Faint Galaxies and Reionization

Steve Furlanetto
UCLA
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Some Context: The Cosmic Dawn and Reionization

"Cosmic Dawn"  Reionization
How do we learn about reionization?
What is reionization?

- Landmark event of first generation of galaxies
- Affects fuel for future generations of galaxies
- Powerful probe of all those galaxies you CAN'T see

A. Mesinger
Galaxies and Reionization

Ionizing Photons

IGM Absorption
Key Expectations For Reionization

- Ionized structures are LARGE: diameter~50 Mpc (~20 arcmin)
  - Sizes depend on galaxy clustering
- Timing depends on integrated source population
- End phases regulated by IGM absorption (transition to Lyman-α forest)

M. Alvarez
Observations of Reionization: Timing

- Free electrons scatter CMB photons
- Planck measurements suggest reionization ended at $z<8$ or so

Planck Collaboration (2016)
Observations of Reionization: Timing

- Free electrons scatter CMB photons
- Planck measurements suggest reionization ended at $z<8$
- Astrophysical measurements are consistent with most of reionization occurring at $z<7.5$
- Depend on interpreting IGM Lyman-$\alpha$ absorption (around quasars and galaxies)

Davies et al. (2018)
Observations of (Not Quite) Reionization: Structure

- Lya forest fluctuates VERY strongly shortly after reionization
- Cannot be explained by a standard model of the ionizing background

Becker et al. (2015)
Two Potential Explanations, with Opposite Predictions!

Option #1: a short mean free path triggers large fluctuations in the ionizing background (Davies & Furlanetto 2016) - possibly even ongoing reionization (Kulkarni et al. 2018)

Option #2: relic temperature fluctuations from extended reionization (D’Aloisio et al. 2016)

Davies et al. (2018)
**Observations!**

- Used narrowband filter on HyperSuprimeCam (fortuitously matching deepest absorption trough at $z=5.7$!)

- Clear DEFICIT of LAEs in this area: points toward ionizing background explanation!

- Lessons:
  - Features in ionizing background occur on large scales ($>10$ Mpc)
  - Redshift information is essential!

Becker et al. (2018)
Observing Reionization with the 21-cm Line

- Observe emission or absorption from neutral hydrogen via 21-cm line
- Disappears during reionization!
- Observed frequencies ~50-200 MHz - hard!

A. Mesinger
21-cm Surveys: HERA

Hydrogen Epoch of Reionization Array (PI: A. Parsons, UC Berkeley)

- Now under construction; complete in ~2020
- Will measure statistical fluctuations in the 21-cm field, not make images!
How do we learn about galaxies during the Cosmic Dawn?
Deep surveys have measured the bright-bright-ism end of the galaxy LF with some precision to $z \sim 10$

Probes of fainter end are more controversial.

This observed LF has no particular surprises: simple galaxy models fit without any real trouble.

No evidence for new physics!

Furlanetto et al. (2017)
Faint Galaxies

BUT key is in the faint end: dominates total emission!

This is ALSO where we might expect new physics

- Pop III sources?
- Bursty dwarf galaxies?
- Globular clusters?
- Who knows?

Furlanetto et al. (2017)
Galaxies Take a "long" Time to Grow!

- Super-simple model of "smooth" galaxy formation
- Final product: halo of mass $10^{11} \, M_{\odot}$ at $z=5$, or $M_{AB} \sim -20$
- Can begin forming stars using conventional methods at $z \sim 25$!
Key Physics:
Pop III -> Pop II Transition

- How does “normal” galaxy formation establish itself?
- Pop III phase likely...
  - Brief (in any given halo)
  - Bursty
- Star formation in small halos is regulated by Lyman-Werner background from massive galaxies
- Need to probe very faint sources!

Mebane et al. (2018)
Signatures of New Physics in Bright Galaxies?

Can we learn about these early stars by looking in detail at bright objects?

Incomplete mixing means Pop III stars continue to form?

Unusual emission lines

Burstiness

Etc.

Sarmento et al. (2018)
Probing the Earliest Phases of Galaxy Formation

Bowman et al. (2018) claimed the first detection of the redshifted 21-cm signal with the EDGES experiment.

Highly controversial and requires confirmation!!!

IF confirmed, important implications for galaxy formation!

Bowman et al. (2018)
EDGES and Galaxies

Timing is most important for galaxy formation

Early signal requires EITHER

- More efficient star formation at higher redshifts
- More efficient star formation in (very) small halos
  (Or both)

Shape still difficult to reproduce...steepness requires very massive sources (Kaurov et al. 2018)

Mirocha & Furlanetto (2019)
EDGES and Galaxies

Requires substantial differences from theoretical expectations and UV LFs

BUT new physics may end at some intermediate time...

Alternate classes of sources?

- Globular clusters?
- Pop III stars?
- AGN?

Mirocha & Furlanetto (2019)
EDGES and Galaxies

Potentially observable with ultra deep fields

Mirocha & Furlanetto (2019)
What are these extra stars?

- Can reasonably get enough Pop III star formation to turn on the 21-cm background (see also Schauer et al. 2019)
- Requires fast heating as well - substantial, rapidly accreting black hole remnant population!
- Just one example of a potential explanation!

Mebane et al. (in progress)
How do we connect the two?
Improved Source Modeling

Reionization (and other radiation backgrounds) depend on source parameters!

Most can be constrained from 21-cm; some improve significantly with LF information

BUT constraints highly dependent on parameterization!

Park et al. (2018)
How do we interpret observations of invisible galaxies?

- Statistical constraints will be highly dependent on parameterization!
  - True of 21-cm, luminosity functions, intensity mapping, etc.

- What is a sensible parameterization of (for example) Pop III star formation?
  - Needs to be connectable to physics we can model, but not locked into any one scenario
  - Ideally has some way to suggest forward progress when we realize the model is broken!

- “Orthogonal” observations will offer one approach

- Or drill down to the details, where ELTs will shine!
Challenges of Cross-Correlation

- 21-cm surveys have VERY POOR angular resolution!
- Not SO bad because features in reionization are also large
- Current plans call for throwing out nearly all modes with angular information
- Detailed cross-correlation requires deep observations (>10^5 galaxies), excellent redshifts (<3% errors), and a large areal coverage (>30 square degrees)

Beardsley et al. (2015)
Challenges of Cross-Correlation

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Beardsley et al. (2015)
Cross-Correlation Can Provide Statistical Constraints on Galaxy Environment

- HERA (and other near-future instruments) CAN offer statistical constraints on ionization fraction over ~arcmin scales
- Act as “source finder” for ELTs at very high redshifts?

Beardsley et al. (2015)
Conclusions

- Reionization measurements require large-scale probes BUT can inform galaxy measurements

- We EXPECT the physics of galaxy formation to change... but only in very small halos!

- An understanding of early galaxies will require complementary information constraining observable galaxy populations AND integrated emission

- Also can inform (and be informed by!) environmental studies