21cm signal predictions at Cosmic Dawn and Reionization with coupled radiative-hydrodynamics

N. J. F. Gillet\textsuperscript{1}\*, D. Aubert\textsuperscript{1}, F. G. Mertens\textsuperscript{2,3} and P. Ocvirk\textsuperscript{1}

\textsuperscript{1}Observatoire Astronomique de Strasbourg, Université de Strasbourg, CNRS UMR 7550, 11 rue de l’Université, 67000 Strasbourg, France
\textsuperscript{2}Kapteyn Astronomical Institute, University of Groningen, PO Box 800, NL-9700 AV Groningen, the Netherlands
\textsuperscript{3}LERMA, Observatoire de Paris, PSL Research University, CNRS, Sorbonne Université, F-75014 Paris, France

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The process of heating and reionization of the Universe at high redshift links small scale structures/galaxy formation and large scale inter-galactic medium properties. Even if the first one is difficult to observe, an observation window is opening on the second one, with the promising development of current and future radio telescopes. They will permit to observe the 21cm brightness temperature global signal and fluctuations. The need of large scale simulations is therefore strong to understand the properties of the IGM that will be observed. But at the same time the urge to resolve the structures responsible of those process is important. We introduce in this study, a coupled hydro-radiative transfer simulations of the Cosmic Dawn and Reionization with a simple sub-grid star formation process developed and calibrated on the state of the art simulation CoDaII. This scheme permits to follow consistently dark matter, hydrodynamics and radiative transfer evolution’s on large scales, while the sub-grid models bridges to the galaxy formation scale. We process the simulation to produce 21cm signal as close as possible to the observations.

Key words: reionization – galaxies: formation – radiative transfer

1 INTRODUCTION

Despite the fact that the first billion years are full of events, the properties of the Universe between the emission of the Cosmic microwave background (CMB) and redshift z=6 are still poorly constrained by observations. It sees the Cosmic Dawn (CD), the birth and growth of the first structures, stars and galaxies, as well as the cosmological change of properties of the inter-galactic medium (IGM), from cold and neutral to hot and ionized during the Epoch of Heating (EoH) and Reionization (EoR). Observational prospects seems promising, with e.g. high redshift galaxies probed by the James Webb Spatial Telescope (JWST) or the avalanche of data from the current and in-development radio telescopes that will measure the IGM properties on large scales. In this work, a special focus will be put on this latter type of instruments such as: LOw Frequency ARray (LOFAR; van Haarlem et al. 2013), which acquires data between 200MHz and 110MHz (between redshift 6 to 12), therefore focusing on the end of the EoH and the EoR. The LOFAR EoR Key Science Project has recently put upper limits on the power spectrum of the cosmic 21cm signal at redshift 9.1 (Mertens et al. 2020). Another instrument, the New Extension in Nançay Upgrading loFar (NENUFAR; Zarka et al. 2012), acquiring data between 85MHz and 30MHz (from redshift 16 to 45) and therefore overlapping with the frequency range of claimed detection of the global signal at redshift 17 of the EDGES instrument (Bowman et al. 2018). In parallel, theoretical modeling of the physics and the signal is ongoing and aims at following the structure and galaxy formation on small scales and its impact on the properties of the IGM on large scales. The theoretical challenge is to do both: resolving the birth and properties of the first galaxies, their photons emission (Lyman-\(\alpha\), x-rays, UV for example) and tracking the evolution of the IGM properties on cosmological distances.

Several groups address this challenge by using analytical models of galaxy formation (most often base on the local collapse mass fraction or halos mass function) and semi-numerical treatments of the Reionization (e.g. Visbal et al. 2012; Fialkov et al. 2014; Park et al. 2019). These methods have the advantage to have a comprehensible set of galaxy formation parameters and to be computationally efficient. Alternatively, others push to directly solve all scales with coupled hydrodynamics-radiative transfer simulations (e.g. Gnedin 2016; Semelin et al. 2017; Ocvirk et al. 2016, 2020). But the trade-off between resolution and volume makes those simulations difficult to realize and costly, while being still limited in the range of halo masses or cosmological scales that can be probed. A final alternative is to perform the radiative transfer in post-process on top of dynamics-only simulations. It uses high resolution dark matter halos to support a galaxy formation model while providing a realistic propagation of photons (e.g. Chardin et al. 2017; Kulkarni et al. 2019; Ross et al. 2019). The gain in computational time can be significant compared to fully coupled simulation but this method...
cannot probe the full extent of the respective feedbacks of matter and radiation.

In this article, we present an alternative to produce large scale-simulations (> 250 cMpc needed for proper IGM properties Iliev et al. 2014; Kaur et al. 2020) in the context of current and future radio experiments of the Cosmic Dawn. It relies on fully-coupled radiative transfer-hydrodynamics and a sub-grid model of galaxy formation at the necessarily moderate resolution (1 cMpc) on such volumes. One of the most pressing challenges in the lack of source formation during the Cosmic Dawn due to the limited resolution in large simulated volumes. Standard sub-grid star formation models cannot create sources in an efficient manner and alternatives must be developed, such as the one we describe here. We propose that the unresolved star formation could be based on state-of-the-art high resolution simulations of the EoR such as CoDaII (Ocvirk et al. 2020). This technique is implemented in the EMMA cosmological simulation code (Aubert et al. 2015) and is demonstrated in the following sections. It permits to have a fully coupled evolution of the radiative field and the IGM gas while the sub-grid source model takes care of the non-resolved structure formation and evolution. We show that this methodology leads to viable and consistent predictions of the 21 cm radio signal from the Cosmic Dawn. We introduce the calibrated sub-grid source formation model in Section 2 and then discuss the resulting large-scale 21cm signal predictions in Section 3.

2 SOURCE FORMATION MODEL AND SIMULATION

In this study we use the ‘full-physics’ cosmological simulation code for reionization EMMA (Aubert et al. 2015) in a large scale/low resolution mode. We extend the code with a new empirical source (star/galaxy) formation model based on the CoDaII simulation that provides more flexibility at high redshift than standard methods and we also add simple prescriptions for the prediction of the 21cm signal.

2.1 Sources

The challenge of large-scale/low-resolution simulations is to assign a production of ionizing photons per volume unit despite the lack of dense, non-linear structures in simulations. At high redshift (z > 6) the main sources of UV photons are young massive stars : we have a cold, dense, non-linear structures in simulations. At high redshift (z = 6) the main sources of UV photons are young massive stars. We hereafter, physical scale quantities are annotated with the letter ‘r’ and comoving one with a ‘c’. Low and high resolution quantities are annotated with ‘L’ and ‘H’, respectively and refer to 1 h⁻¹ cMpc or to the original CoDaII resolution (15.625 h⁻¹ cKpc).

In post-processing, we degrade the simulation outputs on a coarse grid of 64³ cells corresponding to our 1 h⁻¹ cMpc goal resolution. In each cells we compute a ‘coarsened’ density contrast (Δ = ρ/̅ρ) and a ‘coarsened’ star formation rate, using 10 snapshots between redshift 5.7 to 15. This post-processed SFR density of CoDaII simulation is computed in each coarse 1 h⁻¹ cMpc cell as the sum of the stellar particle masses younger than 10 Myr, divided by 10 Myr. Hereafter, high resolution cells are added with a ‘c’. Low and high resolution quantities are annotated with ‘L’ and ‘H’, respectively and refer to 1 h⁻¹ cMpc or to the original CoDaII resolution (15.625 h⁻¹ cKpc).

One might directly apply Eq 1 on the low resolution grid, but it results in a too permissive star formation at high redshift (z≈30). Indeed, the density contrast are smaller at low resolution and at high redshift, therefore having one fixed density threshold would produce an almost flat cosmic SFR evolution with redshift, much too much star at high redshift or not enough at low redshift. We need to change the threshold parameter to mimic the sub-grid collapse structures and control the SFR at high and low redshifts. Furthermore, the classical scheme applied at low resolution cannot take into account the sub-grid quenching of the Reionization on the smallest galaxies. To take this effect into account we derive an empirical model based on the outputs of the CoDaII simulation.

2.1.1 Star formation in CoDaII

The CoDaII simulation has a box of 64 h⁻¹ cMpc side sampled on a Cartesian grid of 4096³ elements. In a very standard manner, the production of stellar particles during the simulation is driven by a SFR density computed at each time step, according to:

$$SFR_L = \varepsilon \rho^1.5, \text{ where } \rho > \rho_s.$$  \hspace{1cm} (1)

In the CoDaII simulation, the SFR is directly proportional to the density at high resolution (z = 0.42) is the star formation efficiency and ρ_s/Ω = Δ_s = 50 is the star formation density threshold (Ω = Ω_b/Ω_0 is the baryonic fraction).

In post-processing, we degrade the simulation outputs on a coarse grid of 64³ cells corresponding to our 1 h⁻¹ cMpc goal resolution. In each cells we compute a ‘coarsened’ density contrast (Δ = ρ/̅ρ) and a ‘coarsened’ star formation rate, using 10 snapshots between redshift 5.7 to 15. This post-processed SFR density of CoDaII simulation is computed in each coarse 1 h⁻¹ cMpc cell as the sum of the stellar particle masses younger than 10 Myr, divided by 10 Myr. Hereafter, high resolution cells are added with a ‘c’. Low and high resolution quantities are annotated with ‘L’ and ‘H’, respectively and refer to 1 h⁻¹ cMpc or to the original CoDaII resolution (15.625 h⁻¹ cKpc).

One might directly apply Eq 1 on the low resolution grid, but it results in a too permissive star formation at high redshift (z≈30). Indeed, the density contrast are smaller at low resolution and at high redshift, therefore having one fixed density threshold would produce an almost flat cosmic SFR evolution with redshift, much too much star at high redshift or not enough at low redshift. We need to change the threshold parameter to mimic the sub-grid collapse structures and control the SFR at high and low redshifts. Furthermore, the classical scheme applied at low resolution cannot take into account the sub-grid quenching of the Reionization on the smallest galaxies. To take this effect into account we derive an empirical model based on the outputs of the CoDaII simulation.

2.1.2 Sub-grid star formation rate

In the CoDaII case, each coarse cell (1 h⁻¹ cMpc) is composed of 64³ high resolution cells. Each of them can be star forming (SFR = Δ L, c.f. Eq 1). Therefore we derive that the low resolution SFR on co-moving scale is defined as follow:

$$SFR_L = \varepsilon_c \Sigma_L^{1.5} \frac{1}{dL^{1.5}},$$  \hspace{1cm} (2)

where ε_c is the proportionality factor that absorb all the constants. The expansion factor dependence comes from the physical to comoving transformation and the power 1.5 dependence to the density (c.f. Eq 1). And we define Σ_c as the star forming gas density at the power 1.5 in each coarse cell: we call it the ‘proxy to the star forming gas: PSFG’. It is computed in the CoDaII simulation post-processed outputs as the sum of the density at power 1.5 of star forming cells:

$$\Sigma_L^2 = \sum_i (\Delta_i^L)^{1.5} \text{ where } \Delta > \Delta_s.$$  \hspace{1cm} (3)

where the iterator i stands for each of the 64³ high resolution cells in a coarse cell of 1 h⁻¹ cMpc³. Fig. 1 presents the PSFG for all coarse cells of 1 h⁻¹ cMpc³ as function of the over-density. The left panel presents the distribution of (Δ_L, Σ_L) pairs in CoDaII at redshift 6 and 15. At high density, Σ_c follows a power law as
a function of the density contrast with a unit slope. The PSFG decreases sharply as the density contrast becomes smaller. And the scatter around the overall trend is large (for example, at $\Delta = 1$, $\Sigma_\text{c}$ covers almost 4 orders of magnitude at redshift 6). The dispersion increases as the density decreases, and at the same time a hard minimum is set, imposed by the CoDaII simulation parameters ($\Sigma_\text{c,min} = 50\,\Omega_0^{-1}$, corresponding to a single high resolution cell above the star formation threshold in one coarse cell).

For the sake of simplicity, we model the mean behavior of the $(\Delta^2, \Sigma^2)$ relation. $\Sigma_\text{c}$ behave as a power law with respect to the density with an exponential cutoff at the low-density end. This model is purely empirical and does not take into account the dispersion induced by the variance in structure formation. But it does take into account the underlying stellar and radiative feedback on the gas density implemented in the CoDaII simulation. The density of star forming gas is parametrized as follow:

$$\Sigma_\text{c} = e_{\text{c}} \Delta 10^{-\Delta_\text{c,}/A},$$

where $e_{\text{c}}$ is fitted at redshift 6 and kept constant at all higher redshifts ($\log_{10}(e_{\text{c}}) = 7.55$). Then, $\Delta_\text{c}$ is adjusted at each redshift independently.

The evolution of the parameter $\Delta_\text{c}$ with redshift is obtained here for the CoDaII simulation. The mean evolution with redshift of the PSFG as function is shown of the right panel of Fig. 1. Nevertheless, its evolution can be freely parametrized (empirically or physically) to explore or accommodate different scenarios and models of star formation, for example the inclusion of POPIII stars, or more simply modulate the time evolution of the cosmic SFR. For sake of simplicity we consider a linear evolution of $\Delta_\text{c}$ with redshift, which is roughly consistent with the evolution given by CoDaII.

2.1.3 Star formation space distribution

At this stage every cell has a non-zero SFR. But, as we expect to have more star formation in the densest regions, we also expect to have no star formation in the most under-dense ones and in between a certain stochasticity. The left panel of Fig. 2 illustrates the stochasticity by presenting the probability for a cell of $1\,h^{-3}\text{Mpc}^3$ to have a non-zero SFR, as function of the density contrast and redshift in the CoDaII simulation. The transition is smooth between high densities that always form stars and the low-density regions that do not. And this transition evolve with redshift, shifting toward low-density regions with time. At $z = 6$, a $1\,h^{-3}\text{Mpc}^3$ volume with an average density has a 50% probability to be star-forming. Another way to visualize the stochasticity and the spatial distribution of the star forming region is to look at the volume filling factor of star forming cells, presented on the right panel of Fig. 2. The blue line shows the SF volume filling factor of the CoDaII simulation, coarsened on scales of $1\,h^{-1}\text{Mpc}$ . The fraction of volume that form stars rise with redshift, with a maximum just below 50% between redshift 6 and 7. It means that, in the CoDaII simulation, almost half of the volume of the Universe is star-forming at redshift 7, smoothed on scale of $1\,h^{-1}\text{Mpc}$ .

The local variations introduce above and the resulting SF spatial distribution will set the spatial evolution of the reionization process. It will affect the HII bubble size distribution and evolution, and the 21cm temperature brightness power spectrum (PS) too. Therefore we introduce here one way to control the star formation distribution in our simulations. We use a minimum stellar mass $M_\text{s}$ and the star formation process is discretized in stellar particles.

With the same scheme as in CoDaII, the number of stellar particle created is drawn from a Poisson distribution. The mean SFR of a coarse cell is set by Eq. 2. Then the mean stellar mass is obtain by multiplying by the time step ($dt$), and the mean number of stellar particles is therfore obtain by dividing by the stellar mass particle $N_\text{s} = \frac{SFR_{\text{c}}}{dt}/M_\star$. In the end, the parameter $M_\star$ does the same as in high-resolution runs. It permits to set a minimum SFR in a cell and to cut star formation where it is too low. However, the physical meaning of $M_\star$ is different. Here it encompass the local variations due to the star formation and unresolved structure formation at the same time. We apply our new parametrization of the source formation on the outputs of the CoDaII simulation. The impact of $M_\star$ on the star formation process is illustrated on the middle and right panel of Fig. 2 with different $M_\star$: $5\,10^5 M_\odot$, $5\,10^6 M_\odot$, $5\,10^7 M_\odot$ (orange, green and red respectively). This parameters controls the distribution of the star formation as a function of the density, as shown on the middle panel of Fig. 2, which automatically translates to the volume filling factor, shown in the right panel. Interestingly, as shown after, as the cosmic star formation density is mostly set by the heaviest regions, these parameters does not affect the global SFR. Therefore, the global SFR and its spatial distribution are almost independent with this parametrization. The parameter $M_\star$ permits to choose between a “diffuse” or a “biased” SFR distribution.

2.2 Simulation’s set

The previously presented star-formation model and an on-the-fly computation of the 21cm signal (presented hereafter) have been added in the hydrodynamics-radiative transfer code EMMA (Aubert et al. 2015). It permits to realize cosmological simulations of the of the CD, EoH and EoR by coupling the evolution of dark matter, baryonic matter, source formation and radiative transfer.

2.2.1 Specifications

We produce a $(512h^{-1}\text{cMpc})^3$ simulation with a resolution of $1h^{-1}\text{cMpc}^3$. The simulation’s specifications are listed on Tab. 1. The source formation starts at redshift 30 and the actual speed of light is used for the radiative transfer, to avoid artifacts as reported in (Deparis et al. 2019; Ocvirk et al. 2019). X-rays are included in those simulation and it is important to recall that Ly-α radiation is not included in the simulation yet. The study of X-ray and Ly-α will be done in the follow-up study.

2.2.2 Results

The cosmic SFR is calibrated to be roughly on or above of the observations at redshift 6 ($3 \times 10^{-2} [M_\odot \text{yr}^{-1} \text{cMpc}^{-3}]$) and $10^{-6} [M_\odot \text{yr}^{-1} \text{cMpc}^{-3}]$) at redshift 30. It accounts for the fact that the cosmic SFR predicted by the simulation contains the contribution of all the galaxies, while the observations are limited to magnitude -17. Fig. 3 presents the cosmic SFR on the left panel and the neutral fraction on the right. The gray area presents the estimated total SFR (Gillet et al. 2020). In the simulation, the evolution of the cosmic SFR with redshift is induced by the evolution of the density distribution and the evolution of the parameter $\Delta_\text{c}$. The ionization history is calibrated in order to have a mid reionization between redshift 6 and 7. The CoDaII averages are also shown in green for comparison. Even with its mass/spatial resolution, the CoDaII is not able to from stars at the early redshift ($z=30$). Here, the new
Figure 1. The proxy to the star forming gas density ($\Sigma$) as function of density ($\Delta$): On the left, the distribution of all coarse cells are shown at redshift 6 and 15, with the fitted function in black. The right panel presents the mean relations and their fits at all available redshifts. Each redshift relation is shifted by 0.2 dex for clarity. Note that at redshift 17 and 20 we do not have access to the full resolution data, but to the $2048^3$ cubes, which explains the difference in resolution accessible in $\Sigma$ for those two redshifts.

Figure 2. On the left panel, the probability for a cell of $1h^{-3}\,\text{Mpc}^3$ of the CoDaII simulation to have a non-zero SFR as function of density and redshift. Line from redshift 5.8 to 6.6 are almost identical and stack. On the middle panel, the same as the left, but only at redshift 7. The CoDaII simulation is the blue line, while the dash orange, green and red are the sub-grid model with $M_* = 5000, 50000, 500000$ $M_\odot$ respectively. On the right panel the volume filing factor of non-zeros SFR cells of $1h^{-3}\,\text{Mpc}^3$, for the CoDaII in blue and the sub-grid models are the same as in the middle panel.

parametrization is able to form stars at the CD, while encompass the sub-grid feedback on SFR at later redshift.

Additionally, Fig. 3 presents the dispersion of the SFR and neutral fraction for sub-cubic-volumes of $64h^{-1}\,\text{Mpc}$ side that can be compared to the volume of the CodII simulation that was used to calibrate the star formation model. The over density of each sub-volume is indicated in red and blue for over and under-dense region respectively. The dispersion in SFR is relatively constant between $z=6$ and 30, and is comparable to the observations uncertainties (illustrated at redshift 6.5 with the cyan error-bars). In the case of the neutral fraction, the dispersion at mid-reionization is slightly smaller that current observations estimation with $\pm0.08$ and the redshift dispersion is about $\pm0.19$ around the average mid-ionization redshift (illustrated with the cyan error-bars). Overall, these results demonstrate that our new star formation model can be made consistent with constraints during the EoR, while providing a sustained star formation during the Cosmic Dawn.
3.1 Simulation of the signal

The formula of the 21cm brightness temperature with respect to the CMB at a given redshift and point in space is given by:

$$\delta T_{21} \approx 27(1 - x_{\text{HI}})(1 + \delta)(1 - \frac{T_{\text{CMB}}(z)}{T_e})C_{\text{cosmo}} \text{ [mK]}$$

$$C_{\text{cosmo}} = \left( \frac{\Omega_b}{0.044} \right) \left( \frac{h}{0.7} \right) \sqrt{\frac{0.27}{\Omega_m}} \sqrt{\frac{1 + z}{10}}$$

where $x_{\text{HI}}$ is the ionization fraction of the gas, $\delta$ is its overdensity, $T_{\text{CMB}}$ the temperature of the CMB and $T_e$ the spin temperature. We neglect the velocity gradient in this study. The spin temperature of the gas can be computed from:

$$T_e = \frac{1 + x_c + x_\alpha}{T_{\text{CMB}}^{-1} + x_cT_K^{-1} + x_\alphaT_c^{-1}}$$

where $T_K$ is the kinetic temperature of the gas, $T_c$ the color temperature of the radiation field at the Ly-α transition, $x_c$ is the collision coupling coefficient and $x_\alpha$ is the coupling coefficient associated with Ly-α pumping.

In this study we do not include the Ly-α radiative transfer, therefore in the following we will consider two regimes. At first we consider a uniform Ly-α coupling factor rising with redshift due to a rising LyA background: $\log_{10}(x_\alpha) = -3/8 z + 7.25$ which mimic the average evolution from Fig 2 of Ross et al. (2019). By doing so we can produce realistic global temperature evolution, but the power spectrum cannot take into account the spatial fluctuations of $x_\alpha$. We also consider the saturated regime, where we assume $x_\alpha \gg 1 + x_c$ everywhere and $T_e = T_c = T_K$.

![Figure 3. SFR and neutral fraction: on the left panel the evolution with redshift of the cosmic star formation rate. The average is shown with the dotted black line. The blue and red lines present the cSFR for sub-cubic volume of 64$h^{-1}\text{cMpc}$ side, the color code for under and over dense region, respectively. The cyan error bar in the inset illustrate the 1-sigma dispersion induced by the large scale density fluctuations at redshift 6.5. The observation points comes from different probes. On the left panel the constrains on the cosmic SFRD are: Bouwens et al. 2014, 2016 in black and violet, McLeod et al. 2016 in blue, Oesch et al. 2013, 2014, 2018 in green and brown and Ishigaki et al. 2018 in pink. On the right panel the constrains on the neutral fraction are: McGreer et al. 2015 are in purple, Greig & Mesinger 2017; Greig et al. 2019 are in orange, Davies et al. 2018 are in green, Bañados et al. 2018 is in red and Wang et al. 2020 in dark blue.](image)
Finally, the collision coupling coefficient accounts for the H-H, H-e, and H-H\(^+\) collisions and is given by:

\[ x_c = \frac{T_10}{A_10} \left( n_i \kappa_{\text{HH}} + n_p \kappa_{\text{PH}} + n_e \kappa_{\text{eH}} \right). \]  

Here, \( \kappa_{\text{HH}} \) is the spin de-excitation rates for each type of collisions and \( n_i \) the densities, \( T_10 = 0.068\,[\text{K}] \) and \( A_10 = 2.85 \times 10^{-15}\,[\text{s}^{-1}] \) is the spontaneous emission rate. The de-excitation rates are taken into account as follow:

- \( \kappa_{\text{HH}} \) is interpolated from Zygelman (2005) Table 2 column 4 for \( 1 < T_k < 300\,\text{K} \) or \( \kappa_{\text{HH}} = 3.1 \times 10^{-11} \kappa_0^3 0.357 e^{-32/T_k} \text{[cm}^3\text{s}^{-1}] \) for \( 300\,\text{K} \leq T_k \) (Kuhlen et al. 2006).
- \( \kappa_{\text{eH}} \) is interpolated from Furlanetto & Furlanetto (2007a) Table 1 for \( 1 < T_k < 10000\,\text{K} \) or \( \kappa_{\text{PH}} = -8.0958 \) for \( 10000\,\text{K} < T_k \) (Liszt 2001).
- \( \kappa_{\text{PH}} \) is interpolated from Furlanetto & Furlanetto (2007b) Table 1 for \( 1 < T_k < 20000\,\text{K} \) or \( \kappa_{\text{PH}} = 2 \kappa_{\text{HH}} \) for \( 20000\,\text{K} \leq T_k \).

The 21cm signal is computed on the fly by the EMMA simulation code for the two Ly-\( \alpha \) regimes (saturated and average background). The power spectrum (PS) of the simulated temperature brightness fields are computed using tools21cm (Giri et al. 2020) in post-processing. The spherically average dimensionless power spectrum (\( \Delta^2(k) \)) is computed using:

\[ \Delta^2(k) = \frac{k^3}{2\pi^2} P(k)(k_x, k_y, k_z), \]

where \( P(k) \) is the power spectrum, and \( k_x \), \( k_y \), and \( k_z \) are the components of the wave-vector along the simulation volume.

### 3.2 Observation of the signal

Being in possession of an ‘ideal’ noiseless 21cm PS from the cosmic dawn, we used \( \text{ps}_\text{EOR} \) \(^1\) to take into account of the UV coverage and the noise level due to the instrument. We focus on the New Extension in Nançay Upgrading IoFar (NENUFAR; Zarka et al. (2012)) observations as we are part of the NENUFAR Cosmic Dawn key project. NENUFAR is a radio interferometer that will observe between 85MHz and 30MHz, covering the CD epoch. Interestingly it covers the 83-73 MHz band where the EDGES collaboration reported a signal detection (Bowman et al. 2018).

Radio interferometers may produce 3D data-cube, 2D on the sky and the third dimension corresponding to the frequency that can be converted in distance/redshift/time assuming a cosmological model. To get as close as possible to the observations we have to construct a data-cube corresponding to the same coverage on the sky and depth in frequency. The observations specifications are listed in Tab. 2 and correspond to the ongoing Cosmic Dawn observation program made with NenuFAR. We focus on the highest frequency band, centered on redshift 17 (corresponding to the EDGES’s claimed detection band). The shape of the observed volume is 2982.29 cMpc on the sky direction and 231.54 cMpc in depth. The volume is divided in 68 \(^2\) pixels on the sky and 51 along the line of sight. As the depth of the data-cube is relatively small (231.54 cMpc) we neglect for the moment the increase of the size with the depth, as well as the time evolution along the frequency (light-cone effects) (Greig & Mesinger 2018); the simulation size (756 cMpc) is larger than the observational depth, a third of box

---

\(^1\) https://gitlab.com/flomertens/ps_eor

### NENUFAR observations specs

| Parameter          | Value                  |
|--------------------|------------------------|
| Band-width         | 9.96 [MHz]             |
| Channel-width      | 195.3 [kHz]            |
| Number of channel  | 51                     |
| Redshift at center | 17                     |
| Frequency at center| 78.91 [MHz]            |
| BW limits          | 83.79-73.83 [MHz]      |
| BW limits redshift | 15.95-18.24            |
| Depth              | 231.54 [cMpc]          |
| Depth resolution   | 4.54 [cMpc]            |
| Field of view      | 16 [\degree]           |
| FoV at center      | 2982.29 [cMpc]         |
| Number of pixels   | 68 \(^2\)              |
| Sky resolution     | 43.857 [cMpc]          |
| Total obs time     | 1000 [h]               |
| Time obs per day   | 8 [h]                  |
| Integration time   | 100 [s]                |

**Table 2. Observation specifications:** First the frequency, secondly the sky and finally the observation time information. The transformations to comoving distance are made at the central redshift, the data-cube is consider as ‘cubic’.

### 3.3 Simulated observations of the 21cm

After the calibration of the SFR and ionization history (c.f. 2.2.2) we analyze the 21cm signal. Fig. 4 presents different quantities related to the 21cm signal. On the left panel, the global average brightness temperature is shown in red. The background color shows the distribution of the brightness temperature with redshift (volume weighted). We note that the brightness temperature is bi-modal between redshift 21 and 8, with a cold and a hot phase. The middle panel presents the power spectrum (for coeval cubes, i.e. not taking into account light-cone effects) at different redshifts and the right panel presents the evolution of some specific \( \Delta^2(k) \) with redshift. The PS presented here are qualitatively similar to simulated expectations (see Greig & Mesinger 2017; Ross et al. 2019; Reis et al. 2020 for examples). Note that above redshift 15 the PS is affected by the missing Lyman-\( \alpha \) transfer. The uniform Ly-\( \alpha \) back-ground reduce uniformly the power at every scale above redshift 15, illustrated on the Fig. 4 right panel with the full lines and the dotted lines illustrate a full Ly-\( \alpha \) coupling at all time. While, the propagation of the Ly-\( \alpha \) photons thought the IGM should induce spatial patterns and so different power evolution with redshift.

Finally, the main goal is to produce a 21cm PS as close as possible to the future observed one. We process this cube through \( \text{ps}_\text{EOR} \) in order to take into account of the UV coverage (see Sec. 3.2). In theory, the PS outputted by \( \text{ps}_\text{EOR} \) should be the same as the one obtain on the ‘perfect’ simulated cubes, in the range of scale well sampled, and in the absence of further distortion. In the present study we do not include other source of noise subtraction or distortion on the signal, like wedge treatment or foreground residuals. The wedge is a portion of the Fourier space where the foreground signal due

---

\(^1\) https://gitlab.com/flomertens/ps_eor
4 CONCLUSIONS

In this paper we introduce a new large scale galaxy formation model in the fully coupled dark matter, hydrodynamics, radiative transfer code EMMA. This empirical model allows the efficient production of large scale low resolution simulations of the CD and EoR with a reduce and flexible set of parameters, based on the results of the state of the art simulation of the Reionization CoDaII. We ran a simulation using this model and predict the associated 21cm signal. We process it up to the prediction of the power spectrum with tools as close as possible to the one used to reduce the observational data. The resulting power spectrum obtained on a $(512 h^{-1} \text{Mpc})^3 / 512^3$ elements of resolution fiducial simulation are qualitatively comparable to state of the art predictions.

We focused on the ongoing observations of the radio telescope NENUFAR, that is covering the cosmic dawn. We predict that our fiducial model should be detected by NENUFAR at redshift 17 at wavenumber between $k = 0.1 h \text{Mpc}^{-1}$ and $k = 0.06 h \text{Mpc}^{-1}$ with 1000h of observations. LOFAR should detect the signal at the same wavenumber at redshift 9.

While waiting for the data acquisition, reduction and analysis we plan to explore the parameter space. Specifically, the next step is to quantify how much a signal detection at $k = 0.1 h \text{Mpc}^{-1}$ and $k = 0.06 h \text{Mpc}^{-1}$ at redshift 17 may constrain our parameters, for example the SFR spatial distribution. A large number of points still have to be addressed, such as, the inclusion of Ly-\(\alpha\) photons is essential for the computation of the 21cm signal, or a sub-grid
treatment of the temperature to take into account of the sub-cell multi-phase of the gas (Ross et al. 2019).

ACKNOWLEDGEMENTS

We thank Anastasia Fialkov for fruitful discussions and sharing data to help the validation of the model. We thank the CoDa Collaboration for sharing the data of the CoDaII simulation.

NG is supported by the University of Strasbourg IDEX post-doctoral grant “Predicting with cosmological simulations the 21cm signal from the Epoch of Reionization for future large radio observatories”.

This work was granted access to the HPC resources of CINES under the allocations 2020-A0070411049 and 2021-A0090411049 “Simulation des signaux et processus de l’aube cosmique et Réionisation de l’Univers” made by GENCI.

This research made use of Astropy Collaboration et al., 2018, AJ, 156, 123; scipy, a Python library for publication quality graphics (Hunter 2007); matplotlib, a Python ecosystem of open-source software for mathematics, science, and engineering (Virtanen et al. 2020) – numpy (Harris et al. 2020) and IPython (Perez & Granger 2007)

REFERENCES

Astropy Collaboration et al., 2018, AJ, 156, 123
Aubert D., Deparis N., Ocvirk P., 2015, MNRAS, 454, 1012
Bañados E., et al., 2018, Nature, 553, 473
Bouwens R. J., et al., 2014, ApJ, 793, 115
Bouwens R. J., et al., 2016, ApJ, 833, 72
Bowman J. D., Rogers A. E. E., Monsalve R. A., Mozdzen T. J., Mahesh N., 2018, Nature, 555, 67
Chardin J., Puchwein E., Haehnelt M. G., 2017, MNRAS, 465, 3429
Davies F. B., et al., 2018, ApJ, 864, 142
Deparis N., Aubert D., Ocvirk P., Chardin J., Lewis J., 2019, A&A, 622, A142
Fialkov A., Barkana R., Visbal E., 2014, Nature, 506, 197
Furlanetto S. R., Furlanetto M. R., 2007a, MNRAS, 374, 547
Furlanetto S. R., Furlanetto M. R., 2007b, MNRAS, 379, 130
Gehlot B. K., et al., 2020, MNRAS, 491, 1980
Giri S., Mellema G., Jensen H., 2020, The Journal of Open Source Software, 5, 2363
Gnedin N. Y., 2016, ApJ, 821, 50
Greig B., Mesinger A., 2017, MNRAS, 472, 2651
Greig B., Mesinger A., 2018, MNRAS, 477, 3217
Greig B., Mesinger A., Bañados E., 2019, MNRAS, 484, 5094
Harris C. R., et al., 2020, Nature, 585, 357–362
Hunter J. D., 2007, Computing in Science and Engineering, 9, 90
Iliev I. T., Mellema G., Ahn K., Shapiro P. R., Mao Y., Pen U.-L., 2014, MNRAS, 439, 725
Ishigaki M., Kawamata R., Ouchi M., Oguri M., Shimasaku K., Ono Y., 2018, ApJ, 854, 73
Kaur H. D., Gillet N., Mesinger A., 2020, MNRAS
Kuhlen M., Madau P., Montgomery R., 2006, ApJ, 637, L1
Kulkarni G., Keating L. C., Haehnelt M. G., Bosman S. E. I., Puchwein E., Chardin J., Aubert D., 2019, MNRAS, 485, L24
Liszt H., 2001, A&A, 371, 698
McGreer I. D., Mesinger A., D’Odorico V., 2015, MNRAS, 447, 499
McLeod D. J., McLure R. J., Dunlop J. S., 2016, MNRAS, 459, 3812
Mertens F. G., et al., 2020, MNRAS, 493, 1662
Ocvirk P., et al., 2016, MNRAS, 463, 1462
Ocvirk P., Aubert D., Chardin J., Deparis N., Lewis J., 2019, A&A, 626, A77
Ocvirk P., et al., 2020, MNRAS
Oesch P. A., et al., 2013, ApJ, 773, 75
Oesch P. A., et al., 2014, ApJ, 786, 108
Oesch P. A., Bouwens R. J., Illingworth G. D., Labbé I., Stefanon M., 2018, ApJ, 855, 105
Park J., Mesinger A., Greig B., Gillet N., 2019, MNRAS, 484, 933
Perez F., Granger B. E., 2007, Computing in Science Engineering, 9, 21
Planck Collaboration et al., 2018, arXiv e-prints. p. arXiv:1807.06209
Reis I., Fialkov A., Barkana R., 2020, MNRAS
Ross H. E., Dixon K. L., Ghara R., Iliev I. T., Mellema G., 2019, MNRAS, 487, 1101
Semelin B., Eames E., Bolgar F., Caillat M., 2017, MNRAS, 472, 4508
Virtanen P., et al., 2020, Nature Methods, 17, 261
Visbal E., Barkana R., Fialkov A., Tseliakhovich D., Hirata C. M., 2012, Nature, 487, 70
Wang F., et al., 2020, ApJ, 896, 23
Zarka P., Girard J. N., Tagger M., Denis L., 2012, in Boissier S., de Laverny P., Nardetto N., Samuel R., Valls-Gabaud D., Wozniak H., eds, SF2A-2012: Proceedings of the Annual meeting of the French Society of Astronomy and Astrophysics. pp 687–694
Zygelman B., 2005, ApJ, 622, 1356
van Haarlem M. P., et al., 2013, A&A, 556, A2

This paper has been typeset from a TeX/LaTeX file prepared by the author.