Implications for the Epoch of Reionization in the Local Universe

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Overview

- **Reionization constraints from the Cosmic Microwave Background** $(z > \sim 6)$
  
  "A projected estimate of the reionization optical depth using the CLASS experiment's sample-variance limited E-mode measurement,"
  

- **Local analogs to reionization-era galaxies** $(z \sim 0.3)$
  
  "A new technique for selecting galaxies leaking Lyman-continuum photons: [S II]-deficiency,"
  

  "The Low-redshift Lyman-continuum Survey: [S II]-deficiency and the leakage of ionizing radiation,"
  

- **Starburst-driven outflows** $(z \sim 0.07)$
  
  "A systematic study of galactic outflows via fluorescence emission: implications for their size and structure,"
  
When did reionization happen?

- **Spectroscopy of distant quasars:** reionization ends by $z \sim 6$ (e.g., Fan+ 2006)

- **The cosmic microwave background:**
  
  - mid-point redshift of reionization $z = 7.7 \pm 0.7$ (Planck 2018 VI)
  
  - future measurements of polarization will tighten the constraint (e.g., CLASS; Watts, BW+ 2018)
How did reionization happen?

- Where did ionizing (Lyman-continuum; LyC) photons come from?
- How did ionizing photons escape into the intergalactic medium?
Star-forming galaxies as ionizing sources

Sufficient to reionize the universe as inferred from the UV luminosity function.

But what makes it possible for LyC to escape into the IGM?

- Neutral H column of \( \sim 10^{-3} \, \text{M}_\odot \, \text{pc}^{-2} \) (\(10^{17} \, \text{cm}^{-2}\)) absorbs all H-ionizing radiation.

The neutral IGM during reionization precludes direct observations of LyC.

\[ \log_{10} \rho_{\text{UV}} \left( \text{ergs s}^{-1} \text{ Hz}^{-1} \text{ Mpc}^{-3} \right) \\
\log_{10} f_{\text{esc,ion}} = 24.90 \]

\[ \log_{10} \rho_{\text{UV}}(z) = 26.11 - 0.19 \, (z - 6) \]

\[(\text{Bouwens+ 2015})\]
A strategy: studying LyC emitters at low redshifts

~ 10 direct detections in recent years, e.g., Borthakur+ 2014; Leitherer+ 2016; Izotov+ 2016, 2018.

Benchmark sample: Green-Pea galaxies, characterized by high \([\text{O } \text{III}] / [\text{O } \text{II}]\) flux ratios.

The Low-redshift LyC Survey (HST-GO-15626; PI A. Jaskot)

66 star-forming galaxies at \(z \sim 0.3\), satisfying at least one of the following criteria:

- \([\text{O } \text{III}] / [\text{O } \text{II}]\) flux ratio > 3
- UV spectral slope < −2
- \(\text{SFR/area} > 0.1 \text{ M} \odot \text{ yr}^{-1} \text{ kpc}^{-2}\).
A new LyC signpost: [S II]-deficiency

The ionization potential for producing [S II] (10.4 eV) < that needed for ionizing H I (13.6 eV).

[S II] emission mostly arises in the partially ionized region, which is expected to be weak when the neutral region is absent to allow LyC to escape.
Definition of $[\text{S}\ II]$-deficiency

Defined with respect to typical SDSS star-forming galaxies — a galaxy’s displacement in $\log([\text{S}\ II]/H\alpha)$ from the ridge line.

(BW+ 2019)
Results from a pilot HST program

Two out of the three [S II]-weak-selected star-forming galaxies are confirmed to be LCEs.

(BW+ 2019)
Results from the Low-z LyC Survey

Density of star-forming galaxies

Results from the Low-z LyC Survey
**Statistical tests**

[S II]-deficiency diagnostic can reliably select candidates of LyC emitters.

Distributions of LCEs differ from that of non-LCEs along the axis of [S II]-deficiency.

Fractions of LCEs detected increase as [S II]-deficiency becomes more prominent.

(BW+ 2021)
Comparisons to other LyC diagnostics

Correlations btw [S II]-deficiency and other diagnostics are weak, indicating that it provides independent information on LyC leakage.

\( r = -0.241^{+0.137}_{-0.121} \) \( p = 0.051^{+0.350}_{-0.049} \)

\( r = -0.040^{+0.134}_{-0.144} \) \( p = 0.429^{+0.392}_{-0.342} \)

(BW+ 2021)
The escape fraction ($f_{\text{esc}}$) is very important for understanding reionization, but remains poorly constrained.

The weak correlation with significant scatter suggests that it is not obvious to infer $f_{\text{esc}}$ from numerical values of [S II]-deficiency.

(BW+ 2021)
The weak correlation may indicate:
• line-of-sight variations caused by porous H I regions (e.g., Steidel+ 2018; Nakajima+ 2020)
• anisotropically escaping LyC photons (e.g., Cen & Kimm 2015)
Conclusions

How did reionization happen?

- Where did ionizing (Lyman-continuum; LyC) photons come from?
  - Star-forming galaxies are the best candidates;
  - We have selected LyC-emitting galaxies based on \([ \text{S} \, \text{II}]\)-deficiency
    - a sign of gas that is optically thin to ionizing radiation;
  - \([ \text{S} \, \text{II}]\)-deficient candidates tend to be strong LyC emitters.

- How did ionizing photons escape into the intergalactic medium?
  - Only a weak correlation is found between numerical values of \([ \text{S} \, \text{II}]\)-deficiency and LyC escape fraction.
    - line-of-sight variations caused by porous H I regions;
    - anisotropically escaping LyC photons.