Spectral Energy Distribution of the First Galaxies: Contribution from Pre-Main-Sequence Stars

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ABSTRACT

One of the major goals of next generation space-borne and ground-based telescopes is to detect and characterize the first galaxies that were in place in the first few hundred million years after the Big Bang. We study the spectral energy distribution (SED) of the first galaxies and discuss the prospects for detection and identification. We consider very young star-forming galaxies at \( z = 10 \) and incorporate the contribution from pre-main-sequence (PMS) stars. Unlike in the present-day galaxies, primordial protostars are not embedded in dusty gas clouds, and hence the light from them can be visible at a wide range of wavelengths. We use MESA code to follow the PMS evolution and use the BT-Settl model of Allard et al. to calculate the SED of individual PMS stars. We show that PMS stars contribute to boost the flux in mid-infrared, and that the galaxy SED at very early evolutionary phases is overall redder than at later phases. The infrared flux contribution is comparable to that caused by emission lines powered by massive stars. We argue that the contribution from PMS stars is important for characterizing young galaxies in the early Universe and also for the target selection with future deep galaxy surveys.

Key words: galaxies: evolution — stars: pre-main-sequence — stars: Population III

1 INTRODUCTION

Recent large observational programmes using optical/infrared and radio telescopes discovered a number of galaxies near the epoch of reionization at \( z = 6 - 7 \) (Yan et al. 2011; Dunlop et al. 2013; Inoue et al. 2016; Hashimoto et al. 2018), and detected promising galaxy candidates even at \( z = 10 \) (Oesch et al. 2018). The distant galaxies discovered so far typically have blue colors (e.g., Bouwens et al. 2014), suggesting a small dust content and/or contribution from peculiar stellar populations such as massive hot stars.

The photometric and spectral features are important to understand the nature of distant galaxies and also for efficiently detecting them. Theoretical studies of the SEDs of the first galaxies (Tumlinson et al. 2000; 2001, Bromm et al. 2001) suggest a few outstanding features of the first galaxies that contain Population III (Pop III) stars. Pop III stars are more compact and hotter than the Pop II counterpart with the same mass (Ezer & Cameron 1971), and hence the first galaxies are expected to have blue SEDs. If Pop III stars contain unusually massive population (e.g., Hirano et al. 2014; 2015), strong emission lines from ionized hydrogen and helium are also expected (Schaerer et al. 2003).

Another interesting possibility especially for the first galaxies is that there could exist a number of stars that are still at the pre-main-sequence (PMS) stages. For local or low-redshift galaxies, the contribution from PMS stars to the total SED is often ignored in ultraviolet to optical wavelengths, because PMS stars are deeply embedded and hidden in dusty star-forming gas clouds. The contribution has been considered for infrared spectra of young galaxies (Leitherer et al. 1996; Zackrisson et al. 2001). Contrasting the first galaxies do not contain a substantial amount of dust. Primordial protostars are embedded in a dense primordial gas cloud (Omukai & Palla 2003; Yoshida et al. 2008), but are not enshrouded with dust, and thus they may be directly visible and can possibly give an appreciable contribution to the integrated SED of the host galaxy.

In this Letter, we calculate the SED of the first galaxies by including the contribution from PMS stars for the first time. We consider cases with and without gas accretion onto PMS stars. We place the model galaxies at \( z = 10 \) and study...
in detail the mid-infrared spectra. Hereafter, we assume the standard ΛCDM cosmology with Ω_m = 1 − Ω_k = 0.308 and H_0 = 67.8 km sec^{-1} Mpc^{-1} (Planck Collaboration 2016).

2 METHODS

We calculate the SED of the first galaxies S(ν, t) (flux per unit frequency at frequency ν and time t) by summing the contributions from main-sequence (MS) stars F_{MS} and from PMS stars F_{PMS} in a time-dependent manner as

\[ S(ν, t) = C \left( \int_{M_{\text{min}}}^{M_{\text{max}}(t)} F_{\text{PMS}}(ν, t) \frac{dN}{dM} dM \right) + \int_{M_{\text{min}}}^{M_{\text{max}}(t)} F_{\text{MS}}(ν, t) \frac{dN}{dM} dM \]

with the stellar mass normalization

\[ C^{-1} = \int_{M_{\text{min}}}^{M_{\text{max}}} \frac{dN}{dM} dM. \]

Here, dN/dM is the number of stars with mass in the range of M ∼ M + dM, and M_{max}(t) is the maximum mass of stars which are still in the PMS phase at t. Massive stars that have reached the MS give the fractional contribution as given by the second term in equation (1). We also add the associated nebular continuum emission powered by the MS stars. Throughout the present paper, we fix the total (PMS + MS) stellar mass of a galaxy to be 10^5 M⊙.

We consider two variations of the stellar initial mass function (IMF) with

\[ \frac{dN}{dM} = \begin{cases} 2C_1M^{-1.3} & (M < 0.5M_☉) \\ C_1M^{-2.3} & (M > 0.5M_☉) \end{cases} \]

(Kroupa) (3)

analogous to the local IMF, and

\[ \frac{dN}{dM} = C_2 \exp \left( - \frac{\log M - \log M_{\text{min}}}{2\Delta^2} \right). \] (Log-normal) (4)

The latter is thought to represent the mass distribution of Pop III stars as determined by Komiyama et al. (2007) who study the origin of carbon-enhanced metal-poor stars. We adopt their preferred values of M_{t} = 10M_☉ and Δ = 0.4. We set the maximum mass M_{max} = 100M_☉ and the minimum mass M_{min} = 0.1M_☉.

2.1 PMS contribution

We follow the evolution of PMS stars with and without mass accretion. To this end, we use the stellar evolution calculation code MESA version 8845 (Paxton et al. 2011, 2013, 2015). Since the default MESA code does not include a module for zero-metallicity Pop III stars, we set the stellar metallicity to be the lowest available value of Z = 0.005Z_☉, and assume that a Pop III stellar SED is well approximated by that of a Z = 0.005Z_☉ star with the same mass. For accreting protostars, we do not include the contribution from accretion luminosity. We have checked that the evolutionary tracks calculated by MESA approximately match to those calculated by another numerical code of Hosokawa et al. (2013).

We adopt the fully convective star of Ushomirsky et al. (1998) as our fiducial model of the initial stellar structure. We use the BT-Settl model to calculate the spectra of PMS stars (Allard et al. 2012). In practice, we input the temperature and the surface gravity calculated by MESA to the BT-Settl code to obtain the spectrum of an individual PMS star. For accreting protostars, we consider the gas accretion rate as a primary physical quantity that determines the final stellar mass. We assign a constant accretion rate to each star and follow the PMS evolution. Figure 1 shows the evolutionary tracks for PMS stars with different masses (top panel) and with different accretion rates (bottom panel).

In order to calculate the emerging galaxy SED, we consider a group of stars with different masses or with different accretion rates. In the case with accretion, we set the initial mass of the protostars to be 1M_☉, because accreting protostars can quickly grow to be more massive than 1M_☉, and because smaller protostars with low accretion rates do not appreciably contribute the total SED. The assigned accretion rate Φ varies from 0 to 6 × 10^{-3} M_☉ yr^{-1}. Note that the typical rate for a primordial protostar is Φ ∼ 10^{-3} M_☉ yr^{-1}. The exact accretion rate depends on a variety of physical properties of the parent cloud and varies over an order of magnitude (e.g., Hirano et al. 2014). To each star, we assign a rate within this range so that the resulting mass spectrum of the group of stars matches the designated IMF (equation [3] or [4]) when all the stars have landed on ZAMS, except that the minimum mass is set to be 1M_☉ because of the above assumption. We assume that mass accretion continues until the stars reach ZAMS. On these assumptions, the mass is simply given as a function of time as

\[ M(t) = \begin{cases} \dot{M} t & (t < t_{\text{ZAMS}}) \\ \frac{M_0}{t_{\text{ZAMS}}} t & (t > t_{\text{ZAMS}}) \end{cases} \]

where t_{ZAMS} is the characteristic evolutionary time to reach ZAMS. We integrate the resulting SEDs of the PMS stars from 0.1M_☉ to 100M_☉ for non-accreting cases and from 1M_☉ to 100M_☉ for accreting cases.

2.2 MS contribution

We use the galaxy spectral evolution code PEGASE (Fioc & Rocca-Volmerange 1997; 2019). The nebular continuum emission is also calculated, for which we set the electron temperature of the ionised gas to be 20000K (e.g. Aller 1984; Ferland 1980; Osterbrock & Ferland 2006). The MS contribution is calculated only for a limited stellar mass range M_{t}(t) to M_{max} for the following reason. A PMS star with mass M_{t}(t) reaches the MS within a certain time t. When we calculate a galaxy’s SED at time t, we include only MS stars with M > M_{t}(t), because stars with lower masses are still in the PMS phase. For comparison, we also calculate the SED assuming all the stars are at ZAMS and show the result in the main plots in Section 3. Since we consider very young galaxies, we do not follow the post-MS evolution.
have an evolutionary time scale of $t$. We have considered cases with an instantaneous "star-burst", which disappears, however, in $10$ years because the massive PMS stars give a large contribution, massive PMS stars quickly evolve to MS (see Figure 1). The slight flux increase around $4 \mu$m is owing to nebular continuum emission powered by MS stars. Other features such as the notable bumps and absorption lines are caused mainly by hydrogen Balmer and Paschen transitions in the atmosphere of PMS stars. In the log-normal IMF case, the total flux is higher than in the Kroupa IMF case because there are more massive and luminous MS stars, thus the PMS contribution is relatively small. The rapid spectral evolution can be understood by noticing that the mid-infrared flux (in observed frame) is contributed predominantly by $10M_\odot$ PMS stars that have an evolutionary time scale of $t \sim 0.1$ Myr. Here, we have considered cases with an instantaneous "star-burst", where all the stars are born at once as PMS stars with fixed masses. We will study the case with continuous star formation in Section 3.3.

### 3 RESULTS

#### 3.1 Case with fixed mass PMS stars

Figure 2 shows our model galaxy SEDs at $z = 10$ with PMS stars at $t = 2 \times 10^4, 5 \times 10^4, 10^5$ yrs after an instantaneous star-burst. There is substantial PMS contribution in mid-infrared, corresponding to rest-frame wavelength $\lambda > 0.5\mu m$, because the PMS stars have low effective temperatures. Massive PMS stars give a large contribution, which disappears, however, in $10^5$ years because the massive stars quickly evolve to MS (see Figure 1). The slight flux increase around $4 \mu$m is owing to nebular continuum emission powered by MS stars. Other features such as the notable bumps and absorption lines are caused mainly by hydrogen Balmer and Paschen transitions in the atmosphere of PMS stars. In the log-normal IMF case, the total flux is higher than in the Kroupa IMF case because there are more massive and luminous MS stars, thus the PMS contribution is relatively small. The rapid spectral evolution can be understood by noticing that the mid-infrared flux (in observed frame) is contributed predominantly by $10M_\odot$ PMS stars that have an evolutionary time scale of $t \sim 0.1$ Myr. Here, we have considered cases with an instantaneous "star-burst", where all the stars are born at once as PMS stars with fixed masses. We will study the case with continuous star formation in Section 3.3.

#### 3.2 Case with accreting protostars

Figure 3 shows the calculated galaxy SEDs with accreting protostars at $t = 1 \times 10^2, 5 \times 10^2, 10^3$ yrs after an instantaneous star formation. The minimum stellar mass of $1 M_\odot$ in this case is greater than in the cases shown in Figure 2. The difference in the flux at short wavelengths (in rest-frame optical to ultra-violet bands) is largely owing to this mass difference; the accreting protostars are less massive and less luminous than when they finally reach MS (Figure 1). Note that we plot the flux per fixed stellar mass of $10^6M_\odot$, and the galaxy is placed at $z = 10$. Note the mid-infrared excess contributed by PMS stars.

#### 3.3 Galaxies with continuous star formation

So far, we have considered galaxies in which star formation takes place instantaneously; all the $10^6M_\odot$ stars are born at
Once. In this case, the PMS contribution to the total SED disappears over a typically short PMS evolutionary time.

In real galaxies, not all the stars are formed at the same time nor in the same region. There must always be PMS stars in a galaxy as long as star formation continues in a star-forming region, or in many different regions that are physically separated. We examine a case with continuous star formation by assuming a constant rate of $10^{2} M_{\odot}$ per year ($10^{6} M_{\odot}$ per 0.1 Myr). For simplicity, we consider non-accreting PMS stars in this section. We calculate the SED of a galaxy where $10^{5} M_{\odot}$ stars are born every $10^{4}$ yr, i.e., the average star formation rate is $10 M_{\odot}$ per year. Figure 4 shows the resulting SED. In this case, the infrared flux contribution from PMS stars is persistent. As long as the gas in the star-forming regions remain nearly primordial and contains only a small dust content, the newly born PMS stars can be visible. Metal-enrichment by supernovae may quickly ruin such conditions, but if star-formation in a galaxy is sustained in a rolling manner in many separate patches, primordial PMS stars may contribute to the infrared flux over a long timescale of the galaxy formation and evolution.

4 DISCUSSION

4.1 Observational feasibility

It is important to study the observational signatures of PMS in the first galaxies and to examine the feasibility of actual observations with future telescopes. Figures 2-4 have shown consistently that the infrared flux of a $10^{5} M_{\odot}$ galaxy is below 1 nano-Jansky, suggesting that it is difficult to detect even with James Webb Space Telescope (JWST). If a primordial star-forming galaxy exists at a lower redshift (e.g., Johnson 2010), and/or with help of gravitational lensing magnification, JWST can possibly detect it, and the PMS contribution may be discerned at near-infrared bands.

A nominal detection limit of 10 nano-Jansky for JWST NIRCam can be reached only by a $10^{3} M_{\odot}$ galaxy at $z = 10$. Although this is not entirely inconceivable, such galaxies are likely to be already metal-enriched (see, e.g., Barrow et al. 2016), and thus the PMS stars formed and evolving in them may be dust-enshrouded.

We have assumed that the light from PMS stars and protostars in the first galaxies can be directly seen. Absorption by a primordial inter-stellar gas or by primordial gas clouds (without dust) is unimportant. Also, even for rapidly accreting protostars, a large fraction of the stellar photosphere may be visible if the accretion occurs through a thin protostellar disc (Hosokawa et al. 2016). The precursors and discs around protostars can modify the emergent SEDs, but the relative luminosity is usually small, and the main contribution in observed-frame infrared bands likely comes from the central stars.

4.2 Line emissions

It is well-known that line emission owing to young stellar populations can boost the flux at the respective wavelengths (e.g., Zackrisson et al. 2001). We calculate the emission line contribution to broad-band photometry. We use Yggdrasil (Zackrisson et al. 2011) that adopts a Pop III star model of Schaerer (2002). In Yggdrasil, we set the gas covering factor $f_{cov} = 0.5$ and choose the Kroupa IMF for Pop III stars. Table 1 lists the calculated magnitude difference $\Delta m$ caused by emission lines in ten JWST bands. Interestingly, the PMS contribution is comparable to, or can be even greater than those from the line emission originating mainly from Balmer and Paschen transitions. Note that we here consider a primordial galaxy, and thus do not include metal lines. For high-redshift galaxies, flux excess in near-infrared is often interpreted as emission line contributions and/or the existence of an old stellar population (e.g., Hashimoto et al. 2018; Tamura et al. 2019). The latter possibility is intriguing because the existence of an old stellar population suggests significant star formation at an even earlier epoch in the cosmic Dark Ages.

$\Delta m = 0.1$...
Table 1. Comparison of the flux contributions from PMS based on the case with Kroupa IMF in Fig 2 in the JWST infrared bands and those from line emissions. We list the magnitude differences. PMS stars in a very young galaxy give comparable contributions to that from emission lines.

| Filter  | $\Delta m_{\text{PMS}}$ | $\Delta m_{\text{line}}$ |
|---------|---------------------|---------------------|
| F444W   | -0.43               | -0.47               |
| F560W   | -0.62               | -0.53               |
| F770W   | -0.61               | -1.35               |
| F1000W  | -0.81               | -0.28               |
| F1130W  | -0.79               | -0.35               |
| F1280W  | -0.75               | -0.73               |
| F1500W  | -0.70               | -0.35               |
| F1800W  | -0.72               | -0.18               |
| F2100W  | -0.59               | -0.95               |

Overall, very young galaxies may contain a certain fraction of PMS stars that contribute an appreciable flux in infrared, and thus it may need to be considered in SED modeling and fitting. A multi-band observation across those listed in Table 1 will allow us to distinguish the PMS contribution from that of line emission. Typically, emission lines cause significant boost in a few particular bands.

5 CONCLUSIONS

We have studied the SEDs of the first galaxies that contain PMS stars. Although the timescale of PMS evolution is short ($\sim 0.1 \text{–} 1 \text{ Myr}$), it may be necessary to include the PMS contribution in order to properly interpret the SED of a young galaxy. The PMS signature appears primarily as an excess in the observed-frame infrared flux especially when a galaxy sustains continuous star formation (Section 3.3). If we do not consider the PMS contribution in SED fitting, we may misestimate the galaxy properties such as the total stellar mass and the star formation history. Although our result may not readily be applicable to galaxies that are already metal- and dust-enriched, galaxies with a low dust content likely exist in the early Universe, and PMS stars might imprint distinct signatures similar to those presented in this Letter. A small mass fraction of PMS stars can contribute to the total infrared luminosity of a galaxy. More detailed study is clearly warranted to understand the photometric and spectral features of young galaxies in the early Universe.

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