Simulating cosmic reionization at large scales

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Presentation by Mike Pagano
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Simulating cosmic reionization at large scales:

1. The geometry of reionization
   - Trying to understand the size and spatial distribution of the ionized and neutral patches and their evolution

2. The 21-cm emission features and statistical signals
   - Approach for direct detection of the epoch of reionization
1. Geometry of reionization

• Previous reionization simulations only small volumes, not exceeding 20 $h^{-1}$ commoving Mpc.
• Need to resolve small galaxy which dominate at early times
• Most methods are based on ray-tracing radiative transfer method, which grows proportionally to number of ionizing sources, limiting size.
New Simulation

- They create the first large-scale radiative transfer simulation with a volume of $(100 \, h^{-1} \, Mpc)^3$
- Use codes PMFAST and $C^2$-RAY to do a N-body simulation that can resolve down to dwarf galaxies
- New Ray-tracing radiative transfer method, correctly track ionization fronts
Assumptions

- Gas closely follows dark matter distribution
- Flat ΛCDM with:
  \[ \Omega_m = 0.27 \]
  \[ \Omega_\Lambda = 0.73 \]
  \[ \Omega_b = 0.044 \]
  - \( h = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \)
  \[ \sigma_8 = 0.9 \]
  - \( n = 1 \)
N-body Simulation

- Resolution: $1624^3 = 4.28 \text{ billion dark matter particles and } 3248^3 \text{ computational cells.}$
- Particle mass: $2.5 \times 10^7 M_\odot$
- Only deal with haloes of 100 or more particles

Early structure formation at $z = 10$
N-body Simulation

- Minimum halo mass of $2.5 \times 10^9 \, M_\odot$, which would be a dwarf galaxy
- The first haloes form at $z \approx 21$, reaching 85,000 haloes by $z \approx 11$, and 0.8 million by $z = 6$. 
Halo Mass Functions

- At lower redshifts ($z \leq 10$) it agrees with Sheth-Tormen (ST) mass function, but overestimates number of haloes at high redshift.
- The Press-Schechter (PS) approximation underestimates the number of rare haloes in the exponential tail.

Blue - Halo mass function
Black - PS
Red - ST
Simulation

- Assume a fixed temperature of $10^4 \text{K}$ everywhere.
- Ionizing sources are based on haloes from simulation. Sources falling within the same cell of the radiative transfer grid are combined together.
Ionizing Flux

\[ \dot{N}_\gamma = f_\gamma \frac{M \Omega_b}{\Delta t_i \Omega_0 m_p}, \quad f_\gamma = f_\star f_{\text{esc}} N_i \]

- \( f_\gamma \) is the efficiency factor
- \( N_\gamma \) is the number of ionizing photons emitted by source per unit time
- \( N_i \) is the total photon production per stellar baryon
- \( f_\star \) is the star formation efficiency
- \( f_{\text{esc}} \) is the ionizing photon escape fraction
Ionizing Flux

- They adopt a $f_\gamma = 2000$
  - either top-heavy intial mass function of $N_i = 50,000$, $f_*=0.2$ and $f_{\text{esc}} = 0.2$
  - or Salpeter IMF with $N_i = 10,000$, $f_*=0.4$ and $f_{\text{esc}} = 0.5$
Geometry of Reionization

- Slices through simulation volume at $z = 18.5, 16.1, 14.5, 13.6, 12.6,$ and $11.3$, neutral = green, ionized = yellow, $\text{H}_\text{II} = \text{red}$
Geometry of Reionization

- First $\text{H}_\text{II}$ regions appear at $z \sim 21.5$, and expand to a few comoving Mpc by $z \sim 18$
- Highly clustered and quickly merge into larger regions
- Early ionization is dominated by local source clustering.

http://www.cita.utoronto.ca/~iliev/xy_f2000_406_5mpc_thick_thin.gif
Geometry of Reionization

- As reionization progresses regions become less clustered and have local overlap.
- Whole box ionized by $z \sim 11.3$

Volume with H$_\text{II}$ regions at redshifts $z=14.74$ and $z=13.62$
Density and Ionization

- No simple relation between mean density of a region and its reionization history, but most overdense regions become ionized first.
- Graph of mass-weighted ionized fraction vs. average density at different redshifts
Density and reionization

- Blue = Evolution of mass-weighted ionized fraction in non-overlapping cubical subregions of different sizes.
- Red = Mean density
- Cyan = Global evolution of mass ionized fraction
Power Spectra

Dotted = Variance of 3D power spectra of neutral gas density
Solid = Total density
Dashed = ionized gas density
“Friends-of-Friends”

- To find individual ionized regions used a “Friends-of-friends” algorithm
  - 2 cells are linked together if their ionized fractions are larger than 0.5
  - This lets them catalogue the H\textsubscript{II} bubbles and their merger history
Size Distribution

- Total bubbles
- At higher redshifts, no large bubbles, and more small-medium sized
- At lower redshifts, mostly dominated by large bubbles

Top - number of $H_{\text{II}}$ bubbles of that size
Bottom - volume filling factor of the bubbles
Size Distribution

- By redshift $z \sim 14.2$ there are three $H_\text{II}$ regions larger than $10^4 \ (h^{-1} \text{ Mpc})^3$ and each occupies a few percent of the total volume.
- By $z \sim 13.6$ they become one large bubble which occupies half the total volume.
- By $z \sim 11.5$, one big large bubble.
Non-Gaussian nature of Reionization

- Probability Distribution Functions
- Left: density in mean density
- Middle: mass ionized fraction
- Right: density in mean ionized density
2. The 21-cm emission features

- Observations of 21-cm line of hydrogen could be a good approach for direct detection of the epoch of reionization.
- The 21-cm radio line is due to a spin-flip transition of neutral hydrogen.
- Needs to be decoupled from the CMB.
Models

- f2000 - model from paper 1
- f250 - efficiency factor of 250
- C add subgrid gas inhomogeneities - with clumping factors - improved small scale clumping

Table 1. Simulation parameters and global reionization history results.

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Comparing the models

- Top - f2000, bottom - f250
- Observationally they correspond to slices through and image-frequency volume
- Reionization occurs at higher redshifts for f2000
Sky Maps

- Sky map as seen at redshifted 21 cm line
- With 3-arcmin FWHM compensated Gaussian beam and 0.2-MHz bandwidth
- Large H$_{II}$ regions are apparent as holes in the radiation map.
Sky Maps

• Although obtaining images of 21-cm emission would be ideal, it's unlikely in the near term because of sensitivity limits and dominate foregrounds.

• Can approximate foregrounds with a slowly varying power law in frequency, subtract signal over a bandwidth, they use 5 MHz
Sky Maps

- Top - sky map
- Bottom - sky map with subtracted a wide 5Mhz band to remove foreground
Rms Fluctuations

- Top - rms fluctuations of the differential brightness temperature versus observed frequency
- Could be something to be observed and see which model is closest
- Peak - universe is 50% ionized by mass

![Graph showing various curves with legend: Blue - f2000, Magenta - f250C, Red - f2000C, Green - f250)]
Non-Gaussianity

- 21-cm signal is also non-Gaussian
Upcoming missions

- PAST
  - Primeval Structure Telescope
- MWA
  - Murchison Widefield Array
- LOFAR
  - Low Frequency Array
- SKA
  - Square Kilometre Array
- GMRT
Summary

• First large-scale radiative transfer simulation, showing final overlap at z~11
• Denser/clumpier gas has shorter recombination times
• Complex relation between density of a region and its ionization state.
• Probability distribution functions are Non-Gaussian, for all models
Summary

• Gradual transition in the 21-cm signal from neutral gas being ionized
• The large-scale geometry of reionization is well resolved in the 21-cm sky map, especially if you subtract out a large-frequency band to eliminate foreground.
• Rms fluctuations hit a maximum at 50% ionization by mass.
• http://www.cita.utoronto.ca/~iliev/xy0_evol.gif
• http://www.cita.utoronto.ca/~iliev/dokuwiki/doku.php?id=simulations