Mon. Not. R. Astron. Soc. **330,** L19–L23 (2002)

Dust and hydrogen molecules in the extremely metal-poor dwarf galaxy SBS 0335−052

Hiroyuki Hirashita,[1★†] Leslie K. Hunt[2] and Andrea Ferrara[1]

[1]*Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi, 5, 50125 Firenze, Italy*

[2]*CAISMI-IRA/CNR, Largo Enrico Fermi, 5, 50125 Firenze, Italy*

Accepted 2001 December 18. Received 2001 December 18; in original form 2001 November 9

ABSTRACT

During the early stages of galaxy evolution, the metallicity is generally low and nearby metal-poor star-forming galaxies may provide templates for primordial star formation. In particular, the dust content of such objects is of great importance, because early molecular formation can take place on grains. To gain insight into primeval galaxies at high redshift, we examine the dust content of the nearby extremely low-metallicity galaxy SBS 0335−052 which hosts a very young starburst ($\lesssim 10^7$ yr). In young galaxies, the dust formation rate in Type II supernovae governs the amount of dust, and by incorporating recent results on dust production in Type II supernovae we model the evolution of dust content. If the star-forming region is compact ($\lesssim 100$ pc), as suggested by observations of SBS 0335−052, our models consistently explain the quantity of dust, far-infrared luminosity, and dust temperature in this low-metallicity object. We also discuss the H_2 abundance. The compactness of the region is important to H_2 formation, because the optical depth of dust for UV photons becomes large and H_2 dissociation is suppressed. We finally focus on implications for damped Lyα systems.

Key words: molecular processes – stars: formation – dust, extinction – galaxies: evolution – galaxies: ISM.

1 INTRODUCTION

How dust forms and evolves in primordial galaxies needs to be considered before we can understand the chemical and thermodynamical evolution of a metal-poor interstellar medium (ISM). Dust grains absorb stellar light and re-emit it in the far-infrared (FIR).[1] Indeed, the FIR spectral range represents a unique opportunity to study the dust properties and distribution, and dedicated space missions are planned in these wavelength bands (ASTRO-F,[2] SIRTF,[3] Herschel,[4] etc.). Dust grains also drastically accelerate the formation rate of molecular hydrogen (H_2), expected to be the most abundant molecule in the ISM. Hydrogen molecules emit vibrational-rotational lines, thus cooling the gas. The cooling rate of a galaxy consequently depends strongly on the dust content and its effect on H_2 abundance.

The production of dust is expected at the final stages of stellar evolution, and Type II supernovae (SNe II) are the dominant source for the production of dust grains in young star-forming galaxies. The formation in stellar winds from evolved low-mass stars can also contribute considerably, but the cosmic time is not long enough for such stars to evolve at high redshift (z). However, dust is also destroyed by SN shocks (Jones, Tielens & Hollenbach 1996). The detailed modelling of dust evolution in star-forming regions therefore requires an accurate treatment of both types of processes.

Here we have developed a model for the evolution of dust content in primordial galaxies. To compare our model with observations, we need age information and the FIR energy distribution. For high-z primordial galaxies, present experiments cannot determine these quantities accurately enough. Nevertheless, because of their low metallicity and active star formation, blue compact dwarf galaxies (BCDs) may be viable candidates for nearby primeval systems. We have focused on the evolution of dust content in one of these, SBS 0335−052, since this object may be experiencing its first burst of star formation (age $\lesssim 10^7$ yr; Vanzi et al. 2000).

In this Letter, we first model the dust content of a young galaxy, the age of which is less than 10^8 yr (Section 2). Then, we compare the model predictions with the observed quantities of the extremely low-metallicity BCD, SBS 0335−052 (Section 3). Finally, we comment on implications for damped Lyα systems (DLAs).

★E-mail: irasita@arcetri.astro.it

†Research Fellow of the Japan Society for the Promotion of Science.

[1] For SBS 0335−052, large energy is emitted in the mid-infrared because the dust temperature is high (Dale et al. 2001). In this Letter, however, we use the term ‘FIR emission’ for the thermal emission from dust grains.

[2] http://www.ir.isas.ac.jp/ASTRO-F/index-e.html

[3] http://sirtf.caltech.edu/

[4] http://astro.estec.esa.nl/First/

2 MODEL DESCRIPTION

2.1 Evolution of dust mass in a young galaxy

We aim at modelling the evolution of dust content in a young galaxy, the age of which is less than 10^8 yr. We focus on the comparison with the extremely metal-poor (1/40 $Z_\odot$) BCD SBS 0335–052, one of the few possible local counterparts of a primordial galaxy in the nearby Universe (Vanzi et al. 2000). Because of its low age, the contribution of winds from late-type stars to dust formation is assumed to be negligible. We consider the dominant (brightest) star-forming complex, and assume that grains produced by SNe II are accumulated within this region. This assumption is consistent with high-resolution infrared imaging observations which reveal that the distribution of dust is as compact as the size of the star-forming region (Dale et al. 2001; Hunt, Vanzi & Thuan 2001).

We start by considering a generic star-forming region in a galaxy. Our model is applicable to young ($<10^8$ yr) bursts. Because of its low age, the contribution of Type Ia supernovae to the total supernova rate is neglected. The rate of SNe II is given by

$$\gamma(t) = \int_{8\,\mathrm{M}_\odot}^{\infty} \psi(t - \tau_m)\phi(m)\,\mathrm{d}m, \tag{1}$$

where $\psi(t)$ is the star formation rate (SFR) at t (we define $t = 0$ at the beginning of the star formation), $\phi(m)$ is the initial mass function (IMF), τ_m is the lifetime of a star, the mass of which is m, and we assumed that stars with $m > 8\,\mathrm{M}_\odot$ produce SNe II. In this Letter, we assume a constant SFR, $\psi = \psi_0$, and a Salpeter IMF ($\psi(m) \propto m^{-2.35}$; the mass range of stars is 0.1–60 $\mathrm{M}_\odot$) to obtain a first estimate. Our assumption of constant star formation is applicable if the time from the starburst is small. Indeed, the difference between the instantaneous burst and the constant star formation history is small on small time-scales ($\lesssim 10^7$ yr, the age of SBS 0335–052; Vanzi et al. 2000).

In general, dust destruction by SNe can be important, but for SBS 0335–052 it is negligible for the following reason. The destruction time-scale τ_{SN} is estimated to be (McKee 1989; Lisenfeld & Ferrara 1998)

$$\tau_{\mathrm{SN}} = \frac{M_{\mathrm{g}}}{\gamma\epsilon M_{\mathrm{s}}(100\,\mathrm{km\,s^{-1}})}, \tag{2}$$

where M_{g} is the total gas mass in a star-forming region, $M_{\mathrm{s}}(100\,\mathrm{km\,s^{-1}}) = 6.8 \times 10^3\,\mathrm{M}_\odot$ (Lisenfeld & Ferrara 1998) is the mass accelerated to $100\,\mathrm{km\,s^{-1}}$ by a SN blast, γ is the SN II rate, $\epsilon \sim 0.1$ (McKee 1989) is the efficiency of dust destruction in a medium shocked by a SN. We assume the relation between stellar mass and lifetime as shown in Inoue, Hirashita & Kamaya (2000a). The SN II rate increases with time, and reaches a constant value, if the star formation rate is constant in time. Numerically, we find that γ (yr^{-1}) $\sim 3 \times 10^{-3}\psi_0$ ($\mathrm{M}_\odot\,\mathrm{yr}^{-1}$) around the age of 5 Myr. We also assume that the star formation efficiency is the order of 5 per cent as known empirically from observations (e.g. Inoue, Hirashita & Kamaya 2000b). This means that $M_{\mathrm{g}}/\psi_0 \sim 20t_{\max}$, where $t_{\max}$ is the possible duration of the star-forming activity. Thus, we finally find that $\tau_{\mathrm{SN}} \gg t_{\max}$. It is probable that $t < t_{\max}$ during the ongoing starburst, and we can safely conclude that the dust destruction can be neglected.

Therefore, the only contribution to total dust mass in the galaxy (M_{d}) comes from the supply from SNe II. Then the rate of increase of M_{d} is written as

$$\dot{M}_{\mathrm{d}} = m_{\mathrm{d}}\gamma, \tag{3}$$

where m_{d} is the typical dust mass produced in a SN II. Todini & Ferrara (2001) showed that m_{d} varies with progenitor mass and metallicity. There is also some uncertainty in the explosion energy of SNe II. The Salpeter IMF-weighted mean of dust mass produced per SN II for (1) $Z = 0$, Case A, (2) $Z = 0$, Case B, (3) $Z = 10^{-2}\,Z_\odot$, Case A, and (4) $Z = 10^{-2}\,Z_\odot$, Case B are (1) 0.22 $\mathrm{M}_\odot$, (2) 0.46 $\mathrm{M}_\odot$, (3) 0.45 $\mathrm{M}_\odot$, and (4) 0.63 $\mathrm{M}_\odot$, respectively (Z is the metallicity, and Cases A and B correspond to low and high explosion energy,[5] respectively). We adopt the average of the four cases, i.e., $m_{\mathrm{d}} \simeq 0.4\,\mathrm{M}_\odot$, but the calculated dust mass is proportional to m_{d}. Therefore, there is uncertainty in m_{d} and M_{d} by a factor of ~ 2. Since we are considering the first burst of star formation, we assume $M_{\mathrm{d}} = 0$ at $t = 0$. Because dust production rate is proportional to γ which is proportional to the star formation rate ψ_0, M_{d} calculated by our model directly scales as ψ_0.

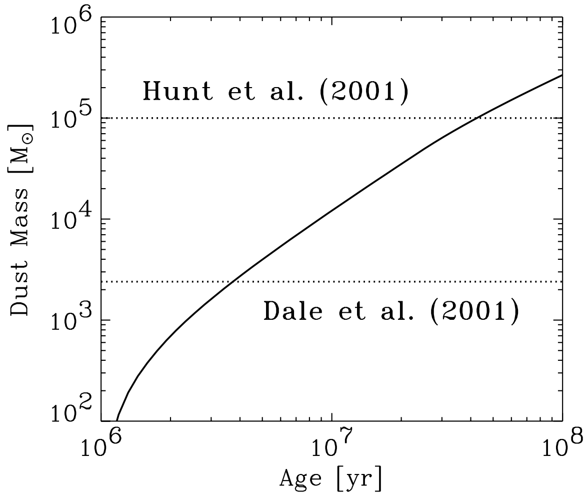

Figure 1. Time evolution of dust amount in a galaxy (solid line). The initial star formation rate is assumed to be $1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$. The horizontal dotted lines show the value determined observationally by Dale et al. (2001) and the upper limit by Hunt et al. (2001).

In Fig. 1, we show the dust mass evolution for a star formation rate of $1\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, a typical value for SBS 0335–052 (Hunt et al. 2001). In Fig. 1, we also show the values of dust masses derived by Dale et al. (2001) and Hunt et al. (2001). The dust mass in Hunt et al. (2001) was calculated with a unit filling factor, and is considered to be an upper limit.

2.2 Dust temperature and FIR luminosity

Probably the most direct way to measure dust content is to observe its FIR emission. We now derive the evolution of FIR luminosity and dust temperature. Because of the large cross-section of dust against ultraviolet (UV) light and the intense UV radiation field in a star-forming galaxy, we can assume that the FIR luminosity is equal to the absorbed energy of OB stellar radiation ($\sim$UV radiation). First, we estimate the optical depth for the UV radiation as follows:

$$\tau_{\mathrm{dust}} \simeq \pi a^2 Q_{\mathrm{UV}} n_{\mathrm{d}} r_{\mathrm{SF}} = \frac{9}{16\pi}\frac{Q_{\mathrm{UV}} M_{\mathrm{d}}}{a\delta r_{\mathrm{SF}}^2}, \tag{4}$$

[5] The kinetic energies given to the ejecta are $\sim 1.2 \times 10^{51}$ erg and $\sim 2 \times 10^{51}$ erg for Case A and Case B, respectively.

where a is the grain radius (spherical grains are assumed), $\pi a^2 Q_{\mathrm{UV}}$ is the typical absorption cross-section for UV light, n_{d} is the number density of grains, r_{SF} is the radius of the star-forming region (a spherical star-forming region is assumed), and δ is the grain material density. We adopt $a \simeq 0.03\mu$m (Todini & Ferrara 2001), $Q_{\mathrm{UV}} \simeq 1$, and $\delta = 2\,\mathrm{g\,cm^{-3}}$ (Draine & Lee 1984). Then we obtain the energy absorbed by dust. We assume that all the absorbed energy is re-emitted in the FIR. Thus, the FIR luminosity L_{FIR} becomes

$$L_{\mathrm{FIR}} = L_{\mathrm{OB}}[1 - \exp(-\tau_{\mathrm{dust}})]. \quad (5)$$

L_{OB} is calculated assuming a mass–luminosity relation of OB stars ($>3\,\mathrm{M_\odot}$; we adopt the fit by Inoue et al. 2000a).

In Fig. 2, we show the evolution of FIR luminosity for $r_{\mathrm{SF}} = 300$, 100, and 30 pc (solid, dotted and dashed lines, respectively). Dale et al. (2001) have estimated that $r_{\mathrm{SF}} \simeq 80$ pc for SBS 0335–052. We re-examine this finding to check the consistency with the dust supply rate from SNe II. The observed FIR luminosity ($\sim 5 \times 10^8\,\mathrm{L_\odot}$) for SBS 0335–052 is reached in 8, 3 and 1.2 Myr for $r_{\mathrm{SF}} = 300$, 100 and 30 pc, respectively.

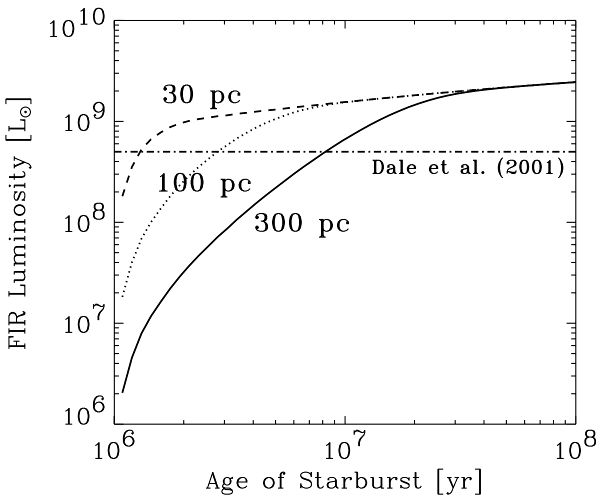

Figure 2. Time evolution of the far-infrared (FIR) luminosity for the same star formation history as in Fig. 1. The radius of the galaxy is assumed to be 300, 100 and 30 pc (solid, dotted and dashed lines, respectively) The observed FIR luminosity is shown by the horizontal dot–dashed line ($\sim 5 \times 10^8\,\mathrm{L_\odot}$; Dale et al. 2001).

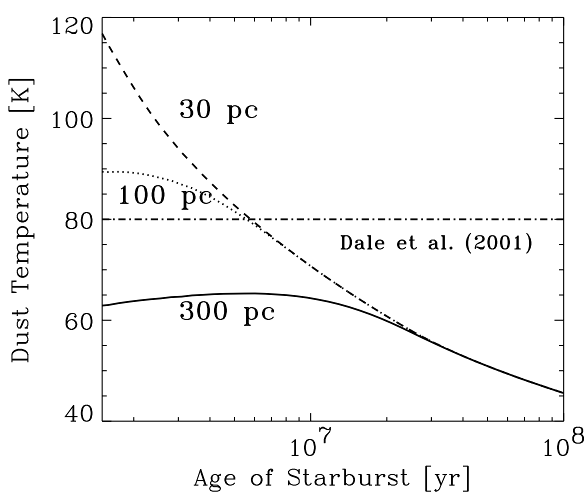

Figure 3. Time evolution of the dust temperature for the same star formation history in Fig. 1. The radius of the star-forming region is assumed to be 300, 100 and 30 pc (solid, dotted, and dashed lines, respectively). The observed dust temperature is shown by the horizontal dot–dashed line (80 K; Dale et al. 2001).

The dust temperature T_{d} is determined from the emissivity given by Draine & Lee (1984); i.e. $Q_{\mathrm{abs}}(\lambda) = 3 \times 10^{-4}(\lambda/100\,\mu\mathrm{m})^{-2}$, where $Q_{\mathrm{abs}}(\lambda)$ is the absorption efficiency (the definition is the same as Draine & Lee) as a function of wavelength λ. Then, we finally obtain the following relation:

$$T_{\mathrm{d}} = 20\left(\frac{L_{\mathrm{FIR}}/\mathrm{L_\odot}}{2.5 \times 10^2 M_{\mathrm{d}}/\mathrm{M_\odot}}\right)^{1/6} \mathrm{K}. \quad (6)$$

In Fig. 3, we show the evolution of dust temperature. The predicted temperature (~ 45–120 K) is higher than that observed in normal spiral galaxies ($\sim$20 K), but such a high temperature ($\sim$80 K; dot–dashed line; Dale et al. 2001) is observed in SBS 0335–052. However, the observed FIR luminosity and temperature are uncertain because the peak of FIR spectrum has not been detected yet. Thus, the three quantities (the size, FIR luminosity, and dust temperature) are simultaneously accounted for by our model. Such a high dust temperature is also predicted for high-z objects (e.g. Totani & Takeuchi 2002).

2.3 H_2 abundance

The abundance of H_2 affects the cooling rate of gas. In particular, to obtain insight into the molecular cooling of a primordial system, nearby star-forming dwarf galaxies constitute an important ‘laboratory’. Thus, we next calculate the evolution of molecular hydrogen fraction.

We assume that molecules form on dust grains and are destroyed (dissociated) by the UV field (both processes occur on a much shorter time-scale than the lifetime of OB stars; Kamaya & Hirashita 2001). Thus, we evaluate the two rates and assume equilibrium. We adopt the formation rate of H_2 by Hollenbach & McKee (1979):

$$R = 0.5 n_{\mathrm{H}}(1 - f_{\mathrm{H_2}}) n_{\mathrm{d}} \pi a^2 \bar{v} S(T), \quad (7)$$

where n_{H} is the number density of hydrogen nuclei, $f_{\mathrm{H_2}}$ is the number fraction in molecules (i.e. $f_{\mathrm{H_2}} n_{\mathrm{H}}/2$ is the number density of H_2), $\bar{v}$ is the mean thermal speed of hydrogen, and $S(T)$ is the sticking coefficient of hydrogen atoms. The latter is given by (Omukai 2000)

$$S(T) = [1 + 0.04(T + T_{\mathrm{d}})^{0.5} + 2 \times 10^{-3} T + 8 \times 10^{-6} T^2]^{-1}$$
$$\times \{1 + \exp[7.5 \times 10^2 (1/75 - 1/T_{\mathrm{d}})]\}^{-1}, \quad (8)$$

where T is the gas temperature. We take $a = 0.03\mu$m (Todini & Ferrara 2001) and $T = 100$ K. The gas temperature is at present poorly constrained by both absorption-line and 21-cm H I observations; however it should represent a reasonable estimate for the temperature of the cold, H_2-forming phase of the Galaxy ISM.

On the other hand, the dissociation rate $I n_{\mathrm{H_2}}$ is estimated empirically by

$$I n_{\mathrm{H_2}} = 2 \times 10^{-11} \left(\frac{I_{\mathrm{UV}}}{2 \times 10^{-3}\,\mathrm{erg\,s^{-1}\,cm^{-2}}}\right) f_{\mathrm{H_2}} n_{\mathrm{H}}\,\mathrm{cm^{-3}\,s^{-1}}, \quad (9)$$

where $I_{\mathrm{UV}} = L_{\mathrm{OB}} \exp(-\tau_{\mathrm{dust}})/r_{\mathrm{SF}}^2$ is the UV radiation field attenuated by dust. We have assumed for normalization that the

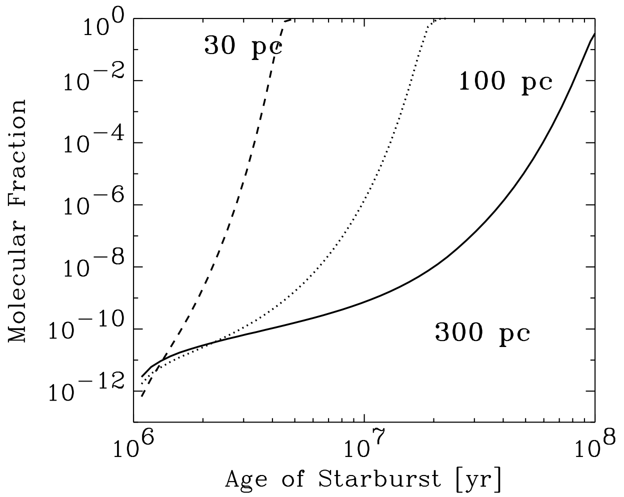

Figure 4. Time evolution of the molecular fraction for the same star formation history in Fig. 1. The radius of the star-forming region is assumed to be 300, 100 and 30 pc (solid, dotted and dashed lines, respectively).

UV radiation intensity and dissociation rate at the solar neighbourhood are 2×10^{-3} erg s^{-1} cm^{-2} and 2×10^{-11} s^{-1} (Jura 1974), respectively, and that In_{H_2} linearly scales with I_{UV}. Equating the two rates, we obtain f_{H_2} as a function of age of burst. For a given amount of dust, f_{H_2} is independent of the hydrogen number density. Thus, we examine the dependence on r_{SF}. Since we assume that $M_d = 0$ at $t = 0$ and consider only the reaction on grains, the initial molecular fraction is assumed to be zero ($f_{H_2} = 0$ at $t = 0$). If H_2 formation in the gas phase is allowed, $f_{H_2} > 0$ at $t = 0$. In this sense, our estimate of f_{H_2} is a lower limit.

The result is shown in Fig. 4 for $r_{SF} = 300$, 100 and 30 pc (solid, dotted, and dashed lines, respectively). The molecular fraction rises because of the shielding of UV radiation by grains. Thus, the dust enrichment by SNe II causes a significant shielding of UV radiation field. Once the column density of H_2 becomes larger than 10^{14} cm^{-2}, the self-shielding effect becomes important (e.g., Draine & Bertoldi 1996). The value corresponds to $f_{H_2} \simeq 3 \times 10^{-9}(n_H/100\,\mathrm{cm}^{-3})^{-1}(r_{SF}/100\,\mathrm{pc})^{-1}$. The emission-line diagnostics by Izotov et al. (1999) and Vanzi et al. (2000) indicate that $n_H \sim 500$ cm^{-3} in the star-forming region of SBS 0335–052. With $n_H = 500$ cm^{-3}, the self-shielding value of f_{H_2} is achieved at the age of 10, 5 and 2 Myr for $r_{SF} = 300$, 100 and 30 pc, respectively.

3 DISCUSSION

3.1 Physical conditions of SBS 0335–052

For the dust mass, Dale et al. (2001) derived the value of $M_d = 2400\,\mathrm{M}_\odot$ from blackbody fitting of the observed spectrum of SBS 0335–052. Hunt et al. (2001) derived an upper limit of $10^5\,\mathrm{M}_\odot$ from the extinction. A starburst of age 3×10^6–5×10^7 yr reproduces those values (Fig. 1). This range is consistent with the age observationally determined by Vanzi et al. (2000). For the dust temperature, it is necessary that the radius of the star-forming region be smaller than 100 pc to explain the 80 K component revealed by *ISO* (Dale et al. 2001), although the temperature may be overestimated because of the contamination of the emission from very small grains heated stochastically.

As observational information on the H_2 abundance, near-infrared emission lines are available. The line intensity is dependent on the excitation mechanism and thus the quantity of H_2 is poorly constrained. However, the detection of the H_2 lines (Vanzi et al. 2000) implies that there is an effective mechanism that shields the UV-dissociative photons. The compactness as observed by Hunt et al. (2001) and Dale et al. (2001) may explain the existence of H_2 for this object (Fig. 4) because of the shielding effects.

Finally, we conclude that if the star-forming region of SBS 0335–052 is compact ($r_{SF} \lesssim 100$ pc) and the gas density is large ($n_H \gtrsim 10^3$ cm^{-3}), the low age, the dust amount, the FIR luminosity, dust temperature and H_2 abundance are mutually consistent and explained by our models.

3.2 Implications for high-redshift galaxies

The main conclusion drawn in this Letter is that star formation activity in extremely metal-poor systems can suffer from extinction. Thus, FIR observations of primeval galaxies are important to observe such dust-enshrouded star formation activity.

Our results for the H_2 abundance are interesting in connection with the recent observations of DLAs. There are several DLAs with abundances of dust and H_2 that are observationally derived. Levshakov et al. (2000) assumed equilibrium between the photodissociation of H_2 by the background UV radiation and formation on grains. They suggested that the small dust number density (as low as 10^{-3} times the Galactic value) can account for the observed small molecular fraction ($f_{H_2} \sim 4 \times 10^{-8}$). We have shown that such a low molecular fraction can be due to the dissociation caused by recently formed OB stars. We also have suggested that if the region is compact and dense, the dust produced by SNe II can shield the UV radiation. This can produce a strong correlation between dust amount and H_2 fraction. Indeed, a correlation between the two quantities has been observationally verified. Some DLAs whose depletion is large show molecular fractions up to 0.2 (Ge, Bechtold & Kulkarni 2001). Such high values are possible when dust shielding of the UV radiation field is effective.

ACKNOWLEDGMENTS

We thank L. Vanzi, the referee, for helpful comments that improved this paper very much. We thank K. Omukai and T. T. Takeuchi for useful and frequent discussions. HH was supported by a Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists.

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