Evolution of Cosmic Molecular Gas Mass Density from $z \sim 0$ to $z = 1$–1.5

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Abstract

We try to constrain the cosmic molecular gas mass density (CMGD) at $z = 1 - 1.5$ and that in the local universe by combining stellar mass functions of star-forming galaxies and their average molecular gas mass fractions against the stellar mass. The average molecular gas mass fractions are taken from recent CO observations of star-forming galaxies at the redshifts. The CMGD is obtained to be $\rho_{\text{HI}} = (6.8 - 8.8) \times 10^7 \ M_\odot \ \text{Mpc}^{-3}$ at $z = 1 - 1.5$ and $6.7 \times 10^7 \ M_\odot \ \text{Mpc}^{-3}$ at $z \sim 0$ by integrating down to 0.03 $M^*$. Although the values have various uncertainties, the CMGD at $z = 1 - 1.5$ is about 10 times larger than that in the local universe. The cosmic star formation rate density (CSFRD) at $z \sim 1 - 2$ is also about 10 times larger than that in the local universe. Our result suggests that the large CMGD at $z = 1 - 1.5$ accounts for the large CSFRD at $z \sim 1 - 2$.

Key words: galaxies: ISM – galaxies: star formation – galaxy: evolution

1. Introduction

Cosmic star formation rate density (CSFRD) at $z \sim 1 - 2$ is considered to be about 10 times larger than that in the present-day universe (e.g., Lilly et al. 1996; Madau & Dickinson 2014), i.e., galaxies were forming stars about 10 times more active on average at that epoch. What is the cause for this large CSFRD? Since stars form in molecular clouds in galaxies, a simple explanation for this is due to a large cosmic molecular gas mass density (CMGD) at the redshift. Another possible cause is a large star formation efficiency at the epoch. Thus, revealing the CMGD is important to understand the evolution of CSFRD. Based on a semianalytic model, Lagos et al. (2011) and Popping et al. (2014) calculated the cosmological evolution of the CMGD. They showed that the CMGD is 5–8 times larger at $z \sim 1 - 2$ than at $z \sim 0$. However, the molecular gas mass depends on prescriptions (such as pressure based, metallicity based) to evaluate the molecular gas mass fraction among various phases of the gas. Hence, observational constraints are desirable.

In order to assess the CMGDs at these redshifts, the most straightforward way would be to derive the molecular gas mass function in the local universe and at $z \sim 1 - 2$ and to integrate them. The molecular gas mass in a galaxy can be derived from its CO(1–0) luminosity. For the local universe, the measurements of the CMGD were made using CO(1–0) luminosity (e.g., Keres et al. 2003; Obreschkow & Rawlings 2009). Using a far-IR- and a B-band-selected sample of galaxies included in the Five College Radio Astronomy Observatory Extragalactic CO survey, Keres et al. (2003) derived a CO luminosity function and a CMGD by adopting a constant CO-to-H$_2$ conversion factor. Obreschkow & Rawlings (2009) applied a variable CO-to-H$_2$ conversion factor (depending on CO luminosity and B-band luminosity) to the CO luminosity function by Keres et al. (2003).

For normal star-forming galaxies at $z \sim 1 - 2$, CO observations of them have been very time-consuming and have been hard to achieve. Such an attempt was made by Walter et al. (2014) in the form of a blank sky survey in the Hubble Deep Field North using the IRAM Plateau de Bure interferometer (PdBI); they obtained CO luminosity functions at $z = 0.34$ (CO(1–0)), 1.52 (CO(2–1)) and 2.75 (CO(3–2)) and derived the CMGD at each redshift. Although they depicted the cosmological evolution of the CMGD, the uncertainty is very large, due to a small number of galaxies from which CO emission lines are detected. More recently, Decarli et al. (2016a) conducted a spectroscopic survey with the Atacama Large Millimeter/submillimeter Array (ALMA) in the Hubble Ultra Deep Field, and the situation is improved.

As an alternative approach to the CMGD, Berta et al. (2013) derived the molecular gas mass in main-sequence galaxies at $z = 0.2 - 3.0$ by using a correlation of molecular gas mass and star formation rate (SFR). But this approach does not fit to our motivation in this study.

The molecular gas mass in a star-forming galaxy can also be derived from the dust mass in the galaxy, by assuming that a gas-to-dust ratio obtained in the local universe can be applied to high-redshift galaxies. However, the possibility that the gas-to-dust ratio at $z \sim 1 - 2$ is several times larger than that in the local universe at the same gas metallicity is pointed out by Seko et al. (2016a, 2016b), though Berta et al. (2016) claim that such evolution is not seen. In this study, considering the possibility of the evolution of gas-to-dust ratio, we derive the molecular gas mass without using the dust mass.

In this study, we take another approach to estimate a CMGD: we combine the average gas mass fraction against stellar mass and the stellar mass function (SMF) of star-forming galaxies. Although the molecular gas mass fractions in CO-detected star-forming galaxies have been individually derived, the fractions tend to be biased toward more active star-forming galaxies with a high specific SFR and gas mass fraction. Thus, unbiased average gas mass fractions against the stellar mass of star-forming galaxies are needed. Thanks to the recent large CO surveys, the average gas mass fraction against the stellar mass of star-forming galaxies at $z \sim 0$ and $z \sim 1 - 2$ has been unveiled. Saintonge et al. (2011a) and Boselli et al. (2014) revealed the molecular gas masses of a few hundred local star-forming galaxies. Tacconi et al. (2010, 2013) studied the molecular gas masses in main-sequence star-forming galaxies at $z \sim 1 - 2.5$ with the IRAM PdBI and showed that the average molecular gas mass fraction increases with decreasing stellar mass. Seko et al. (2016a) have studied the average molecular gas mass in main-sequence galaxies at $z \sim 1.4$ with...
ALMA and extended the trend to the lower stellar mass galaxies.

In this paper, although the average molecular gas mass fraction against stellar mass may still have an uncertainty, nevertheless we try to constrain the CMGD at $z \sim 1 - 1.5$, as well as that in the local universe, adopting this new approach mentioned above. In Section 2, we describe the molecular gas mass fraction and its dependence on the stellar mass, as well as the SMF of star-forming galaxies. Then in Section 3, we present the resulting CMGDs obtained by combining these data and describe their uncertainties. In Section 4, we compare the results with the recent studies and model predictions and discuss implications. As in Madau & Dickinson (2014), the initial mass function (IMF) we use here is the Salpeter IMF with an upper and lower mass of $100 M_\odot$ and $0.1 M_\odot$, respectively. The stellar mass, SFR, and molecular gas mass fraction $f_{mol} = M_{mol}/M_{star}$ that appear below are corrected to those with the Salpeter IMF: $M_{\text{Salpeter}}$ (or SFR$_{\text{Salpeter}}$) = $1.7 \times M_{\text{Chabrier}}$ (or SFR$_{\text{Chabrier}}$). We adopt cosmological parameters of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$.

2. Average Molecular Gas Mass Fraction and SMF

2.1. Average Molecular Gas Mass Fraction against Stellar Mass

Tacconi et al. (2010, 2013) used a sample of main-sequence star-forming galaxies with $M_{star} \geq 4.3 \times 10^{10} M_\odot$ and SFR $\geq 50 M_\odot$ yr$^{-1}$ at $z = 1 - 1.5$ (50 galaxies) observed with IRAM PdBI. The molecular gas masses were derived by adopting the CO(3–2) (CO(2–1)) to CO(1–0) luminosity ratio of 0.5 (0.6) and the CO-to-H$_2$ conversion factor of 4.36 $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. They also derived the molecular gas mass fraction against the stellar mass for which CO emission is significantly detected. Since the CO-detected sample biases to higher specific SFR, they derived the average molecular gas mass fraction in a stellar mass bin by correcting for the specific SFR of observed galaxies. The resulting gas mass fraction at $z = 1 - 1.5$ ranges from $\sim 0.14$ at $M_{star} \sim 3 \times 10^{10} M_\odot$ to $\sim 0.34$ at $M_{star} \sim 6 \times 10^{10} M_\odot$.

Seko et al. (2016a) used a sample of 18 randomly selected main-sequence star-forming galaxies at $z \sim 1.4$. The stellar mass and SFR covered are $M_{star} \geq 4.0 \times 10^9 M_\odot$ and SFR $\geq 20 M_\odot$ yr$^{-1}$, respectively, expanding to the lower stellar mass. Further, the gas metallicity of the target galaxies was obtained with the N2 method (Yabe et al. 2012, 2014). CO(5–4) observations were made with ALMA. The molecular gas mass was derived by adopting the CO(5–4) to CO(1–0) luminosity ratio of 0.23 based on observations of main-sequence star-forming galaxies (sBzK) of $z = 1.5$ by Daddi et al. (2015) and the metallicity-dependent CO-to-H$_2$ conversion factor (Equation (7) by Genzel et al. 2012). To obtain the average value of the fraction at a stellar mass bin, Seko et al. (2016a) performed a stacking analysis including non-CO-detected sample galaxies. The fraction amounts to $\sim 0.72$ at the lowest stellar mass bin of $2 \times 10^{10} M_\odot$.

For the local star-forming galaxies, several surveys were conducted. The CO Legacy Database for Galex Arcsecio SDSS Survey (COLD GASS; Saintonge et al. 2011a) measured the CO(1–0) luminosity for a sample of 350 nearby galaxies ($M_{star} \geq 1.7 \times 10^{10} M_\odot$) using the IRAM 30 m telescope. The CO(1–0) line was detected toward 222 galaxies, and they derived the molecular gas mass and its fraction against the stellar mass by adopting the CO-to-H$_2$ conversion factor of $3.2 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. The CO-detected galaxies are likely to consist mostly of late-type galaxies, by considering their distributions in color, concentration, and stellar mass surface density (Saintonge et al. 2011a); they are considered to be main-sequence galaxies. The average gas mass fraction among the galaxies in a stellar mass bin ranges from 0.03 to 0.06; a slight tendency that the fraction increases with decreasing stellar mass is seen.

In the Herschel Reference Survey (HRS; Boselli et al. 2014), they extended to lower stellar mass ($M_{star} \geq 1.7 \times 10^9 M_\odot$). They also measured the CO(1–0) luminosity for a sample of 225 galaxies consisting of 57 E–S0a-type galaxies and 168 Sa–Iml–BCD-type galaxies. The detection rate is very low for early-type galaxies (16%) and high for late-type galaxies (80%). They derived the molecular gas mass and its fraction against the stellar mass by adopting the CO-to-H$_2$ conversion factor of $3.6 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. The fraction is 0.19 at $M_{star} \sim 2.4 \times 10^9 M_\odot$. There is the same tendency as seen in Saintonge et al. (2011a), that the fraction increases with decreasing stellar mass.

The gas mass fractions against the stellar mass are summarized in Figure 1. Since different CO-to-H$_2$ conversion factors are used to derive the molecular gas mass in the data mentioned above, we recalculated them by adopting the metallicity-dependent CO-to-H$_2$ conversion factor by Leroy et al. (2011, their Figure 6) and Genzel et al. (2012) at $z \sim 0$ and $z = 1 - 1.5$, respectively. (Hereafter, we do not include the helium in the molecular gas mass.) To do this, we estimated the gas metallicity from the mass–metallicity relation at $z \sim 0.1$ by Erb et al. (2006, their Figure 3) and at $z \sim 1.4$ by Yabe et al. (2014) to use the same metallicity calibration.

![Figure 1. Gas mass fraction ($f_{mol} = M_{mol}/M_{star}$) against stellar mass. For all sample data, we corrected to the Salpeter IMF and adopted the metallicity-dependent CO-to-H$_2$ conversion factor by Leroy et al. (2011) and Genzel et al. (2012) at $z \sim 0$ and $z = 1 - 1.5$, respectively. Filled blue squares refer to the average values for the star-forming galaxies at $z = 1 - 1.5$ by Tacconi et al. (2013). Filled blue circles refer to the results of the stacking analysis by Seko et al. (2016a). Filled red squares and circles refer to the average values in local star-forming galaxies by Saintonge et al. (2011a) and Boselli et al. (2014), respectively. Solid lines represent the best-fit function by Popping et al. (2012) (Equation (1)). Shaded regions show the fitting uncertainty based on random realization of the data points.](image-url)
Using these data, we fit the relation with the following function by Popping et al. (2012):

$$f_{\text{mol}}(M_{\text{star}}) = \frac{M_{\text{mol}}}{M_{\text{star}}} = \frac{1}{\exp((\log M_{\text{star}} - A)/B)}, \quad (1)$$

where $A$ and $B$ are constant parameters. This function was designed to match the molecular gas mass fractions against the stellar mass at $0.5 < z < 1.7$ and local data including Saintonge et al. (2011a). The best-fit values are $(A, B) = (6.43, 1.36)$ and $(A, B) = (10.24, 0.51)$ at $z \sim 0$ and $z = 1 - 1.5$, respectively. Note that the original function form is for the fitting to the gas mass fraction of $M_{\text{mol}}/(M_{\text{mol}} + M_{\text{dust}})$ and does not exceed 1.0. Uncertainties ($1\sigma$) of the best-fit functions are shown as the shaded region in Figure 1. We derived the uncertainties by random realizations of the data points according to their errors.

### 2.2. Stellar Mass Function of Star-forming Galaxies

We use the SMFs at $z = 1 - 1.5$ by Tomczak et al. (2014, T14) and Mourtos et al. (2015, M15). At $z \sim 0$, we adopt the SMF of star-forming galaxies by Moustakas et al. (2013). The SMFs are also corrected for the IMF difference.

T14 derived galaxy SMFs over a redshift range of $0.2 < z < 3$ using $\sim 13,000$ galaxies from the FourStar Galaxy Evolution Survey obtained in the Chandra Deep Field South, the Cosmic Evolution Survey, and the Hubble Ultra Deep Field. T14 derived the SMF down to about 1 dex lower stellar mass than those of the previous studies at $0.2 < z < 3$. T14 reached a stellar mass of $6.3 \times 10^8 M_\odot$ at $z = 1 - 1.5$. They separated the full galaxy sample into star-forming and quiescent populations based on a rest-frame $U - V$ versus $V - J$ diagram and then derived the SMF for respective populations. They fitted the SMFs with a double-Schechter function as

$$\Phi(M) dM = e^{-M/M^*} \left[ \Phi_1 \left( \frac{M}{M^*} \right)^{\alpha_1} + \Phi_2 \left( \frac{M}{M^*} \right)^{\alpha_2} \right] dM/M^*, \quad (2)$$

where $M^*$ is the characteristic stellar mass. We derived an SMF of star-forming galaxies at $z = 1 - 1.5$ by combining the best-fit double-Schechter SMFs at $z = 1.0 - 1.25$ and 1.25 - 1.5 (their Table 2).

M15 derived SMFs over a similar redshift range ($0.3 < z < 3.0$) using a combination of the UK Infrared Telescope Infrared Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS), Cosmic Assembly Near-infared Deep Extra-galactic Legacy Survey (CANDELS) UDS and CANDELS the Great Observatories Origins Deep Survey-South (GOODS-S) survey data sets. M15 reached a stellar mass of $3.2 \times 10^8 M_\odot$ at $z = 1 - 1.5$. They selected SF galaxies based on UV classification (contamination by SF galaxies in a quiescent population is estimated to be on average $\sim 2\%$ by using 24 $\mu$m data) and derived an SMF of star-forming galaxies at $z = 1.0 - 1.5$ and fitted with the single-Schechter function. The uncertainties on the SMFs of T14 and M15 include the uncertainties of the UV classification (i.e., contamination due to the color classification), the uncertainties in the SED modeling, the Poisson uncertainties, and cosmic variance.

Moustakas et al. (2013) derived an SMF of nearby galaxies ($z = 0.01 - 0.2$) using $\sim 170,000$ galaxies from the Sloan Digital Sky Survey (SDSS). The SMF in the local universe reached a stellar mass of $1.7 \times 10^9 M_\odot$. They separated the galaxies into star-forming and quiescent populations based on whether they lie on or below the main sequence in the SFR versus stellar mass diagram. We fitted the single-Schechter function and obtained the following best-fit parameters: $(\log M^*/M_\odot, \alpha, \log \Phi^*) = (11.07 \pm 0.02, -1.30 \pm 0.03, -2.98 \pm 0.04)$.

### 3. Cosmic Molecular Gas Mass Density

Combining the dependence of the molecular gas mass fraction on the stellar mass and the SMF, we derived the CMGD as

$$\rho_{\text{mol}} = \int_{M_{\text{min}}}^{M_{\text{max}}} f_{\text{mol}}(M_{\text{stellar}}) \Phi(M_{\text{stellar}}) dM_{\text{stellar}}, \quad (3)$$

where $\Phi(M_{\text{stellar}})$ is the SMF of star-forming galaxies and $f_{\text{mol}}$ refers to $M_{\text{mol}}/M_{\text{stellar}}$ (Equation (1)).

Since we intend to compare the cosmic evolution of the CMGD with that of the CSFRD, obtaining the molecular gas masses in the galaxies in the same stellar mass range as that for the CSFRD is desirable. Madau & Dickinson (2014) derived the CSFRD by integrating the luminosity function from 0.03 $L^*$, where $L^*$ is the characteristic luminosity of the Schechter function. This does not necessarily correspond to stellar mass exactly. But considering the correlation between SFR and stellar mass, i.e., the main sequence for star-forming galaxies, it would be reasonable to choose $M_{\text{min}}$ as $0.03 M^*$ at each redshift. From the best-fit $M^*$, $M_{\text{min}}$ in the local universe is $3.6 \times 10^9 M_\odot$ and that at $z = 1 - 1.5$ is $1.7 \times 10^9 M_\odot$ (T14) and $2.2 \times 10^9 M_\odot$ (M15). As for $M_{\text{max}}$, we take $10^{12} M_\odot$. 

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**Figure 2.** CMGD (left ordinate) and CSFRD (right ordinate) against redshift. The filled red circle and square refer to the CMGD at $z \sim 1 - 1.5$ by adopting SMFs by T14 and M15, respectively. The filled red triangle refers to the CMGD at $z \sim 0$. The vertical solid error bars only include fitting uncertainties of the gas mass fraction and SMF. Dashed error bars at $z \sim 1 - 1.5$ show the possible systematic uncertainty of the CO luminosity ratio of a factor of 3 (see text). These symbols are slightly shifted in the horizontal direction for clarity. We adopt the metallicity-dependent CO-to-H$_2$ conversion factor. Box frames show the results by Decarli et al. (2016a) based on the CO luminosity function. They adopted the conversion factor of $3.6 M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. The open blue circle and triangle show the results by Kerbes et al. (2003) and Ohnishi & Rawlings (2009), respectively. Kerbes et al. (2003) adopted the conversion factor of 4.8 $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$. Ohnishi & Rawlings (2009) used the CO luminosity function by Kerbes et al. (2003) but adopting the CO-luminosity- and $B$-band-luminosity-dependent conversion factor. Semianalytic model predictions for the CMGD by Popping et al. (2014) and Lagos et al. (2011) are also shown. The green solid curve represents the best-fit CSFRD by Madau & Dickinson (2014).
The resulting CMGD at \( z \sim 0 \) is \( 6.7 \pm 0.3 \times 10^6 M_\odot \) Mpc\(^{-3}\) and that at \( z = 1 - 1.5 \) is \( 8.8 \pm 2.5 \times 10^6 M_\odot \) Mpc\(^{-3}\) (T14) and \( 6.8 \pm 3.4 \times 10^7 M_\odot \) Mpc\(^{-3}\) (M15). The results are shown in Figure 2. The results by adopting T14 and M15 agree with each other within the error. Here the uncertainties (\( \sigma \)) shown with solid error bars to the obtained values are calculated from the uncertainties on the molecular gas mass fraction (Equation (1)) and the SMF; we ran \( 10^4 \) realizations assuming that the error distribution for the best-fit values is Gaussian.

The CMGD at \( z = 1 - 1.5 \) is about 10 times larger than that in the local universe. This seems to imply that the large CSFRD uncertainties on the molecular gas mass fraction (however, many uncertainties in deriving the CMGD other than the fitting error on the molecular gas mass fraction and the SMF: (1) CO luminosity ratio, (2) CO-to-H\(_2\) conversion factor, (3) \( f_{\text{mol}} \) in the low stellar mass range, (4) slope of the main sequence, and (5) contribution from ultraluminous infrared galaxies (ULIRGs). We discuss these uncertainties.

(1) To obtain CO(1–0) luminosity, Seko et al. (2016a) assumed a ratio of 0.23 for CO(5–4) luminosity by Daddi et al. (2015). Daddi et al. (2015) reported that CO(5–4) emissions from three main-sequence galaxies (sBzK) at \( z = 1.5 \) are more excited than that of our Galaxy, but are not as excited as that of M82. Meanwhile, Decarli et al. (2016b) recently found that the J-ladders of \( z = 1 - 1.6 \) star-forming galaxies are more similar to that of our Galaxy.

If the CO J-ladder is similar to that of M82 (e.g., Carilli & Walter 2013), the CO(1–0) luminosity would be lower by a factor of \( \sim 3 \). If the ladder resembles that of our Galaxy, it increases by a factor of \( \sim 3 \). Dashed error bars in Figure 2 show the uncertainty. For the CO(3–2) and CO(2–1) lines, the uncertainties are smaller than this.

(2) If we adopt a metallicity-independent CO-to-H\(_2\) conversion factor of 3.6 \( \lesssim L_{\text{CO}} \sim 1 \) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) (not including helium mass), the CMGD decreases by 23% (T14) and 25% (M15) at \( z = 1 - 1.5 \) and 6% at \( z \sim 0 \).

(3) We extrapolated the molecular gas mass fraction to \( M_{\text{star}} = 1.7 \times 10^9 M_\odot \) at \( z = 1 - 1.5 \) to cover a similar stellar mass range to that used for the derivation of the CSFRD. Saintonge et al. (2013) and Dessauges-Zavadsky et al. (2015) show that the molecular gas mass fractions in lensed star-forming galaxies with a stellar mass of \( 2.5 \times 10^9 M_\odot \leq M_{\text{star}} \leq 1.0 \times 10^{10} M_\odot \) at \( z = 1.5 - 3 \) are \( f_{\text{mol}} \sim 1 - 2 \), supporting our extrapolation. However, the average molecular gas mass fraction in star-forming galaxies with a low stellar mass range may be smaller, because the low metallicity and the low gas column density are likely to suppress formation of the molecular component. Although the CO-to-H\(_2\) conversion factors we used are metallicity dependent, we also calculated the CMGD assuming \( f_{\text{mol}} = 1.0 \) (\( f_{\text{mol}} = 0.0 \)) in \( 1.7 \times 10^9 M_\odot < M_{\text{star}} < 2.0 \times 10^9 M_\odot \). The resulting CMGD is reduced by 25% (44%). Further studies of the gas mass fraction in the low stellar mass range are desirable.

(4) If we consider that the slope of the main sequence is slightly flatter (SFR \( \propto L_{\text{star}}^{0.3} \)), \( M_{\text{min}} \) would be 0.007 \( M_\odot \).

In this case, the resultant CMGD increases by 70%–80% at \( z = 1 - 1.5 \) and by 18% at \( z \sim 0 \), although the uncertainties of the fractions and SMFs are larger than those for the case of 0.03 \( M_\odot \).

(5) SMFs of star-forming galaxies used here do not exclude ULIRGs, but here we discuss the contribution to the CMGD from the ULIRGs. The gas mass fractions of ULIRGs at \( z = 1.4 \)–1.7 by Silverman et al. (2015) are the same order as those of main-sequence galaxies. This can also be seen by comparing the stellar mass versus SFR diagram (e.g., Rodighiero et al. 2011, their Figure 1) and the molecular gas mass versus SFR diagram (e.g., Sargent et al. 2014, their Figure 2). Considering that the stellar mass of ULIRGs is about \( 10^{10} - 10^{11} M_\odot \), the number density of ULIRGs (Goto et al. 2015) is more than 10 times smaller than that of main-sequence galaxies with \( M_{\text{star}} = 10^{10} - 10^{11} M_\odot \) (T14; M15). Hence, the contribution to the CMGD from ULIRGs is expected to be small.

The largest uncertainty seems to be the CO luminosity ratio, and the observations in lower CO transitions are more desirable.

4. Discussion and Summary

The CMGD at \( z = 1 - 1.5 \) obtained here is consistent with the recently derived value based on the CO luminosity function at \( z = 1 - 1.7 \) from Decarli et al. (2016a). They derived the CO(2–1) luminosity function and used the CO emission line J-ladder by Daddi et al. (2015). They also concluded that the CMGD at \( z = 1 - 1.7 \) is 3–10 times larger than that in the present-day universe. The CMGDs by Decarli et al. (2016a) are shown in Figure 2 without correcting for the difference of the CO-to-H\(_2\) conversion factor used. Since they used the constant conversion factor of 3.6 \( M_\odot \) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\), we also use the same factor to directly compare with their results. Resulting values are \( 6.5 \times 10^7 M_\odot \) Mpc\(^{-3}\) (T14) and \( 5.1 \times 10^7 M_\odot \) Mpc\(^{-3}\) (M15), which are in the range of \( (3.4 - 12.3) \times 10^7 M_\odot \) Mpc\(^{-3}\) by Decarli et al. (2016a). It should be noted that the CO luminosity corresponding to our \( M_{\text{min}} \) is close to the lowest CO luminosity used by Decarli et al. (2016a).

The CMGD at \( z \sim 0 \) obtained here is about two times smaller than that by Obreschkow & Rawlings (2009) (\( 1.3 \pm 0.5 \times 10^7 M_\odot \) Mpc\(^{-3}\)), which is also shown in Figure 2. They derived the CMGD using the CO luminosity function by Keres et al. (2003) and adopting the CO-luminosity- and B-band-luminosity-dependent CO-to-H\(_2\) conversion factor. Obreschkow & Rawlings (2009) noted that Keres et al. (2003) overestimated the CMGD, due to the constant CO-to-H\(_2\) conversion factor. Although the CO luminosity corresponding to our \( M_{\text{min}} \) is close to the lowest CO luminosity used by Obreschkow & Rawlings (2009), the CMGD does not agree with that by Obreschkow & Rawlings (2009). The cause for this discrepancy is not clear, but it may be worth noting that if we use \( f_{\text{mol}} \) only by Boselli et al. (2014), the CMGD agrees with that by Obreschkow & Rawlings (2009).

We also show the semianalytic model predictions by Lagos et al. (2011) and Popping et al. (2014) of the CMGD in Figure 2. The model predictions roughly agree with the observational results. However, the increase factor of the gas density from \( z \sim 0 \) is rather smaller than that in this study.
In Figure 2, the best-fit CSFRD evolution by Madau & Dickinson (2014) is also plotted, which has an uncertainty of about 0.2 dex, as seen in their Figure 9. The CSFRD increases by about 10 times from $z \sim 0$ to $z \sim 1.5$ (the contribution from ULIRGs at $z = 1 - 1.5$ is not large [10%-40%]; Casey et al. 2012; Goto et al. 2015). Our results show that the CMGD is also about 10 times larger at $z \sim 1.4$ than at $z \sim 0$. Thus, the large CSFRD at $z = 1 - 2$ is considered to be due to the large CMGD at these redshifts. This would be reasonable if we recall that the SFR is mostly proportional to the molecular gas mass in a star-forming galaxy (e.g., Sargent et al. 2014). This also implies that the star formation efficiency is similar at both epochs on average. Seko et al. (2016a) pointed out that the star formation efficiency ($=\text{SFR/molecular gas mass, or gas depletion time}$) is slightly larger at the higher stellar mass than at the lower mass, in contrast to the trend seen in the local universe (Saintonge et al. 2011b; Boselli et al. 2014). Although the trend is slightly different, the values are similar to each other at a stellar mass of $\sim 2 \times 10^{10} M_\odot$, which is almost the middle of the stellar mass sampled in this study.

In this paper, in order to constrain the CMGD at $z = 1 - 1.5$ and that in the local universe, we combined the average molecular gas mass fraction against the stellar mass and the SMF of star-forming galaxies at these redshifts. By integrating down to $0.03 M_\odot$, the CMGD is derived. The obtained CMGD at $z = 1 - 1.5$ is $(6.8 - 8.8) \times 10^7 M_\odot \text{ Mpc}^{-3}$. Although these values still have various uncertainties, this CMGD at $z = 1 - 1.5$ is about 10 times larger than that in the local universe $(6.7 \times 10^5 M_\odot \text{ Mpc}^{-3})$, implying that the large CSFRD at $z = 1 - 1.5$ is due to the large CMGD. The CMGD at the redshift obtained in this study agrees with that recently obtained from integration of the CO luminosity function, indicating that the approach employed here is effective.

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