Redshift Horizon for the Origins Space Telescope from Primordial Dust Emission

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Abstract / We explore the possibility of detecting the first galaxies with the next generation Origins Space Telescope (OST) by applying an analytical model of primordial dust emission. By analysing source densities as a function of redshift (z), and considering deep-field exposures with the Origins Survey Spectrometer, we estimate that the redshift horizon for detecting one individual source would be above z ∼ 7 for systems with dust-to-metal ratios higher than those expected for typical primeval galaxies. On the other hand, if confusion limits could be overcome, the Far-infrared Imager and Polarimeter would enable the detection of more typical fainter systems at z > 7. Given the dependence of the obtained results with the properties of primeval dust, we conclude that the OST could provide important clues to the nature of the interestellar medium in the early Universe.

Keywords / galaxies: high-redshift — galaxies: evolution — galaxies: formation — galaxies: star formation — cosmology: theory

1. Introduction

Primeval galaxies at z ≥ 7 are promising targets for current and upcoming observational facilities operating at different wavelengths, such as the James Webb Space Telescope (JWST), the Atacama Large Millimeter/submillimeter Array (ALMA) and the Square Kilometre Array (SKA), among others. In this context, future space-borne FIR telescopes could play a crucial role on exploring the nature and properties of the first dust-emitting galaxies at the very dawn of star formation (e.g. De Rossi & Bromm 2019). These systems (z ≥ 7) are expected to have very low dust densities and FIR fluxes, being their detection below the capabilities of current and near future observatories (e.g. De Rossi & Bromm 2017).

De Rossi & Bromm (2019) explore in detail the possibility of detecting first galaxies during FIR/sub-mm surveys with a generic FIR telescope. In this work, we implement their methodology to evaluate the possibility of detecting primeval FIR/sub-mm sources at z ≥ 7 with the future Origins Space Telescope (OST), planned for launch in the 2030s. The OST further evolves the concept mission study for the Far-Infrared Surveyor. Among the key science goals for this facility will be the cosmic origin of dust, elucidating the first sources of dust emission, which are beyond the current horizon of observability, given the sensitivity of existing instruments. The OST is expected to attain sensitivities 100-1000 times greater than any previous FIR mission achieving unprecedented depths to study the most distant galaxies. In this manuscript, we focus on the detectability of FIR/sub-mm dust continuum emission from primeval galaxies with the following instruments: the Origins Survey Spectrometer (OSS, concept 2-C2) and the Far-infrared Imager and Polarimeter (FIP, C2). For more details and related documentation regarding the OST, see https://asd.gsfc.nasa.gov/firs/ and https://origins.ipac.caltech.edu/.

2. Dust model

Dust emission was estimated using the methodology described in De Rossi & Bromm (2017) and De Rossi & Bromm (2019), which has proven to be useful for study-
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Figure 1: Impact of variations of model parameters on detections with OSS (band 6). Results correspond to a deep-field exposure ($10^6$ s) within a FoV. Left panel: $M_{\text{min}} - z$ relation. For comparison, different $\nu$-$\sigma$ peaks corresponding to the adopted cosmological model are plotted. Right panel: $N - z$ relation. In both panels, thin and thick lines are associated with the standard and shock size distributions, respectively. The reference model (solid blue line) corresponds to our standard parameters. The effects of variations of model parameters with respect to the standard model are shown with different line styles. In the right panel, the curves that are not shown lie below the plotted region.

Figure 2: Similar to Fig. 1 but for FIP at 250 $\mu$m and during a deep-field exposure within a FoV.

A model galaxy consists of a dark matter halo hosting a central cluster of Pop II stars, surrounded by a mixed phase of gas and dust. Our standard model assumes a dust-to-metal mass ratio $D/M = 5 \times 10^{-3}$, a gas metallicity of $Z_g = 5 \times 10^{-3} Z_\odot$ and a star formation efficiency of $\eta = 0.01$, which are typical values for first galaxies (Greif & Bromm 2006; Mitchell-Wynne et al. 2015; Schneider et al. 2016; see De Rossi & Bromm 2017, 2019 for more details regarding model parameters and the effects of their variations). The spectral energy distribution associated to stars was obtained from YG-GDRASIL model grids (Zackrisson et al. 2011). We considered different silicon-based dust models given in (Cherchneff & Dwek 2010). However, for the sake of clarity, we only present results corresponding to the so-called UM-ND-20 model (see De Rossi & Bromm 2017 for details). We have checked that other chemical compositions of dust lead to similar general trends. For the grain-size distribution, we adopted the ‘standard’ and ‘shock’ prescriptions used in Ji et al. (2014). Dust temperature ($T_d$) was determined assuming thermal equilibrium and dust emissivity was estimated by applying the Kirchhoff’s law for the estimated $T_d$ profile.

By comparing the sensitivity of the OST instrument with the average observed fluxes of galaxies at a given wavelength band, we determine the lowest virial mass ($M_{\text{min}}$) that a galaxy should have to be detected at a
given $z$. The redshift horizon ($z_{\text{int}}$) is defined as the highest $z$ above which the projected number of detected sources per given solid angle ($\Delta \Omega$) is $N < N_{\text{crit}}$, where we here consider $N_{\text{crit}} = 1 - 10$ (see De Rossi & Bromm 2019).

3. Results

For OSS and FIP, the number of detected sources, $N$, was obtained assuming deep-field exposures ($10^6$ s) within each instrument field-of-view (FoV). Deep-field sensitivities were obtained by scaling the expected sensitivities for 1 hr with the square root of the integration time ($10^6$ s). Details regarding the FoV and sensitivity (1 hr) of each instrument were obtained from Meixner et al. (2019).

In the case of OSS, we estimated $M_{\text{min}}$ and $N$ for a deep field exposure in its band 6 ($\lambda = 336 - 589$ µm). We adopt a sensitivity of 2.34 µJy, corresponding to an integration time of $10^6$ s, and a FoV of 3.492 arcmin² (Meixner et al. 2019). As can be seen in Fig. 1, in the case of a very low metallicity of $Z = 5 \times 10^{-3} Z_{\odot}$, $M_{\text{min}}$ ranges between $\sim 10^{12} M_{\odot}$ ($z \approx 20$) and $\sim 10^{14} M_{\odot}$ ($z \approx 7$), with the exact values depending on the size distribution of dust grains. For high dust-to-metal ratios ($D/M = 0.4$) or star formation efficiencies ($\eta = 0.1$), $M_{\text{min}}$ ranges between $\sim 10^{10} M_{\odot}$ ($z \approx 20$) and $\sim 10^{11} M_{\odot}$ ($z \approx 7$), also, with the exact values depending on the size distribution of dust grains. All other assumed parameters predict an intermediate behaviour. Note that, for OSS, $M_{\text{min}}$ decreases towards its minimum value at $z \lesssim 15$. This is caused by the very strong negative K-correction that affects first galaxies at FIR/sub-mm wavelengths, as discussed in detail in De Rossi & Bromm (2019). We also see that OSS would reach the redshift horizon at $z \approx 7 - 8$ only in the case of very high dust-to-metal ratios.

In the case of FIP (unlike the case of OSS), the characteristic wavelength ($\approx 250$ µm) is below the peak of dust emission of our high-$z$ galaxies ($\approx 500$ µm, De Rossi & Bromm 2017, 2019), so their detection is not favoured by the strong negative K-correction that we mentioned before. In addition, FIP will likely be affected by confusion noise during deep exposures. If confusion limits could be overcome (e.g. by applying multi-wavelength analysis), we show below that its high sensitivity would enable the detection of dust continuum emission from typical first galaxies. For FIP, we adopt a sensitivity of 0.15 µJy at 250 µm, corresponding to an exposure of $10^6$ s, and a FoV of $9' \times 13'$. As shown in Fig. 2, for a very low metallicity of $Z_g = 5 \times 10^{-4} Z_{\odot}$, $M_{\text{min}}$ ranges between $\sim 10^{13} M_{\odot}$ ($z \approx 20$) and $\sim 10^{12} M_{\odot}$ ($z \approx 7$), with the exact value depending on the grain size distribution. In the case of high dust-to-metal ratios ($D/M = 0.4$) or star formation efficiencies ($\eta = 0.1$), $M_{\text{min}}$ ranges between $\sim 10^{11} M_{\odot}$ ($z \approx 20$) and $\sim 10^{10} M_{\odot}$ ($z \approx 7$). Other parameter choices predict an intermediate behavior. With respect to the redshift horizon, our reference model predicts $N = 1 - 10$ at $z \approx 7$ and $z \approx 9$, for the standard and shock size distribution, respectively. In the case of $Z_g = 5 \times 10^{-4} Z_{\odot}$, $N(> 7) < 1$; thus, a wider area of the sky should be searched to increase the probability of detecting low metallicity sources. For higher $Z_g$ and $D/M$, the horizon moves towards higher redshifts. For our extreme case of $\eta \approx 0.1$ and a shock grain size distribution, the horizon is reached at $z = 12 - 14$, with other parameter values leading to intermediate behavior.

4. Conclusions

We explore the prospects of detecting the dust continuum emission from first galaxy populations with the next-generation Origins Space Telescope. We focus on OSS and FIP (concept 2) instruments. We consider deep-field exposures adopting similar integration times ($10^6$ s) within each instrument field-of-view (FoV).

During deep-field exposures within a FoV, OSS may be able to detect the dust continuum emission of massive sources with very high dust fractions ($D/M \gtrsim 0.4$). The more elusive fainter galaxies could be observed by gravitational lensing effects. In the case of FIP, deep FoV exposures could allow the detection of more typical primordial galaxies with low metallicities ($\sim 0.005 Z_{\odot}$) and dust-to-metal ratios ($\sim 0.005$). However, such efforts would require the development of techniques that help to overcome confusion noise and remove interlopers at $z < 7$.

Taking into account the sensitivity of the OST redshift horizon to the assumed dust properties, measurements of FIR/sub-mm source densities at $z > 7$ could provide important clues to the nature and origin of the first sources of primordial dust in the early Universe.

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