DUST-TO-GAS RATIO AND METALLICITY IN DWARF GALAXIES

HIROYUKI HIRASHITA\textsuperscript{1,2}

\textsuperscript{1}: Department of Astronomy, Faculty of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502, Japan

\textsuperscript{2}: Research Fellow of the Japan Society for the Promotion of Science

Feb. 3rd, 1999

email: hirasita@kusastro.kyoto-u.ac.jp

ABSTRACT

We examine dust-to-gas ratio as a function of metallicity for dwarf galaxies [dwarf irregular galaxies (dIrrs) and blue compact dwarf galaxies (BCDGs)]. Using a one-zone model and adopting the instantaneous recycling approximation, we prepare a set of basic equations which describes processes of dust formation and destruction in a galaxy. Four terms are included for the processes: dust formation from heavy elements ejected by stellar mass loss, dust destruction in supernova remnants, dust destruction in star-forming regions, and accretion of heavy elements onto preexisting dust grains. Solving the equations, we compare the result with observational data of nearby dIrrs and BCDGs. The solution is consistent with the data within the reasonable ranges of model parameters constrained by the previous examinations. This means that the model is successful in understanding the dust amount of nearby galaxies. We also show that the accretion rate of heavy element onto preexisting dust grains is less effective than the condensation of heavy elements.

Subject headings: dust, extinction — galaxies: evolution — galaxies: ISM — galaxies: irregular

1. INTRODUCTION

Interstellar dust is composed of heavy elements made and ejected by stars. Dwek & Scalo (1980) demonstrated that supernovae are the dominant source for the formation of dust grains. They also showed that the dust is destroyed in supernova shocks (see also
McKee 1989, Jones et al. 1994, and Jones, Tielens, & Hollenbach 1996). Thus, the dust is formed and destroyed in star-forming galaxies.

Some recent galaxy-evolution models treat the evolution of total dust mass as well as that of metal abundance (Wang 1991; Lisenfeld & Ferrara 1998, hereafter LF98; Dwek 1998, hereafter D98; Hirashita 1999, hereafter H99). The processes of dust formation and destruction by supernovae are taken into account in LF98, in order to explain the relation between dust-to-gas mass ratio and metallicity of dwarf irregular galaxies (dIrrs) and blue compact dwarf galaxies (BCDGs). We can find detailed mathematical formulations to calculate the dust mass in any galactic system in D98, which treats the accretion of heavy elements onto preexisting dust grains in molecular clouds in addition to the processes considered in LF98. The model by D98 is successfully applied to nearby spiral galaxies in H99.

It is suggested in D98 that the accretion process onto preexisting dust grains is not effective in dwarf galaxies because of the absence of dense molecular clouds there. If this is true, it is worth estimating the ineffectiveness quantitatively, by which we can obtain an information about molecular clouds in dwarf galaxies. Direct observations of molecular clouds in some dwarf galaxies have been extensively carried out (e.g., Ohta, Sasaki, & Saitô 1988). However, it is generally difficult to observe extragalactic molecular clouds. Thus, theoretical constraints on the nature of molecular clouds are indispensable for investigations on the star formation processes in extragalactic objects.

In this paper, we examine the relation between dust-to-gas ratio as a function of metallicity by using a set of equations in H99. The model is one-zone (i.e., the spatial distribution of physical quantities within a galaxy is not taken into account) and the instantaneous recycling approximation is applied. The main purpose of this paper is to apply the model to dwarf galaxies (dIrrs and BCDGs). First of all, in the next section, we explain the model equation, through which the dust-to-gas ratio as a function of metallicity is calculated. The result is compared with observational data of dIrrs and BCDGs in §3. We present a summary in the final section.

2. REVIEW OF MODEL EQUATIONS

In order to investigate the dust content in galaxies, H99 derived a set of equations describing the dust formation and destruction processes, based on the models in LF98 and D98. In H99, a simple one-zone model for a galaxy is adopted to extract global properties of galaxies. For the model treating the radial distribution of gas, element, and dust in a
The equation set is written as

\[
\frac{dM_g}{dt} = -\psi + E - W, \tag{1}
\]

\[
\frac{dM_i}{dt} = -X_i\psi + E_i - X_iW, \tag{2}
\]

\[
\frac{dM_{d,i}}{dt} = f_{i\text{in},i}E_i - \alpha f_iX_i\psi + \frac{M_{d,i}(1 - f_i)}{\tau_{\text{acc}}} - \frac{M_{d,i}}{\tau_{\text{SN}}} - \delta f_iX_iW. \tag{3}
\]

(See eqs. [1]–[3] in McKee 1989, eqs. [6]–[8] in LF98 and eqs. [1]–[3] in H99.) Here, \(M_g\) is the mass of gas. The metal is labeled by \(i\) (\(i = \text{O, C, Si, Mg, Fe, ...}\)), and \(M_i\) and \(M_{d,i}\) denote the total mass of the metal \(i\) (in gas and dust phases) and the mass of the metal \(i\) in the dust phase, respectively. The star formation rate is denoted by \(\psi\); \(E\) is the total injection rate of mass from stars; \(W\) is the net outflow rate from the galaxy; \(X_i\) is the mass fraction of the element \(i\) (i.e., \(X_i \equiv M_i/M_g\)); \(E_i\) is the total injection rate of element \(i\) from stars; \(f_i\) is the mass fraction of the element \(i\) locked up in dust (i.e., \(f_i = M_{d,i}/M_i\)). The meanings of the other parameters in the above equations are as follows: \(f_{i\text{in},i}\) is the value of the dust mass fraction in the injected material, in other words, the dust condensation efficiency in the ejecta; \(\alpha\) refers to the efficiency of the dust destruction during star formation [\(\alpha = 1\) corresponds to destruction of only the dust incorporated into the star, and \(\alpha > 1\) (\(\alpha < 1\)) corresponds to a net destruction (formation) in the star formation]; \(\tau_{\text{acc}}\) is the accretion timescale of the element \(i\) onto preexisting dust particles in molecular clouds; \(\tau_{\text{SN}}\) is the timescale of dust destruction by supernova shocks; \(\delta\) accounts for the dust content in the outflow (\(\delta = 0\) means no dust in the outflow, while \(\delta = 1\) indicates that the outflow is as dusty as the interstellar medium).

We should comment on the parameter \(\alpha\) here. Since the protostellar disk forms dust, \(\alpha < 1\) is expected. However, as to the circumstellar dust, the timescale of loss of angular momentum through the Poynting-Robertson effect is much shorter than the lifetime of stars (e.g., Rybicki & Lightman 1979). This means that the formed dust is lost effectively. Thus, we reasonably assume that \(\alpha = 1\) hereafter. The formation of planets also contributes to the loss of the dust.

Here, we adopt the same assumption as LF98 and H99: the instantaneous recycling approximation (Tinsley 1980): Stars less massive than \(m_1\) live forever and the others die 1

---

1In this formalism, we assume that the condensation efficiency in stellar winds is the same as that in supernova ejecta.
instantaneously. This approximation allows us to write \( E \) and \( E_i \), respectively, as

\[
E = \mathcal{R}\psi, \quad (4) \\
E_i = (\mathcal{R}X_i + \mathcal{Y}_i)\psi, \quad (5)
\]

where \( \mathcal{R} \) is the returned fraction of the mass that has formed stars which is subsequently ejected into the interstellar space, and \( \mathcal{Y}_i \) is the mass fraction of the element \( i \) newly produced and ejected by stars. \footnote{\( \mathcal{R} = R \) and \( \mathcal{Y}_i = y(1 - R) \) for the notation in LF98.} \( \mathcal{R} \) and \( \mathcal{Y}_i \) can be obtained using the following formulae (Maeder 1992):

\[
\mathcal{R} = \int_{m_1}^{m_u} (m - w_m)\phi(m)dm, \quad (6) \\
\mathcal{Y}_i = \int_{m_1}^{m_u} mp_i(m)\phi(m)dm, \quad (7)
\]

In equation (6), \( \phi(m) \) is the initial mass function (IMF), and \( m_u \) is the upper mass cutoff of stellar mass. The IMF is normalized so that the integral of \( m\phi(m) \) in the full range of the stellar mass becomes 1. Therefore, \( \phi(m) \) has a dimension of the inverse square of the mass.

In equation (7), \( w_m \) is the remnant mass (\( w_m = 0.7M_\odot \) for \( m < 4M_\odot \) and \( w_m = 1.4M_\odot \) for \( m > 4M_\odot \)) and \( p_i(m) \) is the fraction of mass converted into the element \( i \) in a star of mass \( m \).

Using the above parameters \( \mathcal{R} \) and \( \mathcal{Y}_i \), and assuming that \( W \) is proportional to the star formation rate (\( W = w\psi \)), equations (4)–(3) become

\[
\frac{1}{\psi} \frac{dM_g}{dt} = -1 + \mathcal{R} - w, \quad (8) \\
\frac{M_g}{\psi} \frac{dX_i}{dt} = \mathcal{Y}_i, \quad (9) \\
\frac{M_g}{\psi} \frac{dD_i}{dt} = f_{d,i}(\mathcal{R}X_i + \mathcal{Y}_i) - [\alpha - 1 + \mathcal{R} - \beta_{\text{acc}}(1 - f_i) + \beta_{\text{SN}} - w(1 - \delta)]D_i, \quad (10)
\]

where \( D_i \equiv M_{d,i}/M_g = f_iX_i \), and \( \beta_{\text{acc}} \) and \( \beta_{\text{SN}} \) are, respectively, defined by

\[
\beta_{\text{acc}} \equiv \frac{M_g}{\tau_{\text{acc}}\psi} \quad \text{and} \quad \beta_{\text{SN}} \equiv \frac{M_g}{\tau_{\text{SN}}\psi}. \quad (11)
\]

We can regard \( \beta_{\text{acc}} \) and \( \beta_{\text{SN}} \) as constant in time (§6.2 and §8.4 of D98). We note that the Galactic value shows \( \beta_{\text{SN}} \sim 5 \) (LF98). This value corresponds to \( \tau_{\text{SN}} \sim 10^8 \text{ yr} \), which is consistent with Jones et al. (1994) and Jones, Tielens, & Hollenbach (1996). The relation \( \tau_{\text{acc}} \simeq \tau_{\text{SN}}/2 \) (D98) leads to \( \beta_{\text{acc}} \simeq 2\beta_{\text{SN}} \simeq 10 \).
Combining equations (9) and (10), we obtain the following differential equation of $D_i$ as a function of $X_i$:

$$Y_i \frac{dD_i}{dX_i} = f_{in,i}(RX_i + Y_i) - [\alpha - 1 + R - \beta_{acc} + \beta_{SN} - w(1 - \delta)]D_i - \frac{\beta_{acc}D_i^2}{X_i},$$

(12)

where we used the relation, $f_i = D_i/X_i$.

Here, we take $i = O$ to compare the result with the data in LF98. For further quantification, we need to fix the values of $R$ and $Y_i$ for the traced element ($i = O$). The values are given in LF98. The reason why LF98 chose oxygen as the tracer is as follows: (i) Most of oxygen is produced in Type II supernovae which are also responsible for the shock destruction of dust grains; (ii) oxygen is the main constituent of dust grains. The point (i) means that the instantaneous recycling approximation may be a reasonable approximation for the investigation of oxygen abundances, since the generation of oxygen is a massive-star-weighted phenomenon. In other words, results are insensitive to the value of $m_1$. According to LF98, we put $m_1 = 1M_\odot$ and $m_u = 120M_\odot$. We use a power-law form of the IMF: $\phi(m) \propto m^{-x}$. The Salpeter IMF is assumed; i.e., $x = 2.35$ (Salpeter 1955). According to LF98, $(R, Y_O) = (0.79, 1.8 \times 10^{-2})$ for the Salpeter IMF. After the numerical integration of equation (12) by the Runge-Kutta method, we compare the result with observational data of dwarf galaxies in the next section.

3. APPLICATION TO DWARF GALAXIES

To compare the solution of equation (12) with observational data of dust-to-gas ratio, we make an assumption that total mass of dust is proportional to that of oxygen in the dust phase. In other words,

$$D \equiv \sum_i D_i = CD_O,$$

(13)

where $C$ is assumed to be constant for all galaxies. According to Table 2.2 of Whittet (1992), $C \simeq 2.2$ (the Galactic value).

We compare the solution of equation (12) with the data in LF98 (see also the references therein). The data sets of nearby dIrrs and BCDGs are presented in Tables 1 and 2 of LF98, respectively. The observed dust-to-gas ratio is defined as

$$D^{obs} \equiv M_d/M_{HI}.$$

(14)

where $M_d$ and $M_{HI}$ are the total masses of dust and H I gas, respectively. The dust mass is derived from the luminosity densities at the wavelengths of 60 $\mu$m and 100 $\mu$m observed by
IRAS. The dust mass derived from the far-infrared emission is about an order of magnitude smaller than the value found from the analysis of the interstellar extinction (Fig. 2 of LF98). The presence of cold or hot dust, emitting beyond 100 μm and below 60 μm may be responsible for the discrepancy (LF98). Thus, we should keep in mind that the dust-to-gas ratio adopted here is underestimated in this context. However, since we only take into account the H i gas as the gas content and do not consider H₂ gas, the dust-to-gas ratio is overestimated (by a factor of ~2). To sum up, we should keep in mind the uncertainty of an order of magnitude for the dust-to-gas ratio derived from the observation ($D^{\text{obs}}$).

In the following subsections, we compare $D$ calculated by using equations (12) and (13) with $D^{\text{obs}}$. We focus on the two processes of dust formation: One is the condensation of dust from heavy elements ejected by stars, and the other is the accretion onto preexisting dust grains. The efficiency of the former process is denoted by $f_{\text{in}, O}$ and that of the latter by $\beta_{\text{acc}}$. The latter process is not taken into account in LF98. For the dependences of the relation between dust-to-gas ratio and metallicity on IMF, see LF98 and H99.

3.1. Dependence on $f_{\text{in}, O}$

We present the dependence of the result on the value of $f_{\text{in}, O}$ in Figure 1a, in which the solid, dotted, and dashed lines show the $D$–$X_O$ relation for $f_{\text{in}, O} = 0.1, 0.05$ and 0.01, respectively. The other parameters are fixed to $\alpha = 1$, $\beta_{\text{acc}} = 2\beta_{\text{SN}} = 10$, $\delta = 1$ [i.e., $w(1 - \delta) = 0$]. Figure 1a shows that the larger the efficiency of production of dust from heavy elements is, the larger the dust-to-gas ratio becomes. The data points represent the relations between $D^{\text{obs}}$ and $X_O$ of dIrrs and BCDGs in LF98. The filled and open squares show the data points of the dIrrs and the BCDGs, respectively.

In the limit of $X_O \to 0$, the solution reduces to

$$D_O \simeq f_{\text{in}, O} X_O \quad \text{or} \quad D \simeq C f_{\text{in}, O} X_O.$$  (15)

(See also LF98.) This means that $D$ scales linearly with $f_{\text{in}, O}$ for the extremely low metallicity. Thus, $f_{\text{in}, O}$ can be constrained by low-metal galaxies (see also H99). Equation (15) means that we can constrain the parameter $f_{\text{in}, O}$ by examining the relation between $D_O/X_O$ (the fraction of oxygen in the dust phase) and $X_O$. We show this relation in Figure 1b. The parameter adopted for each line is the same as Figure 1a. We also show the data points of the same sample as Figure 1a, assuming $C = 2.2$ for all the galaxies to convert $D^{\text{obs}}$ into $D_O$. Roughly speaking, our model predicts that $D_O/X_O$ is constant in the range of the dwarf galaxies. This indicates that the low-metal approximation used to derive equation (13) is applicable to dwarf galaxies. Thus, we can directly constrain the parameter
$f_{\text{in}, \text{O}}$ by dwarf galaxies. From the data points in Figure 1b, we see $0.01 \lesssim D_{\text{O}}/X_{\text{O}} \lesssim 0.1$ or $0.01 \lesssim f_{\text{in}, \text{O}} \lesssim 0.1$. We note that this range is consistent with the analyses in H99. However, we should keep in mind the uncertainty of the data as described above in this section.

We also see from Figure 1b that the relation between $D_{\text{O}}$ and $X_{\text{O}}$ becomes nonlinear in the relatively high-metal region ($\log X_{\text{O}} > -3$). The behavior of this nonlinear region depends on $\beta_{\text{acc}}$ or $\beta_{\text{SN}}$ (§3.2).

### 3.2. Dependence on $\beta_{\text{acc}}$

We here investigate the dependence of the solution on $\beta_{\text{acc}}$, which is proportional to the accretion efficiency of heavy elements onto the preexisting dust grains (§2). The resulting $D$-$X_{\text{O}}$ relations for various $\beta_{\text{acc}}$ are shown in Figure 2a. We show the cases of $\beta_{\text{acc}} = 5, 10, 20$ (the solid, dotted, and dashed lines, respectively), where the relation $\beta_{\text{acc}} = 2\beta_{\text{SN}}$ is fixed. The other parameters are set to $f_{\text{in}, \text{O}} = 0.05$ ($\sim$ the center of the range constrained in §3.1), $\alpha = 1$, and $\delta = 1$. The value of $\beta_{\text{acc}}$ is determined by the lifetime of molecular clouds (D98). The value $\beta_{\text{acc}} \sim 10$ corresponds to the accretion timescale of $\sim 10^8$ yr (§2). The increase of $\beta_{\text{acc}}$ means that the accretion of heavy elements onto dust becomes efficient. Thus, for a fixed value for the metallicity, dust-to-gas ratio increases as $\beta_{\text{acc}}$ increases.

We also present an extreme case of $\beta_{\text{acc}} = 0$ and $\beta_{\text{SN}} = 5$ (long-dashed line). In this case, the accretion onto preexisting dust grains is neglected. We were not able to reproduce the observational data of nearby spiral galaxies without taking into account the accretion process (D98; H99). However, the solid and long-dashed lines in Figure 2 show that we cannot judge whether the accretion process is efficient or not because of the little difference between the results with and without the accretion process. Thus, the basic equations of LF98, which do not include the term of the accretion were able to explain the observed relation between dust-to-gas ratio and metallicity. We note that the accretion process is properly considered in D98.

The ineffectiveness of the accretion process is understood as follows. Two processes are responsible for the formation of dust in equation (3): the dust condensation from the heavy elements ejected by stars and the accretion of the heavy elements onto preexisting dust grains. The former is expressed as $f_{\text{in}, i}E_i$ and the latter as $M_{d,i}(1 - f_i)/\tau_{\text{acc}}$ (see eq. (3)). We define the following ratio, $A_i$:

$$A_i \equiv \frac{M_{d,i}(1 - f_i)/\tau_{\text{acc}}}{f_{\text{in}, i}E_i}. \quad (16)$$
If $A_i < 1$, the accretion process is ineffective compared with the dust condensation process. We will show that $A_i < 1$ for the sample dwarf galaxies.

Using the instantaneous recycling approximation, $A_i$ is estimated as

$$ A_i \approx \frac{\beta_{\text{acc}}(1 - f_i)D_i}{f_{\text{in},i}(R_X + Y_i)}. \quad (17) $$

Now we put $i = O$. In Figure 2b, we present the relation between $f_O = D_O/X_O$ and $X_O$. The values of parameters for each line is the same as Figure 2a. This figure shows that we can consider that $1 - f_O \sim 1$. Moreover, in the range in which we are interested here, $D_O \approx f_{\text{in},O}X_O$ (eq. [14]), and $R_X \ll Y_O$ (as long as $\log X_O \lesssim -2$ is satisfied). Thus, $A_O$ can be approximated by

$$ A_O \approx \frac{\beta_{\text{acc}}X_O}{Y_O}. \quad (18) $$

If we put $\beta_{\text{acc}} = 10$, and $Y_O = 10^{-2}$, we obtain $\log X_O \lesssim -3$ for the condition $A_O < 1$. This is consistent with Figure 2b, since the difference between the solid and the long-dashed lines is clear for $\log X_O > -3$. Thus, if $\log X_O > -3$ is satisfied, the dust accretion process is more ineffective than the dust condensation process. Actually, even for $\log X_O \sim -2.5$, the difference is within the typical error of the observed values.

The ineffectiveness of the accretion process results from the low metallicity. Thus, in galaxies with high metallicity, the accretion process becomes important. Indeed, D98 and H99 showed that the process is effective in spiral galaxies, whose metallicity is much larger than the dwarf galaxies (H99).

Since we can reproduce the relation between dust-to-gas ratio and metallicity of dwarf galaxies without considering the accretion process, D98 suggested that the accretion process is not efficient in dwarf galaxies because of the lack of dense molecular clouds. This may be true, but seeing that dIrrs and BCDGs show high star formation efficiency (Sage et al. 1992; Israel, Bontekoe, & Kester 1996), there may be a large amount of dense molecular gas in dwarf irregular galaxies. Indeed, we have shown in Figure 2 that the observed relation can be explained even if the efficiency of the accretion process $\beta_{\text{acc}}$ is as high as that in the spiral galaxies considered in H99.

4. SUMMARY AND DISCUSSIONS

Based on the models proposed by LF98 and D98, we have examined the dust content in dIrrs and BCDGs. The basic equations which describes the changing rate of dust-to-gas
ratio include the terms of dust formation from heavy elements ejected by stars, destruction by supernova shocks, destruction in star-forming regions and accretion of elements onto preexisting dust grains (§2). This accretion process is important in molecular clouds, where gas densities are generally high. The results are compared with the observed values of dIrrs and BCDGs. Though the degeneration of the parameter and observational error makes it impossible to determine each of the parameter precisely, we were able to constrain the parameters to some extent.

The efficiency of dust production from heavy element (denoted by $f_{\text{in,i}}$) can be constrained by the galaxies with low metallicity (§3.1). The reasonable range is $0.01 \lesssim f_{\text{in,i}} \lesssim 0.1$, which is consistent with H99. Thus, it is possible to understand the dust amount in dwarf systems as well as that in spiral systems through the model in this paper.

As for the nearby spiral galaxies, unless we take into account the accretion process of heavy element onto the preexisting dust particles, we cannot explain the observed relation between dust-to-gas ratio and metallicity (D98; H99). For the dwarf galaxies, however, we can explain the data without the accretion process (§3.2). This means that the accretion is not effective for dwarf galaxies. Even if the efficiency of the accretion $\beta_{\text{acc}}$, determined by the lifetimes of molecular clouds (D98), is as high as that in spiral galaxies, the accretion is not effective because of the low metallicity in the dwarf galaxies. Therefore, we cannot attribute the ineffectiveness of the dust accretion process to the lack of molecular clouds.

Finally, we note that our model have satisfied one condition which any model must fulfill: The model has to explain the observation of nearby galaxies. Then, it becomes a matter of concern whether our model can explain the galaxies in the high-redshift Universe. For theoretical modeling of the cosmic dust mass, see, e.g., Edmunds & Phillipps (1997). Observationally, it is interesting that high-redshift galaxies found recently have evidences of dust extinction (Soifer et al. 1998; Armus et al. 1998). The number count of galaxies in the far-infrared and submillimeter wavelengths, where dust reprocesses stellar light, is another interesting theme concerning high-redshift dust (e.g., Takeuchi et al. 1999).

We would like to thank the anonymous referee for useful comments which improved this paper. We are grateful to S. Mineshige for continuous encouragement. We thank H. Kamaya, K. Nakanishi, T. T. Takeuchi and T. T. Ishii for kind helps and helpful comments. This work was supported by the Research Fellowship of the Japan Society for the Promotion of Science for Young Scientists. We fully utilized the NASA’s Astrophysics Data System Abstract Service (ADS).
REFERENCES

Armus, L., Matthews, K., Neugebauer, G., & Soifer, B. T. 1998, ApJ, 506, L89
Dwek, E. 1998, ApJ, 501, 643 (D98)
Dwek, E., & Scalo, J. M. 1980, ApJ, 239, 193
Edmunds, M. G., & Phillipps, S. 1997, MNRAS, 292, 733
Hirashita, H. 1999, ApJ, 510, L99 (H99)
Israel, F. P., Bontekoe, Tj. R., & Kester, D. J. M. 1996, A&A, 308, 723
Jones, A. P., Tielens, A. G. G. M., & Hollenbach, D. J. 1996, ApJ, 469, 740
Jones, A. P., Tielens, A. G. G. M., Hollenbach, D. J., & McKee, C. F. 1994, ApJ, 433, 797
Lisenfeld, U., & Ferrara, A. 1998, ApJ, 496, 145 (LF98)
Maeder, A. 1992, A&A, 264, 105
McKee, C. F. 1989, in IAU Symp. 135, Interstellar Dust, ed. L. J. Allamandola & A. G. G. M. Tielens (Dordrecht: Kluwer), 431
Ohta, K., Sasaki, M., & Saitō, M., 1988, PASJ, 40, 653
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley), 153
Sage, L. J., Salzer, J. J., Loose, H.-H., & Henkel, C. 1992, A&A, 265, 19
Salpeter, E. E. 1955, ApJ, 121, 161
Soifer, B. T., Neugebauer, G., Franx, M., Matthews, K., & Illingworth, G. D. 1998, ApJ, 501, L171
Takeuchi, T. T., Hirashita, H., Ohta, K., Hattori, T. G., Ishii, T. T., & Shibai, H. 1999, PASP, in press
Tinsley, B. M. 1980, Fund. Cosmic Phys., 5, 287
Wang, B. 1991, ApJ, 374, 456
Whittet, D. C. B. 1992, Dust in the Galactic Environment (New York: Institute of Physics Publishing), 52
FIGURE CAPTION

FIG. 1a— The relation between the dust-to-gas ratio ($D_O$) and the oxygen abundance ($X_O$) for various $f_{\text{in},O}$ (the condensation efficiency of dust from oxygen atoms). The data points for dIrrs (filled squares) and BCDGs (open squares) are from LF98. The other parameters are fixed to $\beta_{\text{acc}} = 2 \beta_{\text{SN}} = 10$, $\alpha = 1$, and $\delta = 1$. The solid, dotted, and dashed lines represent different values of $f_{\text{in},O}$ (0.1, 0.05, and 0.01, respectively).

FIG. 1b— The relation between $f_O = D_O/X_O$ (the fraction of oxygen in the dust phase) and $X_O$ (oxygen abundance). The values of the parameters and the meanings of the data points are the same as Fig. 1a.

FIG. 2a— The same as Fig. 1a but for the different parameter sets ($f_{\text{in},O} = 0.05$, $\alpha = 1$, $\delta = 1$ and various $\beta_{\text{acc}}$ and $\beta_{\text{SN}}$). The solid, dotted, and dashed lines represent the cases of $\beta_{\text{acc}} = 2 \beta_{\text{SN}} = 5$, 10, 20, respectively. The long-dashed line shows the case of no accretion process onto the preexisting dust grains ($\beta_{\text{acc}} = 0$ and $\beta_{\text{SN}} = 5$). The data points are identical to Fig. 1a.

FIG. 2b— The same as Fig. 1b but for the parameter sets identical to Fig. 2a. The data points are identical to Fig. 1b.
\[ \log \left( \frac{D_0}{X_0} \right) \]

\[ \log X_0 \]

-3.5 -3 -2.5 -3 -2 -1 0