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Imprints of early Universe galaxy formation on the 21-cm signal at cosmic dawn

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Abstract

During the first billion years of our Universe, the first light sources formed. These sources will impact the intergalactic medium, which can be probed using the 21-cm signal. This signal can be found in the radio frequency band and used to study the nature of these first sources. We developed a new semi-analytical framework, ANAXAGORAS, which can accurately model the formation of first galaxies considering all the necessary cooling and feedback processes. We show that presence of molecular hydrogen (H_2) is important for forming the first light sources. We further couple ANAXAGORAS with our 21-cm signal modelling code, HMREIO and develop simulations of the 21-cm signal during the era of first sources. We find that the 21-cm signal can constrain the properties of these sources when observed at redshift $z \gtrsim 9$. During the epoch of reionization, the H_2 cooling becomes inefficient and therefore loses information about the early formation processes.

1 Introduction

Cosmic dawn refers to the period of our Universe when the first luminous sources, such as galaxies and quasi-stellar objects (QSOs), formed. These sources ended the 'cosmic dark ages' and created the conditions for further structure formation in our Universe. See Refs. [1, 2, 3, 4] for a review. Current constraints suggest that this period occurred at times corresponding to a redshift z between 6 and 20. The photons produced by these sources changed the thermal and ionization state of the intergalactic medium (IGM) during these times. We can probe the evolution of the IGM using the 21-cm signal, which is produced by the spin-flip transition of the ground state of the neutral hydrogen [2].

The 21-cm signal produced by the spin-flip transitions in neutral hydrogen in the intergalactic medium during cosmic dawn will be redshifted and observed by the radio telescopes. Several radio experiments are currently attempting to observe this signal. For example, single antenna experiments, such as the Experiment to Detect the Global EoR Signature (EDGES), Shaped Antenna measurement of the background RAdio Spectrum (SARAS) and Radio Experiment for the Analysis of Cosmic Hydrogen (REACH), are focusing on the sky-averaged signal whereas interferometry based telescopes, such as The corresponding quantity observed by the Low-Frequency Array (LOFAR), Hydrogen Epoch of Reionization Array (HERA) and Murchison Widefield Array (MWA), are trying to detect the power spectrum.

The quantity observed by the radio telescopes is known as the differential brightness temperature (δT_b), which is given as [5]

$$dT_b(\mathbf{x},z) \simeq T_0(z)x_{\mathrm{HI}}(\mathbf{x},z)\left[1+\delta_b(\mathbf{x},z)\right] \times \frac{x_\alpha(\mathbf{x},z)}{1+x_\alpha(\mathbf{x},z)}\left[1-\frac{T_{\mathrm{cmb}}(z)}{T_{\mathrm{gas}}(\mathbf{x},z)}\right], \quad (1)$$

which depends on position ($\mathbf{x}$) and redshift (z) [6]. The position-dependent quantities are the neutral fraction (x_{HI}), the baryon overdensity (δ_b), the total UV coupling coefficient (x_α), and the gas temperature (T_{gas}). The background (CMB) temperature (T_{cmb}) is assumed to only evolve with redshift. The amplitude of the differential brightness temperature is given by

$$T_0(z) = 27\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\frac{1+z}{10}\right)^{\frac{1}{2}} \mathrm{mK}, \quad (2)$$

where Ω_m and Ω_b are the cosmic matter and baryon abundances and $h = H_0/100$ (km/s)/Mpc is the dimensionless Hubble parameter.

The state of the IGM is driven by the properties of the first sources, which will be imprinted on the 21-cm signal [7, 8, 9]. Therefore it is vital to model the properties of the first generation of sources. We developed a framework, ANAXAGORAS, to accurately model the formation of these sources from the first principle (Nebrin, Giri, Mellema, in prep). We couple this framework with a 21-signal modelling code, HMREIO [10, 11], to study its impact on the 21-cm observables. In the next section, we describe our modelling framework. We present our results in Section 3 and conclude in Section 4.

2 Modelling methods

We describe our methods to model the first sources and the 21-cm signal in Section 2.1 and 2.2 respectively.

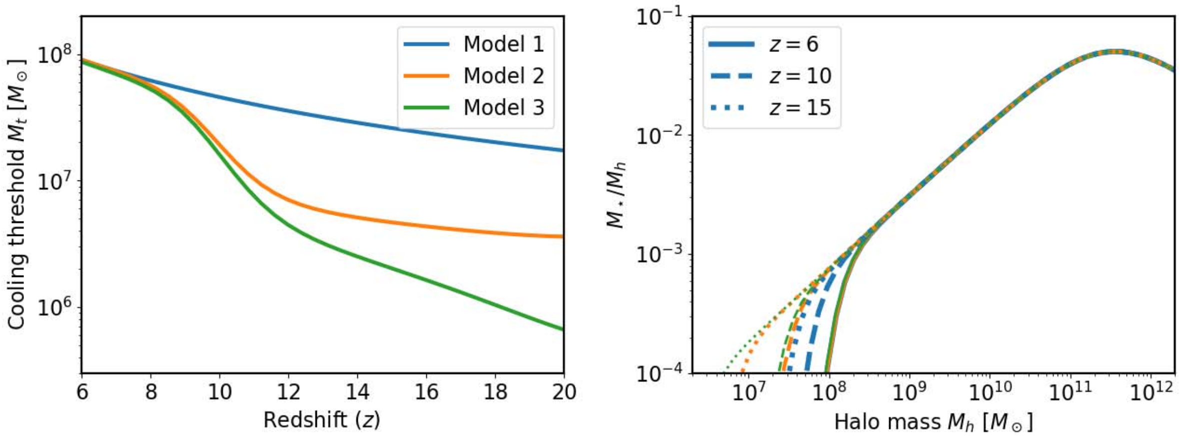

Figure 1. The properties of the first luminous sources modelled in ANAXAGORAS. The left panel shows the minimum mass of dark matter haloes that can sustain star formation in three different models. The right panel gives the stellar-to-halo relation, which can be used to estimate the mass of the luminous sources in various dark matter haloes.

2.1 First luminous sources

We developed a new semi-analytical framework, ANAXAGORAS, which can accurately model the formation of first galaxies by considering the effects of H_2-cooling and formation (in the gas phase and on dust grains), cooling by atomic metals, Lyman-α cooling, photodissociation of H_2 by Lyman-Werner photons (including self-shielding by H_2), photodetachment of H^- by IR photons, photoevaporation by ionization fronts, and the effect of baryon streaming velocities. We compare the calculations to several high-resolution cosmological simulations, showing excellent agreement, and significantly better agreement than earlier analytical models. The detailed description of the framework will be provided in an upcoming paper (Nebrin, Giri & Mellema, in prep).

Here we have considered three representative models to study the impact of the source formation process on the state of the IGM. These models are the following:

- Model 1: The luminous sources are assumed to reside in dark matter haloes with virial temperature of 10^4 K. This has been shown by numerous authors as the limit where atomic hydrogen cooled sources can form [12].
- Model 2: In this model, we carefully estimate the cooling threshold M_t considering the photoionization background from Ref. [13] and the Lyman-Werner background from Ref. [14]. We also consider the baryon streaming velocity that can prevent the baryons from falling into the gravitational potential well of dark matter haloes [15, 16]. Here we assume the streaming velocity to be $50\left(\frac{1+z}{1000}\right)$ km/s.
- Model 3: This model same as Model 2, but ignoring the baryon streaming. Hence, the model helps us understand the influence of photoionization and Lyman-Werner background on first light source formation.

In Figure 1, we show the properties of the sources estimated by ANAXAGORAS in the above three models. Left panel shows the cooling threshold at different redshifts. We see that the cooling threshold is lower in models with H_2-cooling compared to Model 1. Due to the presence of baryon streaming, the threshold values in Model 2 is slightly higher than Model 3. In Model 3, the cooling threshold at high redshifts converges to the dark matter haloes with virial temperature of 500 K, which is consistent with the predictions by Ref. [17]. At low redshifts, all the models converge as cosmic reionization begins that significantly reduces H_2 due to the strong UV background.

In the right panel of Figure 1, we show the stellar-to-halo relation, which is given as

$$\frac{M_\star}{M_h} = \frac{0.1(\Omega_b/\Omega_m)}{\left(\frac{M}{10^{11.5}M_\odot}\right)^{0.49} + \left(\frac{M}{10^{11.5}M_\odot}\right)^{-0.61}} S(M) , \qquad (3)$$

which consists of a double power law multiplied by term

$$S(M) = \left(1 + \left(\frac{M_t}{M}\right)^3\right)^{-3} \qquad (4)$$

to modulate the suppression at small-mass end. The double power law part is taken from Ref. [18], which is consistent with current UV luminosity function observations. $S(M)$ is used to suppress star formation in halo mass below M_t. See the ‘TRUNCATED’ model in Ref. [11] for more details. In Figure 1, we observe varying stellar-to-halo relation for our three models. We model the accretion of mass onto the haloes using the accretion model based on the extended Press-Schechter calculations given in Refs. [10, 11].

2.2 21-cm signal during cosmic dawn

We use our HMREIO framework to model the 21-cm global signal and the power spectrum. We follow the calculation

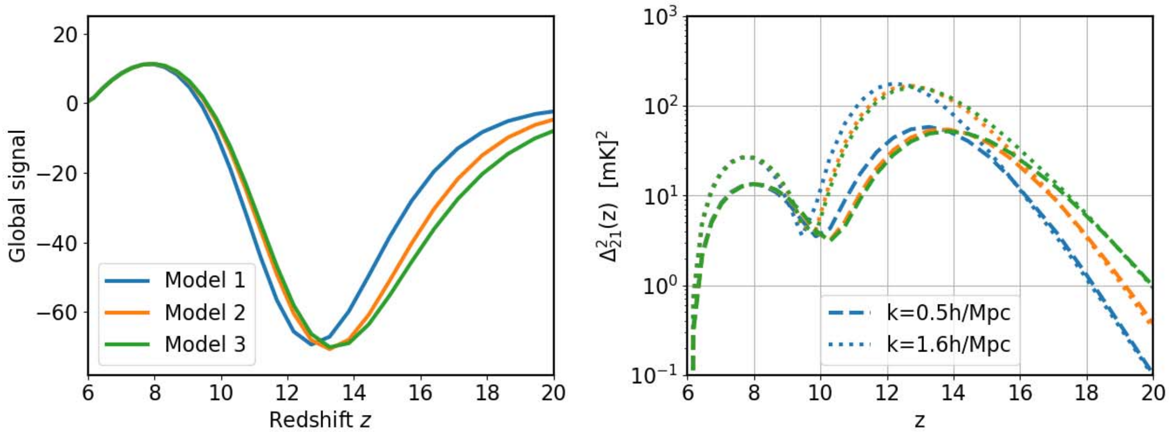

Figure 2. The 21-cm signal predicted by HMREIO. The left panel shows the evolution of the sky-averaged 21-cm signal at various redshifts in three different models. The right panel gives the evolution of the corresponding 21-cm power spectrum at $k = 0.5$ h/Mpc (dashed) and $k = 1.6$ h/Mpc (dotted).

in Ref. [18] to estimate the global signal. To estimate the power spectrum, we use the halo model (HM) formalism [19]. In this formalism, the fluctuations can be divided into two parts, namely the 1-halo (small-scale fluctuation) and 2-halo (large-scale fluctuation) terms. The large-scale signal is assumed to follow the distribution of dark matter haloes. The small-scale fluctuation can be estimated by modelling the signal around each dark matter halo. We refer the readers to Refs. [10, 11] for the detailed description of this formalism built for the high redshift 21-cm signal.

3 Results

Here we present the expected 21-cm signal observations corresponding to our models of the first luminous sources. The left panel of Figure 2 shows the evolution of the 21-cm signal. We can clearly see that the absorption feature appears at earlier times in models with H_2 cooling. This feature in Model 2 is slightly delayed compared to Model 3 due to the baryon streaming that reduces the number density of small mass sources. The differences are quite stark at high redshifts and negligible at low redshifts. This hints that the radio observations should be focused on high redshifts to distinguish between these models.

In the right panel of Figure 2, we show the evolution of the 21-cm power spectra at wave modes $k = 0.5$ h/Mpc (dashed line) and $k = 1.6$ h/Mpc (dotted line). We see similar behaviour as in the case of the global signal. The power spectra consists of multiple features (e.g. peaks at different times for different scales), which gives us an opportunity to better constrain the models. Note that the power spectra from all models converge when cosmic reionization begins as H_2 cooling becomes inefficient during this time.

4 Conclusion

In this work, we present our framework to model the first luminous sources and study their impact on the 21-cm signal observations that will be observed by current and upcoming radio telescopes. The first generation sources or population III stars will reside in small mass haloes. We find that the impact of these sources are more distinguishable in 21-cm signal at high redshifts $z \gtrsim 9$, which corresponds to times before substantial cosmic reionization has happened. Therefore, to constrain the properties of the first sources, we need to focus on observing these high redshift era.

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