The astrophysics of the first galaxies from the 21-cm line

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1 Plan

From Andrei: "A discussion highlighting how the soft UV, ionizing UV, and X-ray properties of the first galaxies are encoded in the patterns and timings of the 21-cm signal. Subtopics could include: the evolution of the IGM ionization and temperature, a discussion of the corresponding sources and sinks, a qualitative discussion how global and interferometric signals can discriminate between different source models, challenges in modelling the cosmic signal and a summary of the available simulation tools."

My plan for each section (in one bullet):

1. Introduction to modeling ionization and thermal histories. Be agnostic about sources.
2. Introduction to sources. What are their spectra like, and what uncertainties remain?
3. Source evolution. How do we model redshift evolution and spatial clustering of sources?
4. Methods for coupling sources and IGM properties, from analytic to (semi-)numerical techniques.
5. Put it all together. Predictions for global signal and power spectrum, build intuition for how parameter variations lead to changes in observables. (maybe merge with previous section)

2 Modeling the History of Ionization, Heating, and Ly-α Coupling (i.e., preliminaries)

The brightness temperature depends on $x_{\text{H I}}$, T_{K}, and J_{α} (see Steve's section for derivations, couplings, etc). This section will focus on how to model those things in a (for now) source agnostic way. I'll cover each quantity in turn, in the time-order they are expected to be dominating the evolution of the 21-cm background.

In this section, define a generic emissivity as $\epsilon_{\nu}(z;R)$, i.e., the emission at frequency ν, redshift z, in some region R (typical units: erg s^{-1} Hz^{-1} cMpc^{-3}). Write down the cosmological RTE for starters (or point to Steve's section if he's got it there).

The Ly-α Background

1. Qualitative discussion of how this background is generated, i.e., it's (mostly) not rest-frame Ly-α emission.
2. Introduce the sawtooth modulation and relationship with the LW background. Discuss cascades through Ly-α, opacity from H_2.
3. How does one solve for J_{α} in practice? Discuss mean background approach in addition to more halo model-like approaches (sawtooth, picket fence, etc.).

X-ray Heating

1. Write down simple ODE for temperature evolution, highlight source term.
2. Write down heating rate as integral over background intensity. Introduce opacity, draw attention to difficulty in X-ray RT. Uncertainties in the intrinsic opacity, X-ray analog of UV escape fraction.
3. Secondary ionization and heating. For now just focus on level of ionization as being important in terms of fractional energy deposition in different channels, defer discussion of ionization as intrinsically interesting thing until next section.

Reionization

1. Introduce two-zone approximation for reionization and the standard reionization equation.
2. Source term: relevant photons have short mean-free paths, so unlike previous two quantities we just basically count photons in Lyman continuum rather than solving RTE (with perhaps some correction for recombinations; see below).
3. Draw attention to escape fraction, include some discussion of what we know about it observationally and what predictions we have for it at high-z.
4. Discuss clumping/recombinations.
5. (Likely) second-order effects like reionization by X-rays, HeII recombination photons.

Note: in principle all the astrophysics is in $\epsilon_\nu(z;R)$, which is still completely unspecified. In the next two sections we focus on *what* sources likely dominate the emission and what we know about their spectra, i.e., we focus on the frequency component of ϵ in §3. In §4, we turn our attention to the z and R dependence, and close in §5-6.

3 The Sources of Ionization, Heating, and Ly-α Emission

Massive Stars

1. Start with discussion of PopIII stars, models for their spectra.
2. Move on to "normal" galaxies, variations in spectra due to metallicity, initial mass function, etc.
3. Mention potential impact of low-mass stars, e.g., IR feedback on PopIII star formation.

Shockwaves and Hot gas

1. Inverse Compton in supernova remants.
2. Cosmic rays
3. Brehmmstrahlung from diffuse ISM.

Accretion onto Compact Objects

1. Solitary PopIII remnants
2. X-ray binaries
3. AGNs.

Keep track of all the different parameters relevant to this stuff in a table?

4 Predictions for Star and Black Hole Formation at High-z

Star Formation

1. Differences in PopIII star formation, predictions for redshift/mass evolution.
2. Prescriptions for the SFE in galaxies.
3. The $f_{\rm coll}$ approach, i.e., how the SF physics gets buried in our semi-analytic and semi-numeric models.

Stellar Remnants

1. Start with PopIII stellar remnants. Reference merger-tree approaches like Tanaka et al.
2. HMXBs. With the exception of Fragos et al., most work doesn't try to forward model these things, instead we just use empirical laws to scale SFRs.

Proto-SMBHs

1. Talk about problems with growing SMBHs from stellar seeds.
2. Introduce the DCBH model.
3. Are we actually sensitive to these objects, or are they too rare? A few studies to lean on here.

5 Modeling Tools

Once we've got a model for ϵ, how do we solve the relevant equations? Lots of trade-offs to consider. This section outlines many different approaches in the literature, starting with efficient-but-very-approximate semi-analytic models, to the intermediately-complicated semi-numeric models, all the way to cosmological simulations.

Analytic and Semi-Analytic Models

1. FZH04 and Jonathan Pritchard's 2007 paper. Barkana papers circa 2005. Excursion set / halo model extensions like Janakee's stuff and my stuff.
2. Matt McQuinn's perturbative approach.
3. Publicly available codes.
4. Limitations

Semi-numeric Models

1. Talk about semi-numeric philosophy. How to operate on density field directly, how to flag cells as ionized, how to do X-ray heating and Ly-α emission efficiently.
2. Publicly available codes: 21CMFAST, SIMFAST21, Anastasia's code (maybe not public?)
3. Limitations

Cosmological Simulations

1. Choices to be made here. Spending resources on galaxies themselves? RT? Large volume? What are the trade-offs and who is doing what?

2. Brief rundown of different RT methods (Eulerian v. Lagrangian or moving mesh)
3. Current results of big simulation suites. How are things looking?
4. Is there a mapping from the parameters of simulations to the parameters of semi-analytic and semi-numeric models?

6 Predictions and Challenges

- What are the generic predictions for the global signal and power spectrum?
- To what extent can we expect to break degeneracies with measurements of both, and/or comparing with galaxy surveys?
- To what extent do different modeling techniques agree?

I might merge this in with the previous section.