Exploiting galaxy-21cm synergies to shed light on the Epoch of Reionization

Pratika Dayal

DELPHi
Exploiting galaxy-21cm synergies to shed light on the Epoch of Reionization

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Linked to galaxy formation

- Minimum mass to which galaxies can form stars
- The star formation rates of early galaxies
- Escape of ionizing radiation
- Dust enrichment of early galaxies
- GW from the early Universe

Linked to reionization

- External (UV) feedback impact
- Key reionization sources (galaxies, BHs or..?)
- Using combination of galaxy and large scale data to constrain reionization topology and history in era of 21cm cosmology

Linked to cosmology

How can early galaxies be used to probe the cosmological model, specially in context of Dark Matter models

Outstanding challenges

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How can early galaxies be used to probe the cosmological model, specially in context of Dark Matter models
Key collaborators and collaborations

Volker Bromm: University of Texas at Austin, USA
Benedetta Ciardi: Max Planck Institute for Astrophysics, Germany
Tirthankar Choudhury: National Centre for Radio Astronomy, India
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Hiroyuki Hirashita: ASIAA, Taiwan
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Catherine Trott: ICRAR, Perth, Australia
Livia Vallini: Nordita, Stockholm, Sweden
Gustavo Yepes: Universita Autonoma di Madid, Spain…
Modelling reionization: evolution of volume filling fraction of ionized hydrogen

\[
\frac{dQ_{II}}{dt} = \frac{dn_{int} f_{esc}}{dz} \frac{1}{n_H} - \frac{Q_{II}}{t_{rec}} \frac{dt}{dz}
\]

\[
t_{rec} = \frac{1}{\chi n_H (1 + z)^3 \alpha_B C f_{\text{fn}}(\text{space}, \text{time})}
\]
SFR density (used to model reionization) extremely uncertain at $z>8$. 

Figure 28: The evolution of the cosmic star formation rate density (SFRD) above a star-formation limit of $0.7M_\odot/yr$ corresponding to $M_{UV} \approx 17.7$. The points show data collected by Bouwens et al. [428, 518, orange filled circles], the CLASH lensing surveys [light blue filled circles; 514, 515, 516], Ellis et al. [513, purple filled circles], McLeod et al. [482, red filled squares], Oesch et al. [426, green filled squares] and Oesch et al. [509, maroon filled triangle]. The downward facing arrows showing upper limits are from Ellis et al. [513, purple] and Oesch et al. [426, green]. The black lines shows DELPHI results integrated down to a UV magnitude limit of $M_{UV} = 17.7$ (solid line), $M_{UV} = 15$ (dashed line) and for all galaxies (dot-dashed line). The dot-dashed gold line and the dashed red line show results from the DRAGONS project and the EAGLE simulations, respectively. We also show the SFRD-$z$ trend inferred from low-$z$ galaxies which evolves as $/ (1 + z)^{3.6}$ (short-dashed blue line) with $z>8$. The blue solid line shows $/ (1 + z)^{10.9}$ (long-dashed blue line) as compared to the shallower SFRD inferred for lower redshift data [e.g. 428, 404]. Of course, it must be noted that the implicit assumption in all these conversions is that the SFR has remained constant for about a 100 Myrs prior to observations; this conversion would face an upward revision by a factor of about 2 if these galaxies had particularly young ages [e.g. 431].

We then compare these observations to theoretical models (DELPHI, DRAGONS and EAGLE) finding that these results, whilst agreeing with observations at $z<8$, do not show the steep drop at $z>8$ [e.g. 509] as compared to the shallower SFRD inferred for lower redshift data [e.g. 428, 404].

It must be noted that inferring the UV luminosity density has been a herculean task at these high-$z$ due to a number of complexities including: the contamination from emission line galaxies, from local (L, M, T or Y) dwarfs and/or AGN, the impact of cosmic variance given the small fields and the uncertainties associated with the adopted lensing magnifications. Despite these complications, the data inferred from all fields is in excellent agreement as shown in the same figure. Given the paucity of statistics, however, the $z$-evolution of the SFRD has remained a matter of debate, with observational works finding a much steeper slope of $/ (1 + z)^{10.9} \pm 2.5$ at $z>8$ [e.g. 509] as compared to the shallower SFRD $/ (1 + z)^{3.6}$ inferred for lower redshift data [e.g. 428, 404]. Of course, it must be noted that the implicit assumption in all these conversions is that the SFR has remained constant for about a 100 Myrs prior to observations; this conversion would face an upward revision by a factor of about 2 if these galaxies had particularly young ages [e.g. 431].
The source term: (some) basic problems

SFR density (used to model reionization) extremely uncertain at $z>8$. 

Dayal & Ferrara, 2018, Physics Reports, Volume 780, pg. 1-64
The impact of reionization feedback on galaxy formation

Neutral hydrogen: $T = T_{\text{CMB}}$  
Ionized hydrogen: $T \sim 20,000$ K
The impact of reionization feedback on galaxy formation

- The UVB created during reionization can suppress the gas mass of low-mass galaxies, flattening the faint-end slope.

- Variation of faint end slope of UV LF in multiple JWST fields can be used to explore fluctuating UVB (fixing critical mass value)

  Choudhury & PD, 2019
Key sources of reionization remain hidden.

Key reionization sources depend on SF efficiency (impacted by UV feedback) and the escape fraction.

PD & Ferrara, 2018, Physics Reports, 780, 1
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Key sources and topology (patchiness) of reionization fundamental open questions
Lyman Alpha emitters (LAEs) : a new probe of the patchiness and topology of reionization

This naturally implies a (huge?) sub-population of galaxies hidden in the Lyman Alpha, with more & more becoming visible as reionization proceeds.
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The full LAE model: SPH+radiative transfer

1. SPH simulations *(GADGET3)*

2. Intrinsic spectrum *(SB99)*

3. SNII dust enrichment

4. RT - pCRASH

5. IGM Transmission

Dayal+10,12; Hutter+14,15,16
Reionization hints from clustering evolution of LAEs

Reionization progress decreases measured clustering of LAEs

McQuinn+08; Hutter, PD+2016
First evidence for an over-dense reionized patch

Clustered galaxies preferentially visible in Lyman Alpha

Castellano, PD+2016; Castellano+2017
Cross-correlating 21cm data with (spectroscopically confirmed) galaxy data will be key to yield information on reionization sources & topology.
The SKA EoR “synergy” group

• Enormous efforts in trying to link observed 21cm emission with underlying galaxy/QSO populations to shed light on reionization sources & topology.

• We require information on fields, survey volumes/depths to calculate and co-ordinate best possible survey strategies.

• Targeting collaborations with Subaru, WFIRST, Euclid and E-ELT.

• Co-ordinators: Pratika Dayal, Andrea Ferrara, Eric Zackrisson
Relation between LAEs, reionization and 21cm brightness temperature

Lying in over-dense and highly ionized regions, LAEs show much lower 21cm brightness temperatures than average

Combining 21cm and LAE data should allow us to differentiate between an IGM that is xx% ionized to one that is completely neutral.

The 21cm-LAE cross-correlation: hints on neutral fraction

\[ \langle x_{\text{HI}} \rangle = 0.50 \]

\[ \langle x_{\text{HI}} \rangle = 0.10 \]

\[ \langle x_{\text{HI}} \rangle = 0.25 \]

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\[ \langle x_{\text{HI}} \rangle = 10^{-4} \]

\[ \langle x_{\text{HI}} \rangle = 0.35 \]

\[ \langle x_{\text{HI}} \rangle = 0.07 \]

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\[ \langle x_{\text{HI}} \rangle = 0.52 \]

Vrbanec et al. (2016)

Sobacchi et al. (2016)

Hutter et al. (2017)

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Anne Hutter & Pratika Dayal

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Measuring 21cm brightness temperature in regions with/without LAEs can tell us if reionization proceeded inside out or outside-in.

Hutter, PD et al., decadal paper, arXiv: 1903.03628
Survey parameters to optimise the 21cm-LAE correlation

Key issue: As volume decreases, thermal noise increases. As number of LAEs decrease, shot noise increases.

Solution: 25 deg² surveys (Subaru/WFIRST) targeting intermediate luminosity LAEs most optimal - but smaller volumes can be compensated by probing to lower Lya luminosities

Hutter, Trott & Dayal 2018;
Hutter, Dayal et al, 2019 (Astro 2020 white paper)
Summary

- Modelling reionization still open problem due to key physical uncertainties for both galaxies and IGM (z-evolution of cosmic SFRD, fesc, C).

- Due to these issues, sources and topology of reionization remain outstanding problems in astrophysics.

- Galaxy (specially LAEs)-21cm correlations will be invaluable in shedding light on the reionization state (fraction of neutral hydrogen) and topology.

- 25 deg2 surveys (Subaru/WFIRST) targeting intermediate luminosity LAEs most optimal - trade-off between volume and Lya luminosity limit.

- Contact Pratika Dayal, Andrea Ferrara or Erik Zackrisson for comments for/questions for/join the SKA EoR Synergy group.