Hunt for Molecules
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DUST AND MOLECULES IN EARLY GALAXIES: PREDICTION AND STRATEGY FOR OBSERVATIONS

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Abstract. The interplay between dust and molecules is of fundamental importance in early galaxy evolution. First we present the prediction for the dust emission from forming galaxies. Then we discuss the observational strategy for molecules in early galaxies by infrared absorption lines of a bright continuum source behind the clouds. By combining these two approaches, we will be able to have a coherent picture of the very early stage of galaxy evolution.

1 Introduction

At the very first phase of the Universe, there have been almost no structures, as seen in the tiny fluctuation of the cosmic microwave background. In contrast, today we observe a variety of cosmic structures, from planes to the large-scale structure in the Universe. In addition, the Big Bang nucleosynthesis produced only light elements, while the present Universe is rich in heavy elements. Thus, galaxy formation may be the most important event in the cosmic history.

Active star formation is followed by heavy element production from the birth and death of stars. The produced heavy elements generally exist in the form of small solid particles, i.e., dust. Dust grains play very important roles in galaxy evolution. First, they scatter and absorb short wavelength photons and finally re-emit the energy in the infrared (IR). This makes the

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galaxy evolutions seen in the optical/ultraviolet and in the IR very different (see Takeuchi et al. 2005c). Another important role of dust grains is that they work as a catalyst of molecular formation (e.g. Hirashita et al. 2002, Hirashita & Ferrara 2002). This process is particularly important in the very early phase of galaxy evolution, because hydrogen molecules are very important coolant of gas in the very metal-poor phase of galaxies. Without dust, star formation does not proceed effectively (Hirashita & Ferrara 2002).

From this point of view, we focus on the two kinds of systems. We first discuss young galaxies with active dust production. We will see that their appearance is different from dusty IR luminous galaxies at lower redshift (e.g., Takeuchi et al., 2001a,b). We discuss the observability of their continuum radiation from dust. Then we move the topic to dense gas systems with little metal/dust. On the eve of the active dust production, they might contain a large amount of hydrogen molecules. We consider the direct measurement of the hydrogen molecules in such protogalactic clouds through the absorption lines in the IR.

2 Dust Emission from Forming Galaxies

2.1 SED Model for Forming Galaxies

We present a brief outline of our model framework. All the details are given in Takeuchi et al. (2003, 2005b), and Takeuchi & Ishii (2004).

Nozawa et al. (2003) investigated the formation of dust grains in the ejecta of Population III SNe, whose progenitors are initially metal-free. They considered unmixed and uniformly mixed cases in the He core. In the unmixed case, the original onion-like structure of elements is preserved, and in the mixed case, all the elements are uniformly mixed in the helium core.

For the chemical evolution, we use a closed-box model with the Salpeter initial mass function $\phi(m) \propto m^{-2.35}$ with mass range of $(m_\mathrm{l}, m_\mathrm{u})$= (0.1 $M_\odot$, 100 $M_\odot$). We neglect the contribution of SNe Ia and winds from low-mass evolved stars to dust formation, because we consider timescales smaller than 10^9 yr. The interstellar medium is treated as one zone, and the growth of dust grains by accretion is neglected. Within the short timescale considered here, this can be assumed safely. We also neglect the destruction of dust grains within the young age considered. Finally, we assume a constant SFR for simplicity.

Very small grains cannot establish thermal equilibrium with the ambient radiation field, a phenomenon which is called stochastic heating. For the specific heat, we adopt a multidimensional Debye model (e.g. Draine & Li 2001) for carbon and silicate grains. For other species, we adopt the classical three-dimensional Debye model with a single Debye temperature. The emission from dust is calculated basically according to Draine & Anderson (1985). Total dust emission is obtained as a superposition of the emission from each grain species. We constructed $Q(a, \lambda)$ of each grain species from available experimental data via Mie theory. When the dust opacity becomes large, we should consider the self-absorption of IR emission by dust. This is treated by a thin shell approximation.

2.2 Results and Discussions

2.2.1 Evolution of IR SED

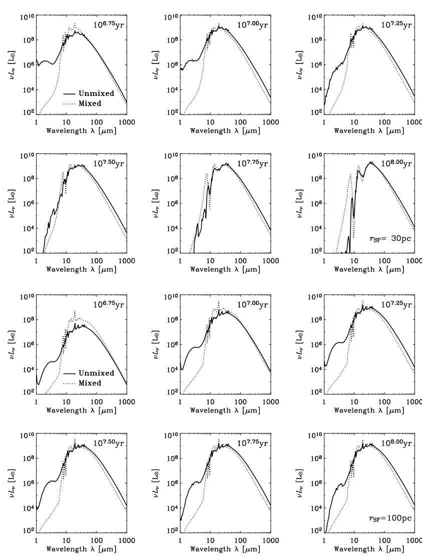

Fig. 1. The evolution of the IR SED of a very young galaxy (left six panels: $r_{\rm SF} = 30\,\rm pc$; right six panels: $100\,\rm pc$).

We first show the evolution of the IR SED of forming galaxies based on our baseline model in Figure 1. For these calculations we adopt a star formation rate SFR $= 1\,M_{\odot}\,\mathrm{yr}^{-1}$. We adopt $r_{\rm SF} = 30$ pc and 100 pc. In a very young phase (age $= 10^{6.75}$–$10^{7.25}$ yr), unmixed-case SED has an enhanced NIR–MIR continuum. After $10^{7.25}$ yr, the NIR–MIR continuum is extinguished by the self-absorption in the case of $r_{\rm SF} = 30$ pc. In contrast, the self-absorption is not significant for $r_{\rm SF} = 100$ pc. In both cases, the SEDs peak at a wavelength $\lambda \simeq 20$–$30\,\mu$m.

2.2.2 A nearby forming galaxy, SBS 0335−052

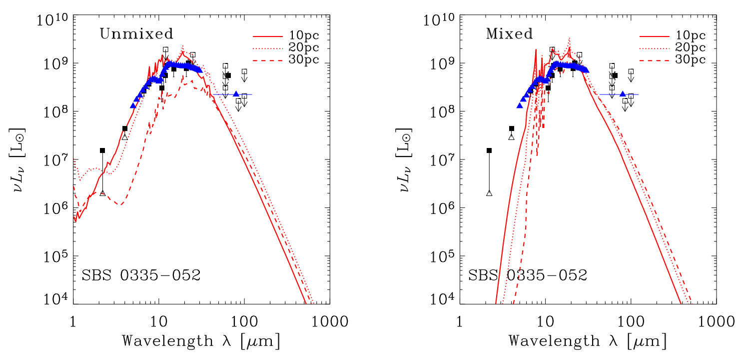

Fig. 2. The model for the SED of a nearby star-forming dwarf galaxy SBS 0335−052

Although it is still difficult to observe galaxies in their very first phase of the SF, we can compare the model with a local counterpart of such galaxies. SBS 0335−052 is a local galaxy (~ 54 Mpc) with SFR $= 1.7\,M_{\odot}\,\mathrm{yr}^{-1}$ and extremely low metallicity $Z = 1/41\,Z_{\odot}$. This galaxy is known to have an unusual IR SED and strong flux at N–MIR. It has a very young starburst (age < 5 Myr) without significant underlying old stellar population. Houck et al. (2004) presented new data of the MIR SED by *Spitzer*. We have calculated the SED for $r_{\rm SF} = 10$, 20, and 30 pc. The SFR is fixed to be $1.7\,M_{\odot}\,\mathrm{yr}^{-1}$, and the age is $10^{6.5}$ yr. We present the model and the observed SED of SBS 0335−052 in Figure 2. The very strong N–MIR continuum of

SBS 0335−052 is well reproduced by the SED of unmixed case, but the mixed case seriously underpredicts its MIR continuum. This suggests that we may determine the dust production (unmixed or mixed) of SNe through the observation of the N–MIR SEDs of forming galaxies.

2.2.3 Toward higher redshifts

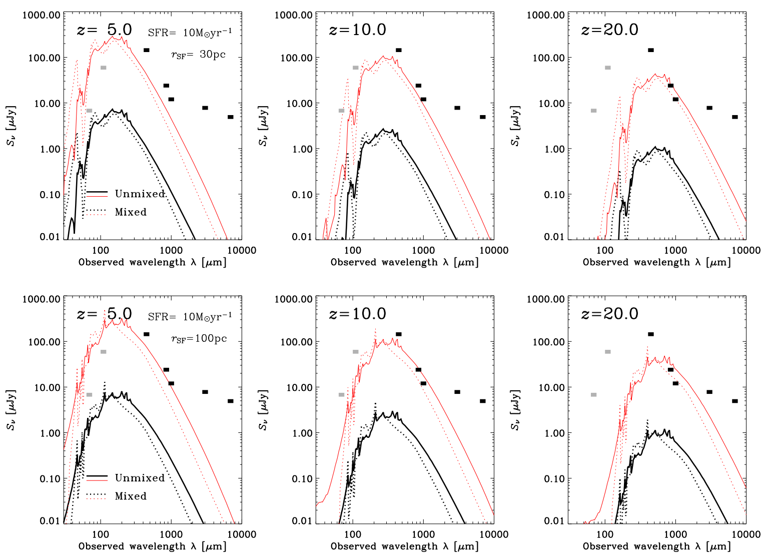

Fig. 3. The expected flux densities of a dwarf forming galaxy at $z = 5, 10$, and 20. Gray and black tick marks are the confusion limits of *Herschel* and the detection limits of an ALMA 8-hour survey. The *Herschel* confusion limits are taken from Lagache et al. (2003).

Consider a dark halo of mass $\sim 10^9\ M_\odot$, then it is expected to contain a gas mass $\simeq 10^8\ M_\odot$. We calculate the SEDs for a dwarf forming galaxy. If gas collapses on the free-fall timescale with an efficiency of $\epsilon_{\rm SF}$ (we assume $\epsilon_{\rm SF} = 0.1$), we obtain the following evaluation of the SFR (Hirashita & Hunt

2004):

$$\mathrm{SFR} \simeq 0.1 \left(\frac{\epsilon_{\mathrm{SF}}}{0.1}\right) \left(\frac{M_{\mathrm{gas}}}{10^7\ M_\odot}\right)^{3/2} \left(\frac{r_{\mathrm{SF}}}{100\ \mathrm{pc}}\right)^{-3/2} [M_\odot \mathrm{yr}^{-1}]\ . \tag{2.1}$$

If we consider $M_{\mathrm{gas}} \simeq 10^8\ M_\odot$, we have $\mathrm{SFR} \simeq 3(r_{\mathrm{SF}}/100\ \mathrm{pc})^{-3/2}\ M_\odot\ \mathrm{yr}^{-1}$. Thus, we consider a dwarf galaxy with $\mathrm{SFR} = 10\ M_\odot \mathrm{yr}^{-1}$ as an example, and we adopt $r_{\mathrm{SF}} = 30$ pc and 100 pc. The age is set to be 10^7 yr. We show the expected SEDs for such galaxies at $z = 5$, 10, and 20 in Figure 3. It seems almost impossible to detect such objects by *Herschel* or ALMA. However, gravitational lensing works very well as a natural huge telescope. This is depicted by the thin lines in Figure 3 (with magnification factor 40). If we suppose a cluster of galaxies at $z_{\mathrm{l}} \simeq 0.1$–$0.2$ whose dynamical mass M_{dyn} is $5 \times 10^{14}\ M_\odot$, and use number counts of high-z forming galaxies presented by Hirashita & Ferrara (2002), we have an expected number of galaxies suffering a strong lensing to be $\simeq 1$–5 with detection limit 1 μJy.

3 Direct Measurement of H_2 by IR Absorption Lines

3.1 Basic Idea

Molecular hydrogen is the predominant constituent of the dense gas in the Universe. While in the local Universe, molecules containing heavy elements (e.g. CO, H_2O) are good tracers of the amount of molecular hydrogen, they are expected to be significantly depleted in the early Universe. We need a technique for measuring molecular hydrogen directly. Petitjean et al. (2000) have reported a direct measurement of H_2 molecules in the UV. The transition probabilities of ionization and dissociation lines are so large that they are useful for detecting thin layers and small amounts of the molecular gas, but useless for detecting dense gas clouds.

In contrast, molecular hydrogen has well-known vibrational and rotational transitions at IR wavelengths. Their transition probabilities are very small because hydrogen molecule, a diatomic molecule of two identical nuclei, has no allowed dipole transitions. Hence, they are useful tools to analyze dense ($> 10\ \mathrm{cm}^{-3}$) and hot (> 300 K) gas. Ciardi & Ferrara (2001) calculated expected emission line intensities of molecular hydrogen, but unfortunately, their direct measurement was found to be very difficult due to their weakness. However, if there is a strong IR continuum source behind or in the molecular gas cloud, absorption measurements of these lines may be possible. This idea is presented by Shibai et al. (2001).

We should note that the absorption by dust in the cloud is usually larger than the absorption by H_2 molecules. However, since our target is a primordial gas cloud whose metallicity is significantly lower than the Galactic value, the lines can be detected in absorption against bright IR sources. Such observations will be feasible with the advent of proposed space missions for large IR telescope facilities. Here we focus on *SPICA* (Ueno et al. 2000).

3.2 Calculation

Assuming a uniform, cool gas cloud ($kT_{\rm ex} \ll h\nu$), the optical thickness of the line absorption, $\tau_{\rm line}$ is

$$\tau_{\rm line} \simeq \frac{\lambda^3}{8\pi}\left(\frac{g_u}{g_\ell}\right) A_{u\ell} N_\ell \frac{1}{\Delta V} \tag{3.1}$$

where the subscripts u and ℓ indicate the upper and lower levels of a transition, g_u and g_ℓ are the degeneracy of each state respectively, $A_{u\ell}$ is the Einstein's A coefficient, N_ℓ is the column density of the molecules in the lower state, and ΔV is the line width in units of velocity. Here we assume that almost all the molecules occupy the lowest energy state. The absorption line flux in the extinction free case, $I^{\rm abs}_{\rm line,0}$, is given by

$$I^{\rm abs}_{\rm line,0} = S\Delta\nu\left(1 - e^{-\tau_{\rm line}}\right) \tag{3.2}$$

where $\Delta\nu$ is the line width in units of frequency and S is the continuum flux density of the IR source behind the cloud. Assumed parameters in this calculation are listed in Table 1. Next, we consider the dust extinction which is denoted by

$$\tau_{\rm dust}(\lambda) = 1.086\left(\frac{A_\lambda}{A_V}\right)\left(\frac{A_V}{N_{\rm H}}\right)_\odot Z\, N_{\rm H} \tag{3.3}$$

The extinction spectrum of Mathis (1990) is adopted for (A_λ/A_V), and the extinction efficiency is assumed to be proportional to the relative heavy element abundance, and $(A_V/N_{\rm H})_\odot$ is the conversion factor from A_V to

Table 1. Parameters assumed for the present calculation

Ortho : Para	3 : 1
HD/H_2	10^{-5}
Intrinsic Flux of Source	10 mJy
Line width	100 $\mathrm{km\,s^{-1}}$
Detection Limit (*SPICA* 5σ)	5×10^{-21} $\mathrm{W\,m^{-2}}$
Detectable Optical Thickness	> 0.01
Dust Extinction Model	Mathis (1990)

N_H for the local abundance. We then obtain the absorption line flux with extinction, $I_\mathrm{line}^\mathrm{abs}$,

$$I_\mathrm{line}^\mathrm{abs} = I_\mathrm{line}^\mathrm{abs,0} e^{-\tau_\mathrm{dust}} = S\Delta\nu \left(1 - e^{-\tau_\mathrm{line}}\right) e^{-\tau_\mathrm{dust}} \,. \tag{3.4}$$

3.3 Results

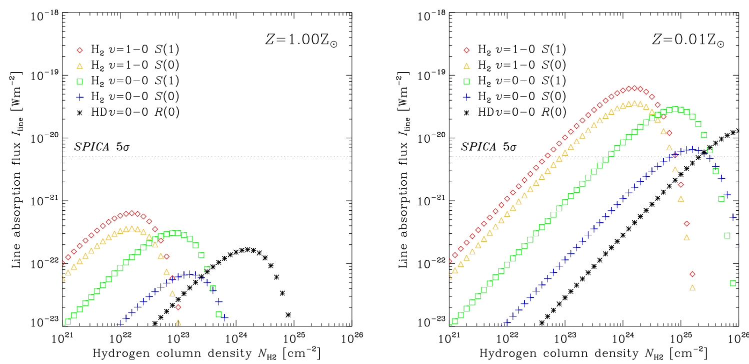

Fig. 4. Left panel: the absorption line flux expected for a cloud with the Milky Way heavy element abundance ($Z = 1$) in front of a 10 mJy source. Right panel: same as (a) but the heavy element abundance is $Z = 0.01$.

The calculation was made for the five lines listed in Table 2. Left panel of Figure 4 shows the absorption line flux expected for a cloud with the local heavy element abundance in front of a 10 mJy source. The absorption fluxes are far smaller than the 5σ expected sensitivity of the *SPICA* mission

Table 2. Parameters of the Line Transitions

Transition	Wavelength [μm]	A coefficient [s^{-1}]	A_λ/A_V
H_2 $v = 1-0$ $S(1)$	2.12	3.47×10^{-7}	0.11
H_2 $v = 1-0$ $S(0)$	2.22	2.53×10^{-7}	0.11
H_2 $v = 0-0$ $S(1)$	17	4.77×10^{-10}	0.020
H_2 $v = 0-0$ $S(0)$	28	2.95×10^{-11}	0.011
HD $v = 0-0$ $R(0)$	112	2.54×10^{-8}	0.0011

(Ueno et al. 2000). On the other hand, right panel of Figure 4 shows the result for the case in which the heavy element abundance is 1 % of that of the local one. All five lines populate parameter space above or near the limit.

We have assumed an intrinsic continuum flux density of 10 mJy at the line wavelength. We examined some existing QSOs as template sources (for the details, see Shibai et al. 2001). If we have objects at $z = 5$ at least as luminous as our template sources, it is possible to observe absorption in H_2 lines of 17, 28, and 112 μm respectively. The redshifted 112 μm line will be in the submm range and may not be observable by IR missions, but ALMA should be able to observe it. Unfortunately, it is very difficult to observe the absorption of 2.2 μm lines since the expected flux density based on dust emission spectrum will be too faint.

3.4 What can we learn from the absorption lines of these clouds?

First we simply estimate the column density of a protogalactic hydrogen cloud. Here we assume that the size of the cloud R is a few kpc and that the gas mass M is $\sim 10^{11}\ M_\odot$. Such a large reservoir of molecular gas has been discovered at high redshift (Papadopoulos et al. 2001). Such clouds have column density of

$$N_{H_2} \simeq 4 \times 10^{23} [\mathrm{cm}^{-2}]\, f \left(\frac{R}{3\ \mathrm{kpc}}\right)^{-2} \left(\frac{M}{10^{11} M_\odot}\right) \tag{3.5}$$

where f is the mass fraction of the molecular clouds to the total gas mass, and M is the total gas mass of the protogalaxy. The radius will be finally a few kpc. In a realistic situation, a primordial cloud may evolve dynamically on a free-fall timescale, which is much shorter than the timescales of cosmological structure evolution. Therefore, observed properties are specific to the redshift at which the cloud absorption is measured. Hence, since we will obtain redshift z, and velocity dispersion ΔV, we can trace the dynamical evolution of a primordial cloud at high-z. The *SPICA* mission will provide us with the information on the massive objects ($> 10^{11}\ M_\odot$) at $z < 5$. We still have to wait for more sensitive facilities for the observational approach to the Population III objects, whose physical properties are theoretically predicted by recent extensive investigations, because they are located at higher redshift and their typical mass is small (e.g., Nishi & Susa 1999). When we estimate the detectability of such objects by other facilities, the algorithm constructed in this paper can be applied straightforwardly.

4 Conclusion

We first present our dust emission model from forming galaxies, which is based on a new theory of SN II dust production. The model roughly reproduces the observed SED of a local low-metallicity dwarf SBS 0335−052 which has a peculiar strong and MIR-bright dust SED. We also calculated the SED of a very high-z forming small galaxy. Although it may be intrinsically too faint to be detected even by ALMA 8-hour survey, the gravitational lensing can make it feasible.

Then we propose a method to measure the amount of H_2 in primordial low-metallicity cloud in an IR spectra of QSOs. If the metallicity of the cloud is low ($Z \sim 0.01 Z_\odot$), dust extinction is so weak that 17 and 28 μm lines are detectable by *SPICA* for objects at $z < 5$. For very high-z Population III objects, ALMA will be useful. By this observation, we can trace back the dynamical evolution of early collapsing objects at very high-z.

By combining these two approaches, we will be able to have a coherent picture of the very early stage of galaxy evolution, from the pristine gas phase to active dust production phase.

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