Infrared Emission from High-Redshift Galaxies in Cosmological SPH Simulations

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Abstract. We compute the infrared (IR) emission from high-redshift galaxies in cosmological smoothed particle hydrodynamics (SPH) simulations by coupling the output of the simulation with the population synthesis code ‘GRASIL’ by Silva et al. Based on the stellar mass, metallicity and formation time of each star particle, we estimate the full spectral energy distribution (SED) of each star particle from ultraviolet (UV) to IR, and compute the luminosity function of simulated galaxies in the Spitzer broadband filters for direct comparison with the available Spitzer observations.

1 Introduction

A significant fraction of the energy density in the Universe comes from the IR emission reprocessed by dust. Therefore we need to take into account this conversion process from stellar UV photons to dust thermal emission in IR in order to estimate the total cosmic SFR density in the Universe properly. The observations by the Spitzer Space Telescope give us excellent opportunities to test our models of galaxy formation and evolution.

Theorists have utilized both semianalytic models and cosmological hydrodynamic simulations of galaxy formation to understand the history of cosmic star formation (e.g., Kauffmann & Haehnelt 2000; Nagamine et al. 2000, 2001). However, so far the modeling of dust extinction and the energy conversion from UV to IR have not been considered in detail in these modeling (but see Lacey et al. 2007, 2010). In this article, we report the preliminary results of our attempt to compute the IR emission from simulated galaxies in cosmological hydrodynamic simulations.

2 Numerical Simulation and Method

Cosmological hydrodynamic simulations allow us to model galaxy formation starting from high-z to the present time without any assumptions on the dynamics of collapsing gas or merging dark matter halos. We use the updated version of the GADGET-3 SPH code (originally described in Springel 2005). Our code includes radiative cooling by H, He, and metals (Choi & Nagamine 2009b), heating by a uniform UV background radiation, star formation (SF, Choi & Nagamine 2009a), supernova feedback, a phenomenological model for galactic winds (Choi & Nagamine 2010), and a sub-resolution model of multi-
Figure 1. SEDs of different emitting physical components within the GRASIL model: stars (top left), molecular clouds (MC; top right), cirrus (bottom left), and total (bottom right). The time evolution of a single stellar population is shown from $t = 1$ Gyr to 12 Gyr from top to bottom in each panel. Dust absorbs the UV photons, and re-emit the energy in the IR as the molecular cloud and cirrus emission.

phase ISM \cite{SpringelHernquist2003}. Once the gas density exceeds the SF threshold density, a star particle is allowed to be born from a gas particle at each time-step in order to statistically reproduce the computed SFR on average. We use a series of simulation runs with different box sizes (comoving 10, 34, and $100h^{-1}$Mpc) and resolution to cover a wide range of galaxy masses.

The GRASIL code \cite{Silvaetal1998} computes the time-dependent SEDs of simulated galaxies in the wavelengths of $100\,\text{Å} < \lambda < 1\,\text{m}$ for a given stellar population (Figure 1), taking into account of the dust extinction processes that convert the UV photons into IR. We apply the GRASIL code to compute the IR emission of each star particle based on its mass, formation time, and metallicity, treating each star particle as an instantaneous starburst of single stellar population. We then co-add the spectra of all constituent star particles to obtain the spectra of simulated galaxies. The Salpeter \cite{1955PhFl...8..257S} IMF has been assumed.

3 Results

The left panel of Figure 2 shows an example SED of a simulated galaxy at $z = 3$ with a stellar mass $M_* \sim 10^{10} M_\odot$. One can see that some UV photons are absorbed by dust and re-emitted as the dust thermal emission with a peak near 100 $\mu$m.
Infrared Emission from High-$z$ Galaxies

Figure 2. Left: Total SED from UV to IR of a simulated galaxy at $z = 3$, computed by coupling the GADGET-3 output and the GRASIL code. Right: AB magnitude luminosity functions (LFs) in the Spitzer broadband filters of 160, 70, 24, 8, 5.8, 4.5, 3.6 $\mu$m, from right to left. The latter four LFs are almost overlapping each other.

Figure 3. Stellar mass vs. AB magnitude (left) and galaxy metallicity vs. AB magnitude (right) for simulated galaxies at $z = 3$.

Once we obtain the full SED of simulated galaxies, we first compute the AB magnitudes using the Spitzer broadband filters, and examine the luminosity functions as shown in the right panel of Figure 2. We find that the simulated galaxies are brighter in the longer wavelength filters, although we still need to identify the exact cause of this trend.

Figure 3 shows the relation between the AB magnitude, stellar mass, and metallicity of simulated galaxies at $z = 3$. As expected, more massive galaxies have brighter AB magnitudes. We also see that in general, the higher mass galaxies have higher metallicities. However, the scatter in metallicity for the luminous galaxies is much larger compared to when it is plotted against galaxy stellar mass, presumably owing to dust extinction and re-emission processes.

Figure 4 compares the monochromatic rest-frame luminosity functions at 8 and 24 $\mu$m of simulated galaxies at $z = 2$ against observed data. The agreement between the two is quite good, except for the last data point at the lowest luminosity, where the observation might be suffering from the flux limit.

Summary. We presented the preliminary results of our initial attempt to calculate the IR emission from high-$z$ galaxies in our cosmological hydrodynamic simulations. The resulting rest-frame luminosity functions at 8 $\mu$m and 24 $\mu$m
Figure 4. Monochromatic rest-frame LFs at 8 and 24 µm for $z = 2$ simulated galaxies, compared against observational data by Caputi et al. (2007) and Rodighiero et al. (2009). The downturn of simulated LFs at low-luminosity end is due to the resolution limit of this simulation with a comoving box size of $10h^{-1}$Mpc.

agree very well with the observations, which is very encouraging. Through more detailed analyses on the relationship between star formation histories, metallicities, and IR luminosities, we hope to gain more insight on the physical properties of IR galaxies observed by the Spitzer.

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