Astro2020 Science White Paper

Detecting Metal-Free Forming Galaxies at High Redshift

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☐ Formation and Evolution of Compact Objects ☐ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☑Galaxy Evolution ☐ Multi-Messenger Astronomy and Astrophysics

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1. Metal-Free Forming Galaxies

Recent ALMA discoveries of $z > 8$ galaxies, such as MACS0416-Y1 at $z = 8.31$ (Tamura et al. 2018), A2744-YD at $z = 8.38$ (Laporte et al. 2017), and MACS1149-JD1 at $z = 9.11$ (Hashimoto et al. 2018), clearly indicate that our observational capabilities are now starting to penetrate well into the epoch of reionization. With the launch of JWST only 2 years away (in 2021), it is reasonable to assume that we will soon know much more about the properties of young galaxies at $z \sim 8 - 10$, which are thought to have played an important (and likely the dominant) role in reionizing the Universe. Some of such *JWST*-discovered high-redshift galaxies may even turn out to be the long sought-after Population III (Pop III) galaxies, exhibiting the spectral signatures produced by a metal-free environment (e.g., a large equivalent width of Lyα emission, strong He II emission). Although these prospects are quite exciting, they pose an interesting question in the context of the 2020 decadal survey: what will be the next frontier in the study of high-redshift galaxies beyond what we can do with the powerful combination of ALMA and *JWST*?

One answer to this question is to focus our attention to the detection of the first-generation "forming" galaxies that are emerging out of metal-free gas clouds at the end of the cosmic dark ages. Here, by "forming", we denote galaxies that are yet to form stars, meaning that the source of luminosity is the gravitational energy released by the contraction of clouds under their self-gravity, rather than stellar radiation. From the observer's point of view, detection of such forming galaxies presents a clear and well-defined problem since such metal-free gas clouds have only two channels for cooling: via molecular hydrogen (H_2) emission and Lyα emission if the clouds are massive enough to achieve a virial temperature of $> 10^4$ K.

2. Theoretical Background

Formation of first stars and galaxies has been a major focus of theoretical studies over the years. Here we will provide a brief summary of a current theoretical picture as the background (see Ciardi & Ferrara 2005, Bromm & Yoshida 2011, Yoshida et al. 2012, Bromm 2013, Greif 2015, and Barkana 2016 for review).

In the framework of the standard ΛCDM model, we expect the first (i.e., Pop III) stars to form in dark matter (DM) minihalos of around $10^6\,\mathrm{M_\odot}$ at redshifts $z \simeq$ 20–30, cooling via H_2 molecular lines (Haiman et al. 1996; Tegmark et al. 1997; Yoshida et al. 2003). The first stars formed in such a metal-free environment are believed to be quite massive ($> 100\,\mathrm{M_\odot}$; e.g., Hirano et al. 2015), and would emit strong H_2-dissociating UV radiation (e.g., Omukai & Nishi 1999) and produce powerful supernova explosions (Bromm et al. 2003), essentially shutting off subsequent star formation. For this reason, these minihalos are not regarded as "first galaxies" although they are the sites of the first-star formation. In this white paper, we will not discuss the detectability of H_2-emitting gas clouds in these $10^6\,\mathrm{M_\odot}$ DM minihalos because their H_2 lines are simply too faint and therefore too difficult to detect in the foreseeable future.

The next generation of star formation will then take place in more massive halos ($\sim 10^8\,\mathrm{M_\odot}$) collapsing at $z \sim 10$, whose virial temperature is high enough ($> 10^4$ K) to sustain cooling due to atomic hydrogen (e.g., Oh & Haiman 2002). These so-called "atomic cooling halos" hosting the second generation of stars are often considered as "first galaxies" (Bromm & Yoshida 2011).

Note that according to this current standard picture, first galaxies are not necessarily metal-free (Pop III), which is often taken as the observational definition of the first galaxies. In fact, "This popular definition of a first galaxy may be misleading and may render any attempts to find first galaxies futile from the very outset" (Bromm & Yoshida 2011). This is because it is difficult to prevent minihalos, i.e., the building blocks of first galaxies, from forming massive Pop III stars and chemically enriching their surroundings through SNe explosions. In other words, to produce genuine Pop III galaxies, it is necessary to inhibit star formation in the progenitor mini-halos by suppressing the formation of molecular hydrogen in them. This would require H_2-dissociating Lyman-Werner (LW) background radiation in the Far-UV (11.2–13.6 eV photons) and the source of such radiation before the formation of Pop III galaxies. This leads to a scenario in which the first galaxies that appeared in the Universe (in the chronological sense) were mostly Pop II galaxies; Pop III galaxies would appear subsequently in underdense regions where the star formation in minihalos were suppressed by radiation emitted by stars/galaxies formed earlier in overdense regions. For this reason, Pop III galaxies may be considered as the second-generation galaxies containing first-generation stars (e.g., Johnson et al. 2008; Trenti & Stiavelli 2009; Johnson 2010; Stiavelli & Trenti 2010; Johnson et al. 2013).

Adopting this theoretical picture as the baseline, we assume here for the sake of discussion that massive ($M_{\rm h} \sim 10^{11}$–$10^{12}\,{\rm M}_\odot$) Pop III forming galaxies do exist at high redshift in underdense regions that are exposed to a strong Far-UV radiation produced by surrounding star-forming galaxies.

One interesting implication from this theoretical picture is that Lyα emission emitted by such massive Pop III forming galaxies may survive because these objects are likely located in large H II bubbles produced by surrounding star-forming galaxies. Considering that H_2 and Lyα emission lines are the only observables for such massive metal-free forming galaxies, this is quite important, suggesting the possibility that these objects may be studied via sensitive near-infrared observations (e.g., narrow-band imaging, spectroscopy).

3. Strategy and Feasibility

To detect the H_2 and Lyα emission emitted by these forming galaxies at high redshift, we will need observational capabilities to perform sensitive far-infrared (e.g., the Origins Space Telescope) and near-infrared observations (e.g., TMT, GMT), respectively.

For the detectability of Pop III forming galaxies via H_2 and Lyα emission, we refer to the model calculations by Omukai & Kitayama (2003) as a guide. Because of the reduced cooling efficiency due to the absence of metal lines, Pop III systems with $M_{\rm h} \gtrsim 10^{12}\,{\rm M}_\odot$ cannot cool appreciably within the halo merging timescale, constantly heated by infalling subhalos. As a result, the most H_2-luminous Pop III forming galaxies are expected to be those with a halo mass of $\simeq 10^{11}\,{\rm M}_\odot$; H_2 line luminosities will decline sharply for higher-mass systems. The $z = 8$ $M_{\rm h} = 10^{11}\,{\rm M}_\odot$ Pop III forming galaxy model[1] by Omukai & Kitayama (2003) predicts the luminosity of the brightest H_2 line (0–0 S(3)) to be $3.3 \times 10^7\,{\rm L}_\odot$. Other theoretical studies predicted similar H_2 line luminosities (e.g., Mizusawa et al. 2005; Gong et al. 2013).

Figure 1 shows halos with $M_{\rm h} > 10^{11}\,{\rm M}_\odot$ (the blue dots) superimposed on the background ionization field from the simulated tomographic map at $z = 8$, both projected from a 100-Mpc thick slice (see Sobacchi & Mesinger 2014 for the methodology of the simulation). The figure

[1]The fiducial model with $f_{\rm trb} = 0.25$.

shows that halos are significantly clustered toward the center of H II bubbles (seen as bright white spots) because these halos are the sites of star formation and therefore the sources of ionizing radiation. These H II bubbles have a size of 20–30 Mpc (comoving), corresponding to approximately 10′ on the sky.

Note that the virial temperature of a $M_{\rm h} \simeq 10^{11}\,{\rm M}_{\odot}$ halo is high enough ($> 10^4$ K) to sustain H I atomic cooling. As a result, these massive forming galaxies are also expected to be strong Lyα emitters (The source of Lyα emission here is the release of gravitational energy due to the contraction of pristine gas clouds and not the radiation from young stars). In fact, the Lyα line is more luminous ($4.9\times10^7\,{\rm L}_{\odot}$) than any of the individual H_2 lines, although the total H_2 line luminosity is $\sim 10^8\,{\rm L}_{\odot}$, exceeding that of Ly$\alpha$.
The observations discussed here are undoubtedly challenging, but considering their scientific importance, they merit further observational and theoretical discussions.

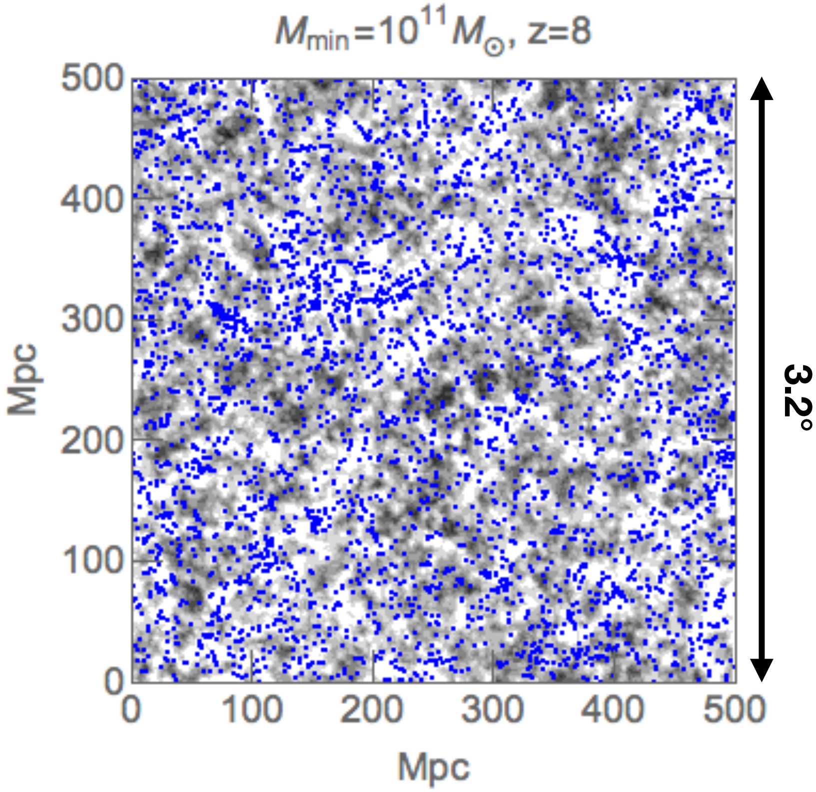

Figure 1: Distribution of dark halos with $M_{\rm h} \geq 10^{11}\,{\rm M}_{\odot}$ at $z = 8$ (blue dots) superimposed on the background ionization field (grey scale) taken from the simulated tomographic map at $z = 8$ shown over an area of 500 Mpc (comoving) on a side, which corresponds to 3.2 deg. This map was smoothed over a scale of 30 Mpc. The darker (brighter) regions correspond to more neutral (ionized) regions. Both distributions were projected from a 100-Mpc thick slice at $z = 8$. The map of ionization field was produced based on the FULL model of Sobacchi & Mesinger (2014). The figure was taken from Egami et al. (2018).

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