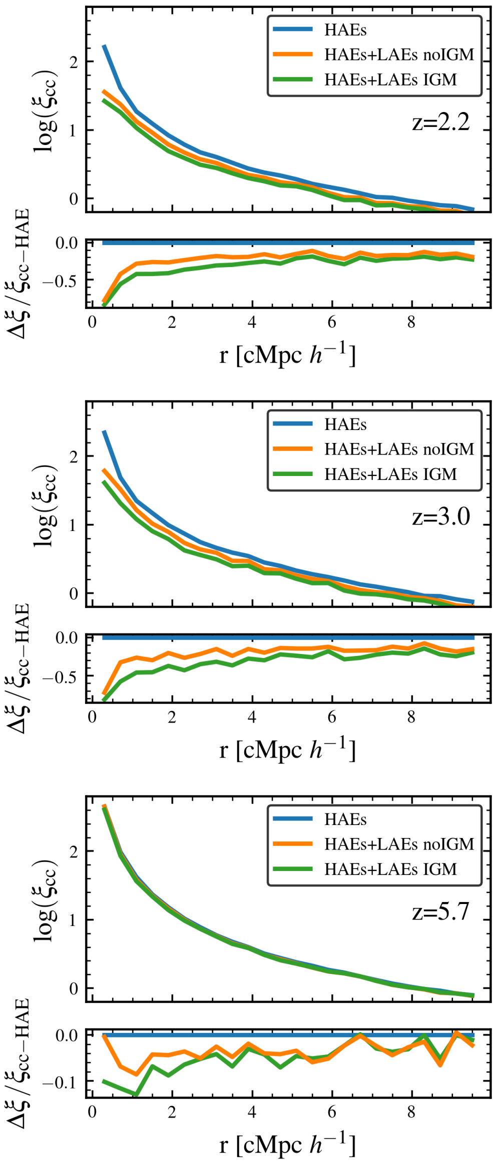

Figure 2: Cross-correlation functions for HAEs and HAEs+LAEs for $z = 2.2$ (upper panel), $z = 3.0$ (middle panel) and $z = 5.7$ (lower panel). Solid blue line represent HAEs, which are not affected by IGM at any redshift. Green and orange lines represent HAEs+LAEs from the model with and without IGM effect respectively. For each redshift we estimate the difference of the clustering relative to the HAEs, where $\Delta\xi$ represents the difference between the cross-correlation ($\xi_{\rm cc}$) of the HAE population and the cross-correlation of the HAE+LAE population.

that allows the scape of the Lyα photons.

$$\xi_{cc}(r) = \frac{DD(r)}{N_{\rm c} n_{\rm gal} \Delta V(r)} - 1, \qquad (1)$$

where $DD(r)$ is the total number of galaxies around central objects at a distance $r \pm \Delta r/2$, $N_{\rm c}$ is the total number of central objects in the simulation box, $n_{\rm gal}$ is the mean number density of galaxies, and $\Delta V(r)$ is the volume of a spherical shell of radius r and width Δr.

5. Conclusions

By means of the GALFORM semi-analytic model, we created a galaxy catalogue that includes Lyα radiative transfer of both ISM and IGM. We studied the spatial segregation of LAEs with respect to HAEs around protoclusters at $z = 2.2$, $z = 3.0$ and $z = 5.7$.

We find no significant depletion of LAEs in the densest regions of a sample of 1048 simulated protoclusters at $z = 2.2$. We compare our results with observations performed by Shimakawa et al. (2017) of the protocluster USS-1558 located at $z = 2.53$, and notice that the behaviour of this protocluster may be due to cosmic variance.

At $z = 2.2$ and $z = 3.0$ the difference in the clustering of HAEs and HAEs+LAEs may arise because the radiative transfer inside galaxies induce selection effects over galaxy properties. HAEs+LAEs tend to have lower star formation rates, lower metallicities and inhabit less massive halos than HAEs, hence their clustering is lower. We find no significant impact of the IGM at these redshifts at small scales.

At $z = 5.7$, where we would expect a mild effect of the IGM scattering on Lyα photons, we find an almost indistinguishable impact on clustering. This may be related to the bubbles of ionized material in which protoclusters inhabit, that facilitates the scape of Lyα photons.

Acknowledgements: This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the Marie Sklodowska-Curie grant agreement No 734374. TH acknowledges Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Argentina, for their supporting fellowships. SAC acknowledges funding from CONICET (PIP-0387), Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT, PICT-2013-0317), and Universidad Nacional de La Plata (G11-150), Argentina.

References

Adams S.M., et al., 2015, MNRAS, 448, 1335
Baugh C.M., et al., 2019, MNRAS, 483, 4922
Calzetti D., 2013, *Star Formation Rate Indicators*, 419
Dijkstra M., 2017, arXiv e-prints, arXiv:1704.03416
Gurung-López S., et. al., 2019, MNRAS, 490, 733
Gurung-López S., et al., 2019a, MNRAS, 486, 1882
Gurung-López S., et al., 2019b, arXiv e-prints, arXiv:1904.04274
Hayashi M., et al., 2012, ApJ, 757, 15
Kashikawa N., et al., 2007, AJ, 663, 765–773
Kennicutt Robert C. J., 1998, ARA&A, 36, 189
Lacey C.G., et al., 2016, MNRAS, 462, 3854
Le Fevre O., et al., 1996, ApJL, 471, L11
Orsi A., Lacey C.G., Baugh C.M., 2012, MNRAS, 425, 87
Orsi Á., et al., 2014, MNRAS, 443, 799
Orsi Á.A., et al., 2016, MNRAS, 456, 3827
Overzier R.A., et al., 2009, MNRAS, 394, 577
Pentericci L., et al., 1997, A&A, 326, 580
Planck Collaboration, et al., 2016, A&A, 594, A13
Shimakawa R., et al., 2017, MNRAS, 468, L21
Venemans B.P., et al., 2002, ApJ, 569, L11
Venemans B.P., et al., 2007, A&A, 461, 823