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Chemical Evolution and Far-Infrared Emission of Galaxies

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Abstract: Infrared (IR) dust emission from galaxies is frequently used as an indicator of star formation rate (SFR). However, the effect of dust-to-gas ratio, or amount of dust, on the conversion law from IR luminosity to SFR has not been considered. In this paper, we present a convenient formula including the effect. In order to obtain the dependence of the dust-to-gas ratio, we extend the formula derived in our previous paper, in which a theoretical formula converting IR luminosity to SFR was derived. That formula was expressed as $\mathrm{SFR}/(M_\odot\ \mathrm{yr}^{-1}) = \{3.3\times10^{-10}(1-\eta)/(0.4-0.2f+0.6\epsilon)\}(L_{\mathrm{IR}}/L_\odot)$, where f is the fraction of ionizing photons absorbed by hydrogen, ϵ is the efficiency of dust absorption for nonionizing photons, η is the cirrus fraction of observed dust luminosity, and L_{IR} is the observed luminosity of dust emission in the 8–1000-μm range. Throughout the current discussion, we construct an algorithm to relate f and ϵ, both of which depend on the dust-to-gas ratio, to the metallicity, by adopting a galactic relation between dust-to-gas ratio and metallicity. Thus, we estimate the metallicity dependence of our formula. We apply the result to the cosmic star formation history and find that the comoving SFR at $z\sim3$ calculated from previous empirical formulae is underestimated by the factor of 4. Finally, we comment on the HII/L2 mission (SPICA).

1. INTRODUCTION

When we want to know the entire evolutionary history of galaxies, it can be estimated from their color and metallicity. The evolution of the color and the metallicity results from the superposition of the successive star formation during the lifetime of the galaxies. Thus, if we wish to reveal the evolution of the galaxies, we always need to estimate the star formation rate (SFR) on a galactic-wide scale. There are many methods to estimate the SFR of galaxies from observational quantities (Kennicutt 1998a). In this paper, we are especially interested in the conversion formulae from Infrared (IR) emission of the galaxies to their SFR. For example, Kennicutt (1998b) estimated SFR from IR luminosity for starburst galaxies. Buat & Xu (1996) adopted an empirical approach by utilizing the observed relation between the ultraviolet (UV) luminosity and the IR luminosity. However, the dependence of the dust-to-gas ratio on the relation between IR luminosity and SFR is not well understood.

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Recently, Inoue, Hirashita, & Kamaya (2000) (hereafter IHK00) derived a theoretical conversion formula from IR luminosity to the SFR by developing a standard model of H II region by Petrosian et al. (1972). The current paper examines the dependence of metallicity and/or dust-to-gas ratio on the conversion factor of IHK00. Fortunately, it is possible for us to perform this, since the effects of the metallicity and the dust-to-gas ratio are well parameterized in their formula. In this paper, we quantitatively examine the importance of the metallicity to our conversion law, the conclusion being that the dependence is not always negligible when we compare SFRs of very young galaxies and those of present galaxies. Another approach to the IR luminosity from a chemical evolution model is described in Takagi et al. (1999), which is based on a spectral synthesis model.

2. SFR FROM IR LUMINOSITY

In this section, we derive the metallicity dependence of the conversion formula by IHK00. It is convenient to define the factor $C_{\rm IR}$ as

$$\mathrm{SFR} = C_{\rm IR} L_{\rm IR}, \tag{1}$$

$$C_{\rm IR} \equiv \frac{3.3\times 10^{-10}(1-\eta)}{0.4-0.2f+0.6\epsilon}\,[M_\odot\ \mathrm{yr}^{-1}\ L_\odot^{-1}]. \tag{2}$$

where f is the fraction of ionizing photons absorbed by hydrogen, ϵ is the efficiency of dust absorption for nonionizing photons, $L_{\rm IR}$ is the observed luminosity of dust in the wavelength range of 8–1000 μm, and η is the cirrus fraction of $L_{\rm IR}$. We focus on the dependence of $C_{\rm IR}$ on the metallicity. The dependence of $C_{\rm IR}$ on the dust-to-gas ratio is included through f and ϵ as described later in this section[1]. Then, using the relation between the dust-to-gas ratio and the metallicity, we will obtain the metallicity dependence of $C_{\rm IR}$. We assume Case B, where the optical depths of the Lyman series are large enough.

2.1 Dependence of f on the Dust-to-Gas Ratio

The dependence of f on the dust-to-gas ratio is obtained from Spitzer (1978, hereafter S78). We define $\tau_{\rm S,d}$ and $\tau_{\rm S,H}$ as the optical depths of the dust and the neutral hydrogen atoms, respectively, for the Lyman-continuum photons over a path length equal to the Strömgren radius $r_{\rm S}$ (see S78 for the definition of $r_{\rm S}$). Since the radius of a dust-free H II region is estimated to be $r_{\rm S}$, it is useful to normalize the length scale by $r_{\rm S}$.

First, we calculate $\tau_{\rm S,d}$ for an H II region. See Hirashita et al. (2000) for the calculation. The numerical value of $\tau_{\rm S,d}$ will be presented later (eq. 5). Next, we estimate the fraction of the ionizing photons absorbed by dust grains. Due to the grain absorption, the size of an H II region is smaller than $r_{\rm S}$. In other words, if we define $y_{\rm i}$ as the ionization radius normalized by $r_{\rm S}$, $y_{\rm i} < 1$. (Without dust grains, $y_{\rm i} = 1$.) A useful relation between $\tau_{\rm S,d}$ and $y_{\rm i}$ is given in Table 5.4 of S78, where $y_{\rm i}$ is estimated from the following expression (eq. 5.29 of S78):

$$3\int_0^{y_{\rm i}} y^2 e^{y\tau_{\rm S,d}}\,\mathrm{d}y = 1. \tag{3}$$

Using $y_{\rm i}$, the fraction of the ionizing photons absorbed by hydrogen, f, is expressed as

$$f = y_{\rm i}^3. \tag{4}$$

[1] Although $(1-\eta)$ may depend on the dust-to-gas ratio, it is difficult to determine the dependence. Then, in this paper, we focus our attention on only f and ϵ.

This is the same as f in equation (2).

Of course, when we consider the dependence of f on the dust-to-gas ratio, uncertainty exists: The number of ionizing photons per H II region is unknown, since the typical number and mass function of OB stars in an H II region is difficult to determine exactly. Fortunately, for our aim to find the dependence of $\mathcal{D}$ on SFR, this is resolved by calibrating the "Galactic" f with the value of Orion Nebula (Petrosian et al. 1972). According to them, $f = 0.26$ in the Nebula. They also commented that the value explains the typical infrared-to-Lyα (Lyman α) luminosity ratio of Galactic H II regions. Adopting $f = 0.26$ for the typical value of the Galaxy, we obtain $\tau_{\mathrm{S,d}} = 2.7$ for the typical Galactic H II regions. Hence we write

$$\tau_{\mathrm{S,d}} = 2.7\left(\frac{\mathcal{D}}{6\times 10^{-3}}\right), \tag{5}$$

so that $\tau_{\mathrm{S,d}} = 2.7$ for the Galactic dust-to-gas ratio ($\mathcal{D} \sim 6\times 10^{-3}$). If we assume $n_{\mathrm{H}} = 10^2\ \mathrm{cm}^{-3}$, $N_{\mathrm{u}} \simeq 3.0\times 10^{49}\ \mathrm{s}^{-1}$ to be consistent with equation (5). Here, we note that the net effect of the mass function and number of OB stars is included in equation (5) by adopting a set of reasonable normalizations. This simplicity is meaningful for our motivation which is to find the dependence of $\mathcal{D}$ on C_{IR}. Combining equation (5) with equation (3), indeed, we obtain f as a function of $\mathcal{D}$.

2.2 Dependence of ϵ on the Dust-to-Gas Ratio

In IHK00, ϵ is defined by

$$\epsilon \equiv 1 - e^{-\tau_{\mathrm{nonion}}}, \tag{6}$$

where τ_{nonion} is the mean optical depth of dust for nonionizing photons. That is, ϵ represents the efficiency of the dust absorption averaged for nonionizing UV and visible photons. IHK00 estimated $\epsilon = 0.9$ ($\tau_{\mathrm{nonion}} = 2.3$) from the averaged visual extinction of Usui et al. (1998)'s sample ($A_V \sim 1$ mag) and the Galactic extinction curve between 1000 Å and 4000 Å by Savage & Mathis (1979). This wavelength range is wide enough for our purpose, since most of the nonionizing photons from OB stars are emitted at wavelengths much shorter than 4000 Å.

It is obvious that τ_{nonion} depends on the dust-to-gas ratio. If the column density of gas contributing to the absorption of nonionizing photons is fixed, τ_{nonion} is proportional to the dust-to-gas ratio. Since we are interested in the dependence of $\mathcal{D}$ on SFR, we simply express the relation $\tau_{\mathrm{nonion}} \propto \mathcal{D}$. Here, we determine the numerical value of τ_{nonion} as

$$\tau_{\mathrm{nonion}} = 2.3\left(\frac{\mathcal{D}}{6\times 10^{-3}}\right), \tag{7}$$

so that τ_{nonion} becomes 0.92 for the Galactic dust-to-gas ratio. By combining equations (6) and (7), we obtain ϵ as a function of $\mathcal{D}$.

2.3 Cirrus Fraction

The fraction of the cirrus component, η, remains to be determined. In this paper, an empirical value of η is simply adopted. According to Lonsdale Persson & Helou (1987), $\eta \sim 0.5$–0.7 for their sample spiral galaxies, we use $\eta = 0.5$ as adopted in IHK00 (the averaged value for Usui et al. 1998's sample) for the current estimate for our SFR or C_{IR}. We need to find the variation of the cirrus fraction owing to that of $\mathcal{D}$. However, it is very difficult for us to determine it reasonably. Hence, as only a first step, we adopt a constant η. This means that we assume a universal η for all galaxies. Unfortunately, this assumption of $\eta = 0.5$ breaks if we are interested in the starburst galaxies. When we examine the sample of starburst galaxies, indeed, it is reasonable to assume $\eta = 0.0$ (e.g. IHK00). Here, we only comment that ambiguity of the factor 2 or 3 on SFR exists owing to the assumption of $\eta = 0.5$.

2.4 Dependence of $C_{\rm IR}$ on the Dust-to-Gas Ratio

In the above subsections, we have expressed f and ϵ as functions of the dust-to-gas ratio of $\mathcal{D}$, while η is treated as a constant. We also assume a typical star-forming region where mean density is about 10^2 cm^{-3} and production rate of ionizing photons is about 3.0×10^{49} s^{-1}. Then, we can express $C_{\rm IR}$ defined in equation (2) as a function of the dust-to-gas ratio. In Figure 1, we present $C_{\rm IR}$ as a function of $\mathcal{D}$, where we adopt $\eta = 0.5$ (§2.3). From this figure, we find that the coefficient of the conversion from IR light to SFR becomes about 4 times smaller for $\mathcal{D} \sim 6 \times 10^{-3}$ (the Galactic value) than that for $\mathcal{D} \sim 6 \times 10^{-5}$ (0.01 times the Galactic value).

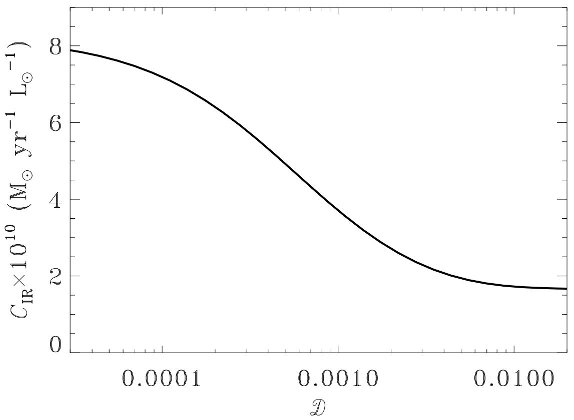

Fig. 1: $C_{\rm IR}$ (conversion coefficient from the dust luminosity to the star formation rate) as a function of the dust-to-gas ratio, $\mathcal{D}$.

3. METALLICITY DEPENDENCE

In order to obtain the metallicity dependence of $C_{\rm IR}$ (eq. 2), which depends on the dust-to-gas ratio as shown in the previous section, we must relate $\mathcal{D}$ and the metallicity. Here, we adopt the latest relation proposed in Hirashita (1999a, b). He constructed a new evolutionary model of dust in the galactic environment, emphasizing the importance of the dust growth via the accretion of metal elements in the cool and neutral components of interstellar medium (ISM). Then, his relation between $\mathcal{D}$ and metallicity explained the observational relation for both the giant and dwarf galaxies. Here, we present that well-fitting model[2] by Hirashita (1999a, b)

[2] As for the parameters in Hirashita (1999a, b), we choose the values as $f_{\rm in,\,O} = 0.1$ and $\beta_{\rm acc} = 2\beta_{\rm SN} = 10$.

in Figure 2, where the observational data are also shown. We adopt this line as the relation between the dust-to-gas ratio and the metallicity.

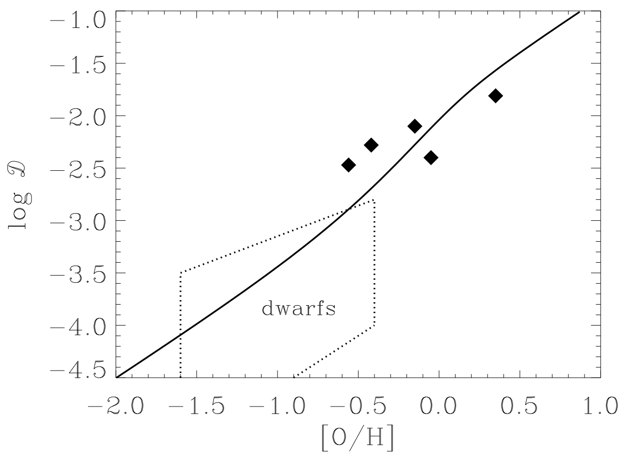

Fig. 2: Relation between the dust-to-gas ratio $\mathcal{D}$ and oxygen abundance [O/H]. The solid line represents the well-fitted model by Hirashita (1999a, b). The observed relations for nearby spiral galaxies are presented with the square Issa et al. (1990). The area marked with dwarfs represents a typical locus of dwarf irregular galaxies and blue compact dwarf galaxies (Lisenfeld & Ferrara 1998).

Once we accept the relation in Figure 2, we relate $C_{\rm IR}$ and [O/H] by using the relation between the dust-to-gas ratio and $C_{\rm IR}$ (Figure 1). Here, we note that [O/H] $= x$ means that the abundance of oxygen is 10^x times the solar value. The relation between $C_{\rm IR}$ and [O/H] is presented in Figure 3. We see that if [O/H] in the ISM evolves from -2 to 0 via chemical evolution, the coefficient of the conversion from IR light to SFR becomes about 4 times smaller.

Now let us remember that $\eta = 0.5$ is assumed. In the beginning of a galaxy's evolution, we can expect a starburst phase. In such a situation, $\eta = 0.0$ may be reasonable. Thus, the conversion factor of $C_{\rm IR}$ can be estimated as 1.6×10^{-9} during the starburst era of galaxies. Since $C_{\rm IR}$ with $\eta = 0.5$ is accepted for moderate phases of star formation at the present epoch, the increment of $C_{\rm IR}$ for starburst galaxies with low metallicity is about ten. Thus, we should never forget the ambiguity via the assumption of a constant η. For this point to be resolved, we should model the dependence of $(1-\eta)$ on $\mathcal{D}$. Unfortunately, with our current knowledge, it seems to be impossible to construct a physically reasonable model. Therefore, we only comment that the evolution model of $(1-\eta)$ along $\mathcal{D}$ or metallicity is a very challenging problem.

4. COMMENTS ON COSMIC STAR FORMATION HISTORY

One of the observational tests for scenarios of structure formation in the Universe is to determine the cosmic star formation history. The cosmological evolution of SFR is derived from the comoving density of galactic light. For example, Madau et al. (1996) applied the conversion formula from UV light to the SFR and showed that the SFR as a function of the redshift z seems to have a peak at $z \sim 1$–2. The diagram has been revised and discussed by

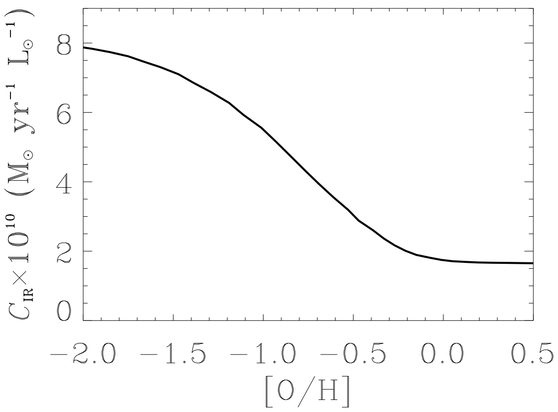

Fig. 3: $C_{\rm IR}$ (conversion coefficient from the dust luminosity to the star formation rate) as a function of the oxygen abundance, [O/H].

many authors (e.g. Steidel et al. 1999), commonly referred to as the Madau plot.

The cosmic SFR at $z \sim 3$ has been investigated extensively. Meurer et al. (1999) estimated the UV luminosity density corrected for the dust absorption at $z \sim 3$. The cosmic SFR at $z \sim 3$ is also determined from the dust-emission at the sub-millimeter (sub-mm) observational wavelength (Hughes et al. 1998; Barger et al. 1998). Observations of the dust emission have an importance that the absorbed light by the dust grains in the UV–visible range is "recovered" in the longer wavelength range. We can convert the sub-mm light to the SFR along the similar way proposed in IHK00. If we take into account the chemical evolution of galaxies on a cosmological timescale, we must examine the increment of metallicity on the conversion formula, which is mainly introduced via f and ϵ. In this paper, then, we have re-formulated the conversion law of IHK00.

According to such a motivation, we apply the results obtained in the previous sections, especially Figure 3 and its related discussions, to the cosmic star formation history. We focus on the evolution of $C_{\rm IR}$ along the metal enrichment history. As known very well, the conversion from metallicity to z is not uniquely determined. As a first step, however, we consider the evolution of our conversion law along the metal enrichment with the aid of previous research which determined the metallicity as a function of z.

In order to determine the effect of the cosmic star formation history on the metal enrichment, we adopt Pei et al. (1999) as a recent modeling of the cosmic chemical evolution. That is, we assume the evolution of metallicity as shown in the second column of Table 1. They modeled the evolution of dust amount as well as metallicity and considered the absorption and reprocessing of light by dust. They corrected the extinction in the Madau plot by using their model. Though their treatment of the evolution of the dust-to-gas ratio is not just the same as our treatment, for readers' convenience, we present a relation between the metallicity and the redshift z from their Figure 8. A consistent model is needed if we translate exactly the evolution of $C_{\rm IR}$ along the metallicity to that along z in the future.

We also present $C_{\rm IR}$ in the third column of Table 1. Here, we convert the metallicity (the second column of Table 1) by using the relation derived in §3 (see also Figure 3). In the

Table 1: Metallicity and C_{IR} as functions of z.

z	$\log(Z/Z_\odot)$	C_{IR} $[M_\odot\ \mathrm{yr}^{-1}\ L_\odot^{-1}]$
0.0	0.00	2.0×10^{-10}
0.5	-0.22	2.7×10^{-10}
1.0	-0.48	4.0×10^{-10}
2.0	-1.02	6.5×10^{-10}
3.0	-1.50	7.6×10^{-10}
4.0	-1.79	7.9×10^{-10}
5.0	-1.88	8.0×10^{-10}

conversion, we assume that $\log(Z/Z_\odot) = [\mathrm{O/H}]$. From Table 1, we see that the factor C_{IR} is about 4 times larger at $z \sim 3$ than that at $z \sim 0$. Thus, we should carefully consider the chemical evolution of galaxies if we determine the cosmic star formation history from the dust emission within the accuracy of factor of 4. Our formulation in this paper will be useful in the conversion from the comoving luminosity density in the IR–sub-mm range to the comoving SFR density.

Finally, we should mention that Pei et al. (1999)'s model treats averaged quantities for each redshift and focuses only on the redshift dependence. Thus, our Table 1 must be applied to the data averaged for each z. In other words, we should not apply them to each individual galaxy at z. For each galaxy, Figure 3 should be used instead after their metallicity is known.

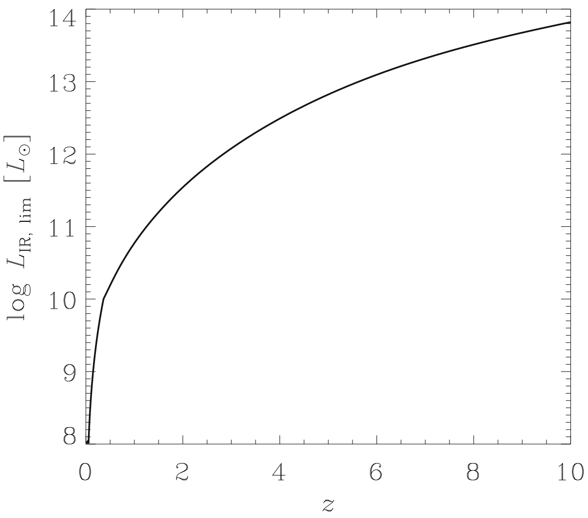

Fig. 4: Minimum of the detected IR luminosity as a function of z. The detection limit of HII/L2 is applied.

5. COMMENT ON THE HII/L2 MISSION

So far, extragalactic source counts in the mid-IR to far-IR wavelengths are determined by mainly IRAS and ISO. In the near future, further development in those wavelengths is expected owing to various projects. Thus, the cosmic SFH will be determined in the near future. This paper will be developed to contribute to the future projects.

If we adopt a 100-μm band, the HII/L2 mission (SPICA) will detect galaxies whose luminosity is greater than $L_{\rm IR,\,lim} \sim 3 \times 10^{10} L_\odot$ at $z \sim 1$ as shown in Figure 4. In calculating $L_{\rm IR,\,lim}$, we adopt the model spectra by Takeuchi et al. (1999) and the detection limit is set as 1 mJy (Nakagawa et al. 1998). This luminosity is within the range of the normal spiral galaxies. Hence, we obtain the sample of normal galaxies with the data of $L_{\rm IR}$. If we observe their metallicity, we will obtain all the information that is needed to reveal the SFR at $z \sim 1$. SFR at higher redshifts can also be estimated with more infrared-luminous galaxies. Here, we should note that the SFR should be derived in a way consistent with the chemical evolution of the Universe, since the conversion formula from IR luminosity to the SFR depends on metallicity. We note that the observation at the wavelength as long as possible in the sub-mm range is favorable for the redshifted spectrum at $z \sim 1$.

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