

Study of Interstellar Medium in Star-Forming Galaxies at the Violent Epoch of Galaxy Evolution



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Abstract

It is crucial to study properties of interstellar medium (ISM) in star-forming galaxies for understanding galaxy evolution. Especially, the study of ISM at the violent epoch of galaxy evolution, the redshift around 2, is very important to unveil galaxy evolution because galaxies are considered to be evolving dramatically at this epoch.

In order to investigate the properties of ISM at that epoch, we conducted observations of molecular gas and dust in star-forming galaxies at $z \sim 1.4$. Sample galaxies are located on the main-sequence at this redshift and their gas-phase metallicity is measured with the near-infrared spectroscopic observations. Using ALMA, we carried out observations of $^{12}\text{CO}(J = 5 - 4)$ and dust thermal continuum emission toward 20 galaxies which cover the wide ranges of stellar mass and metallicity. Using the Nobeyama 45 m radio telescope, we also made $^{12}\text{CO}(J = 2 - 1)$ observations toward 6 galaxies with near solar metallicity which are clearly detected in mid- and far-infrared.

Masses of molecular gas and its fractions against stellar mass in these main-sequence galaxies at $z \sim 1.4$ are significantly larger than those in local spiral galaxies. The molecular gas mass fraction decreases with increasing stellar mass; the relation holds for galaxies with four times lower stellar mass than that covered in the previous studies, and the molecular gas mass fraction decreases with increasing metallicity. The depletion time tends to decrease with increasing stellar mass and metallicity though the trend is not so significant, which contrasts with the trends in local galaxies. Masses of dust are slightly larger than those in local spiral galaxies. We derived gas-to-dust ratios and found they are 3 – 4 times larger than those in local galaxies.

We constrain the rate of gas inflow into and outflow from a main-sequence galaxy at $z \sim 1.4$ by fitting a simple analytic model for the chemical evolution in a galaxy to the observational data of the stellar mass, metallicity, and molecular gas mass fraction. The best-fit inflow and outflow rates are ~ 1.7 and ~ 0.4 in units of star formation rate (SFR), respectively. The inflow rate is roughly comparable to the sum of the SFR and outflow rate, which supports the equilibrium model for galaxy evolution; i.e., all inflow gas is consumed by star formation and outflow.

Contents

List of Figures	ix
List of Tables	xi
1 Introduction	1
1.1 History of cosmic star-formation rate density	1
1.2 Main sequence of star-forming galaxy	4
1.3 Chemical evolution of star-forming galaxies	7
1.4 Gas flows for galaxy evolution	11
1.5 Studies of interstellar medium in main-sequence galaxies	12
1.5.1 Local galaxies	13
1.5.2 High redshift galaxies	15
1.6 Motivation of this thesis	17
2 Sample & Observations	19
2.1 Sample	19
2.1.1 Near-infrared spectroscopic sample at $z \sim 1.4$	19
2.1.2 Galaxy sample for ALMA	21
2.1.3 Galaxy sample for the Nobeyama radio telescope	23
2.2 Observations	24
2.2.1 Observations with ALMA	24
2.2.2 Observations with Nobeyama radio telescope	26
2.3 Data reductions	26
2.3.1 Reduction for ALMA data	26

2.3.2	Reduction for Nobeyama data	33
3	Molecular gas properties at $z \sim 1.4$	35
3.1	Results of ALMA observations for CO emission lines	35
3.1.1	Individual Galaxy	35
3.1.2	Stacking analysis	38
3.1.3	Relations for subsamples with fixed metallicity and fixed stellar mass	44
3.2	Results of Nobeyama observations	47
3.2.1	CO($J = 2 - 1$) spectra	47
3.2.2	Molecular gas mass and its fraction	48
3.3	Molecular gas mass against SFR, and gas depletion time	49
4	Dust properties and gas-to-dust mass ratio at $z \sim 1.4$	55
4.1	Results of ALMA observations for dust thermal emissions	55
4.1.1	Individual Galaxy	55
4.1.2	Stacking analysis	58
4.2	Dust mass for Nobeyama galaxy sample	60
4.3	Gas-to-dust ratio	61
5	Constraint on the inflow and outflow rates at $z \sim 1.4$	65
5.1	Observational data	65
5.2	Chemical evolution model containing gas flows	67
5.3	Results	69
5.4	Discussion	69
6	Concluding remarks	83
6.1	Summary	83
6.2	Future prospects	86
6.2.1	CO observations with wider range of stellar mass and metallicity at the violent epoch of galaxy evolution	86
6.2.2	Properties of ISM in star-forming galaxies at $z = 0.1 - 1$	87

Acknowledgements	91
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References	96
-------------------	-----------

List of Figures

1.1	Illustration of the model for galaxy evolution.	2
1.2	History of cosmic star formation rate density.	3
1.3	Bimodal distribution of galaxies in a color-color diagram.	5
1.4	Main sequence of star-forming galaxies.	6
1.5	Distribution of Sérsic index in the SFR-stellar mass diagram.	7
1.6	Velocity maps of star-forming galaxies at $z \sim 2$	8
1.7	Evolution of stellar mass-metallicity relation.	9
1.8	Molecular gas-to-stellar mass ratio against stellar mass.	12
1.9	Molecular gas-to-stellar mass ratio against metallicity.	13
1.10	Gas-to-dust mass ratio in nearby galaxies.	15
1.11	Distribution of molecular gas mass fraction in main-sequence galaxies at $z \sim 1.2$ and $z \sim 2.2$	16
2.1	Galaxy sample for observations with ALMA.	20
2.2	Galaxy sample for observations with the Nobeyama 45 m telescope. . .	24
2.3	ALMA result for each galaxy: growth curve of S/N, integrated CO(5 – 4) intensity map, CO(5 – 4) spectrum, and continuum map.	27
2.4	Same as Figure 2.3 but for other galaxies.	28
2.5	Same as Figure 2.3 but for other galaxies.	29
2.6	Same as Figure 2.3 but for other galaxies.	30
2.7	Same as Figure 2.3 but for other galaxies.	31
2.8	Same as Figure 2.3 but for other galaxies.	32
3.1	CO-detected galaxies with ALMA.	36

3.2	CO(5 – 4) luminosity against stellar mass and metallicity.	37
3.3	Molecular gas mass against stellar mass and metallicity.	39
3.4	Molecular gas mass fraction against stellar mass and metallicity.	40
3.5	Stacked integrated CO(5 – 4) intensity maps and line profiles of the subsamples with smaller/larger stellar mass.	41
3.6	Stacked integrated CO(5 – 4) intensity maps and line profiles of the subsamples with lower/higher metallicity.	43
3.7	Molecular gas mass fraction against stellar mass for the subsamples with almost the same metallicity.	45
3.8	Molecular gas mass fraction against metallicity for the subsamples with almost the same stellar mass.	46
3.9	Spectra obtained with the Nobeyama 45 m telescope.	47
3.10	SFR against molecular gas mass.	50
3.11	Depletion time of molecular gas (SFRs from extinction-corrected UV luminosity density).	52
3.12	Depletion time of molecular gas (SFR from total infrared luminosity and extinction-uncorrected UV luminosity density).	53
4.1	Continuum-detected galaxies with ALMA.	56
4.2	Dust mass against stellar mass and metallicity.	58
4.3	Stacked continuum maps.	59
4.4	Gas-to-dust ratio against metallicity.	62
4.5	Gas-to-dust ratio against luminosity density at a rest wavelength of 0.5 mm for galaxies with $12 + \log(\text{O}/\text{H}) > 8.6$	63
5.1	Least χ^2 fitting results.	66
5.2	χ^2 contour map.	68
5.3	Fitting results with the Chabrier IMF for the derivation of stellar masses.	72
5.4	Fitting results for the subsamples with lower/higher metallicity.	73
5.5	Fitting results with the CO luminosity ratio of 0.12.	74
5.6	Fitting results with the CO luminosity ratio of 0.46.	75

5.7	Fitting results with the Galactic CO-to-H ₂ conversion factor.	76
5.8	Fitting results for the subsamples with lower/higher metallicity and using the Galactic CO-to-H ₂ conversion factor.	77
5.9	Fitting results with the assumption of $M(\text{HI}) = 0.5M(\text{H}_2)$	78
5.10	Fitting results with the assumption of $M(\text{HI}) = M(\text{H}_2)$	79
5.11	Fitting results with the assumption of $M(\text{HI}) = 2M(\text{H}_2)$	80
5.12	Fitting results with the assumption of $M(\text{HI}) = 3M(\text{H}_2)$	81

List of Tables

2.1	ALMA sample.	22
2.2	Nobeyama sample.	25
3.1	Results of the ALMA observations.	38
3.2	Results of the Nobeyama observations.	49
4.1	Results of the ALMA observations.	57
4.2	Dust mass and gas-to-dust ratio of Nobeyama galaxy sample.	60

Chapter 1

Introduction

Galaxy evolution is one of the important research problems in astronomy. A galaxy is a system which is mainly composed of stars, gas, dust, and dark matter. A galaxy evolves by transforming gas into stars; in a galaxy, gas gather via self-gravity, stars form from the gas, stars eject the gas and metals through mass loss and supernova explosions into interstellar space, and next generation of stars form from the metal-polluted gas. During these processes, gas flows into/from a galaxy from/into intergalactic space (Figure 1.1). Therefore, galaxy evolution is regarded as the mass assembly history of gas and stars.

1.1 History of cosmic star-formation rate density

One of the important processes of galaxy evolution is star formation. Revealing the activity level of star formation through the cosmic history leads to the understanding of galaxy evolution. The star-formation rate (SFR) is an indicator for the activity level of star formation. The cosmic SFR density at any redshift was measured with various wavelengths. One major approach to derive the cosmic SFR density is to construct UV luminosity functions and measure the UV luminosity densities (e.g., Lilly et al. 1996; Madau et al. 1996; Wyder et al. 2005; Schiminovich et al. 2005; Dahlen et al. 2007; Reddy & Steidel 2009; Robotham & Driver 2011; Cucciati et al. 2012; Bouwens et al. 2012a,b; Schenker et al. 2013). Lilly et al. (1996) firstly showed that the ultra-violet (UV) luminosity density increases with increasing redshift and

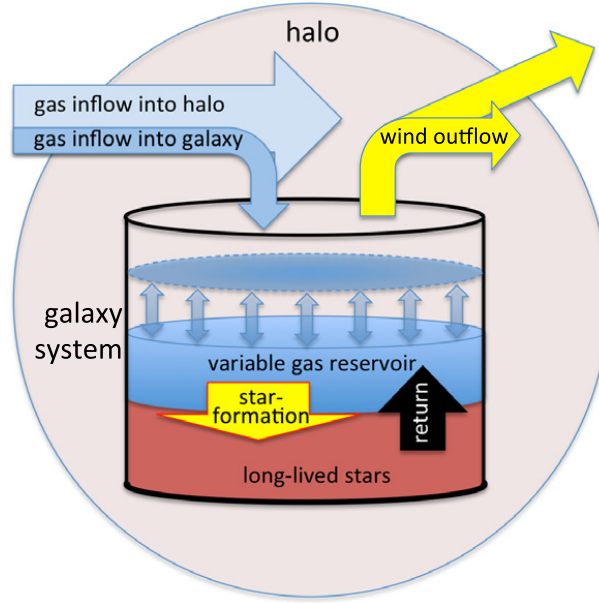


Figure 1.1: Illustration of the gas-regulated model (taken from Lilly et al. 2013), in which the SFR is regulated by the mass of gas in a reservoir within the galaxy. Gas flows in to the halo, some fraction of which also flows into the galaxy system and adds to the gas reservoir. Stars continuously form out of the reservoir. A fraction of the stellar mass is immediately returned to the reservoir, along with newly produced metals. Finally, some gas may be expelled from the system, and possibly from the halo.

that at $z \sim 1$ is more than tenfold larger than that in the present epoch. Madau et al. (1996) used Lyman Break Galaxies and found that the cosmic SFR density at $z = 3 - 4$ is comparable or larger than the local value but significantly smaller than that at $z \sim 1$. Deeper observations in rest-UV wavelength allow us to measure more accurate cosmic SFR density and that at higher redshift. Cucciati et al. (2012) derived UV luminosity functions and cosmic SFR densities from $z = 0.1$ to 4 and found that the cosmic SFR density peaks at $z = 2 - 3$. Bouwens et al. (2012b) studied UV luminosity functions and dust-extinction in star-forming galaxies at $z=4$ to 8 and found the monotonical decline of cosmic SFR density from $z = 4$ to 8. Because the UV radiation is absorbed by interstellar dust, however, there is a possibility that the UV flux from heavily dust-obscured galaxies at higher redshift is not detected, thus the cosmic SFR density at higher redshift might be underestimated.

Another approach to derive the cosmic SFR density is to construct infrared (IR) luminosity functions and calculate the IR luminosity density (e.g., Sanders et al. 2003;

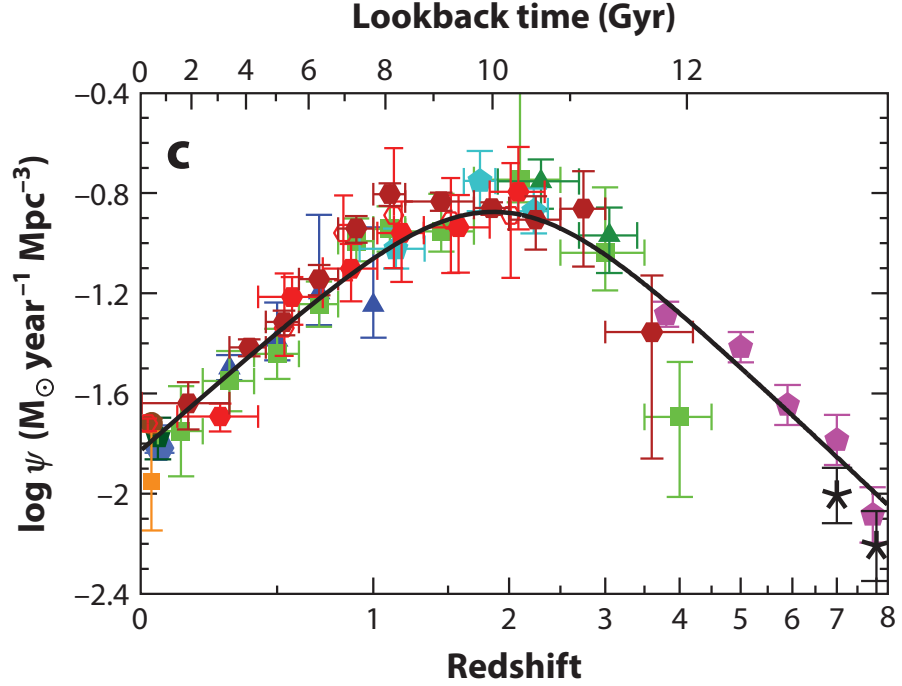


Figure 1.2: History of cosmic star formation rate density (taken from Madau & Dickinson 2014). The star formation rate densities derived from extinction corrected far-UV luminosities (blue-gray hexagon: Wyder et al. 2005, blue-gray triangles: Schiminovich et al. 2005, dark green pentagon: Robotham & Driver 2011, green squares: Cucciati et al. 2012, turquoise pentagons: Dahlen et al. 2007, dark green triangle: Reddy & Steidel 2009, magenta pentagons: Bouwens et al. 2012a,b, black crosses: Schenker et al. 2013) and IR luminosities (brown circle: Sanders et al. 2003, dark orange square: Takeuchi et al. 2003, red open hexagons: Magnelli et al. 2011, red filled hexagons: Magnelli et al. 2013, dark red filled hexagons: Gruppioni et al. 2013) are plotted. The solid curve represent the best-fit star formation rate density.

Takeuchi et al. 2003; Magnelli et al. 2011, 2013; Gruppioni et al. 2013). Sanders et al. (2003) and Takeuchi et al. (2003) derived the IR luminosity function in the local universe with Infrared Astronomical Satellite (IRAS) data. Magnelli et al. (2011) used deep images at $24 \mu\text{m}$ and $70 \mu\text{m}$ in the Great Observatories Origins Deep Survey (GOODS) North and South fields taken with Multi-Band Imaging Photometer for *Spitzer* (MIPS: Rieke et al. 2004) on the *Spitzer* space telescope. They constructed the IR luminosity function at $z = 0.4 - 2.3$ and found that the cosmic SFR density strongly increases with the increasing redshift from $z = 0$ to 1.3, but that is roughly constant at higher redshift up to $z = 2.3$. Magnelli et al. (2013) also constructed the IR luminosity function up to $z \sim 2$ but using the deep images at $70 \mu\text{m}$, $100 \mu\text{m}$,

and $160\ \mu\text{m}$ in the GOODS-N/S fields taken with the Photodetector Array Camera and Spectrometer (PACS: Poglitsch et al. 2010) on the *Herschel* space telescope. The result for the evolution of cosmic SFR density by Magnelli et al. (2013) supports that given by Magnelli et al. (2011). Gruppioni et al. (2013) used PACS images in the GOODS-N/S, Cosmic Evolution Survey (COSMOS), and Extended Chandra Deep Field South (ECDFS) fields and computed the IR luminosity function up to $z \sim 4$. They also showed that the IR luminosity density increases with redshift from $z = 0$ to 1, and that is roughly constant from $z = 1$ to 3, but that at $z \sim 3.5$ is smaller than that at $z \sim 2$. Because the IR luminosity detected in these images is still large at high redshift, the deeper images taken with high angular resolution in far-IR wavelength will make accurate luminosity functions and there is a possibility that the cosmic SFR density derived from IR luminosity functions changes at high redshift.

Recently, Madau & Dickinson (2014) compiled the previous studies and recalculated the cosmic SFR density (Figure 1.2). The cosmic SFR density rapidly increases from $z = 8$ to 2, peaks at $z \sim 2$, and gradually declines toward present epoch. Therefore, galaxies were most active at $z \sim 2$, i.e., violently evolved in this epoch. It is crucial to study the galaxies at this violent epoch of galaxy evolution ($z \sim 2$) for the understanding of galaxy evolution.

1.2 Main sequence of star-forming galaxy

Wide and deep galaxy surveys in multi-wavelength allow us to investigate galaxies at a wide range of redshifts with statistically large galaxy sample. The Sloan Digital Sky Survey (SDSS) provides colors in large amount of galaxies. The distribution of galaxies in the color-color diagram and/or color-magnitude diagram is strongly bimodal: red sequence for quiescent galaxies and blue cloud for star-forming galaxies (e.g., Strateva et al. 2001; Blanton et al. 2003; Baldry et al. 2004; Hogg et al. 2004; Blanton 2006; Schawinski et al. 2014). The spectral energy distribution (SED) fitting enables us to derive several important quantities of galaxies such as photometric redshifts, stellar masses, SFRs, and dust attenuation. The photometric redshifts allowed us to determine the rest frame colors of galaxies at high redshift. Recent deep

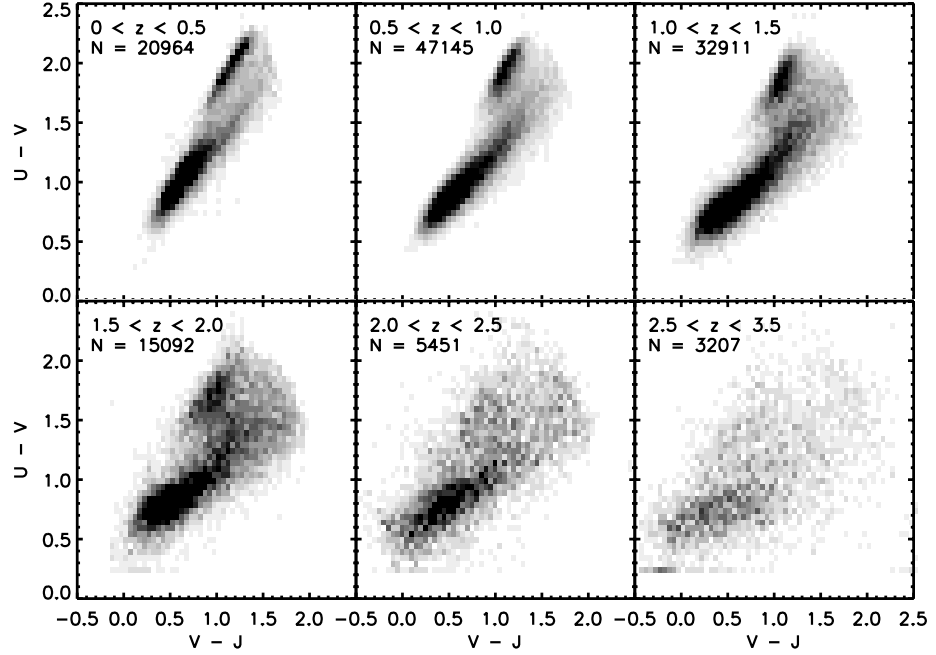


Figure 1.3: The rest-frame $U - V$ vs. $V - J$ color-color diagram for galaxies in each redshift bin (taken from Muzzin et al. 2013). The bi-modality between quiescent galaxies and star-forming galaxies can be clearly seen in the galaxy population up to $z \sim 2$. Thereafter the bi-modality becomes less pronounced. The number of galaxies used is shown at the upper left corner in each panel.

survey showed that the bimodal distribution in the color-color and/or color-magnitude diagram is hold up to $z \sim 2.5$ (Figure 1.3) (e.g., Cirasuolo et al. 2007; Brammer et al. 2009; Drory et al. 2009; Muzzin et al. 2013).

From a past decade, studies of the distribution of galaxies in the diagram of SFR versus stellar mass is one of the main topic for galaxy evolution. Brinchmann et al. (2004) found a tight correlation between stellar mass and SFR in local star-forming galaxies ($z < 0.2$). After that, a lot of studies found that this correlation is seen at each redshift and evolves with redshift (Figure 1.4) (e.g., Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Salim et al. 2007; Rodighiero et al. 2010, 2011; Whitaker et al. 2012, 2014; Speagle et al. 2014). This correlation is called “main sequence” of star-forming galaxies and galaxies located on the main sequence in the diagram of SFR versus stellar mass are called “main-sequence galaxies”. Starburst galaxies which show much larger SFRs than main-sequence galaxies are located above the main sequence in the diagram. On the other hand, passive galaxies are located below

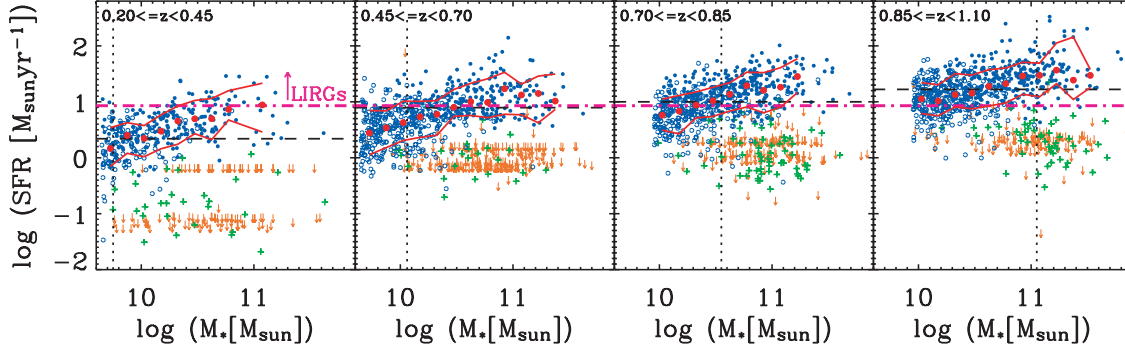


Figure 1.4: SFR versus stellar mass for galaxies at $z = 0.2 - 0.45$ (left), $z = 0.45 - 0.7$ (middle left), $z = 0.7 - 0.85$ (middle right), and $z = 0.85 - 1.1$ (right) in the Extended Groth Strip field (taken from Noeske et al. 2007). Filled blue circles refer galaxies with MIPS $24\ \mu\text{m}$ detection and DEEP2 emission lines. Open blue circles represent galaxies with blue $U - B$ colors but without $24\ \mu\text{m}$ detection. Green symbols refer to galaxies with no $24\ \mu\text{m}$ detection, and red $U - B$ colors, mostly LINER/AGN candidates. Orange arrows represent galaxies with no robust $24\ \mu\text{m}$ detection or emission lines. Red circles show the median of $\log(\text{SFR})$ in mass bins of $0.15\ \text{dex}$ for star-forming galaxies shown with blue symbols. Red solid lines include 34% of the star-forming galaxies above and 34% below the median of $\log(\text{SFR})$. Horizontal black dashed line: SFR corresponding to the $24\ \mu\text{m}$ 80% completeness limit at the center of each redshift bin; $24\ \mu\text{m}$ -detected galaxies above the magenta dot-dashed line are luminous IR galaxies (LIRGs). The black dotted vertical line marks $> 95\%$ completeness.

the main sequence in the diagram. Since the number density of luminous infrared galaxies (main-sequence galaxies are main population) is about ten times larger than that of ultra-luminous infrared galaxies (starburst galaxies are main population) up to $z \sim 2$, even though the SFR of starburst galaxies are several times larger than that of main-sequence galaxies, main-sequence galaxies mainly contribute to the cosmic SFR density. Since main-sequence galaxies are primary population at each epoch, it is necessary to investigate the properties of main-sequence galaxies for the understanding of galaxy evolution.

The properties of main-sequence galaxies have been gradually revealed. For example, the optical and near-IR deep images with high angular resolution taken with the *Hubble* space telescope (*HST*) enabled us to investigate the distribution of the stellar component. According to the results of Sérsic profile fit to the stellar surface density distribution shows that the median Sérsic index of main-sequence galaxies is ~ 1 (Figure 1.5), which is the typical value of the disk component of local spiral galaxies

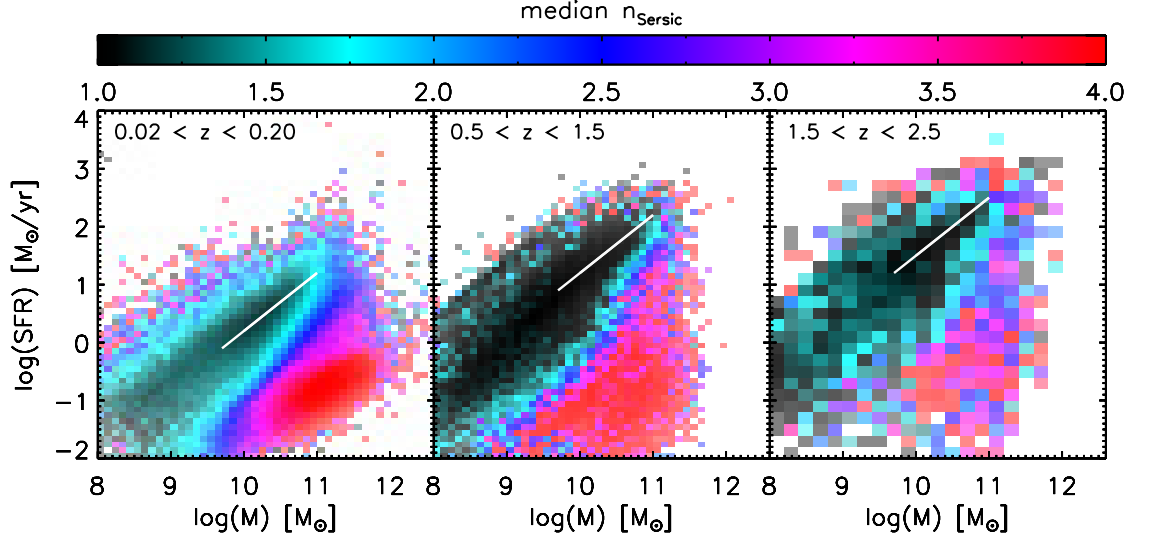


Figure 1.5: Surface brightness profile shape in the SFR-stellar mass diagram in each redshift bin (taken from Wuyts et al. 2011). A “structural main sequence” is clearly present at all observed epochs, and well approximated by a constant slope of 1 and a zero point that increases with increasing redshift (white line).

(Wuyts et al. 2011). Moreover, the advent of near-IR integral field spectrographs, such as NIFS (Near-Infrared Integral Field Spectrometer), SINFONI (Spectrograph for INtegral Field Observations in the Near Infrared) and KMOS (*K*-band Multi-Object Spectrograph), allows us to reveal the kinematics of main-sequence galaxies at the violent epoch of galaxy evolution (e.g., Förster Schreiber et al. 2006, 2009, 2011; Wisnioski et al. 2015; Stott et al. 2016; Wuyts et al. 2016). These studies showed that the 30 – 80% of main-sequence galaxies at $z = 1 - 2.5$ have the rotation-dominated disks but the velocity dispersion is larger than that in local disk galaxies (Figure 1.6).

1.3 Chemical evolution of star-forming galaxies

As described above, since stars eject the gas with metals through mass loss and supernova explosions into interstellar space, chemical enrichment in ISM proceeds. Since the amount of metals in ISM represents the past star-forming activity, the gas-phase metallicity (hereafter, metallicity) is a key parameter for the understanding of galaxy evolution. But, the metallicity is also affected by gas flows between a galaxy and intergalactic space. On the other hand, the stellar mass also represents the star

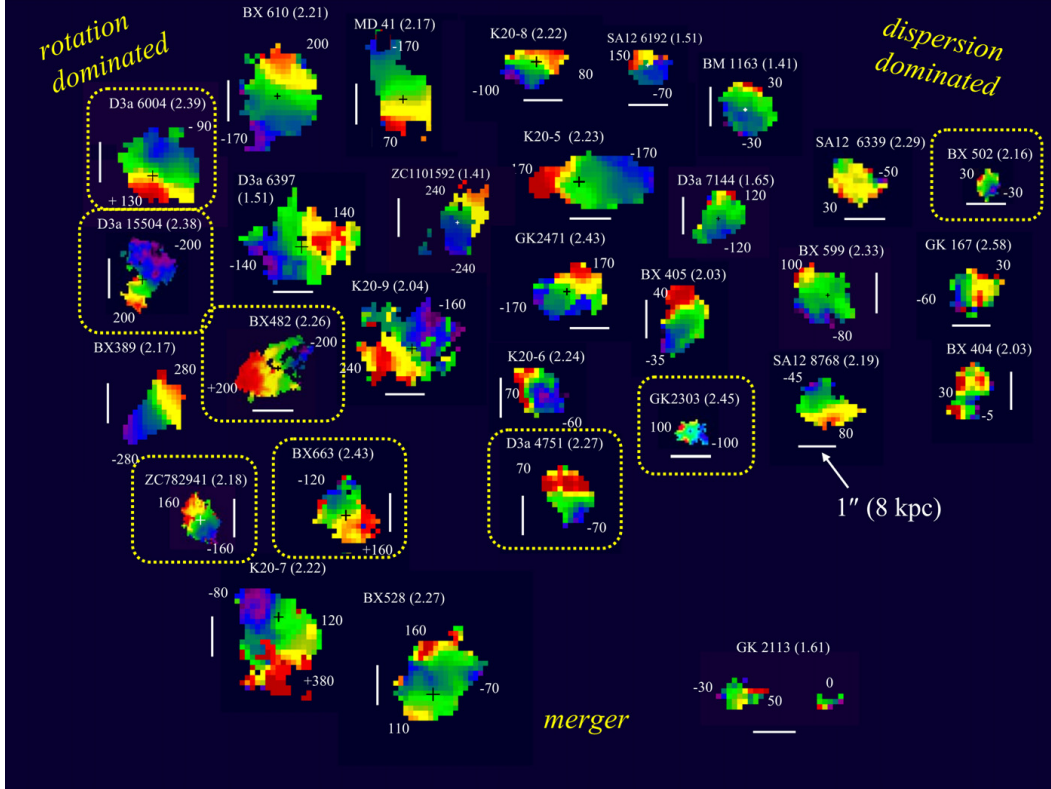


Figure 1.6: Velocity fields for 30 star-forming galaxies at $z \sim 2$ derived from the $\text{H}\alpha$ emission line taken with the SINFONI (taken from Förster Schreiber et al. 2009). The color coding is such that blue to red colors correspond to the blueshifted to redshifted line emission with respect to the systemic velocity. The minimum and maximum relative velocities are labeled for each galaxy (in km s^{-1}). The white bars correspond to $1''$, or about 8 kpc at $z \sim 2$. The galaxies are approximately sorted from left to right according to whether their kinematics are rotation-dominated or dispersion-dominated, and from top to bottom according to whether they are disk-like or merger-like. Galaxies observed with the aid of adaptive optics are indicated by the yellow rounded rectangles.

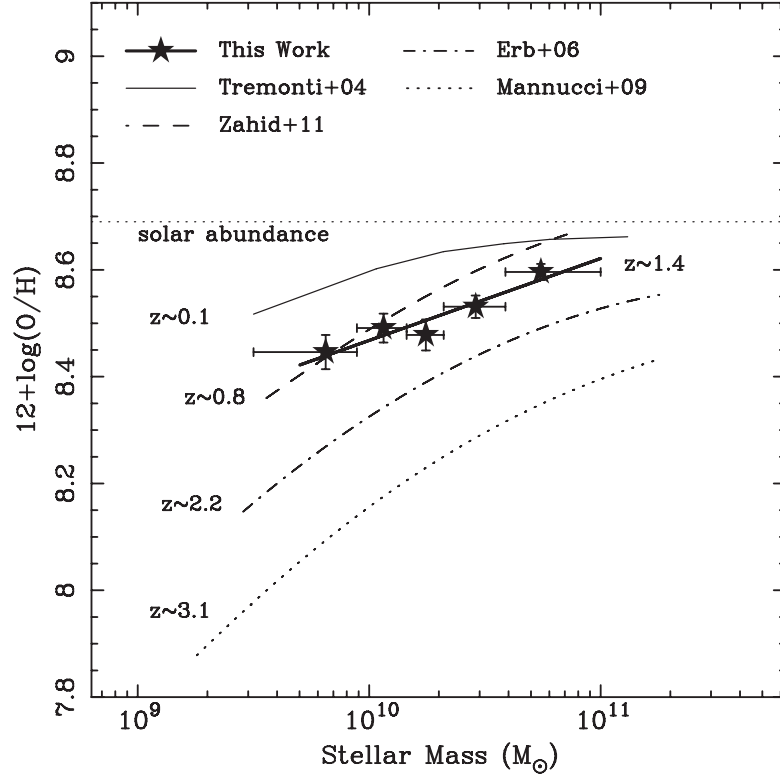


Figure 1.7: Mass-metallicity relation at $z \sim 0.1$ (thin solid line: Tremonti et al. 2004), $z \sim 0.8$ (dashed line: Zahid et al. 2011), $z \sim 1.4$ (stars and thick solid line: Yabe et al. 2014), $z \sim 2.2$ (dashed-dotted line: Erb et al. 2006), and $z \sim 3.1$ (dotted line: Mannucci et al. 2009) (taken from Yabe et al. 2014). For each line, the stellar mass range actually observed is presented. The horizontal dotted line indicates solar metallicity.

formation history, and it is less affected by the gas flows. Therefore, the relation between the stellar mass and metallicity is useful to unveil the star formation history together with the gas flows.

By using the spectroscopic data of star-forming galaxies (~ 50000 objects) in SDSS, Tremonti et al. (2004) established the relation between stellar mass and metallicity of galaxies at $z \sim 0.1$ (thin solid line in Figure 1.7). These two parameters are well-correlated; galaxies with larger stellar mass tend to have higher metallicity (hereafter, mass-metallicity relation). Erb et al. (2006) conducted the near-IR spectroscopy toward 87 star-forming galaxies at $z \sim 2.2$ with the Near-Infrared Spectrograph (NIR-Spec). They divided the sample into six stellar mass bins, constructed the composite spectra in each bin, and derived the metallicities in each bin. The mass-metallicity relation of star-forming galaxies at $z \sim 2.2$ shows the same trend of local galaxies

(dashed-dotted line in Figure 1.7), but the metallicity at fixed stellar mass is significantly lower than local value. Mannucci et al. (2009) made spectroscopy of 10 galaxies at $z \sim 3$ using SINFONI. The mass-metallicity relation at $z \sim 3$ (dotted line in Figure 1.7) shows the same trend as local one but the metallicity at fixed stellar mass is significantly lower than that at $z \sim 2.2$. Therefore, the mass-metallicity relation can be considered to evolve with redshift. However, some studies claim that a general relation (fundamental plane) exists in the 3D space of stellar mass, metallicity, and SFR, on which all the data points of both local and high-redshift star-forming galaxies reside (e.g., Mannucci et al. 2010; Yabe et al. 2015b).

The advent of multi-object spectrograph in the wavelength of optical-to-near-IR, such as VIMOS (VIsible MultiObject Spectrograph), DEIMOS (DEep Imaging Multi-Object Spectrograph), GMOS (Gemini Multi-Object Spectrograph), MOIRCS (Multi-Object Infrared Camera and Spectrograph), FMOS (Fiber Multi-Object Spectrograph), and MOSFIRE (Multi-Object Spectrometer for Infra-Red Exploration), enables us to observe a large number of star-forming galaxies and to cover the primary emission lines ($H\beta$, [OIII], $H\alpha$, [NII]) up to $z \sim 2.5$, thus we can trace the mass-metallicity relation at high redshift (e.g., Hayashi et al. 2009; Zahid et al. 2011; Yabe et al. 2012, 2014, 2015b; Sanders et al. 2015). Zahid et al. (2011) presented the mass-metallicity relation at $z \sim 0.8$ (dashed line in Figure 1.7) by using ~ 1350 star-forming galaxies observed in the Deep Extragalactic Evolutionary Probe 2 (DEEP2) survey, which used the DEIMOS. The relation at this redshift comes between that in the local universe and $z \sim 2.2$. Yabe et al. (2014) carried out the near-IR spectroscopy of star-forming galaxies at $z \sim 1.4$ with the FMOS and detected $H\alpha$ emission line from ~ 340 galaxies. They separated the $H\alpha$ detected galaxies into 5 stellar mass bin and constructed the mass-metallicity relation at this redshift (stars and thick solid line in Figure 1.7). The relation at $z \sim 1.4$ comes between that at $z \sim 0.8$ and $z \sim 2.2$. Several theoretical studies have tried to reproduce and predict the mass-metallicity relations at each redshift (e.g., Kereš et al. 2005; Finlator & Davé 2008; Bouché et al. 2010; Lilly et al. 2013). As noted in the beginning of this section, since gas flows are related to the metallicity in a galaxy, revealing the relations between stellar mass, metallicity, and gas content will provide a step closer to reveal galaxy evolution.

1.4 Gas flows for galaxy evolution

Gas inflow and outflow play a very important role in galaxy evolution. There is indirect evidence for the existence of gas inflow. First, the difference in the abundance distribution between observations and the closed-box model prediction (e.g., van den Bergh 1962), called the G-dwarf problem, which can be explained by the inflow of primordial gas (e.g., Larson 1972). Further evidence is that the timescale of gas depletion in star-forming galaxies at low redshift (e.g., Wong & Blitz 2002; Saintonge et al. 2011b) and high redshift (e.g., Tacconi et al. 2010, 2013). is significantly shorter than that for building up their stellar masses (Bouché et al. 2010), thus requiring gas inflow to sustain their star formation activity. Gas outflow is found in local (e.g., Salak et al. 2013) and distant (e.g., Weiner et al. 2009; Steidel et al. 2010; Genzel et al. 2011) star-forming galaxies. Weiner et al. (2009) found that the outflow is ubiquitous at $z \sim 1.4$ and the outflow rate is of the same order of magnitude as the SFR in galaxies.

Because inflow and outflow affect the gas mass (and its fraction) and gas-phase metallicity in a galaxy, efforts have been made to constrain the inflow and outflow rates to reproduce the observational relations such as the stellar mass-metallicity relation by using cosmological simulations (e.g., Kereš et al. 2005; Finlator & Davé 2008) and analytic models (e.g., Bouché et al. 2010; Lilly et al. 2013). Some of the studies showed that galaxies evolve while maintaining the balance between the amounts of inflow gas, star formation, and outflow: $\text{inflow} = \text{star formation} + \text{outflow}$. Such a scenario is called the “equilibrium model” for galaxy evolution. By using near-infrared spectroscopy of star-forming galaxies at $z \sim 2$ (Erb et al. 2006), Erb (2008) derived gas-phase metallicities from emission lines and gas mass fractions from extinction corrected $\text{H}\alpha$ luminosities by assuming the Kennicutt-Schmidt law. Then, she derived the inflow and outflow rates at $z \sim 2$ by fitting a simple analytic model for the chemical evolution in a galaxy to these quantities. Her result supports the equilibrium model. Yabe et al. (2015a) tried to constrain the cosmic evolution of inflow and outflow rates by using the chemical evolution model and their near-infrared spectroscopic data at $z \sim 1.4$ (Yabe et al. 2014) and observational data at $z \sim 1.4$ and 2 in the literature (Peeples &

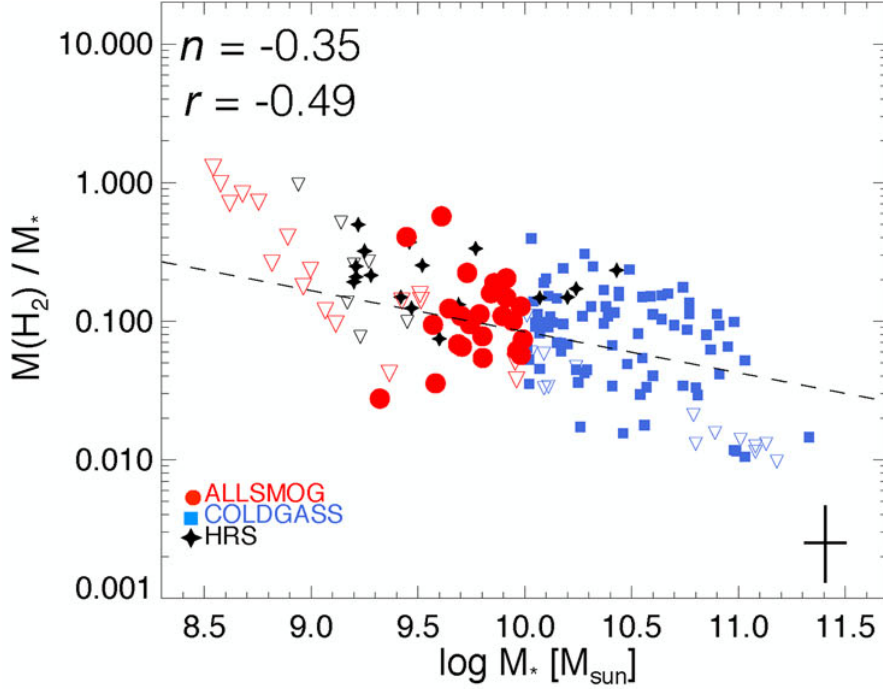


Figure 1.8: Molecular gas-to-stellar mass ratio against stellar mass in local galaxies (taken from Bothwell et al. 2014), whose molecular gas masses are derived with metallicity-dependent CO-to-H₂ conversion factors. Blue, black, and red symbols refer to the results by COLD GASS, HRS, and ALLSMOG, respectively. Filled and open symbols represent the CO detected and undetected galaxies, respectively. Black dashed lines show linear fits to all three samples. the slope of fits (n) and Pearson correlation coefficients (r) is given at the top left corner. Typical error is given at the bottom right corner.

Shankar 2011; Erb et al. 2006:respectively). They also derived gas-phase metallicities from emission lines and gas mass fractions at $z \sim 1.4$ and 2 from extinction corrected H α luminosities by assuming the Kennicutt-Schmidt law. They found the inflow, outflow, and SFRs decreased while satisfying the equilibrium condition at all redshifts. However, no studies constrain the inflow and outflow rates at $z > 1$ with chemical evolution models using molecular gas observations for the gas mass fraction.

1.5 Studies of interstellar medium in main-sequence galaxies

Since galaxies evolve by transforming gas into stars, the study of the interstellar medium (ISM) in galaxies is indispensable for a complete understanding of galaxy

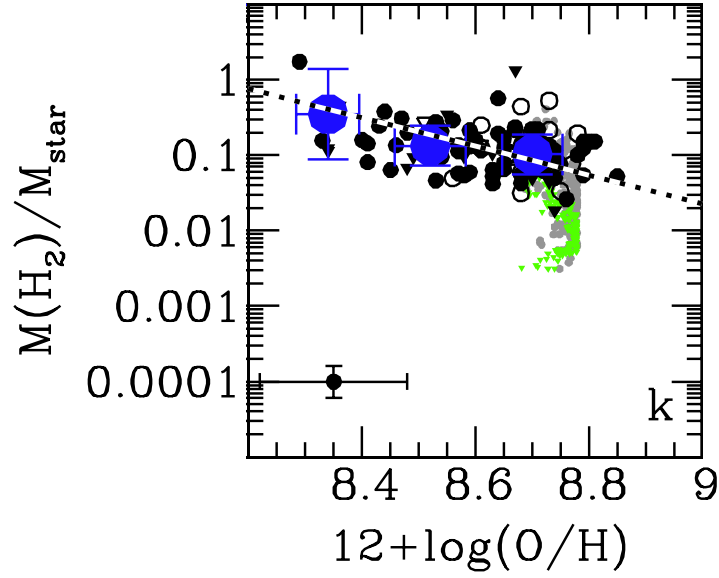


Figure 1.9: Molecular gas-to-stellar mass ratio against metallicity in local galaxies (taken from Boselli et al. 2014b), whose molecular gas masses are derived with H -band luminosity-dependent CO-to- H_2 conversion factors. Circles indicate detected galaxies, triangles upper limits in HRS. Grey and green symbols refer to the detected and undetected COLD GASS objects, respectively. The big blue symbols give the mean values and the standard deviation (in log scale) considering only CO detected late-type objects in HRS. Black dotted line indicates the bisector fit determined using only detected, late-type galaxies. The typical error on the data is given at the bottom left corner.

evolution. The mass of molecular gas and its fraction against stellar mass in a galaxy are key parameters to trace galaxy evolution and to understand a stage of the evolution. The mass of dust also has information about the history of star formation, because dust is made from metals which are ejected by stars. Since the stellar mass and metal increase as the galaxy evolves, revealing relations among parameters of ISM, stellar mass, and metallicity leads to unveil the processes of galaxy evolution.

1.5.1 Local galaxies

In the local universe, several large CO surveys have been conducted (e.g., Young et al. 1995; Saintonge et al. 2011a; Boselli et al. 2014a; Bothwell et al. 2014). Five College Radio Astronomy Observatory (FCRAO) extragalactic CO survey observed 300 nearby galaxies, which were selected with criteria of $B_T < 13.0$, $S_{60} > 5$ Jy, or $S_{100} > 10$ Jy, where B_T is total blue magnitude, S_{60} is flux density in $60 \mu\text{m}$, and

S_{100} is that in $100\ \mu\text{m}$ (Young et al. 1995). The survey of CO Legacy Data base for the GASS (*GALEX* Arecibo SDSS (Sloan Digital Sky Survey) Survey) observed ~ 350 galaxies with the stellar mass of $M_* = 10^{10-11.5} M_\odot$ at $z = 0.025 - 0.05$ (COLD GASS: Saintonge et al. 2011a). *Herschel* Reference Survey observed 225 galaxies with the stellar mass of $M_* = 10^{9-11} M_\odot$ at the distance of $15 - 25$ Mpc (HRS: Boselli et al. 2014a). APEX (Atacama Pathfinder EXperiment) Low-redshift Legacy Survey for MOlecular Gas is observing ~ 100 galaxies with the stellar mass of $M_* = 10^{8.5-10} M_\odot$ at $z = 0.01 - 0.03$ (ALLSMOG: Bothwell et al. 2014). According to the results of these surveys, the molecular gas mass fraction against stellar mass ($M_{\text{mol}}/(M_{\text{mol}} + M_*)$) is $1 - 30\%$ in local star-forming galaxies, especially $< 10\%$ for the galaxies with $M_* > 10^{10} M_\odot$. Figure 1.8 shows the molecular gas-to-stellar mass ratio against stellar mass revealed by these studies. The molecular gas-to-stellar mass ratio significantly decreases with increasing stellar mass. Figure 1.9 shows the molecular gas-to-stellar mass ratio against metallicity. The molecular gas-to-stellar mass ratio seems to decrease with increasing metallicity.

At $z = 0.1 - 0.4$, the number of CO observations are limited (e.g., Geach et al. 2011; Matsui et al. 2012; Bauermeister et al. 2013; Morokuma-Matsui et al. 2015). Geach et al. (2009, 2011) carried out CO observations toward 7 main-sequence galaxies located in the outskirt of the rich cluster Cl 0024 + 16 at $z = 0.395$. The survey of Evolution of molecular Gas in Normal Galaxies observed 31 star-forming galaxies at $z = 0.05 - 0.53$ with the stellar mass of $M_* > 10^{10.5} M_\odot$ (17 out of 31 galaxies are main sequence galaxies) (EGNoG: Bauermeister et al. 2013). Morokuma-Matsui et al. (2015) observed 12 main-sequence galaxies at $z = 0.1 - 0.2$ with the stellar mass range of $M_* = 10^{10.6-11.3} M_\odot$. These observations showed that the molecular gas mass fraction is $\sim 10 - 30\%$ which is higher than that in the local star-forming galaxies ($z < 0.1$) with the similar stellar mass ($M_* > 10^{10.5} M_\odot$). However, galaxy samples of these studies tends to be biased to galaxies with the larger specific SFR ($\text{sSFR}/\text{sSFR}_{\text{MS}} > 1$; here, sSFR_{MS} is the specific SFR of the center of the main sequence).

Dust plays an important role in formation of hydrogen molecules and in the cooling of the ISM. Thus, revealing gas-to-dust mass ratios is also important for the under-

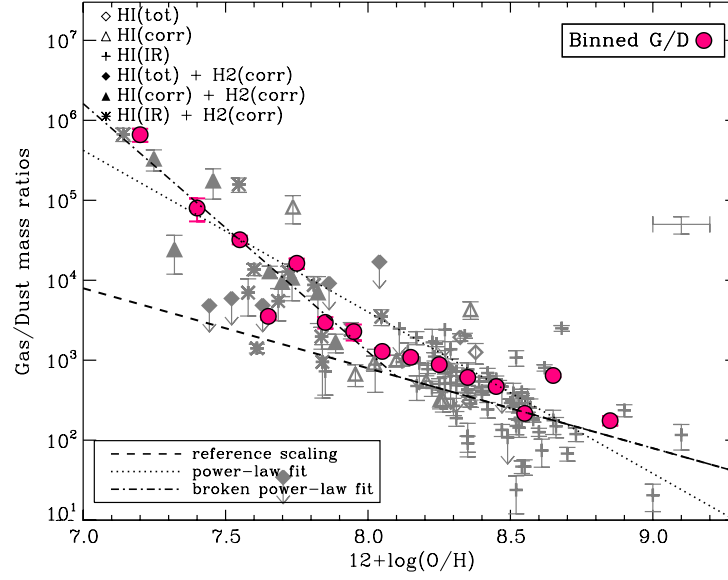


Figure 1.10: Gas-to-dust mass ratio in nearby galaxies (taken from Rémy-Ruyer et al. 2014). Individual galaxies are represented with gray symbols. Pink filled circles refer to the values in each metallicity bin. The dashed line represents the reference scaling of the G/D with metallicity (not fit to the data). The dotted and dash-dotted lines represent the best power-law and best broken power-law fits to the data. The metallicity-dependent CO-to-H₂ conversion factor is adopted for the derivation of molecular gas mass.

standing of galaxy evolution. Leroy et al. (2011) used the data of HI mass, molecular gas mass, and dust mass in the Milky Way Galaxy and nearby galaxies (M31, M33, Large Magellanic Cloud, Small Magellanic Cloud, and NGC6822) and derived the gas-to-dust ratio against metallicity. They found that the gas-to-dust ratio decreases with increasing metallicity. Rémy-Ruyer et al. (2014) also showed the same trend with more star-forming galaxies covering wider range of metallicity (Figure 1.10).

1.5.2 High redshift galaxies

Recently, high-sensitivity radio telescopes have enabled us to detect CO emission from massive main-sequence galaxies at $z = 1 - 2.5$ (e.g., Daddi et al. 2008, 2010a; Tacconi et al. 2010, 2013). Daddi et al. (2008) firstly obtained CO($J = 2 - 1$) emission lines from two massive star-forming galaxies at $z = 1.5$ using the Institut de Radioastronomie Millimétrique (IRAM) Plateau de Bure Interferometer (PdBI) and showed that these galaxies are gas-rich systems. Daddi et al. (2010a) found that

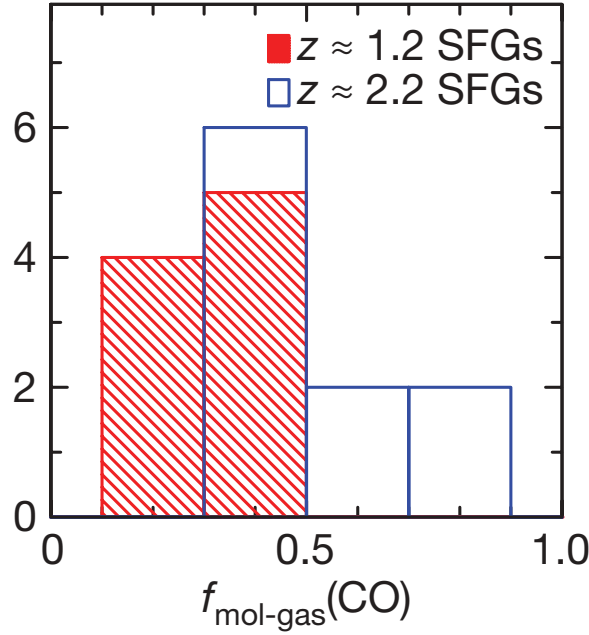


Figure 1.11: Distribution of molecular gas mass fractions for the main-sequence galaxies at $z \sim 1.2$ (red) and $z \sim 2.2$ (blue) (taken from Tacconi et al. 2010). The Galactic conversion factor is used for derivation of molecular gas mass. The fractions at these redshift is significantly higher than that in local star-forming galaxies.

additional four main-sequence galaxies at $z = 1.5$ also show higher molecular gas mass fraction (the average value of the six galaxies is 57%) than local star-forming galaxies with the similar stellar mass. Tacconi et al. (2010) showed that the molecular gas mass fraction in main-sequence galaxies increases with increasing redshift using CO data of about a dozen of galaxies at $z \sim 1.2$ and $z \sim 2.2$ (Figure 1.11). These results indicate that large amount of molecular gas remains in high-redshift galaxies, and galaxies evolve by consuming the gas. Tacconi et al. (2013) conducted and compiled CO observations of 73 main-sequence galaxies (52 galaxies were newly detected) at $z = 1 - 2.5$ with stellar mass of $M_* > 2.5 \times 10^{10} M_\odot$. The average molecular gas mass fraction at $z \sim 1.2$ and $z \sim 2.2$ is 33% and 47%, respectively; the value at $z \sim 1.2$ is corrected for the sample bias to the larger specific SFR by assuming the depletion time of molecular gas is constant for whole main-sequence galaxies. The fraction is still larger than that in the local spiral galaxies. Tacconi et al. (2013) also showed that the molecular gas mass fraction at $z \sim 1.2$ decreases with increasing stellar mass in the mass range of $10^{10.5-11.2} M_\odot$, which is the same trend in local galaxies. Although

these fundamental pictures at high redshift are gradually revealed, the stellar mass of these galaxy samples is large and the relation between molecular gas and metallicity remains to be veiled.

The recent advent of detectors in the mid/far-IR and submillimeter wavelengths, such as *Spitzer*/MIPS, *Herschel*/PACS and Spectral and Photometric Imaging Receiver (SPIRE: Griffin et al. 2010), and Atacama Large Millimeter/submillimeter Array (ALMA), enables us to investigate dust emission from high-redshift galaxies on the main sequence (e.g., Elbaz et al. 2011; Magdis et al. 2012a; Magnelli et al. 2012; Scoville et al. 2014, 2016). These studies found that the dust mass is larger than local star-forming galaxies with similar stellar mass. Magnelli et al. (2014) derived mean dust temperature in star-forming galaxies up to $z = 2$ in the SFR-stellar mass parameter space by stacking the far-IR data in each bin and using the modified black body. Several studies estimate the gas mass in star-forming galaxies at high redshift from the dust mass by assuming the local gas-to-dust ratio (e.g., Magdis et al. 2011, 2012a). However, Saintonge et al. (2013) used lensed main-sequence galaxies at $z = 1.5 - 3$ and showed that the ratio is a factor of 2 larger than that in nearby galaxies at a fixed metallicity. Whether the gas-to-dust ratio at $z \sim 1 - 2$ is the same as local values is still under discussion.

1.6 Motivation of this thesis

As mentioned in the previous sections, revealing the properties of molecular gas and dust in main-sequence galaxies at the violent epoch of galaxy evolution is inevitable for the understanding of galaxy evolution. However, the molecular gas mass and its fraction in main-sequence galaxies at this epoch against lower stellar mass ($M_* < 10^{10.5} M_\odot$) and metallicity have not been studied yet. Furthermore, the gas-to-dust ratio at this epoch is still under discussion. To overcome these circumstances, the CO and dust observations toward main-sequence galaxies with known metallicity at the violent epoch of galaxy evolution is required. Then, we examine scenarios of galaxy evolution by comparing the observational results with theoretical models containing star formation, chemical enrichment, and gas flows.

In this thesis, we present the galaxy sample in chapter 2, and show the properties of molecular gas in main-sequence galaxies at $z \sim 1.4$ in chapter 3. In chapter 4, the dust properties and gas-to-dust ratios are described. In chapter 5, we try to constrain the inflow and outflow rates at this redshift by comparing the observational results with a simple analytic chemical evolution model. The summary and future prospects are described in Chapter 6. Throughout this thesis, we adopt the standard Λ -cold dark matter (Λ -CDM) cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_{\text{M}} = 0.3$, and $\Omega_{\Lambda} = 0.7$. This thesis is based on my refereed papers “Constraint on the gas-to-dust ratio in massive star-forming galaxies at $z \sim 1.4$ ” (Seko et al. 2014), “Properties of the interstellar medium in star-forming galaxies at $z \sim 1.4$ revealed with ALMA” (Seko et al. 2016a), “Gas-to-dust ratios in massive star-forming galaxies at $z \sim 1.4$ ” (Seko et al. 2016b), and “Constraint on the inflow/outflow rates in star-forming galaxies at $z \sim 1.4$ from molecular gas observations” (Seko et al. 2016c). My contributions to this work are (1) sample constructions, (2) preparations of the observations, (3) observations, (4) data reduction and other analyses, and (5) large part of discussions.

Chapter 2

Sample & Observations

2.1 Sample

2.1.1 Near-infrared spectroscopic sample at $z \sim 1.4$

Sample galaxies at $z \sim 1.4$ used in this thesis are taken from Yabe et al. (2012) and Roseboom et al. (2012). Yabe et al. (2012) used deep multi-wavelength data in the Subaru-XMM Newton Deep Survey (SXDS; Furusawa et al. 2008) field; the far-UV and near-UV data were taken from the *Galaxy Evolution Explorer* (GALEX) archived image (GR6), U -band images were taken from the Canada-France-Hawaii Telescope Legacy Survey (CFHTLS) wide surveys, the optical images (B , V , R_C , i' , and z' -bands) were taken from the SXDS, the near-infrared images (J , H , and K_S -bands) were taken from the Data Release (DR) 8 version of the United Kingdom Infra-Red Telescope (UKIRT) Infrared Deep Sky Survey (UKIDSS) Ultra Deep Survey (UDS), and the *Spitzer* Infrared Array Camera (IRAC) images (3.6, 4.5, 5.8, and 8.0 μm) were taken from the *Spitzer* public legacy survey of the UKIDSS UDS (SpUDS). Photometric redshifts (z_{phot}) were derived with Hyperz (Bolzonella et al. 2000). Stellar masses were derived by fitting the spectral energy distribution (SED; Sawicki 2012) with the optical to mid-infrared data by employing the population synthesis model by Bruzual & Charlot (2003). SFRs were derived from rest-frame UV luminosity densities, corrected for the dust extinction estimated from the rest-frame UV slopes. In both stellar mass and SFR, the Salpeter IMF (Salpeter 1955) with a mass range

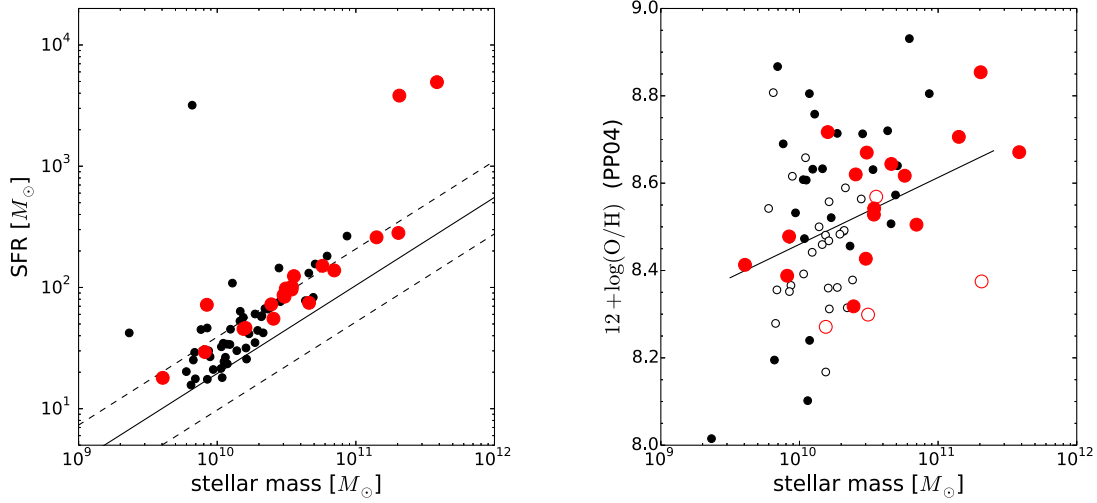


Figure 2.1: (Left) Galaxy sample in the SXDS field in the stellar mass-SFR diagram. Circles show 71 H α emitting galaxies at $z \sim 1.4$ by Yabe et al. (2012). Among them, large red circles show 20 galaxies observed with ALMA. SFRs are derived from extinction-corrected UV luminosity densities. (Right) Galaxy sample in the SXDS field in the stellar mass-metallicity diagram. The metallicities are derived from H α and [NII] λ 6584 emission lines (Pettini & Pagel 2004). Large red symbols show the ALMA sample galaxies. Objects with [NII] λ 6584 lines with $S/N \geq 1.5$ and $S/N < 1.5$ are indicated by filled and open circles, respectively, i.e., open circles represent upper limits on metallicity.

of $0.1 - 100 M_{\odot}$ was adopted. Yabe et al. (2012) selected star-forming galaxies at $1.2 \leq z_{\text{phot}} \leq 1.6$ with $K_S < 23.9$ mag (AB magnitude) and stellar mass $\geq 10^{9.5} M_{\odot}$. Among them, they selected galaxies for which the expected H α flux is larger than $1.0 \times 10^{-16} \text{ erg s}^{-1} \text{ cm}^{-2}$ in order to make an efficient survey.

Using this sample, Yabe et al. (2012) carried out near-infrared spectroscopic observations with the FMOS (Kimura et al. 2010) on the Subaru telescope. H α emission lines were significantly detected for 71 star-forming galaxies. The stellar mass and SFR for these are shown with circles in the left panel of Figure 2.1. The spectroscopic redshift (z_{spec}) was derived using the H α emission line. They derived the gas-phase metallicity with the N2 method by using the H α and [NII] λ 6584 emission lines (Pettini & Pagel 2004). The metallicity against stellar mass is plotted in the right panel of Figure 2.1 with filled circles for galaxies with the [NII] line with signal-to-noise ratio (S/N) ≥ 1.5 and with open circles for galaxies with the [NII] line with $S/N < 1.5$.

Roseboom et al. (2012) used the $24 \mu\text{m}$ image in the Cosmological Evolution

Survey (COSMOS) field taken with the MIPS and the 250, 350, and 500 μm images taken with the SPIRE as a part of the *Herschel* Multi-tiered Extragalactic Survey (HerMES; Oliver et al. 2012). They extracted sources from the 24 μm image and cross-matched the sources with the publicly available *HST* Advanced Camera for Surveys (ACS;) I_{F814W} -band catalogue by Leauthaud et al. (2007). They performed photometry for the SPIRE images. They selected galaxies at $0.65 \leq z_{\text{phot}} \leq 1.75$ derived by Ilbert et al. (2009) and conducted near-infrared spectroscopic observations toward the selected galaxies with the FMOS. $\text{H}\alpha$ emission lines were detected for 85 galaxies. The spectroscopic redshift was derived using the $\text{H}\alpha$ emission line. They also derived the gas-phase metallicity with the N2 method. Because the stellar mass and SFR for this sample were not available by Roseboom et al. (2012), we derived the stellar mass and SFR with the same method as those in the SXDS field, using the photometry data in Muzzin et al. (2013).

It should be noted that Yabe et al. (2015b) showed that the nitrogen-to-oxygen abundance ratio in star-forming galaxies at this redshift is significantly higher than the local value at a fixed metallicity and stellar mass, and thus there is a possibility that the metallicity derived with the N2 method is systematically overestimated by $0.1 - 0.2$ dex.

2.1.2 Galaxy sample for ALMA

We selected 20 of the 71 $\text{H}\alpha$ detected galaxies in the SXDS field as ALMA targets to cover a wide range of stellar mass ($4 \times 10^9 - 4 \times 10^{11} M_{\odot}$) and metallicity ($12 + \log(\text{O}/\text{H}) = 8.2 - 8.9$) and to trace these distributions rather uniformly. The selected sample galaxies are shown with large red circles in Figure 2.1 and listed in Table 2.1. Almost all of our sample galaxies lie on the main sequence. The two most massive galaxies (SXDS1_35572 and SXDS1_79307) show very high SFRs, and these may not be on the main sequence. The estimation of SFR may not be correct for these two galaxies due to, for example, the uncertainty in the dust extinction. Nevertheless, we included these two galaxies to examine their nature. It turned out later that no far-infrared continuum toward these galaxies was detected by *Herschel*,

Table 2.1: ALMA sample.

ID	RA ^a (J2000)	DEC ^a (J2000)	z_{spec}^b	M_* ^c ($M_\odot$)	metallicity ^d ($12 + \log(O/H)$)	SFR ^e ($M_\odot \text{ yr}^{-1}$)	SFR ^f ($M_\odot \text{ yr}^{-1}$)
SXDS1_13015	02:17:13.63	-05:09:39.8	1.451	$(2.0^{+0.5}_{-0.2}) \times 10^{11}$	$8.85^{+0.04}_{-0.04}$	282	392 ± 50
SXDS1_1723	02:17:32.70	-05:13:16.5	1.467	$(3.1^{+3.0}_{-2.0}) \times 10^{10}$	< 8.30	98	< 107
SXDS1_31189	02:17:13.68	-05:04:07.7	1.394	$(8.2^{+2.7}_{-6.0}) \times 10^9$	$8.39^{+0.08}_{-0.13}$	29	< 55
SXDS1_33244	02:16:47.40	-05:03:28.1	1.474	$(5.7^{+1.7}_{-1.2}) \times 10^{10}$	$8.62^{+0.05}_{-0.07}$	151	90 ± 33
SXDS1_35572	02:17:34.65	-05:02:39.0	1.347	$(3.8^{+0.1}_{-1.1}) \times 10^{11}$	$8.67^{+0.08}_{-0.09}$	4938	< 31
SXDS1_42087	02:17:24.36	-05:00:44.9	1.594	$(3.6^{+2.2}_{-2.5}) \times 10^{10}$	< 8.57	124	118 ± 43
SXDS1_59863	02:17:45.88	-04:54:37.6	1.448	$(1.4^{+0.1}_{-0.1}) \times 10^{11}$	$8.71^{+0.03}_{-0.04}$	259	< 87
SXDS1_59914	02:17:12.98	-04:54:40.4	1.460	$(7.0^{+0.0}_{-2.6}) \times 10^{10}$	$8.51^{+0.06}_{-0.07}$	138	< 105
SXDS1_67002	02:19:02.65	-04:49:55.9	1.281	$(3.5^{+4.7}_{-0.1}) \times 10^{10}$	$8.54^{+0.06}_{-0.08}$	101	41 ± 13
SXDS1_68849	02:17:00.28	-04:48:14.5	1.325	$(2.5^{+2.1}_{-1.9}) \times 10^{10}$	$8.62^{+0.04}_{-0.05}$	55	< 74
SXDS1_79307	02:17:05.79	-04:51:25.7	1.575	$(2.1^{+0.0}_{-0.0}) \times 10^{11}$	< 8.38	3822	< 67
SXDS1_79518	02:18:59.06	-04:51:24.9	1.330	$(2.5^{+0.8}_{-0.2}) \times 10^{10}$	$8.32^{+0.09}_{-0.14}$	73	< 71
SXDS2_13316	02:17:39.03	-04:44:41.8	1.446	$(8.4^{+1.6}_{-3.5}) \times 10^9$	$8.48^{+0.05}_{-0.07}$	72	< 76
SXDS2_22198	02:17:53.42	-04:42:53.4	1.499	$(1.6^{+0.1}_{-0.1}) \times 10^{10}$	$8.72^{+0.07}_{-0.09}$	46	66 ± 17
SXDS3_101746	02:18:04.18	-05:19:38.3	1.335	$(4.0^{+1.3}_{-0.8}) \times 10^9$	$8.41^{+0.07}_{-0.09}$	18	< 75
SXDS3_103139	02:16:57.65	-05:14:34.9	1.382	$(1.5^{+0.7}_{-0.1}) \times 10^{10}$	< 8.27	45	< 39
SXDS3_110465	02:18:20.95	-05:19:07.7	1.458	$(3.1^{+2.3}_{-0.8}) \times 10^{10}$	$8.67^{+0.03}_{-0.03}$	84	< 92
SXDS5_19723	02:16:24.37	-05:09:18.1	1.533	$(3.4^{+1.0}_{-2.5}) \times 10^{10}$	$8.53^{+0.08}_{-0.13}$	96	< 54
SXDS5_28019	02:16:08.53	-05:06:15.6	1.348	$(3.0^{+1.7}_{-2.2}) \times 10^{10}$	$8.43^{+0.09}_{-0.15}$	87	110 ± 31
SXDS5_9364	02:16:33.81	-05:13:44.7	1.441	$(4.6^{+2.3}_{-1.7}) \times 10^{10}$	$8.64^{+0.04}_{-0.05}$	102	121 ± 43

^a The accuracy of coordinates in the K -band image is $\sim 0.''2 - 0.''3$.

^b Derived from H α wavelength in vacuum. The error is typically ± 0.001 .

^c We adopted the Salpeter IMF (Salpeter 1955). The SFR is derived from extinction-corrected UV luminosity density. The error in SFR is typically 15%.

^d Derived from H α and [NII] λ 6584 calibrated by Pettini & Pagel (2004).

^e SFR is derived from extinction-corrected H α luminosity density. The error in SFR is typically 10%.

^f Sum of SFR from $L_{\text{IR}}(8 - 1000 \mu\text{m})$ from our dust continuum observations and SFR from extinction-uncorrected UV luminosity densities.

i.e., $\text{SFR} \leq 50 M_{\odot} \text{ yr}^{-1}$ (Elbaz et al. 2011). The SFR of SXDS1_35572 derived from the $\text{H}\alpha$ luminosity is $16 M_{\odot} \text{ yr}^{-1}$ (extinction uncorrected) and $537 M_{\odot} \text{ yr}^{-1}$ (extinction corrected), which is larger than the upper limit from *Herschel* data. Thus, the correction of dust extinction may be overestimated. The SFR of SXDS1_79307 from the extinction-uncorrected $\text{H}\alpha$ luminosity is $427 M_{\odot} \text{ yr}^{-1}$. One reason for this large SFR may be that an OH airglow sky emission comes very close to the position of the $\text{H}\alpha$ and we could not completely remove the sky emission. Because the X-ray luminosities ($L_{\text{X}(2-10 \text{ keV})}$) of our sample galaxies are less than $10^{43} \text{ erg s}^{-1}$, they are not X-ray-bright active galactic nuclei.

2.1.3 Galaxy sample for the Nobeyama radio telescope

Among the galaxy sample in the SXDS and COSMOS fields, we selected galaxies at $1.2 \leq z_{\text{spec}} \leq 1.6$ with a metallicity of $12 + \log(\text{O}/\text{H}) > 8.6$ to reduce the uncertainty of the CO-to- H_2 conversion factor. In order to derive the far-IR luminosity and the dust mass, we further required that the galaxies are detected with MIPS in $24 \mu\text{m}$ and with SPIRE in 250 and $350 \mu\text{m}$. For the galaxies in the SXDS field, MIPS data were taken from the DR2 version of the SpUDS (J. Dunlop et al. in preparation). SPIRE data were taken from the DR1 version of the HerMES. Object detection and photometry were performed using SExtractor (Bertin & Arnouts 1996). For the galaxies in the COSMOS field, the photometric data of MIPS and SPIRE were taken from Roseboom et al. (2012). We selected sources that appear isolated in the $24 \mu\text{m}$ image, allowing us to obtain the reliable flux density in mid-/far-IR. In fact, the images at 250 and $350 \mu\text{m}$ do not show serious contamination of target galaxies by adjacent sources.

Among these selected galaxies, we chose galaxies that are located around the main sequence of star-forming galaxies (Daddi et al. 2010a). We selected 6 galaxies and they are shown in Table 2.2. Although the metallicity of COSMOS_9 is only an upper limit (8.68), since the galaxy is massive ($M_{*} \sim 6.7 \times 10^{10} M_{\odot}$) the real value of the metallicity is expected to be near solar according to the mass-metallicity relation. Table 2.2 shows SFR derived from extinction-corrected UV luminosity density and from the sum of the $24 \mu\text{m}$ luminosity density and extinction-uncorrected UV luminosity

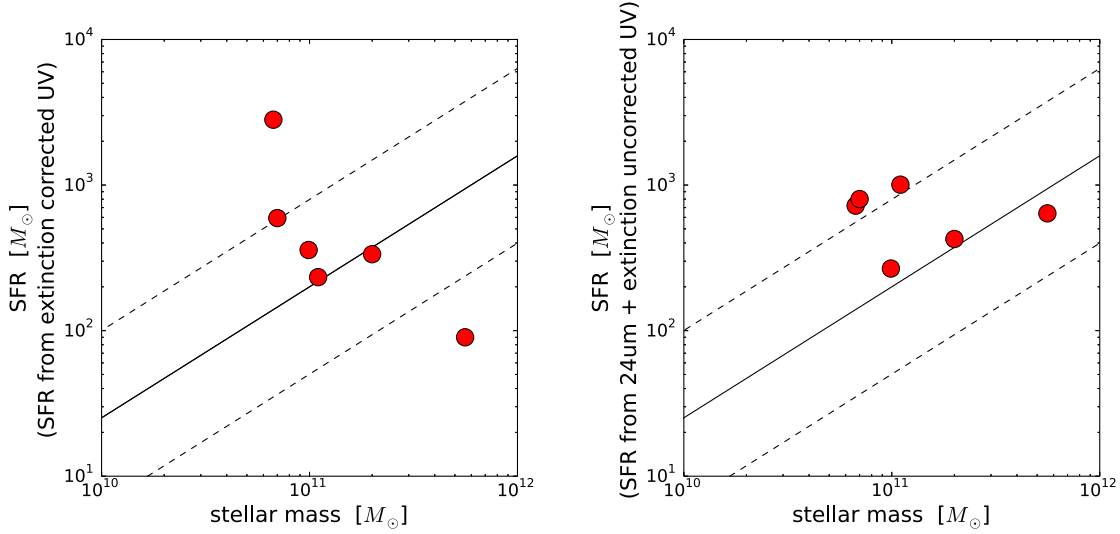


Figure 2.2: Galaxy sample for the observations with the Nobeyama radio telescope in a stellar mass-SFR diagram. SFRs are derived from extinction-corrected UV luminosity densities (left), and from the sum of SFRs from 24 μ m and SFRs from extinction-uncorrected UV luminosity densities (right). The solid line represents the main sequence derived by Daddi et al. (2010a) for galaxies at $z \sim 2$. The dashed lines show scatters of ± 0.6 dex.

density, and they are shown in the left and right panels of Figure 2.2, respectively.

2.2 Observations

2.2.1 Observations with ALMA

We made $^{12}\text{CO}(J = 5 - 4)$ observations toward the 20 galaxies using ALMA. The observations were carried out in 2012 August 9, 11, 15, and 26 during the ALMA cycle0 session (ID=2011.0.00648.S, PI=K. Ohta). The on-source time for each galaxy was 8–15 min. The number of 12 m antennas was 23–25. The observed frequencies were 222.094 GHz to 252.583 GHz (band-6). We used four correlator setups. The frequencies of local oscillator in each setup were 231.198 GHz, 236.168 GHz, 240.380 GHz, and 244.166 GHz. To cover the CO emission lines of all the sample galaxies, we set three or four spectral windows (SPWs) in each correlator setup. Each SPW had a bandwidth of 1.875 GHz. The spectral resolution was 488.28 kHz, corresponding to a velocity resolution of $0.58 - 0.66 \text{ km s}^{-1}$ at the observed frequency range. The FWHM of primary beam was about $26''$. The flux calibration was made with the Ganymede,

Table 2.2: Nobeyama sample.

Source	RA (J2000.0)	Dec (J2000.0)	z_{spec}	metallicity ($12 + \log(\text{O}/\text{H})$)	M_* ($M_\odot$)	SFR ^{a,b} ($M_\odot \text{ yr}^{-1}$)	SFR ^{a,c} ($M_\odot \text{ yr}^{-1}$)
SXDS1_12778	02:19:09.45	-5:09:49.0	1.396	$8.66^{+0.09}_{-0.13}$	5.6×10^{11}	90	639
SXDS1_13015	02:17:13.63	-5:09:39.8	1.451	$8.85^{+0.04}_{-0.04}$	2.0×10^{11}	335	426
SXDS3_80799	02:17:30.04	-5:24:31.6	1.429	$8.66^{+0.02}_{-0.02}$	1.1×10^{11}	233	1006
COSMOS_9	10:00:08.76	+2:19:02.3	1.461	< 8.68	6.7×10^{10}	2812	722
COSMOS_50	10:01:40.28	+2:33:30.9	1.21	$8.84^{+0.11}_{-0.11}$	7.0×10^{10}	593	801
COSMOS_53	10:01:36.15	+2:20:04.3	1.21	$8.68^{+0.11}_{-0.11}$	9.9×10^{10}	358	267

^a We adopted the Salpeter IMF (Salpeter 1955).

^b SFRs are derived from extinction-corrected UV luminosity densities.

^c SFRs are calculated by summing the SFRs derived from 24 μm flux densities and derived from UV luminosity densities.

Uranus, and Callisto. The phase calibrator was J0204 – 170. The bandpass calibrator was J2253 + 161.

2.2.2 Observations with Nobeyama radio telescope

We made $^{12}\text{CO}(J = 2 - 1)$ line observations toward the 6 star-forming galaxies on 2013 March 23 – 26 and May 16 – 18 (SXDS1_12778 and SXDS3_80799), on 2014 March 22, 23, and 25 (COSMOS_9 and COSMOS_50) and 2015 January 29, 31, and February 1 (COSMOS_53 and SXDS1_13015) using the Nobeyama 45 m telescope. The observing frequencies were 93.677 to 104.316 GHz calculated from the spectroscopic redshifts. We used the two-beam sideband-separating SIS receiver for z-machine with dual polarization (TZ receiver; Nakajima et al. 2013). The half-power beam width at these frequencies was $\sim 17''$. We used the flexible FX-type spectrometer (spectral analysis machine for the 45 m telescope (SAM45); Iono et al. 2012). We can use up to 16 spectral windows (SPWs) and choose the bandwidth of each SPW from several modes between 16 MHz and 2 GHz. To cover the wider range of velocity, we selected the 2 GHz mode. The frequency width of one channel is 488.28 kHz, because each array has 4096 channels. The image rejection ratios in the adopted frequency range were mostly more than 10 dB. The system noise temperature (T_{sys}) was typically 130 – 240 K. The accuracy of telescope pointing was checked every 50 min using observations of SiO maser sources (*o* Cet and R Leo) near the galaxy sample. During the observations, the pointing accuracy was within $4''$.

2.3 Data reductions

2.3.1 Reduction for ALMA data

Data reduction was carried out with the Common Astronomy Software Applications (CASA: McMullin et al. 2007) version 4.2 package in a standard manner. The delivered data which were calibrated had problems; the coordinates of the phase calibrator were wrong for three correlator setups (15 target galaxies) and the data of the flux calibrator for a SPW in one correlator setup was flagged for some unknown reason. The coordinates of the phase calibrator were found to be systematically shifted by the

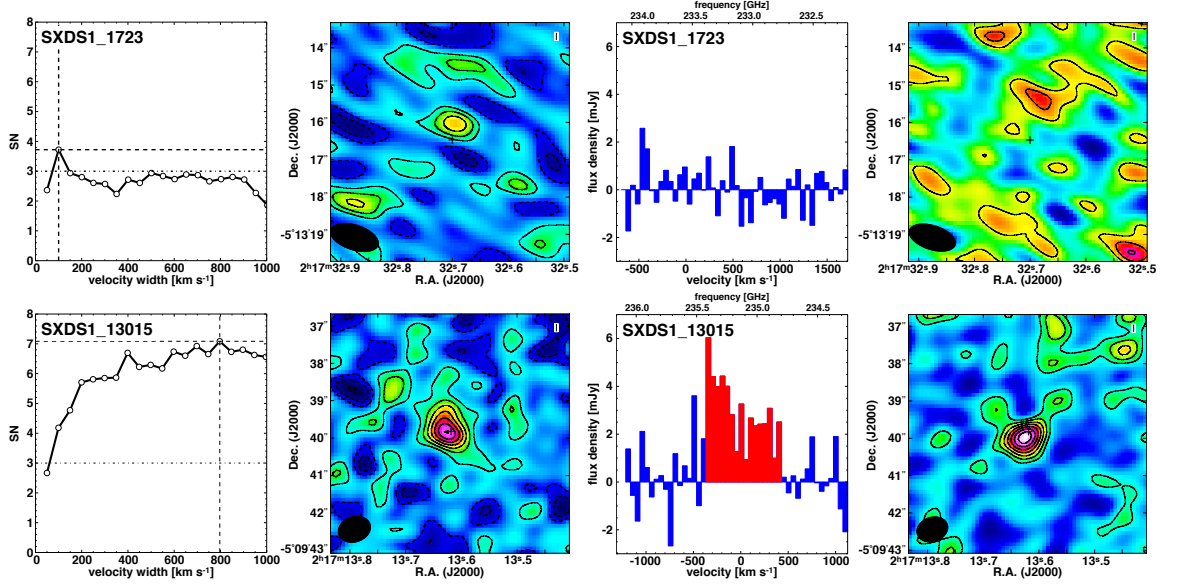


Figure 2.3: (Left) Growth curve of signal-to-noise ratio against integrated velocity width. Horizontal dashed line and dashed-dotted line refer to the peak S/N and the S/N of 3, respectively. The vertical dashed line refers to the integrated velocity width adopted. (Center left) Integrated CO(5 – 4) intensity map. The integrated velocity width is shown with a vertical dashed line in the growth curve of signal-to-noise ratio. Contours represent -2σ , -1σ (dashed lines), 1σ , 2σ , 3σ , ... (solid lines). The cross refers to the peak position in the K -band image. The filled black ellipse in the bottom left corner shows the synthesized beam size. (Center right) CO(5 – 4) spectrum. The zero velocity is derived from the spectroscopic redshift of the $H\alpha$ line. For the CO-detected galaxies, the spectra are made in the region where S/N is larger than 1 around the source, and the CO emission line is shown in red. For non-detected galaxies, the spectra are made in the central box. (Right) Continuum map. Contours represent 1σ , 2σ , 3σ , ... (solid lines). The cross refers to the peak position in the K -band image. The filled black ellipse again shows the synthesized beam size.

$0''.3$ in right ascension and $0''.04$ in declination. Since this shift is not negligible for stacking analysis, we made re-calibrations with the corrected coordinates of the phase calibrator and with the interpolated value for the flagged data of the flux calibrator. We used the 2012 models of the Solar system objects for flux calibrations.

We subtracted the continuum emission in uv-data by using the CASA task UVCONTSUB. Continuum maps were made by combining both the lower side band (LSB) and upper side band (USB) data in line-free frequencies. The maps were made with the CASA task CLEAN with natural weighting. The center position of each map coincided with the centroid of the galaxy in the K -band image. The number of iteration was zero (i.e., dirty maps) because the signal-to-noise ratios of the detected sources

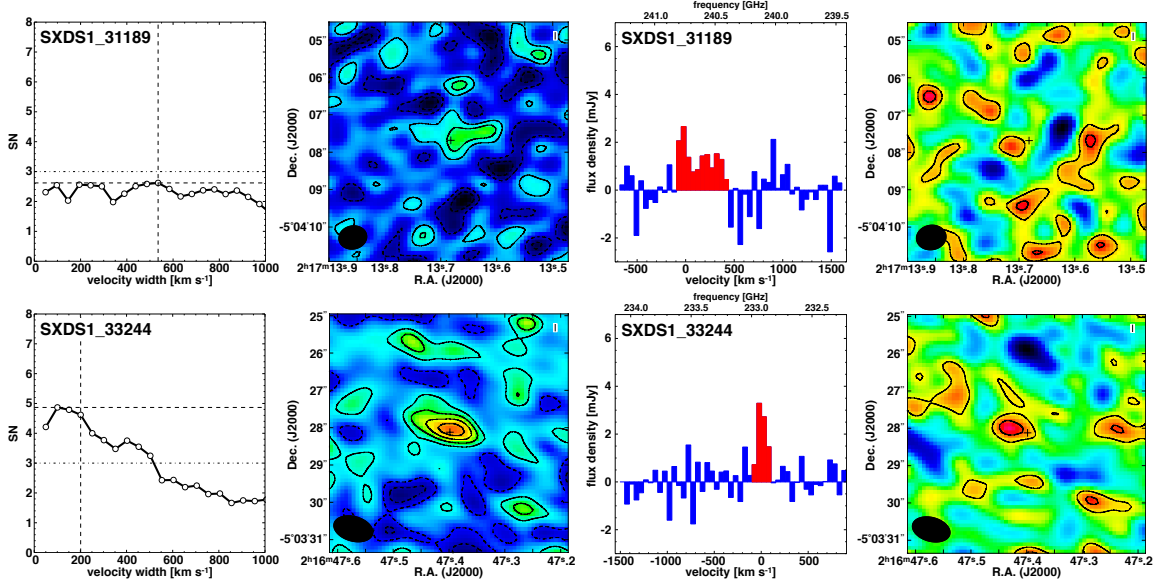


Figure 2.4: Same as Figure 2.3 but for other galaxies.

were not high and we were afraid the uncertainty in the maps increases by CLEAN. In addition, since we will discuss the results both for individual galaxy and stacked data below, we employ the same reduction procedure for detected and non-detected galaxies. It should be also noted that no strong sources exist in the fields of view. The synthesized beam size was $0''.6 - 1''.3$. The noise level of continuum map was $0.04 - 0.1 \text{ mJy beam}^{-1}$ (Table 4.1). For the CO emission studies, we made channel maps from the continuum subtracted data with a velocity resolution of $\sim 50 \text{ km s}^{-1}$; the noise level of each channel map was $0.5 - 1 \text{ mJy beam}^{-1}$.

Source detection

The following procedure is employed to search for CO emission lines: the redshifts of our sample galaxies are known from the near-infrared spectroscopic observations of $\text{H}\alpha$ emission lines. Thus we derive the “zero velocity” by reference to this redshift. We define the “central box,” which is the region within $\pm 0.5''$ in R.A. and decl. from the map center. Since the angular resolution of our observations is $0''.6 - 1''.3$, the peak position of any CO emission is reasonably expected to be in the central box if $\text{S/N} \geq 2$.

Using the CASA task IMMOMENTS, we make zeroth-order moment maps (in-

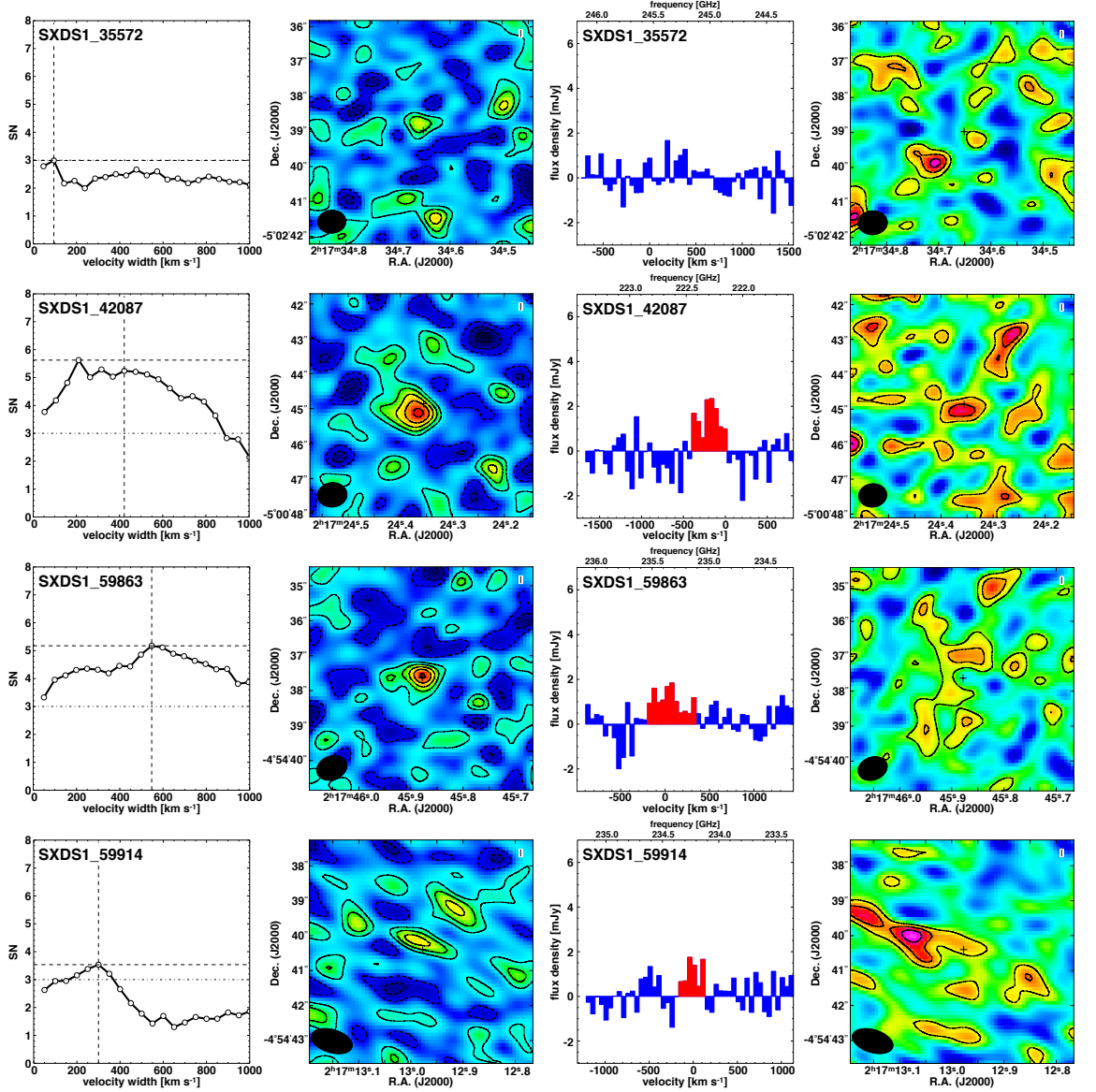


Figure 2.5: Same as Figure 2.3 but for other galaxies.

egrated intensity maps) by changing the velocity width ($\Delta v = 50 - 1000 \text{ km s}^{-1}$) centered at the zero velocity. We measure the S/N in the central box for each integrated intensity map and make a curve of S/N growth against the velocity width. We regard the feature as a candidate for detection if the following criteria are satisfied: the highest S/N in the growth curve is > 3 , the S/Ns within a velocity width $\pm 50 \text{ km s}^{-1}$ from the velocity width giving the highest S/N are also > 3 , and the peak positions in the maps lie within the central box.

Since the accuracy of the zero velocity is $\sim 150 \text{ km s}^{-1}$, there may be a more

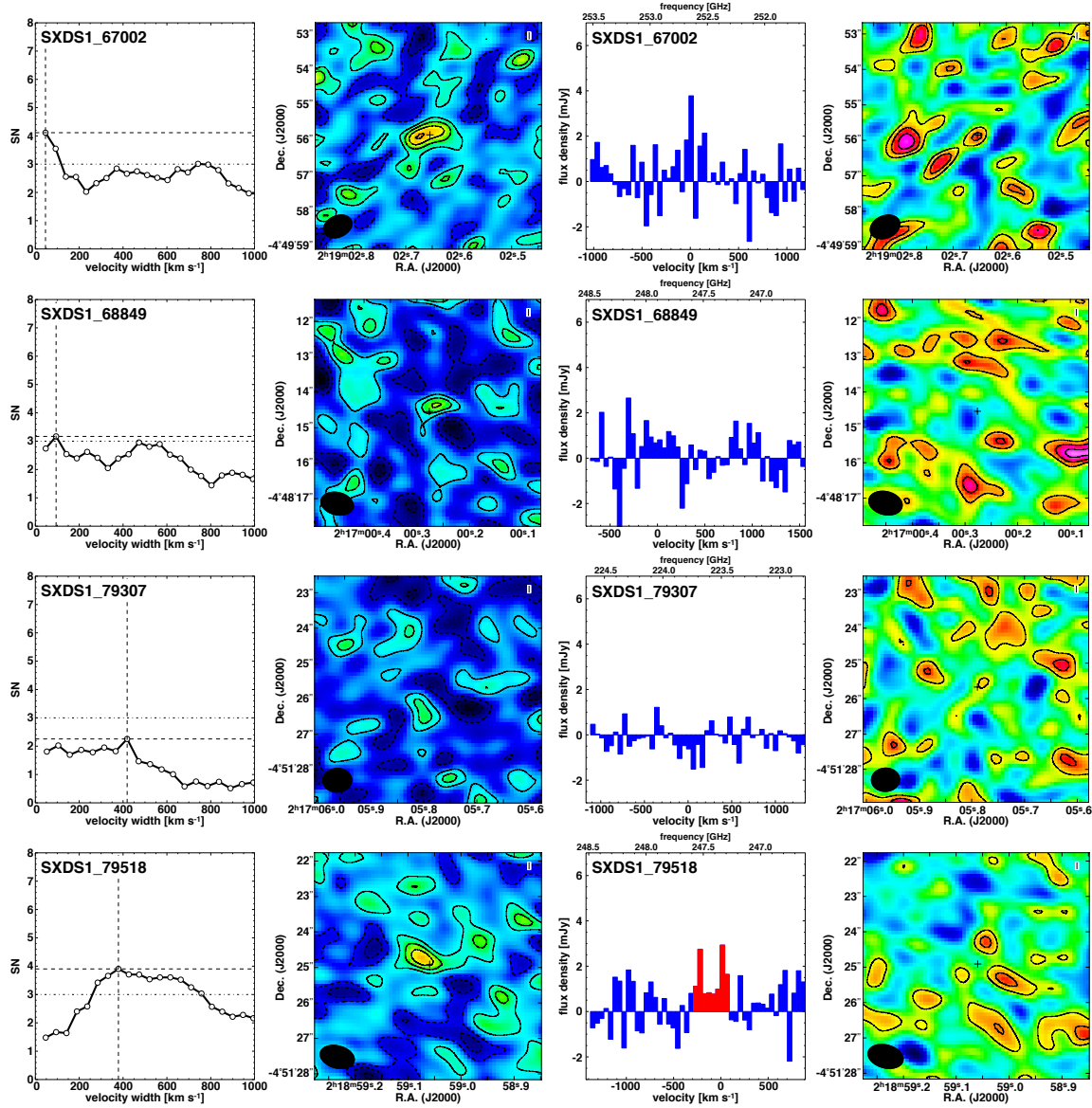


Figure 2.6: Same as Figure 2.3 but for other galaxies.

appropriate choice of zero velocity. Thus, we change the “central velocity” of the integrated intensity maps within $\pm 200 \text{ km s}^{-1}$ from the zero velocity and repeat the analysis for all targets.

From the two analyses mentioned in the above two paragraphs, we take the combination of the central velocity and velocity width that produces the peak with the highest S/N in the central box. Ten such sources are regarded as candidates for detection.

Next, we make a spectrum of the candidate in the region with $\text{S/N} > 1$ around

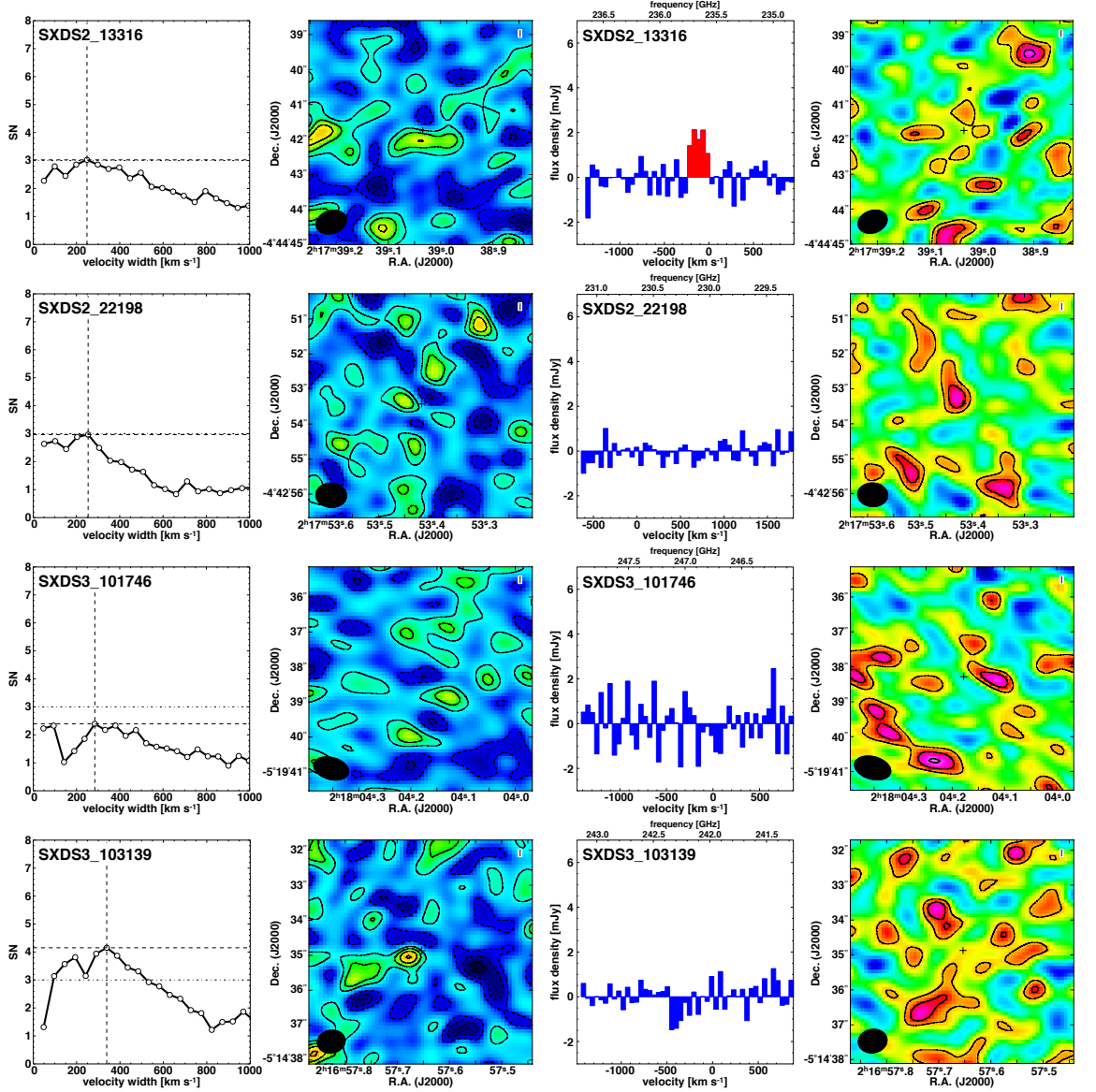


Figure 2.7: Same as Figure 2.3 but for other galaxies.

the candidate in the integrated intensity map. If CO emission is also seen adjacent to the velocity width adopted above, we make the integrated intensity map including this velocity range and check whether the map satisfies the criteria mentioned above. Finally, when S/N in the spectrum smoothed with the integrated velocity width is > 3 , we consider the CO emission to be detected.

In the case of SXDS1.31189, the S/Ns in the integrated intensity maps for all velocity widths are slightly less than 3, but the emission line is clearly seen in the spectrum at zero velocity. Thus, we consider the CO emission line to be detected. In

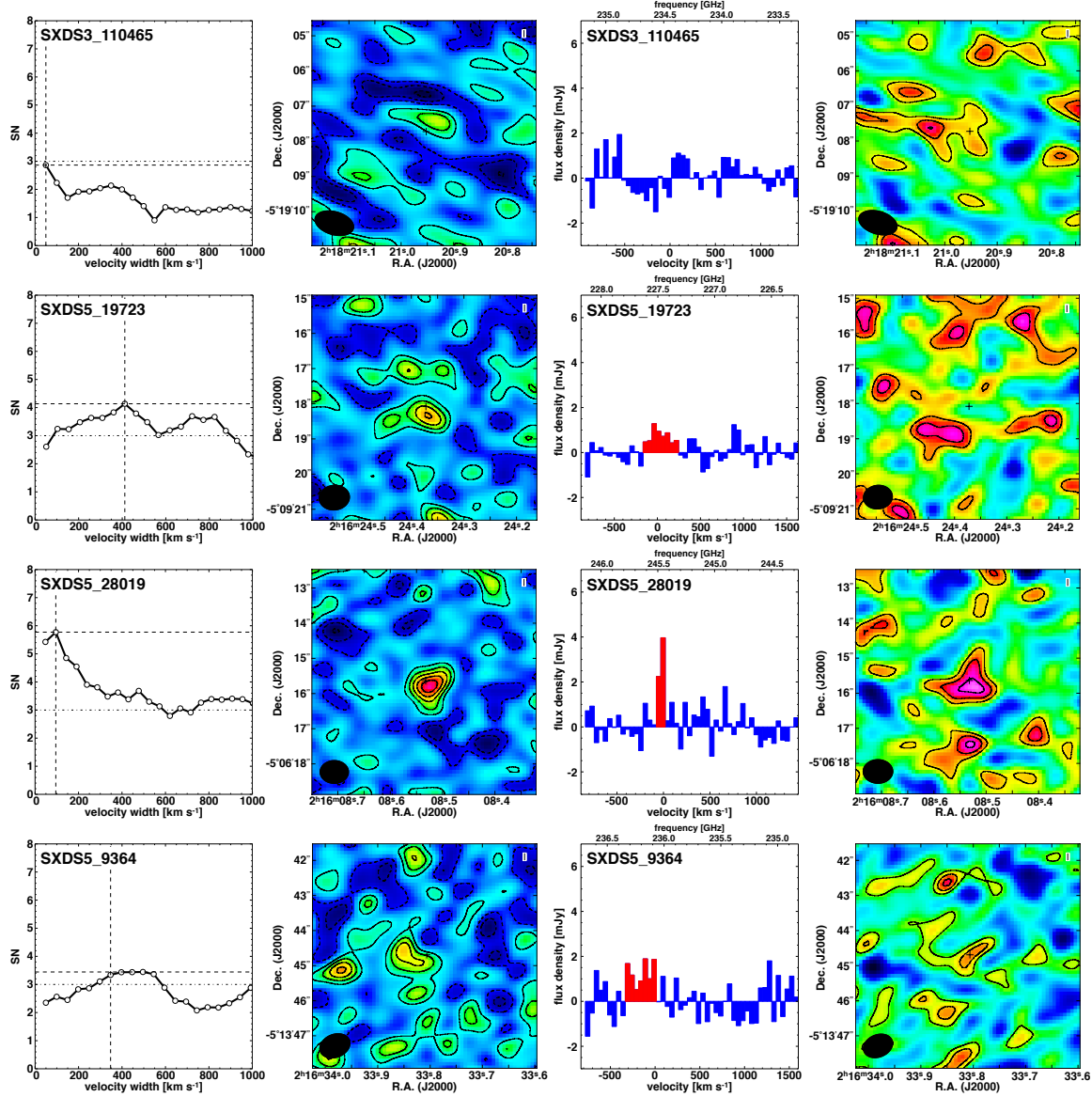


Figure 2.8: Same as Figure 2.3 but for other galaxies.

the case of SXDS2_13316, the S/N is ~ 3 at the velocity width of 250 km s^{-1} , but it is slightly less than 3 when the velocity width changes by $\pm 50 \text{ km s}^{-1}$. Again, the emission line is very clearly seen in the spectrum. Thus, we also consider this CO emission line to be detected. In Figures 2.3–2.8, we show the S/N growth curves, the integrated intensity maps made with the velocity width shown in the growth curves, and the CO($J = 5 - 4$) line profiles. The peak positions of all the detected source are within $\pm 0''.3$ in R.A. and decl. from the map center, confirming that the size of the central box is appropriate.

For the detection of dust thermal emissions, we use the continuum map (right panels of Figures 2.3 – 2.8). We consider detections for cases where the peak S/N in the central box is > 3 , and marginal detections if the peak S/N is $2 - 3$.

2.3.2 Reduction for Nobeyama data

We used the NEWSTAR software for the data reduction. Data taken under the conditions of a wind speed of less than 5 m s^{-1} were used. In addition, we flagged data with a poor baseline by visual inspection. We used three flagging criteria in order to check the robustness of our result. All analyses showed similar results. After flagging, the effective integration time per galaxy was $2.2 - 8.5$ hours. All data were converted from the antenna temperature (T_A) to the main beam temperature (T_{mb}). The main beam efficiencies were 0.36 for SXDS1_12778 and SXDS3_80799, 0.38 for COSMOS_9 and COSMOS_50, and 0.42 for COSMOS_53 and SXDS1_13015. The root-mean-square noise temperature in the T_{mb} scale was $0.7 - 2.2$ mK after binning to 50 km s^{-1} resolution.

Chapter 3

Molecular gas properties at $z \sim 1.4$

3.1 Results of ALMA observations for CO emission lines

3.1.1 Individual Galaxy

We detected CO($J = 5 - 4$) emission lines from 11 galaxies. These galaxies are shown with filled red circles in the diagrams of SFR versus stellar mass and metallicity versus stellar mass (Figure 3.1). The CO lines tend to be detected for galaxies with more massive/higher SFR on average. No clear dependence on metallicity is seen, though the average metallicity of the detected galaxies is slightly larger than that of the non-detected galaxies. CO emission lines were not detected for the most massive two galaxies (SXDS1-35572 and SXDS1-79307), suggesting that the estimation of SFR is not correct for these two.

The CO($J = 5 - 4$) line luminosity ($L'_{\text{CO}(5-4)}$) is given as

$$L'_{\text{CO}(5-4)} = 3.25 \times 10^7 S_{\text{CO}(5-4)} \Delta v \nu_{\text{rest}(5-4)}^{-2} D_L^2 (1+z)^{-1}, \quad (3.1)$$

where $L'_{\text{CO}(5-4)}$ is measured in K km s⁻¹ pc², $S_{\text{CO}(5-4)} \Delta v$ is the observed CO(5 - 4) integrated flux density in Jy km s⁻¹, $\nu_{\text{rest}(5-4)}$ is the rest frequency of the CO(5 - 4) emission line in GHz, and D_L is the luminosity distance in Mpc. For the non-detected galaxies, we make channel maps with a velocity resolution of 200 km s⁻¹, and measure

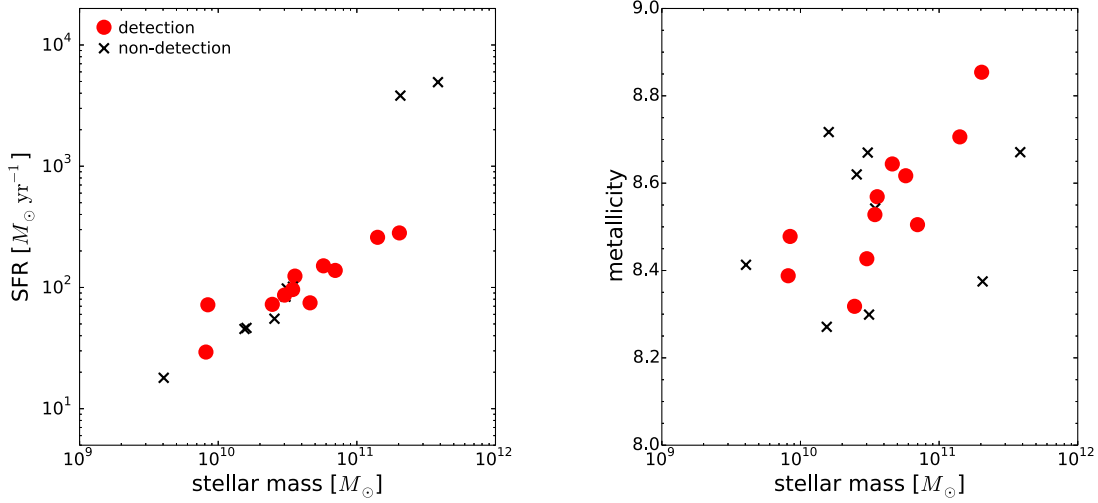


Figure 3.1: The location of the observed galaxies in the diagrams of SFR vs. stellar mass (left) and metallicity vs. stellar mass (right). Filled red circles refer to the galaxies for which CO($J = 5 - 4$) emission lines are detected. Crosses show the non-detections.

the noise levels (σ_{200}), because the FWHMs of the detected CO emission lines range from 45 km s^{-1} to 490 km s^{-1} and the average FWHM is about 200 km s^{-1} . We take a $2\sigma_{200}$ upper limit for the CO($5 - 4$) flux density and a velocity width of 200 km s^{-1} . CO($5 - 4$) luminosities and upper limits are shown in Table 3.1 and plotted against stellar mass and metallicity in Figure 3.2. The CO luminosities of the detected galaxies (filled red circles) appear to increase with increasing stellar mass and metallicity.

The molecular gas mass is derived from

$$M_{\text{mol}} = \alpha_{\text{CO}} L'_{\text{CO}(1-0)}. \quad (3.2)$$

To derive the molecular gas mass, the CO($5 - 4$)/CO($1 - 0$) luminosity ratio is needed. According to a study of the luminosity ratios in three sBzK galaxies at $z \sim 1.5$ (Daddi et al. 2015), the average CO($5 - 4$)/CO($1 - 0$) luminosity ratio is 0.23, corresponding to $S_{\text{CO}(5-4)}\Delta v / S_{\text{CO}(1-0)}\Delta v \sim 6$, with an uncertainty of a factor of 2. We adopt this value for the conversion of CO($5 - 4$) luminosity to CO($1 - 0$) luminosity. In local galaxies the value of α_{CO} correlates with gas metallicity: the value of α_{CO} is larger in galaxies with lower metallicity (e.g., Arimoto et al. 1996; Leroy et al. 2011). A similar relation is found in star-forming galaxies at $z = 1 - 2$ (Genzel et al. 2012). We adopt

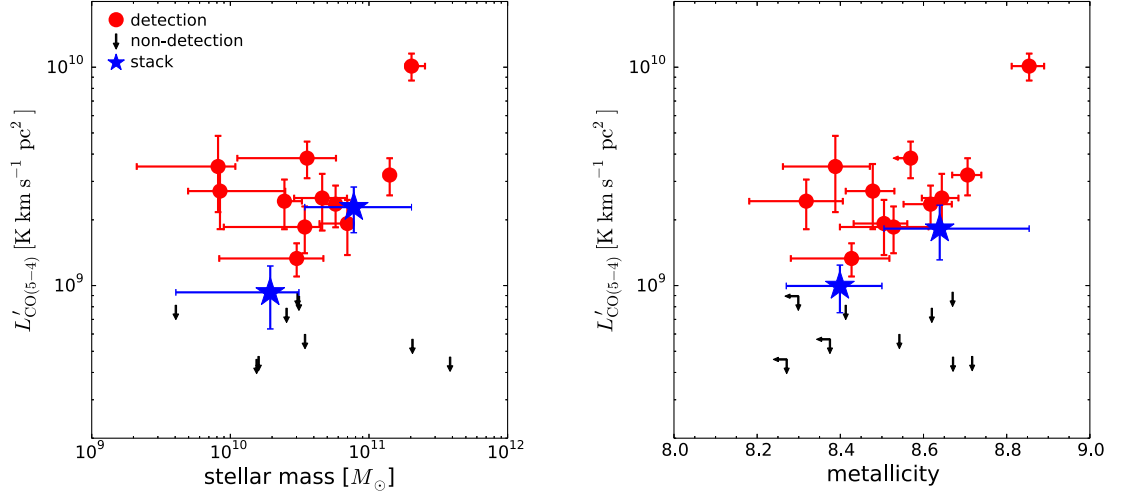


Figure 3.2: CO(5 – 4) luminosity plotted against stellar mass (left) and metallicity (right). Filled red circles refer to the CO-detected galaxies and arrows show the upper limits. Filled blue stars refer to the results of stacking analysis for the subsamples with larger/smaller stellar mass in the left panel and the subsamples with higher/lower metallicity in the right panel (see Section 3.1.2).

Equation (7) of Genzel et al. (2012):

$$\log(\alpha_{\text{CO}}) = -1.3 \times (12 + \log(\text{O}/\text{H}))_{\text{Denicol\'o 02}} + 12 \quad (3.3)$$

where $12 + \log(\text{O}/\text{H})_{\text{Denicol\'o 02}}$ is metallicity calibrated by Denicol\'o et al. (2002). Since we use the metallicity calibration of Pettini & Pagel (2004), we convert the metallicity using an empirical relation between the two metallicity calibrations of Kewley & Ellison (2008). Derived molecular gas masses are listed in Table 3.1 and plotted against stellar mass and metallicity in Figure 3.3. The uncertainty given to the molecular gas mass is based on the S/N of the integrated intensity map and does not include the uncertainty of the luminosity ratio and α_{CO} (uncertainty of a factor of ~ 2). For the detected galaxies (filled red circles), the molecular gas mass does not seem to depend on stellar mass and metallicity. The derived molecular gas mass fractions against stellar mass are also listed in Table 3.1 and plotted against stellar mass and metallicity in Figure 3.4. For the detected galaxies (filled red circles), the molecular gas mass fraction decreases with increasing stellar mass. This trend is the same as in previous studies (e.g., Tacconi et al. 2013). We show that the trend holds in galaxies

Table 3.1: Results of the ALMA observations.

ID	$\int S_{\text{CO}(5-4)} dv$ (Jy km s ⁻¹)	$L_{\text{CO}(5-4)}$ (10 ⁹ K km s ⁻¹ pc ²)	$M_{\text{gas}}^{\text{a}}$ (10 ¹⁰ $M_{\odot}$)	$f_{\text{gas}}^{\text{b}}$
SXDS1_13015	2.31 ± 0.33	10 ± 1	11 ± 2	0.36 ± 0.05
SXDS1_1723	< 0.20	< 0.9	< 4.2	< 0.57
SXDS1_31189	0.86 ± 0.33	3.5 ± 1.3	12 ± 4	0.94 ± 0.04
SXDS1_33244	0.52 ± 0.11	2.4 ± 0.5	4.2 ± 0.9	0.42 ± 0.08
SXDS1_35572	< 0.12	< 0.5	< 0.8	< 0.02
SXDS1_42087	0.73 ± 0.14	3.8 ± 0.7	7.6 ± 1.5	0.68 ± 0.15
SXDS1_59863	0.74 ± 0.14	3.2 ± 0.6	4.8 ± 0.9	0.25 ± 0.04
SXDS1_59914	0.43 ± 0.12	1.9 ± 0.5	4.5 ± 1.3	0.39 ± 0.08
SXDS1_67002	< 0.17	< 0.6	< 1.3	< 0.27
SXDS1_68849	< 0.21	< 0.8	< 1.4	< 0.35
SXDS1_79307	< 0.11	< 0.6	< 2.0	< 0.09
SXDS1_79518	0.66 ± 0.17	2.4 ± 0.6	11 ± 3	0.81 ± 0.05
SXDS2_13316	0.62 ± 0.21	2.7 ± 0.9	6.8 ± 2.3	0.89 ± 0.12
SXDS2_22198	< 0.10	< 0.5	< 0.7	< 0.30
SXDS3_101746	< 0.22	< 0.8	< 2.5	< 0.86
SXDS3_103139	< 0.12	< 0.5	< 2.4	< 0.61
SXDS3_110465	< 0.21	< 0.9	< 1.5	< 0.33
SXDS5_19723	0.38 ± 0.09	1.9 ± 0.4	4.1 ± 1.0	0.54 ± 0.14
SXDS5_28019	0.35 ± 0.06	1.3 ± 0.2	3.9 ± 0.7	0.57 ± 0.16
SXDS5_9364	0.58 ± 0.17	2.5 ± 0.7	4.2 ± 1.2	0.48 ± 0.13

^a We adopted the CO(5 − 4)/CO(1 − 0) luminosity ratio of 0.23 (Daddi et al. 2015) and a metallicity-dependent CO-to-H₂ conversion factor shown by Equation (3.3) (Genzel et al. 2012).

^b $f_{\text{gas}} = \frac{M_{\text{gas}}}{(M_{\text{gas}} + M_{\star})}$.

with lower stellar mass than have been observed in previous studies. Furthermore, we found that the molecular gas mass fraction decreases with increasing metallicity.

3.1.2 Stacking analysis

Since the CO emission lines from about half of our sample galaxies are not detected, we carried out a stacking analysis to examine the relations against stellar mass and metallicity. For the stacking analysis, we use images without applying cleaning (i.e., dirty maps). The images are stacked on a pixel-by-pixel basis using a weighted average. The weights are calculated as $1/\sigma^2$, where σ is the rms noise level in each map. Lindroos et al. (2015) constructed an algorithm for *uv*-stacking, and they found that image-stacking produced similar results to *uv*-stacking. To study the properties of

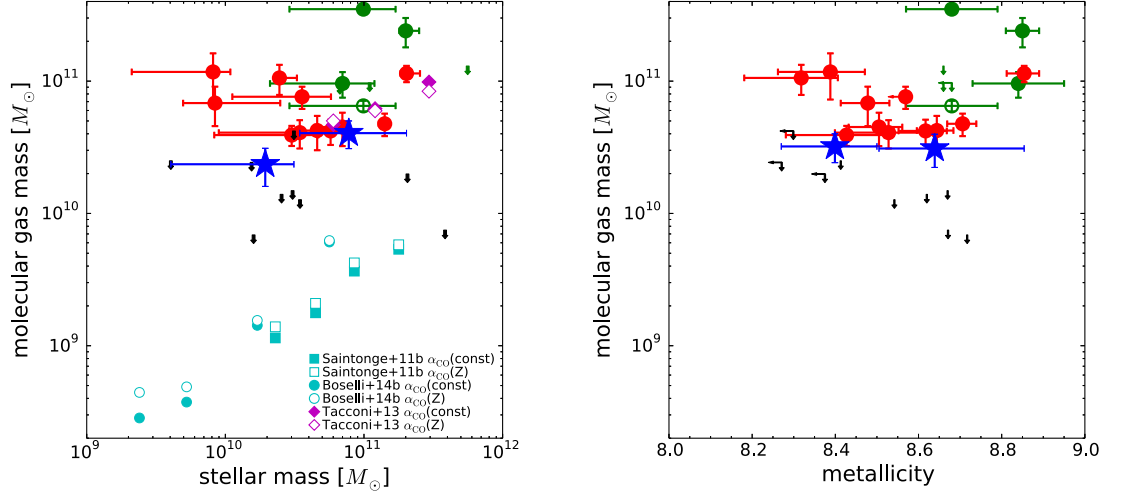


Figure 3.3: Molecular gas mass plotted against stellar mass (left) and metallicity (right). For the ALMA sample, we adopted a CO(5 – 4)/CO(1 – 0) luminosity ratio of 0.23 and the metallicity-dependent CO-to-H₂ conversion factors shown in Equation 3.3. For the Nobeyama sample, we adopted a CO(2 – 1)/CO(1 – 0) luminosity ratio of 0.76 and the Galactic conversion factor ($= 4.36 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$). Filled red circles, arrows, and filled blue stars are the same as those in Figure 3.1. Filled green circles and arrows represent Nobeyama galaxy sample, and the open green circle represents COSMOS.53 using the ULIRG-like conversion factor ($= 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$) for the derivation of molecular gas mass. Filled cyan squares and circles refer to the average values in local galaxies with a constant CO-to-H₂ conversion factor given by Saintonge et al. (2011a) and Boselli et al. (2014b), respectively. Filled magenta diamonds refer to the average values at $z \sim 1.5$ with the Galactic conversion factor (Tacconi et al. 2013). Open cyan and magenta symbols show the values obtained with a metallicity-dependent CO-to-H₂ conversion factor. See text for more details.

the ISM in main-sequence galaxies, we did not include the two most massive galaxies, SXDS1_35572 and SXDS1_79307, in our stacking analysis.

For the stacking analysis of CO emission lines, we used channel maps with 50 km s^{-1} bins over a range of $\pm 1000 \text{ km s}^{-1}$ from the zero velocities. Then, we stacked the maps at the same velocity. The detection criteria for the stacked maps are the same as those for the individual galaxies. Error bars of integrated intensity are derived from a random resampling of stacked galaxies. The molecular gas mass is derived using the same CO luminosity ratio and metallicity-dependent CO-to-H₂ conversion factor as those used for individual galaxies. The stellar mass and redshift of the stacks are taken to be average values of the stacked galaxies. The metallicity is also derived from stacked

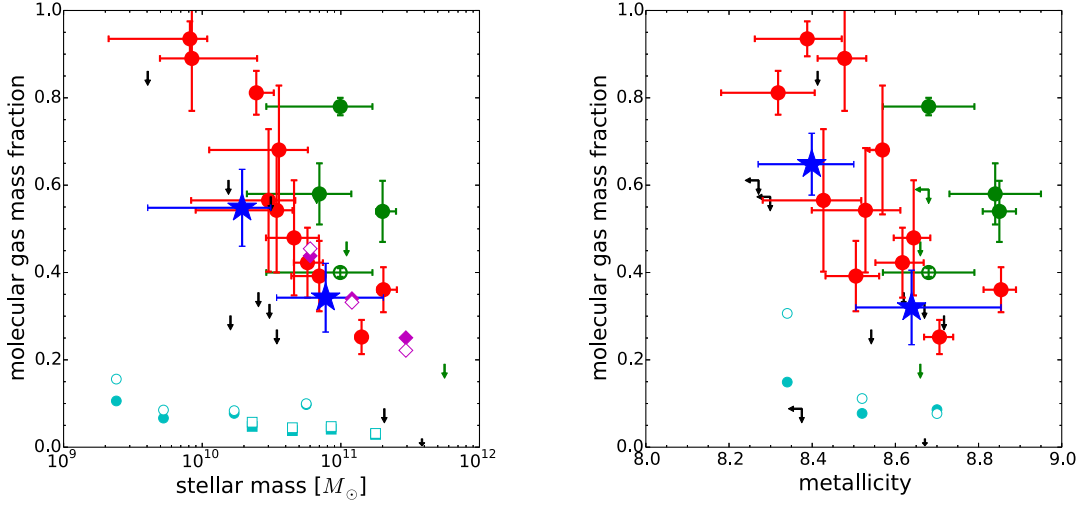


Figure 3.4: Molecular gas mass fraction plotted against stellar mass (left) and metallicity (right). Symbols are the same as those in Figure 3.3

FMOS spectra (details are described in Yabe et al. 2012, 2014).

Stacking analysis of subsamples with larger/smaller stellar mass

In order to examine the dependences of molecular gas mass and gas mass fraction on stellar mass, we carried out a stacking analysis for subsamples with smaller stellar mass ($(0.4 - 3.1) \times 10^{10} M_{\odot}$, 10 galaxies) and larger stellar mass ($(3.4 - 20) \times 10^{10} M_{\odot}$, 8 galaxies). The noise levels in the channel maps for these subsamples are similar (~ 0.25 mJy beam $^{-1}$ at a velocity resolution of 50 km s $^{-1}$). The resulting stacked images for subsamples with smaller and larger stellar mass are shown in the left panels of the top and bottom rows of Figure 3.5, respectively. The stacked profiles are shown in the right panels of Figure 3.5. The integrated intensity maps are made with the velocity range shown with red in the profiles. The CO emissions are significantly detected for both subsamples. CO(5 – 4) line luminosities are $(9.3 \pm 3.0) \times 10^8$ K km s $^{-1}$ pc 2 and $(2.3 \pm 0.5) \times 10^9$ K km s $^{-1}$ pc 2 for the subsamples with smaller and larger stellar mass, respectively, and are plotted against stellar mass in the left panel of Figure 3.2 (filled blue stars). We carried out Welch’s t test to evaluate the significance of the difference between the stacked values of the subsamples. Here, the null hypothesis is that mean values of both subsamples are equal. The significance level for the null hypothesis is

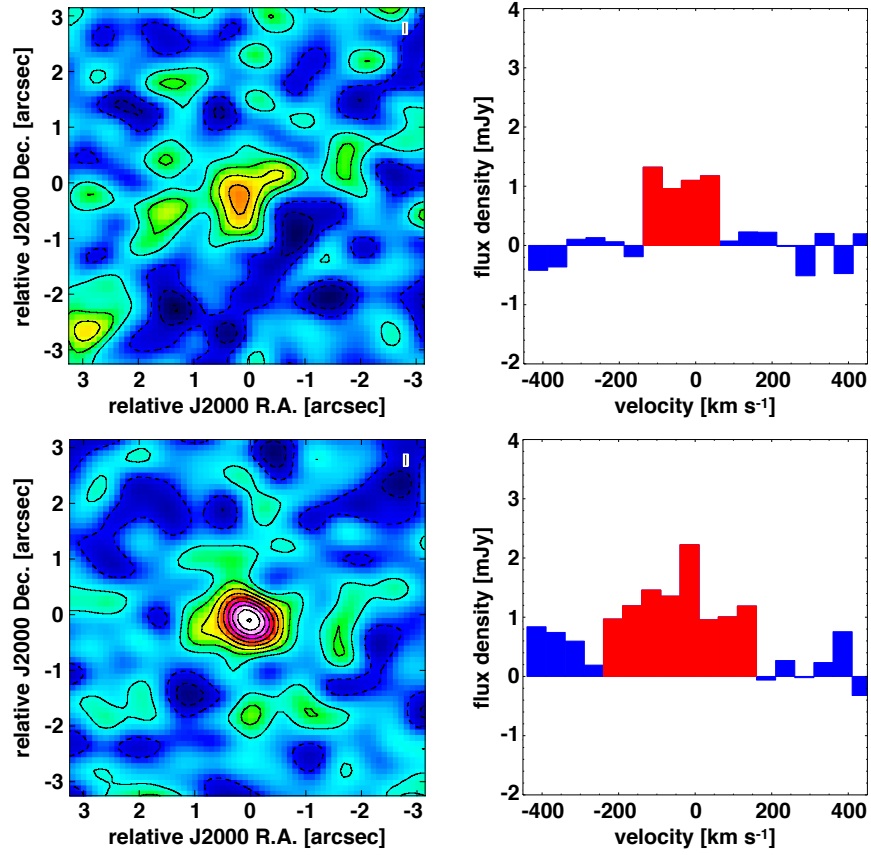


Figure 3.5: (Top left) Stacked integrated CO(5 – 4) intensity map of the subsample with smaller stellar mass. Contours represent -2σ , -1σ (dashed lines), 1σ , 2σ , 3σ , ... (solid lines). (Top center) Stacked CO(5 – 4) spectrum of the subsample with smaller stellar mass. CO emission is shown in red, which also indicates the velocity range to make the intensity map. The zero velocity is derived by reference to the spectroscopic redshift of H α emission. The spectrum is made in the region where S/N > 1 around the stacked source. (Top right) Stacked continuum map of the subsample with smaller stellar mass. Contours represent 1σ , 2σ , 3σ , ... (solid lines). (Bottom) Same as the top row, but for the stacking analysis of the subsample with larger stellar mass.

0.003%. Thus we see that the CO luminosity increases significantly with increasing stellar mass. The resulting molecular gas masses of the subsamples with smaller and larger stellar mass are $(2.4 \pm 0.7) \times 10^{10} M_{\odot}$ and $(4.0 \pm 1.0) \times 10^{10} M_{\odot}$, respectively, and are plotted in the left panel of Figure 3.3 (filled blue stars).

We compare the results with those in local galaxies (COLD GASS and HRS). Because the studies in local galaxies used a Chabrier IMF, we converted the stellar mass and SFR to those with a Salpeter IMF by multiplying by 1.7 (Speagle et al. 2014). In addition, the CO-to-H₂ conversion factor used in the studies does not include the

helium mass and is not corrected for metallicity dependence. Thus, in the left panel of Figure 3.3, we also plot the local molecular gas mass considering a 30% contribution of helium (filled cyan symbols) and the metallicity-dependent CO-to-H₂ conversion factor (open cyan symbols: Leroy et al. 2011; Bolatto et al. 2013). We estimated the metallicity of the local sample from the mass-metallicity relation in the local universe, whose metallicity is derived based on the N2 method (Erb et al. 2006). Erb et al. (2006) derived the local relation with the N2 method by using the galaxies in the Sloan Digital Sky Survey (SDSS) to compare the relation at $z \sim 2$. The study of molecular gas at $z \sim 1.5$ by Tacconi et al. (2013) also used a Chabrier IMF and the Galactic CO-to-H₂ conversion factor ($\sim 4.36 M_{\odot} \text{ K km s}^{-1} \text{ pc}^2$; including helium mass). We converted the stellar mass and SFR to those with a Salpeter IMF, and we plotted the molecular gas mass in the left panel of Figure 3.3 (filled magenta diamonds) and plotted that derived with the metallicity-dependent CO-to-H₂ conversion factor given by Equation (3.3) (open magenta diamonds). The metallicity was estimated from the mass-metallicity relation at $z \sim 1.4$ (Yabe et al. 2014). The molecular gas masses of our sample galaxies are significantly larger than those in local star-forming galaxies with similar stellar mass ($M_{\text{mol}} \sim 3 \times 10^9 M_{\odot}$, Saintonge et al. 2011a). The molecular gas mass seems to increase with increasing stellar mass (significance level for the null hypothesis is 0.25%).

The gas mass fractions are 0.55 ± 0.09 and 0.34 ± 0.08 for the subsamples with smaller and larger stellar mass, respectively, and are plotted against stellar mass in the left panel of Figure 3.4 (filled blue stars). These gas mass fractions are also significantly larger than those in local star-forming galaxies ($f_{\text{mol}} \sim 0.08$, Saintonge et al. 2011a). The gas fraction decreases significantly with increasing stellar mass (significance level for the null hypothesis is 0.01%). This trend is the same as that in local galaxies (e.g., Saintonge et al. 2011a; Boselli et al. 2014b) and in previous studies at similar redshift (e.g., Tacconi et al. 2013), but our sample extends to the lower stellar mass.

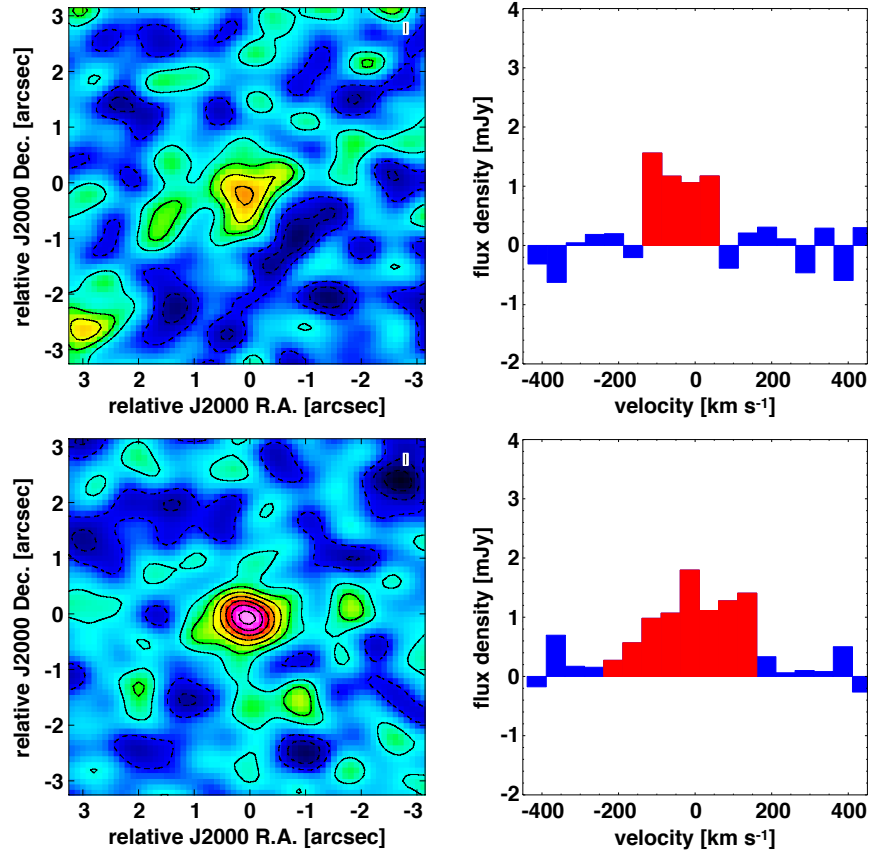


Figure 3.6: Same as Figure 3.5, but for the stacking analysis of the lower metallicity subsample (top) and the higher metallicity subsample (bottom).

Stacking analysis of subsamples with higher/lower metallicity

In order to examine the dependences of molecular gas mass and gas mass fraction on metallicity, we made stacking analysis for subsamples with lower metallicity ($12 + \log(\text{O}/\text{H}) < 8.5$, 7 galaxies) and higher metallicity ($12 + \log(\text{O}/\text{H}) > 8.5$, 10 galaxies). We exclude SXDS1.42087 because the metallicity is an upper limit ($12 + \log(\text{O}/\text{H}) < 8.57$). The noise levels in the channel maps of these subsamples are similar ($\sim 0.25 \text{ mJy beam}^{-1}$ at a velocity resolution of 50 km s^{-1}). The resulting stacked images for subsamples with lower metallicity and higher metallicity are shown in left panels of the top and bottom rows of Figure 3.6, respectively. The stacked profiles are shown in the right panels of Figure 3.6. The integrated intensity maps are made with the velocity range shown in red in the profiles. The CO emissions are significantly detected for both subsamples. CO(5 – 4) line luminosities are $(1.0 \pm 0.3) \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$ and $(1.8 \pm 0.5) \times 10^9 \text{ K km s}^{-1} \text{ pc}^2$ for the lower

and higher metallicity subsamples, respectively, and are plotted against metallicity in the right panel of Figure 3.2 (filled blue stars). The CO luminosity seems to increase with increasing metallicity (significance level for the null hypothesis is 0.1%). The resulting molecular gas masses of the lower and higher metallicity subsamples are $(3.2 \pm 0.8) \times 10^{10} M_{\odot}$ and $(3.1 \pm 0.9) \times 10^{10} M_{\odot}$, respectively, and are plotted in the right panel of Figure 3.3 (filled blue stars). The molecular gas mass does not depend on metallicity (significance level for the null hypothesis is 82%). In this figure, the result in local star-forming galaxies is not shown. Because Boselli et al. (2014b) showed the ratio of molecular gas mass to stellar mass but did not show the stellar mass for the metallicity-based analysis, we were not able to calculate the molecular gas mass.

The gas mass fractions are 0.65 ± 0.07 and 0.32 ± 0.09 for the lower and higher metallicity subsamples, respectively, and are plotted against metallicity in the right panel of Figure 3.4 (filled blue stars). The molecular gas mass fraction decreases significantly with increasing metallicity (significance level for the null hypothesis is less than 0.001%).

3.1.3 Relations for subsamples with fixed metallicity and fixed stellar mass

The relations between gas mass or its fraction and stellar mass or metallicity are examined. Due to the mass-metallicity relation, however, the dependences on stellar mass and metallicity are not clearly separated. Thus we next investigate the dependence on just stellar mass or metallicity by using a stacking analysis.

First, to avoid the metallicity effect, we made the stacking analysis for subsamples with smaller $((1 - 4) \times 10^{10} M_{\odot})$ and larger $((4 - 15) \times 10^{10} M_{\odot})$ stellar mass but with almost the same metallicity (8.50 – 8.75). The subsamples with smaller and larger stellar mass include five and four galaxies, respectively. We exclude SXDS1_42087 because the metallicity is an upper limit of $12 + \log(\text{O}/\text{H}) < 8.57$. The average stellar mass and stacked metallicity of the subsample with smaller stellar mass are $2.8 \times 10^{10} M_{\odot}$ and 8.61 and those of the subsample with larger stellar mass are

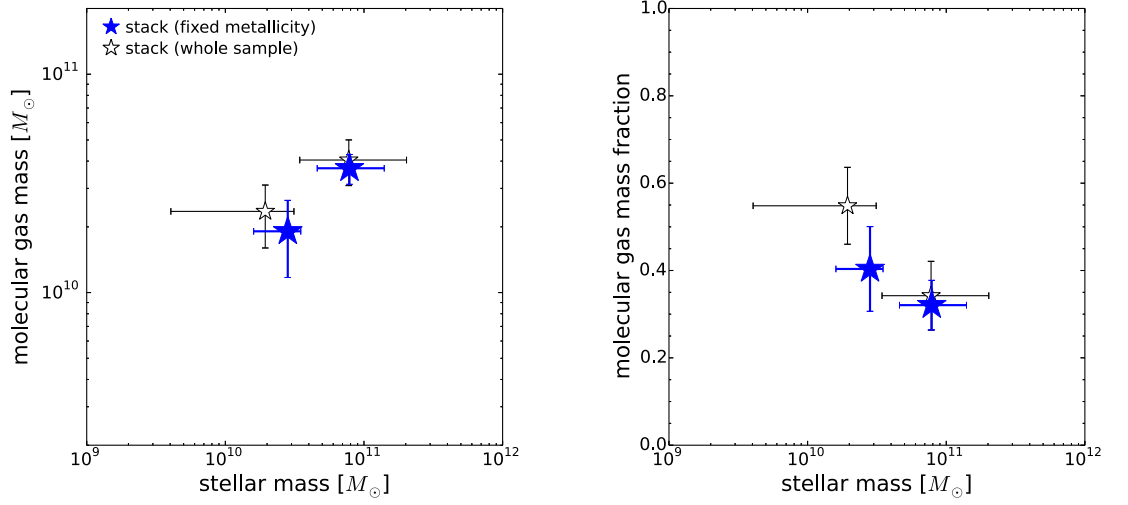


Figure 3.7: Molecular gas mass (left) and molecular gas mass fraction (right) against stellar mass. Large filled blue stars refer to the stacking analysis for the subsamples with larger/smaller stellar mass but with almost the same stacked metallicity. Small open stars refer to the stacking analysis for the subsamples with larger/smaller stellar mass using the whole sample.

$7.9 \times 10^{10} M_\odot$ and 8.63. According to the mass-metallicity relation at $z \sim 1.4$ (e.g., Yabe et al. 2014), the difference in stellar mass in these subsamples ($2.8 \times 10^{10} M_\odot$ and $7.9 \times 10^{10} M_\odot$) produces the difference in metallicity of 0.07. Thus, the difference in metallicity in these subsamples (8.61 and 8.63) does not trace the mass-metallicity relation and it is reasonable to consider that only the stellar mass effect can be seen. The resulting molecular gas masses of the subsamples with smaller and larger stellar mass are $(1.9 \pm 0.7) \times 10^{10} M_\odot$ and $(3.7 \pm 0.6) \times 10^{10} M_\odot$, respectively. We plot the result in the left panel of Figure 3.7 (filled blue stars). The trend for the gas mass (significance level for the null hypothesis is 0.4%) is the same as that for the whole sample of galaxies (open stars). The gas mass fractions are 0.40 ± 0.10 and 0.32 ± 0.06 for the subsamples with smaller and larger stellar mass, respectively. We plot the result in the right panel of Figure 3.7 (filled blue stars). Although the trend for the gas mass fraction seems to be the same as that for whole sample (open stars), it is not so significant (significance level for the null hypothesis is 18%).

Next, to avoid the stellar mass effect, we made the stacking analysis for subsamples with lower (< 8.55) and higher ($8.6 - 8.8$) metallicity but with comparable stellar

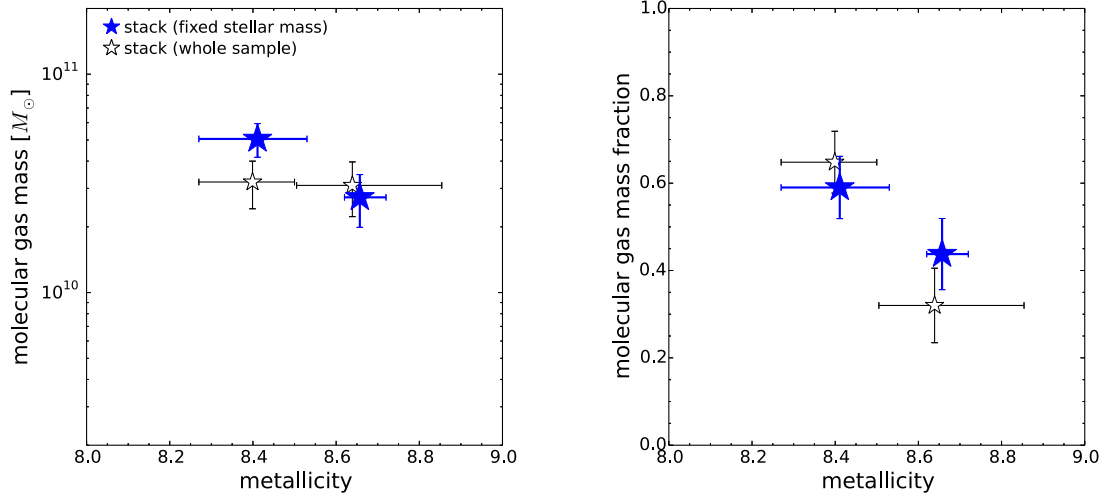


Figure 3.8: Molecular gas mass (left) and molecular gas mass fraction (right) are plotted against metallicity. Large filled blue stars refer to the stacking analysis for the subsamples with higher/lower metallicity but with the same average stellar mass. Small open stars refer to the stacking analysis for the subsamples with higher/lower metallicity using the whole sample.

mass ($10^{10-11} M_\odot$). The subsamples with lower and higher metallicity both include five galaxies. The average stellar mass and stacked metallicity of the lower metallicity subsample are $3.5 \times 10^{10} M_\odot$ and 8.41, and those of higher metallicity subsample are $3.5 \times 10^{10} M_\odot$ and 8.66. Since there is no difference in stellar mass in these subsamples, it is reasonable to conclude that only the metallicity effect can be seen. The resulting molecular gas masses of the lower and higher metallicity subsamples are $(5.3 \pm 0.9) \times 10^{10} M_\odot$ and $(2.8 \pm 0.8) \times 10^{10} M_\odot$, respectively. We plot the results in the left panel of Figure 3.8 (filled blue stars). The molecular gas mass decreases with increasing metallicity (significance level for the null hypothesis is 0.2%); this trend is different from that for the whole sample of galaxies (open stars). The gas mass fractions are 0.60 ± 0.07 and 0.45 ± 0.08 for the lower and higher metallicity subsamples, respectively. We also plot the result in the right panel of Figure 3.8 (filled blue stars). The gas mass fraction seems to decrease with metallicity (significance level for the null hypothesis is 1.3%), which is the same trend as seen for the whole sample of galaxies (open stars).

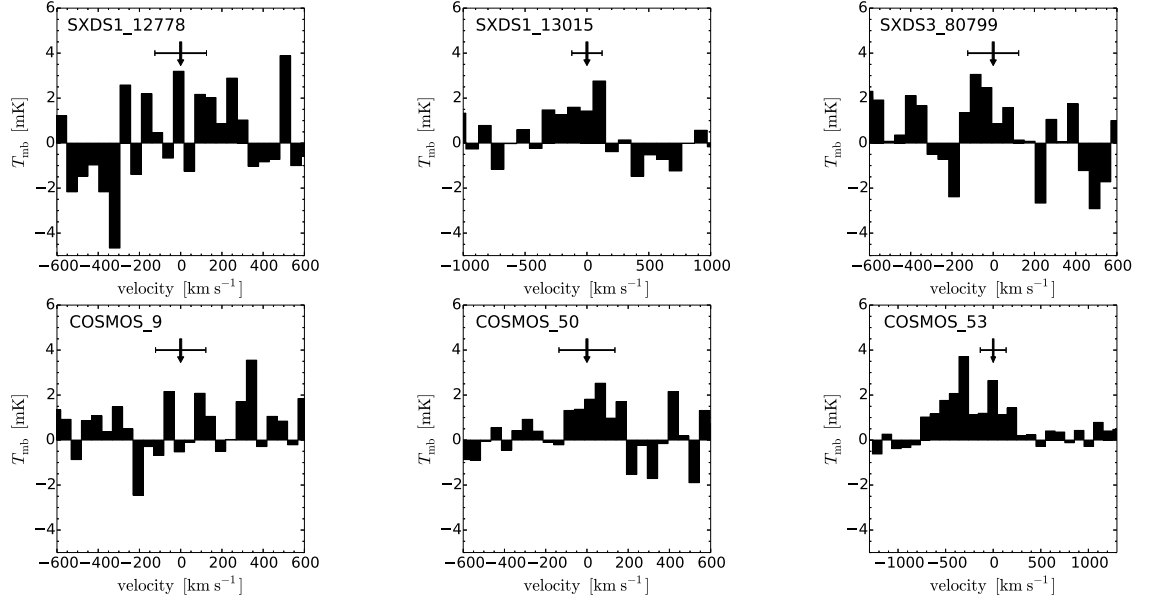


Figure 3.9: CO(2-1) spectra taken with the Nobeyama 45 m telescope. Spectra are binned with a 50 km s^{-1} velocity width for SXDS1_12778, SXDS3_80799, COSMOS_9, and COSMOS_50 and with a 100 km s^{-1} velocity width for SXDS1_13015 and COSMOS_53. Arrows show the velocity zero points for CO lines expected from spectroscopic redshifts by $\text{H}\alpha$ observations. Horizontal bars show the uncertainty of the velocity zero points.

3.2 Results of Nobeyama observations

3.2.1 CO($J = 2 - 1$) spectra

The spectra obtained with the Nobeyama 45 m telescope are shown in Figure 3.9. The arrow in each panel shows a velocity zero point obtained from the spectroscopic redshift of the $\text{H}\alpha$ observations. The horizontal bar shows the uncertainty of the velocity zero point due to the uncertainty of the redshift. The CO(2-1) emission line was detected toward SXDS1_13015, COSMOS_50, and COSMOS_53. The spectrum of SXDS1_13015 shows a velocity width of 500 km s^{-1} , and the noise level at a velocity resolution of 500 km s^{-1} (σ_{500}) is 0.41 mK. The signal-to-noise ratio (S/N) of SXDS1_13015 at the 500 km s^{-1} resolution is 4.1. The spectrum of COSMOS_50 shows a velocity width of 300 km s^{-1} , and the noise level at the velocity resolution (σ_{300}) is 0.35 mK. The S/N of COSMOS_50 at the 300 km s^{-1} resolution is 4.6. The spectrum of COSMOS_53 shows a velocity width of 1000 km s^{-1} , and the noise level at the velocity resolution (σ_{1000}) is 0.16 mK. The S/N of COSMOS_53 at the 1000 km s^{-1}

resolution is 10.5. The velocity width is larger than the typical value ($\sim 200 \text{ km s}^{-1}$) for main-sequence galaxies at a similar redshift (e.g., Tacconi et al. 2013; and the Section 3.1.1 in this thesis). We checked an I_{F814W} -band image taken with ACS on the *HST* (Koekemoer et al. 2007). The image of COSMOS_53 shows that the target may be a merging system; thus, the CO emission line may include both merging galaxies. In the spectra of SXDS3_80799, a weak signal-like feature is seen close to the expected zero point with a velocity width of $\sim 200 - 250 \text{ km s}^{-1}$. The noise level at a velocity resolution of 250 km s^{-1} (σ_{250}) is 0.7 mK. The S/N of SXDS3_80799 at the 250 km s^{-1} resolution is 2.4. The spectrum of SXDS1_12778 also shows a weak signal-like feature at a $\sim 200 \text{ km s}^{-1}$ offset from the arrow with a velocity width of 250 km s^{-1} . The noise level (σ_{250}) is 1.0 mK. The S/N of SXDS1_12778 at the 250 km s^{-1} resolution is 1.8. However, the emission-like feature is not seen in the spectrum of COSMOS_9. These signal-like features may be real, but the S/N is not good enough to be significant. Hence, we do not regard these features as being a significant signal, and we put upper limits on the CO ($2 - 1$) fluxes of the targets.

3.2.2 Molecular gas mass and its fraction

We calculated the CO($J = 2 - 1$) line luminosity with the equation (3.1) but with the rest frequency of the CO($2 - 1$) emission line ($\nu_{\text{rest}(2-1)}$) instead of $\nu_{\text{rest}(5-4)}$. The average CO($2 - 1$)/CO($1 - 0$) luminosity ratio of sBzK galaxies at $z \sim 1.5$ is 0.76, corresponding to $S_{\text{CO}(5-4)}\Delta v / S_{\text{CO}(1-0)}\Delta v \sim 3$ (Daddi et al. 2015). We adopted this value for the conversion of CO($2 - 1$) luminosity to CO($1 - 0$) luminosity. The values of Δv for SXDS1_13015, COSMOS_50, and COSMOS_53 are 500 km s^{-1} , 300 km s^{-1} , and 1000 km s^{-1} , respectively. For other CO non-detected galaxies, we derived the $2\sigma_{250}$ upper limit of the CO($1 - 0$) luminosity assuming a velocity width of 250 km s^{-1} . The derived CO($1 - 0$) luminosities of the galaxies are shown in Table 3.2.

According to the studies of CO-to- H_2 conversion factor at $z = 1 - 2$, α_{CO} is close to the Galactic value for the main-sequence galaxies with the solar metallicity (Daddi et al. 2010a; Genzel et al. 2012). Since the galaxies selected have metallicities close to the solar metallicity, we adopt the Galactic α_{CO} value of $4.36 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ (in-

Table 3.2: Results of the Nobeyama observations.

Source	$L'_{\text{CO}(1-0)}$ (K km s ⁻¹ pc ²)	M_{mol}^a ($M_{\odot}$)	f_{mol}
SXDS1_12778	$< 2.9 \times 10^{10}$	$< 1.3 \times 10^{11}$	< 0.19
SXDS1_13015	$(5.4 \pm 1.3) \times 10^{10}$	$(2.4 \pm 0.6) \times 10^{11}$	0.54 ± 0.07
SXDS3_80799	$< 2.2 \times 10^{10}$	$< 9.7 \times 10^{10}$	< 0.47
COSMOS_9	$< 2.2 \times 10^{10}$	$< 9.7 \times 10^{10}$	< 0.59
COSMOS_50	$(2.2 \pm 0.5) \times 10^{10}$	$(9.6 \pm 2.1) \times 10^{10}$	0.58 ± 0.07
COSMOS_53	$(8.1 \pm 0.8) \times 10^{10}$	$(3.5 \pm 0.3) \times 10^{11}$	0.78 ± 0.02
		$(6.5 \pm 0.6) \times 10^{10b}$	0.40 ± 0.01^b

^a We adopted $\alpha_{\text{CO}} = 4.36 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.

^b We adopted $\alpha_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$.

cluding helium mass). For COSMOS_53, since it is possible that this galaxy is undergoing a merging, we also derived the molecular gas mass adopting the Ultra-luminous IR galaxies (ULIRG)-like conversion factor ($0.8 M_{\odot} (\text{K km s}^{-1} \text{ pc}^2)^{-1}$; Downes & Solomon 1998). Resulting molecular gas masses of detected galaxies are $(9.6 - 35) \times 10^{10} M_{\odot}$ as given in Table 3.2 and plotted in Figure 3.3 (green symbols). The uncertainty given to the molecular gas mass is based on the S/N of the spectrum and does not include the uncertainty of the luminosity ratio and conversion factor. We adopted the uncertainty of stellar mass of 70% for the galaxies in the COSMOS field which is a typical value of the galaxy sample in the COSMOS field. The fractions of molecular gas against stellar mass of detected galaxies are $0.5 - 0.8$ (for COSMOS_53, $f_{\text{mol}} = 0.4$ with the ULIRG-like conversion factor) These values are plotted in Figure 3.4 (green symbols). These values are in agreement with results of our ALMA observations.

3.3 Molecular gas mass against SFR, and gas depletion time

We examine the location of our sample galaxies in the diagram of SFR versus molecular gas mass. In the left panel of Figure 3.10, the SFRs are derived from extinction-corrected UV luminosity densities. In the right panel of Figure 3.10, the SFRs are sum of the SFRs from total IR luminosities ($L_{\text{IR}}(8 - 1000 \mu\text{m})$, Kennicutt 1998) and the SFRs from extinction-uncorrected UV luminosity densities, and are listed

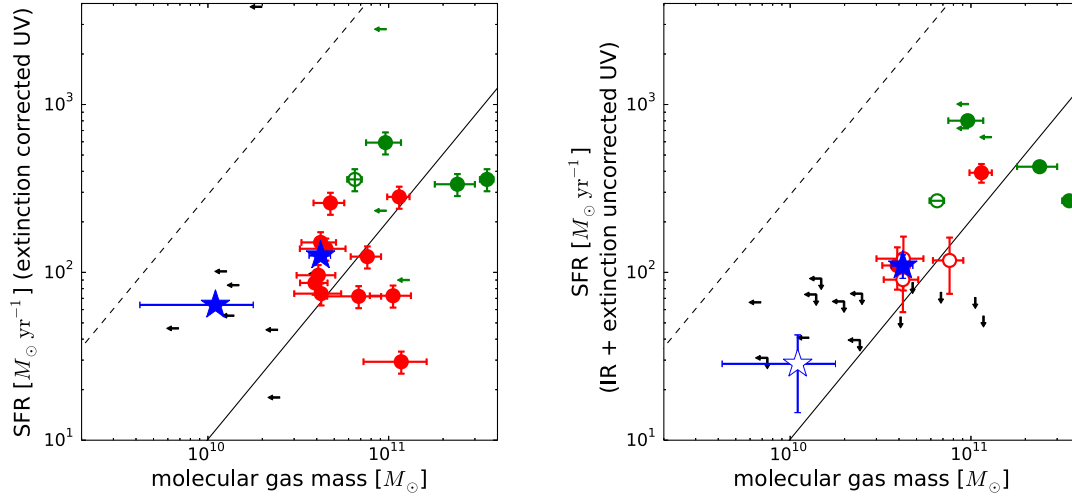


Figure 3.10: SFR against molecular gas mass. (Left) SFRs are derived from extinction-corrected UV luminosity densities. Filled red circles refer to the CO-detected galaxies and black left arrows show the CO-non-detected galaxies. Filled blue stars refer to the results of stacking analysis for the ALMA subsamples of CO-detected and CO-non-detected galaxies. Green symbols show the Nobeyama galaxy sample (the open circle refer to the COSMOS_9 with the ULIRG-like conversion factor). (Right) SFRs are the sum of the SFRs from total infrared luminosities and the SFRs from extinction-uncorrected UV luminosity densities. Filled red circles refer to the both CO- and dust-detected galaxies. Down-arrows show the dust non-detected galaxies but CO emissions are detected. Green symbols, stars, and left arrows are the same as those in the left panel. Open symbols represent the marginal detections of dust continuum emission. Solid and dashed lines represent the sequences of normal star-forming galaxies (e.g., local spirals and sBzK galaxies) and starburst galaxies (e.g., local ULIRGs and SMGs), respectively, given by Daddi et al. (2010b)

in Table 2.1 and 2.2. For the ALMA galaxy sample, L_{IR} are derived by fitting a template SED of main-sequence galaxies at $z \sim 1.5$ (Magdis et al. 2012a) to the continuum data (see Section 4.1). For the dust-detected galaxies, the SFRs from L_{IR} and extinction-uncorrected UV luminosity densities roughly agree with those from extinction-corrected UV luminosity densities. For the Nobeyama galaxy sample, the SFRs were calculated by summing the SFRs from $24 \mu\text{m}$ and the SFRs from extinction-uncorrected UV luminosity densities, since the $24 \mu\text{m}$ luminosity density is well correlated with total IR luminosities. In this figure, the solid line represents the sequence of normal star-forming galaxies (e.g., local spiral galaxies and sBzK galaxies), and the dashed line represents the sequence for starburst galaxies (e.g., local

ULIRGs and distant submillimeter galaxies (SMGs)) given by Daddi et al. (2010b). Most CO-detected galaxies are located around the solid line.

We carried out a stacking analysis of CO emissions for ALMA subsamples with CO-detected galaxies ($M_{\text{mol}} \geq 3.9 \times 10^{10} M_{\odot}$) and CO-non-detected galaxies (almost all of them have $M_{\text{mol}} < 2.5 \times 10^{10} M_{\odot}$). We do not include SXDS1_35572 and SXDS1_79307 as discussed previously. The CO emissions are significantly detected for both subsamples. The resulting molecular gas masses of CO-detected and CO-non-detected subsamples are $(4.2 \pm 0.6) \times 10^{10} M_{\odot}$ and $(1.1 \pm 0.7) \times 10^{10} M_{\odot}$, respectively. The results of the stacking analysis are plotted in the left panel of Figure 3.10 (filled blue stars). The SFRs derived from extinction-corrected UV luminosity densities are taken to be average values of the stacked galaxies. The results of the stacking analysis for the subsamples of CO-detected and CO-non-detected galaxies are located slightly above the sequence of normal star-forming galaxies and at the middle of the sequences of normal star-forming galaxies and starburst galaxies, respectively.

To derive the SFRs from the L_{IR} , we also carried out a stacking analysis for the same subsamples to see the continuum emission (see section 4.1.2). The dust emission is significantly detected for the subsamples with CO detected, and marginally detected for the subsamples with CO not detected. The resulting SFRs of CO-detected and CO-non-detected subsamples are $(109 \pm 18) M_{\odot} \text{ yr}^{-1}$ and $(28 \pm 14) M_{\odot} \text{ yr}^{-1}$, respectively. Here, the SFRs derived from extinction-uncorrected UV luminosity densities are taken to be average values of the stacked galaxies. The results of the stacking analysis are plotted in the right panel of Figure 3.10 (blue stars), and are located slightly above the sequence of normal star-forming galaxies.

The depletion time of molecular gas is derived from

$$t_{\text{dep}} = \frac{M_{\text{mol}}}{\text{SFR}}. \quad (3.4)$$

The derived depletion times are plotted against stellar mass and metallicity in Figure 3.11. Here, SFRs are derived from extinction-corrected UV luminosity densities. For the detected galaxies, the depletion time decreases with increasing stellar mass and metallicity.

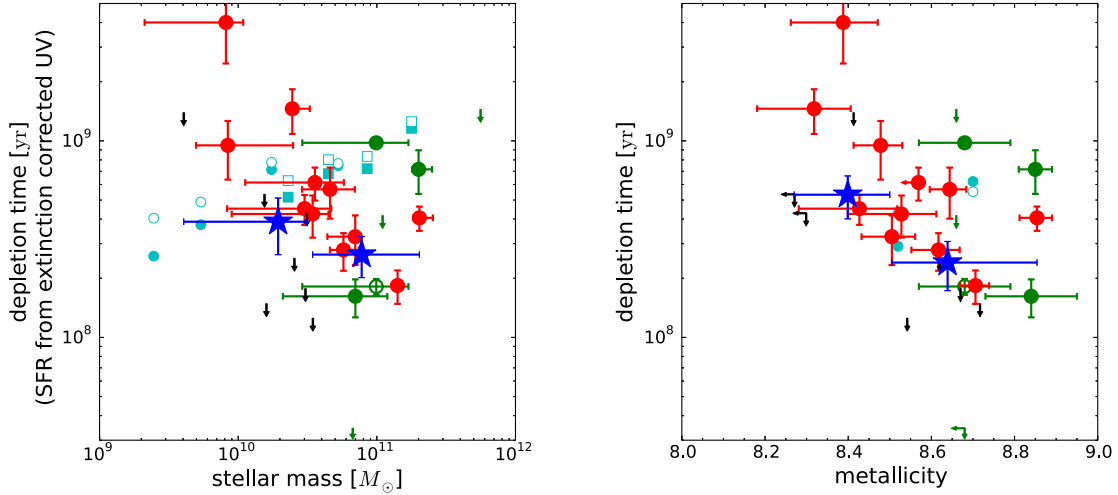


Figure 3.11: Depletion time of molecular gas calculated with SFRs from extinction-corrected UV luminosity density against stellar mass (left) and against metallicity (right). Symbols are the same as those in Figure 3.3.

We carried out a stacking analysis for ALMA subsamples with smaller and larger stellar mass using the same subsamples as in the former part of Section 3.1.2. The SFR is taken to be the average of the values of the stacked galaxies. The resulting depletion times are $(3.9 \pm 1.2) \times 10^8$ yr and $(2.6 \pm 0.6) \times 10^8$ yr for the subsamples with smaller and larger stellar mass, respectively, and are plotted against stellar mass in the left panel of Figure 3.11 (filled blue stars). These values are significantly smaller than those in local star-forming galaxies with similar stellar mass (e.g., Saintonge et al. 2011b; Boselli et al. 2014b). While the depletion time increases with stellar mass in local galaxies, it seems to decrease in the star-forming galaxies at $z \sim 1.4$, though the trend is not so significant (significance level for the null hypothesis is 1.0%).

We carried out a stacking analysis for ALMA subsamples with lower and higher metallicity using the same subsamples as in the latter part of Section 3.1.2. The resulting depletion times are $(5.3 \pm 1.3) \times 10^8$ yr and $(2.4 \pm 0.7) \times 10^8$ yr for the lower and higher metallicity subsamples, respectively, and are plotted against metallicity in the right panel of Figure 3.11 (filled blue stars). The depletion time decreases with increasing metallicity (significance level for the null hypothesis is 0.07%), while it seems to increase in local star-forming galaxies.

In Figure 3.12, we also plot depletion times calculated with SFRs from L_{IR} and

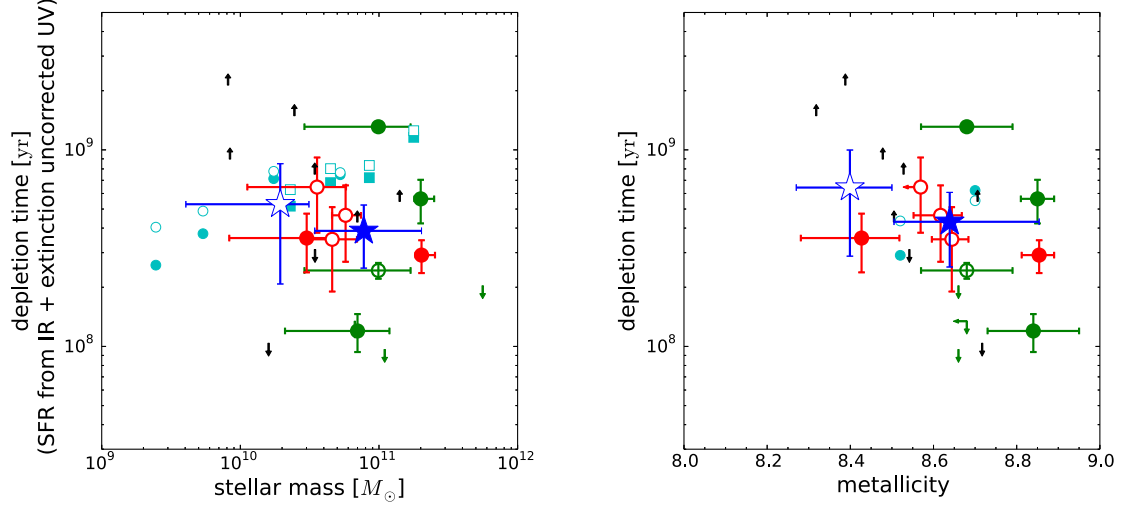


Figure 3.12: The depletion time of molecular gas calculated with SFR from total infrared luminosity and extinction-uncorrected UV luminosity density is plotted against stellar mass (left) and against metallicity (right). Filled red circles refer to the both CO- and dust-detected galaxies. Open red circles refer to the CO-detected and marginally dust-detected galaxies. Filled/open blue stars refer to the results of stacking analysis (open symbol refers to galaxies with marginally detected dust emission). Arrows show the upper and lower limits. Green symbols are the same as those in Figure 3.10.

extinction-uncorrected UV luminosity densities for ALMA sample and from $24\ \mu\text{m}$ and extinction-uncorrected UV luminosity densities for Nobeyama sample. From the stacking analysis, SFRs are $(45 \pm 12)\ M_\odot\ \text{yr}^{-1}$ and $(105 \pm 21)\ M_\odot\ \text{yr}^{-1}$ for the subsamples with smaller and larger stellar mass, respectively, and the resulting depletion times are $(5.3 \pm 3.2) \times 10^8\ \text{yr}$ and $(3.9 \pm 1.4) \times 10^8\ \text{yr}$, respectively (left panel of Figure 3.12 (blue stars)). The depletion time seems to decrease with increasing stellar mass, though the trend is not significant (significance level for the null hypothesis is 24%). SFRs are $(50 \pm 16)\ M_\odot\ \text{yr}^{-1}$ and $(72 \pm 13)\ M_\odot\ \text{yr}^{-1}$ for the lower and higher metallicity subsamples, respectively, and the resulting depletion times are $(6.4 \pm 3.6) \times 10^8\ \text{yr}$ and $(4.3 \pm 1.8) \times 10^8\ \text{yr}$, respectively (right panel of Figure 3.12 (blue stars)). Although the depletion time seems to decrease with increasing metallicity, the trend is not significant (significance level for the null hypothesis is 19%). A similar trend is also seen.

In all cases, the depletion time tends to decrease with increasing stellar mass and

metallicity, which contrasts with the trends in local star-forming galaxies, where the depletion time increases with increasing stellar mass and metallicity (e.g., Saintonge et al. 2011b; Boselli et al. 2014b). This means that the average star formation efficiency of galaxies with larger stellar mass and metallicity is higher at high redshift, but lower in the local universe compared with that of galaxies with smaller stellar mass and metallicity.

Chapter 4

Dust properties and gas-to-dust mass ratio at $z \sim 1.4$

4.1 Results of ALMA observations for dust thermal emissions

4.1.1 Individual Galaxy

We detected continuum emission from two galaxies with $S/N > 3$. For five objects, the emissions are marginally detected with $2 < S/N < 3$. The positions of these galaxies are in good agreement with the centroid of each galaxy in the K -band image. The detected and marginally detected galaxies are shown with filled circles and open circles, respectively, in the diagrams of stellar mass versus SFR and stellar mass versus metallicity (Figure 4.1). Continuum emission seems to tend to be detected for more massive galaxies and galaxies with higher metallicity.

The continuum emission is considered to originate from dust thermal emission. The dust mass (M_{dust}) is derived as

$$M_{\text{dust}} = \frac{S_{\text{cont}} D_L}{(1+z) \kappa_d(\nu_{\text{rest}}) B(\nu_{\text{rest}}, T_{\text{dust}})}, \quad (4.1)$$

where S_{cont} is the observed flux density of dust thermal continuum emission, $\kappa_d(\nu_{\text{rest}})$ is the dust mass absorption coefficient in the rest-frame frequency (~ 570 GHz; rest-

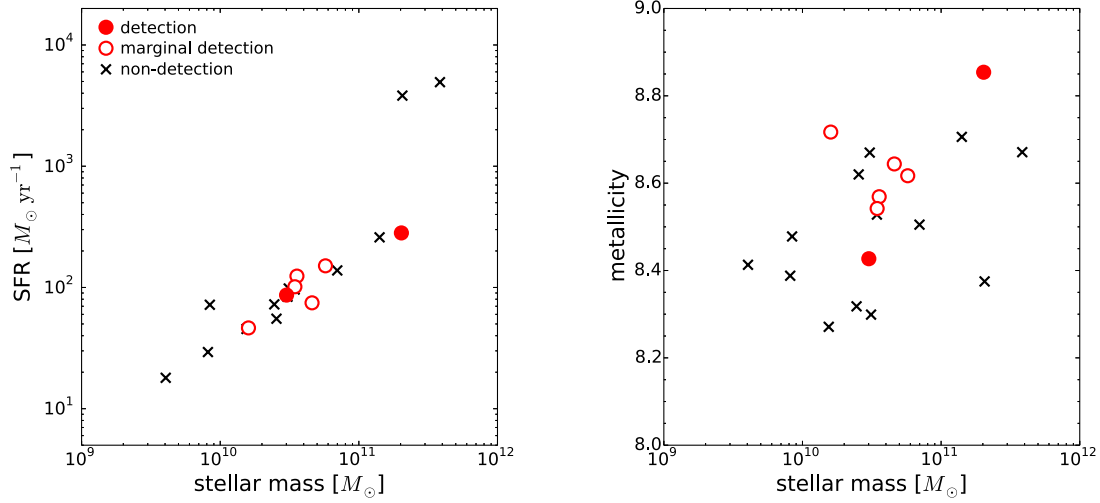


Figure 4.1: Observed galaxies in the diagrams of SFR vs. stellar mass (left) and metallicity vs. stellar mass (right). Filled and open red circles refer to the galaxies for which the continuum emissions are significantly and marginally detected, respectively. The crosses show non-detections.

frame wavelength is ~ 0.5 mm), T_{dust} is the dust temperature, and $B(\nu_{\text{rest}}, T_{\text{dust}})$ is the Planck function. κ_{d} varies with frequency as $\kappa_{\text{d}} \propto \nu^{\beta}$, where β is the dust emissivity index. We adopt $\kappa_{\text{d}}(125 \mu\text{m}) = 1.875 \text{ m}^2 \text{ kg}^{-1}$ (Hildebrand 1983), and $\beta = 1.5$. Magnelli et al. (2014) derived dust temperatures of star-forming galaxies in the stellar mass-SFR diagram at $z = 0 - 2.3$. According to their results, the dust temperatures of main-sequence galaxies at $z = 1.2 - 1.7$ are 25 – 35 K. We adopt a temperature of 30 K. We take a 2σ upper limit as S_{cont} , where σ is the rms noise level in the continuum map. The derived dust masses are given in Table 4.1 and plotted against stellar mass and metallicity in Figure 4.2. The uncertainty in the dust mass is calculated from the S/N of the continuum map. The dust mass can change by a factor of 1.2 when we adopt dust temperatures of 25 or 35 K with a dust emissivity index of 1.5, and change by a factor of 2 when we adopt a dust emissivity index of 1.0 or 2.0 with a dust temperature of 30 K. No clear dependence on stellar mass or metallicity is seen.

Table 4.1: Results of the ALMA observations.

ID	$S_{\text{continuum}}^a$ (mJy)	M_{dust}^b ($10^7 M_{\odot}$)	Gas-to-Dust Ratio (mJy/beam)	noise level ^c	beam size, PA
SXDS1_13015	0.86 ± 0.11	47 ± 6	241 ± 46	0.09	$0''.85 \times 0''.65$, 108°
SXDS1_1723	< 0.20	< 11	—	0.10	$1''.28 \times 0''.64$, 72°
SXDS1_31189	< 0.12	< 6.6	> 1783	0.06	$0''.80 \times 0''.66$, 100°
SXDS1_33244	0.18 ± 0.07	9.9 ± 3.9	423 ± 188	0.07	$1''.04 \times 0''.64$, 75°
SXDS1_35572	< 0.08	< 4.4	—	0.04	$0''.84 \times 0''.68$, 93°
SXDS1_42087	0.19 ± 0.07	11 ± 4	722 ± 300	0.06	$0''.80 \times 0''.66$, 96°
SXDS1_59863	< 0.18	< 9.9	> 480	0.09	$0''.85 \times 0''.65$, 110°
SXDS1_59914	< 0.20	< 11	> 408	0.10	$1''.20 \times 0''.65$, 73°
SXDS1_67002	0.09 ± 0.04	4.9 ± 2.2	< 261	0.07	$0''.87 \times 0''.63$, 114°
SXDS1_68849	< 0.18	< 9.8	—	0.09	$0''.96 \times 0''.65$, 76°
SXDS1_79307	< 0.12	< 6.7	—	0.06	$0''.80 \times 0''.66$, 93°
SXDS1_79518	< 0.18	< 9.8	> 1079	0.09	$1''.02 \times 0''.65$, 75°
SXDS2_13316	< 0.14	< 7.7	> 885	0.07	$0''.86 \times 0''.64$, 109°
SXDS2_22198	0.10 ± 0.04	5.5 ± 2.2	< 124	0.04	$0''.86 \times 0''.68$, 86°
SXDS3_101746	< 0.18	< 9.8	—	0.09	$1''.06 \times 0''.65$, 74°
SXDS3_103139	< 0.08	< 4.4	—	0.04	$0''.83 \times 0''.68$, 100°
SXDS3_110465	< 0.18	< 9.9	—	0.09	$1''.13 \times 0''.65$, 74°
SXDS5_19723	< 0.08	< 4.4	> 921	0.04	$0''.83 \times 0''.68$, 97°
SXDS5_28019	0.28 ± 0.08	15 ± 4	256 ± 86	0.04	$0''.85 \times 0''.68$, 90°
SXDS5_9364	0.24 ± 0.10	13 ± 6	320 ± 162	0.08	$0''.87 \times 0''.64$, 112°

^a The average observed wavelength is ~ 1.3 mm, thus the average rest-frame wavelength is ~ 0.5 mm.

^b We used a modified blackbody model adopting a dust temperature of 30 K and a dust emissivity index of 1.5.

^c Noise level in the continuum map.

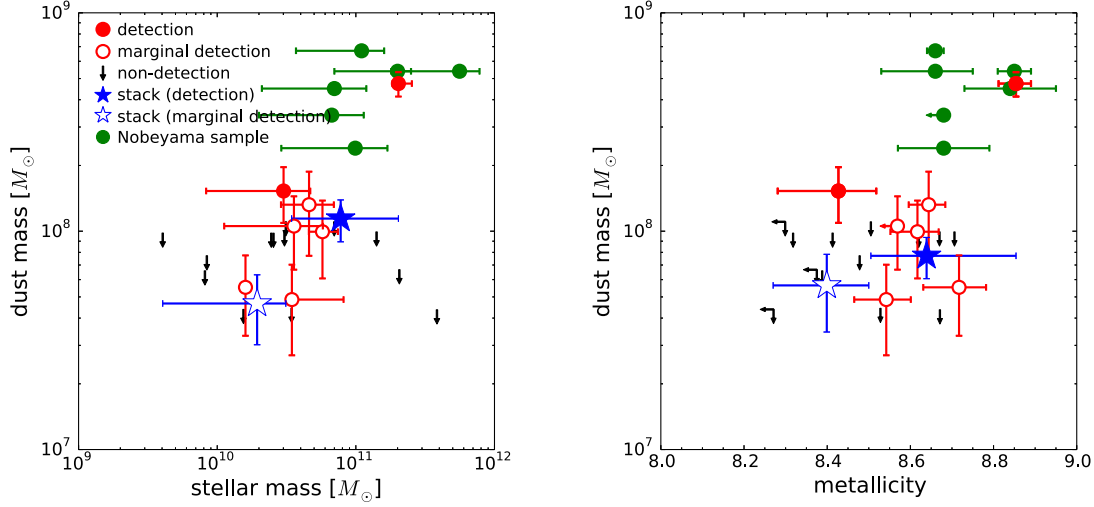


Figure 4.2: Dust mass against stellar mass (left) and against metallicity (right). Dust masses are derived using a modified blackbody model by assuming a dust temperature of 30 K for the ALMA sample and 35 K for the Nobeyama sample and a dust emissivity index of 1.5. The filled and open red circles refer to the galaxies for which the continuum emissions are significantly and marginally detected with ALMA, respectively. Arrows show the upper limits. Filled/open blue stars refer to the results of the stacking analyses for the subsamples with larger/ smaller stellar mass in the left panel and the subsamples with higher/lower metallicity in the right panel. The filled green circles refer to the Nobeyama galaxy sample.

4.1.2 Stacking analysis

Since the dust thermal continuum emissions from most of the observed galaxies are not detected, we carried out a stacking analysis to examine the dependence on stellar mass and metallicity. For the stacking analysis of dust thermal emission we used uncleaned images. The images are stacked on a pixel-by-pixel basis using a $1/\sigma^2$ weighted average. We do not include SXDS1_35572 and SXDS1_79307 as discussed previously. The detection criteria are the same as those for the individual galaxies. The dust mass is derived with the same dust temperature and dust emissivity index as for the individual galaxies. Error bars are derived from a random resampling of the stacked galaxies.

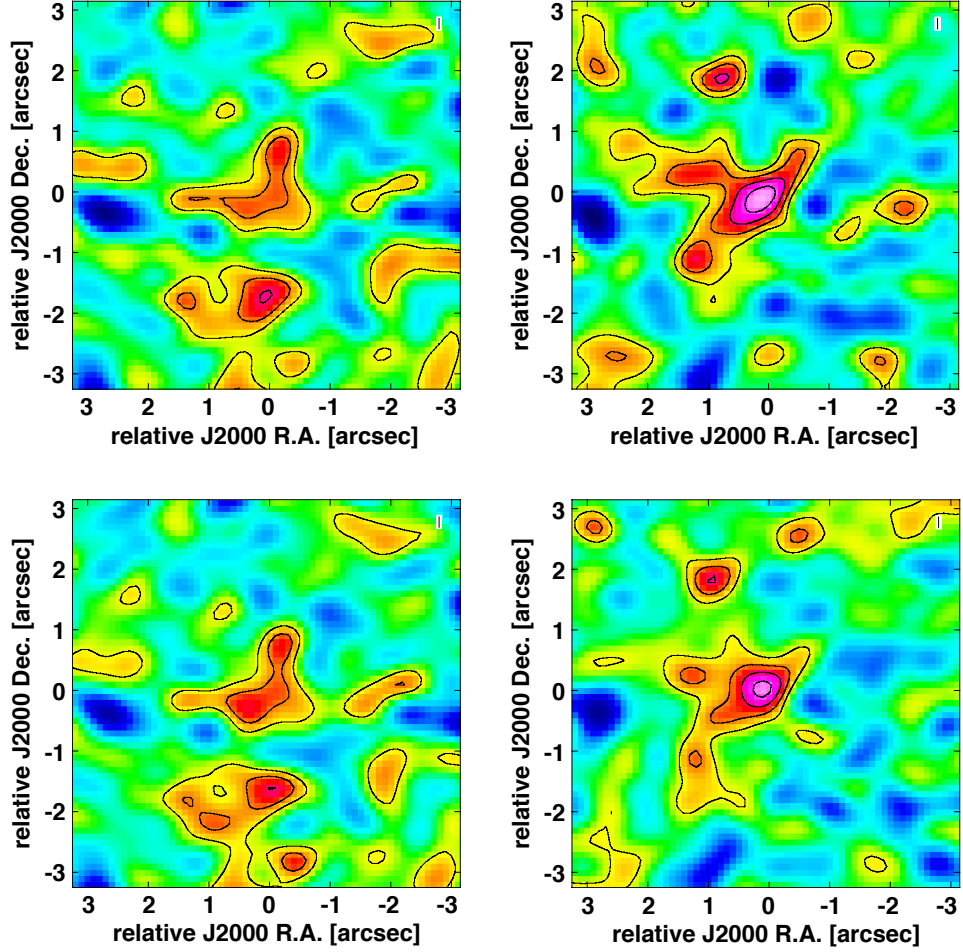


Figure 4.3: Stacked continuum maps of the subsamples with smaller stellar mass (top left), larger stellar mass (top right), lower metallicity (bottom left), higher metallicity (bottom right). Contours represent 1σ , 2σ , 3σ , ... (solid lines).

Stacking analysis of subsamples with larger/smaller stellar mass

To study the stellar mass dependence of dust mass, we carried out a stacking analysis with the subsamples used in the former part of Section 3.1.2. The stacked continuum maps for the subsamples with smaller and larger stellar mass are shown in the top left and right panel of Figure 4.3, respectively. The dust emission is marginally detected for the subsamples with smaller stellar mass, and significantly detected for the subsamples with larger stellar mass. The derived dust masses are $(4.7 \pm 1.6) \times 10^7 M_{\odot}$ and $(1.1 \pm 0.3) \times 10^8 M_{\odot}$ for the subsamples with smaller and larger stellar mass, respectively, and are plotted in the left panel of Figure 4.2 (blue stars). These dust

Table 4.2: Dust mass and gas-to-dust ratio of Nobeyama galaxy sample.

Source	M_{dust} ($M_{\odot}$)	Gas-to-dust ratio
SXDS1_12778	5.4×10^8	< 240
SXDS1_13015	5.4×10^8	440 ± 110
SXDS3_80799	6.7×10^8	< 150
COSMOS_9	3.4×10^8	< 290
COSMOS_50	4.5×10^8	220 ± 50
COSMOS_53	2.4×10^8	1450 ± 140^a 265 ± 25^b
^a We adopted $\alpha_{\text{CO}} = 4.36 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$.		
^b We adopted $\alpha_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^2)^{-1}$.		

masses are slightly larger than those in local galaxies with similar stellar mass (Rémy-Ruyer et al. 2014). The dust masses increase with increasing stellar mass (significance level for the null hypothesis is 0.03%).

Stacking analysis of subsamples with higher/lower metallicity

To study the metallicity dependence of dust mass, we carried out a stacking analysis with the subsamples used in the latter part of Section 3.1.2. The stacked continuum maps for the subsamples with lower and higher metallicity are shown in the bottom left and right panel of Figure 4.3, respectively. The dust emission is marginally detected for the subsamples with lower metallicity, and significantly detected for the subsamples with higher metallicity. The derived dust masses are $(5.6 \pm 2.2) \times 10^7 M_{\odot}$ and $(7.7 \pm 1.7) \times 10^7 M_{\odot}$ for the subsamples with lower and higher metallicity, respectively, and are plotted in the right panel of Figure 4.2 (blue stars). Although the dust mass seems to increase with increasing metallicity, the trend is not significant (significance level for the null hypothesis is 5.8%).

4.2 Dust mass for Nobeyama galaxy sample

The dust mass is derived with the equation (4.1). Since the S/N is much better in the 250 μm data of SPIRE than in 350 μm , we adopted a 250 μm flux density for S_{cont} which corresponds to $\sim 105 \mu\text{m}$ in the rest-frame wavelength. We adopted the same

values of κ_d and β as those adopted for ALMA galaxy sample. Since the galaxy sample for the Nobeyama observations is clearly detected in 250 μm and 350 μm images and tends to be located in the upper part of the main sequence, we adopted a typical dust temperature for galaxies with higher specific SFRs among main-sequence galaxies. The dust mass can change by a factor of ~ 1.8 when we adopt a dust temperature of 30 or 40 K. The uncertainty arising from β is 10% when adopting $\beta = 1.0$ or 2.0, since we use the flux density at the rest wavelength of 105 μm and κ_d at 125 μm . The derived dust masses are $(2.4 - 6.7) \times 10^8 M_\odot$, which are given in Table 4.2 and plotted in Figure 4.2 (filled green circles).

4.3 Gas-to-dust ratio

Since the molecular gas masses and dust masses have been obtained, we determine gas-to-dust mass ratios in the main-sequence galaxies at $z \sim 1.4$, excepting seven galaxies for which only upper limits on both the molecular gas mass and dust mass are obtained in the ALMA observations. The derived gas-to-dust ratios are shown in Table 4.1 and Table 4.2 and plotted in Figure 4.4. The results of the stacking analyses for the ALMA subsamples with lower and higher metallicity are also plotted with blue stars. The gas-to-dust ratios in the subsamples with lower and higher metallicity are 568 ± 261 and 401 ± 142 , respectively, and are 3 – 4 times larger than those in local galaxies at a fixed metallicity (Leroy et al. 2011; Rémy-Ruyer et al. 2014). Moreover, although the gas-to-dust ratios for local galaxies include the HI mass, the ratios at $z \sim 1.4$ do not, and so the gas-to-dust ratio in our sample galaxies must be larger than the values derived here. Therefore, care should be taken in deriving molecular gas mass from dust mass by assuming the gas-to-dust ratio in local galaxies.

It is worth mentioning that while we derive the dust mass using a modified blackbody model with a fixed dust temperature and dust emissivity index, the dust masses in the local galaxies shown in Figure 4.4 are derived by adopting the models of (Draine & Li 2007:hereafter DL07 models) using Herschel/PACS and SPIRE data. Magdis et al. (2012a) showed that dust masses derived using modified blackbody models with dust temperatures derived by fitting (average temperature is 33 K) and the same

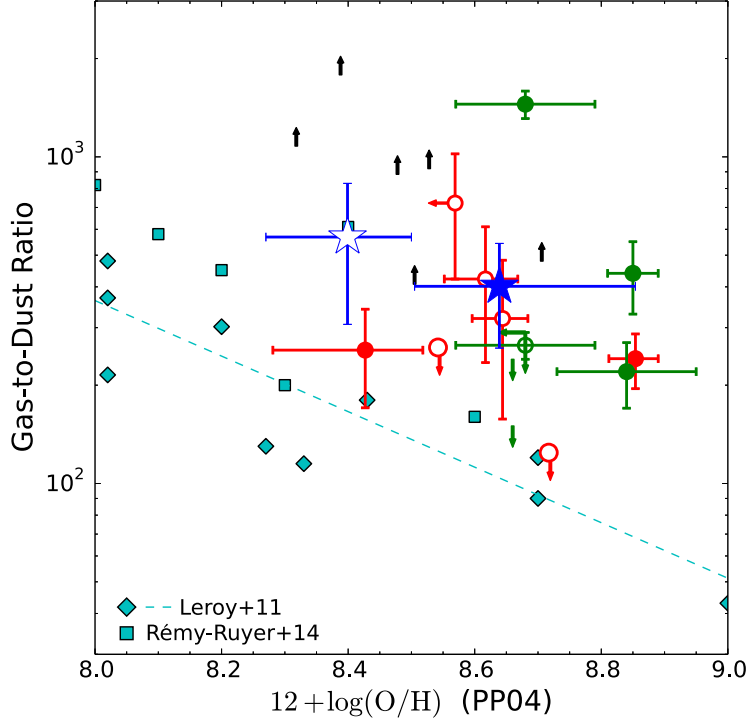


Figure 4.4: Gas-to-dust ratio against metallicity. Filled and open red circles refer to the galaxies from which dust emission is detected significantly and marginally, respectively. Black arrows show the lower limit. Filled/open blue stars refer to the results of stacking analysis for the subsamples with higher/lower metallicity (open symbol refers to marginal detection of dust). Filled green circles and arrows refer to the Nobeyama galaxy sample. The open green circle represent COSMOS_53 using the ULIRG-like conversion factor for the derivation of molecular gas mass. Cyan diamonds and the cyan dashed line represent local galaxies studied by Leroy et al. (2011), and cyan squares represent the average values in local galaxies shown by Rémy-Ruyer et al. (2014). (Metallicities are calibrated using Pettini & Pagel (2004).)

fixed dust emissivity index ($\beta = 1.5$) are about half those derived by DL07 models. Hence the gas-to-dust ratios of our samples plotted in Figure 4.4 would be lower by ~ 0.3 dex if we used DL07 models. The ratios are still larger by about a factor of 2. This result that gas-to-dust ratios in the main-sequence galaxies at $z \sim 1.4$ are about twice those for local galaxies is similar to results obtained for lensed galaxies on the main sequence at $z = 1.4 - 3.1$ (Saintonge et al. 2013). If $T_{\text{dust}} = 35$ K is assumed for ALMA galaxy sample, the gas-to-dust ratios are larger than those with $T_{\text{dust}} = 30$ K by ~ 0.1 dex. One galaxy, SXDS1_13015, is observed in both ALMA and

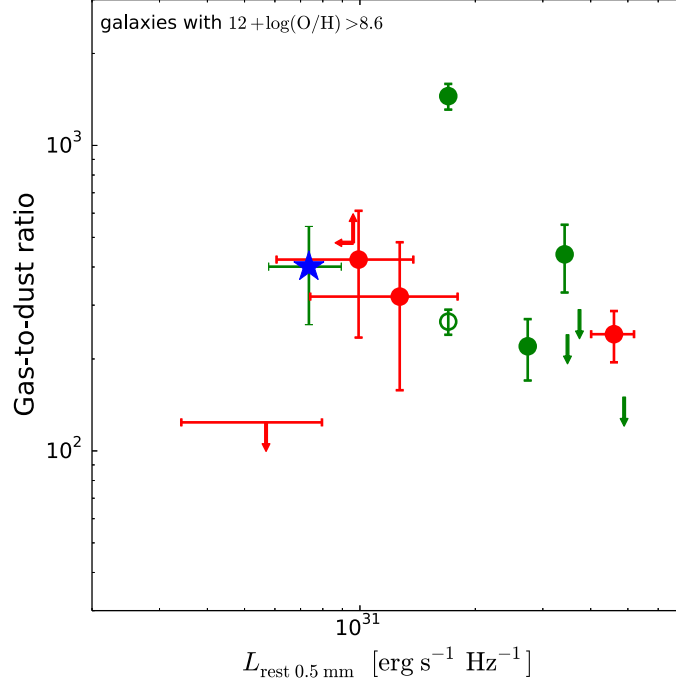


Figure 4.5: Gas-to-dust ratio against luminosity density at a rest wavelength of 0.5 mm for galaxies with $12 + \log(\text{O}/\text{H}) > 8.6$. Symbols are the same as those in Figure 4.4.

Nobeyama observations. By adopting the same conversion factor and dust temperature, the gas-to-dust ratio derived with the ALMA result is in agreement with that with the Nobeyama result. The gas-to-dust ratio at $z \sim 1.4$ seems to decrease with increasing metallicity. Although this trend is the same as that in local galaxies (Leroy et al. 2011; Rémy-Ruyer et al. 2014), the trend is not significant since the uncertainty of our results is large (significance level for the null hypothesis is 16%).

To examine the dependence of the gas-to-dust ratio on far-IR luminosity density, we plot the gas-to-dust ratios in the star-forming galaxies with the solar metallicity ($12 + \log(\text{O}/\text{H}) > 8.6$) against the rest-frame luminosity density at 0.5 mm ($L_{\text{rest } 0.5 \text{ mm}}$; Figure 4.5). Although it may be better to see the dependence on the total infrared luminosity rather than the luminosity density, since we only have the flux densities in band 6 for almost all of the ALMA sample and the total luminosity depends on the SED, we use $L_{\text{rest } 0.5 \text{ mm}}$ to avoid the uncertainty. The luminosity densities of the Nobeyama galaxy sample are estimated from the best-fitting model SED by Chary & Elbaz (2001). The gas-to-dust ratio does not seem to depend on

the luminosity density at 0.5 mm. Although most of the ratios are $\sim 200 - 500$ (if we use the ULIRG-like conversion factor for COSMOS_53), the lower and upper limits indicate that star-forming galaxies with the solar metallicity at $z \sim 1.4$ probe a wide range of gas-to-dust ratios.

Chapter 5

Constraint on the inflow and outflow rates at $z \sim 1.4$

5.1 Observational data

We use our ALMA results of stacking analysis for the subsamples with smaller and larger stellar mass shown in Section 3.1.2. The average stellar mass is $1.9 \times 10^{10} M_{\odot}$ and $7.8 \times 10^{10} M_{\odot}$ for the subsamples with smaller and larger stellar mass, respectively. The stacked metallicities for the subsamples with smaller and larger stellar mass are $0.66 \pm 0.06 Z_{\odot}$ and $0.91 \pm 0.07 Z_{\odot}$, respectively. The gas mass fractions (including the helium mass) for the subsamples with smaller and larger stellar mass are 0.55 ± 0.09 and 0.34 ± 0.08 , respectively. The stellar masses, gas mass fractions, and metallicities of the subsamples are plotted with red stars in Figure 5.1 together with individual galaxies (black symbols); the left, middle, and right panels are diagrams of gas mass fraction versus stellar mass (μ versus M_*), metallicity versus gas mass fraction (Z versus μ), and metallicity versus stellar mass (Z versus M_*), respectively. In Figure 5.1, the results for ~ 340 star-forming galaxies at $z \sim 1.4$ by (Yabe et al. 2015a) are also plotted (blue squares) and are consistent with the results obtained in this study. They stacked the near-infrared spectroscopic data for the subsamples separated into five stellar mass bins. They derived metallicities with the N2 method and gas mass fractions from the H α luminosities and sizes of galaxies by applying the

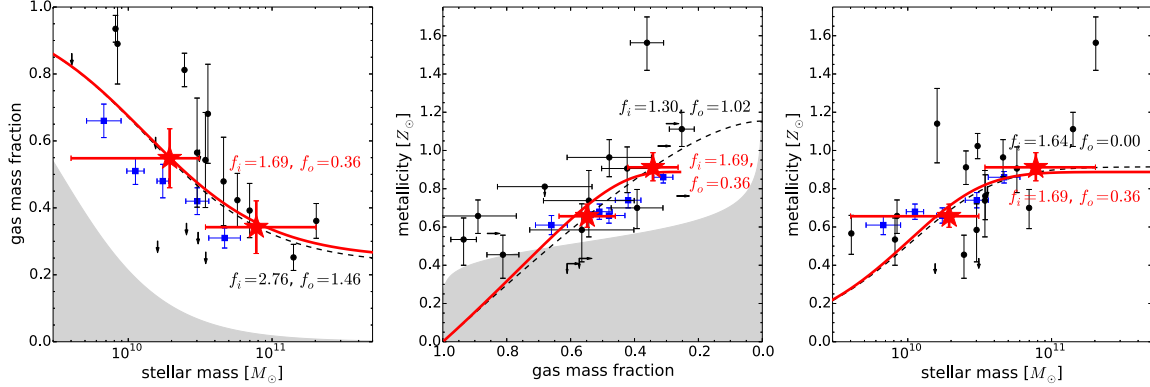


Figure 5.1: Diagrams of gas mass fraction vs. stellar mass (left), metallicity vs. gas mass fraction (middle), and metallicity vs. stellar mass (right). Red stars represent the results of the stacking analysis for the subsamples with smaller/larger stellar mass. Black circles and arrows refer to the results for individual galaxies from Seko et al. (2016a). Blue squares represent the results of Yabe et al. (2015a), who derived the gas mass fractions by using the Kennicutt-Schmidt law. The red solid line shows the best-fit model derived from the joint fitting. The black dashed line shows the best-fit model derived from fitting in each panel. The gray shaded region represents our CO observational limit (see the text for details).

Kennicutt-Schmidt law.

The observational limits of the gas mass fraction are shown in the left and middle panels of Figure 5.1 with gray shades. The noise level of the CO stacking analysis for both subsamples (~ 0.25 mJy) gives an upper limit of the CO(1-0) luminosity of $\sim 4.3 \times 10^8$ K km s $^{-1}$ pc 2 by assuming a velocity width of 200 km s $^{-1}$, which is the average full width at half maximum of the detected CO emission lines from Seko et al. (2016a), and the same CO luminosity ratio above. This limit leads to an upper gas mass fraction at a fixed stellar mass (left panel of Figure 5.1) and at a fixed metallicity (middle panel of Figure 5.1), if we assume the stellar mass-metallicity relation at $z \sim 1.4$ (Yabe et al. 2014) and the metallicity-dependent CO-to-H $_2$ conversion factor (Genzel et al. 2012). In the middle panel of Figure 5.1, the upper limit of the gas mass fraction is very high at lower metallicity. This is because the stellar mass-metallicity relation we adopted implies a very small stellar mass for the lower metallicity galaxies, resulting in a very large gas mass fraction. A few of our galaxies are located in the gray shaded region in the middle panel of Figure 5.1. This is because they show large deviations from the assumed stellar mass-metallicity relation.

5.2 Chemical evolution model containing gas flows

We compare the observational data with an analytic model for chemical evolution in a galaxy considering the gas inflow and outflow. Based on the description by Matteucci (2001) the equation for the evolution of gas is given as

$$\frac{dM_{\text{gas}}}{dt} = -(1 - R)\psi(t) + A(t) - W(t), \quad (5.1)$$

where R is the total mass fraction which is restored to the ISM by a stellar generation, $\psi(t)$ is SFR, $A(t)$ is the inflow (accretion rate), and $W(t)$ is the outflow (wind) rate. The evolution of metal mass in gas phase is given as

$$\frac{d(ZM_{\text{gas}})}{dt} = -(1 - R)Z(t)\psi(t) + y_Z(1 - R)\psi(t) + Z_A A(t) - ZW(t), \quad (5.2)$$

where Z is the gas phase metallicity, y_Z is the yield, and Z_A is the metallicity of inflow gas. These equations are given by adopting the instantaneous recycling approximation. We adopted $y_Z = 1.5 Z_{\odot}$ in this work, which is the value used by Erb (2008) and Yabe et al. (2015a). The inflow rate and outflow rate are assumed to be proportional to the SFR such as $A(t) = f_i(1 - R)\phi(t)$ and $W(t) = f_o(1 - R)\phi(t)$, respectively, and the inflow gas is assumed to be primordial ($Z_A = 0$). The assumption of an outflow rate proportional to the SFR would be appropriate if the galactic winds are mainly driven by supernovae explosions. The assumption of an inflow rate proportional to SFR would be reasonable if the amount of inflow gas is closely related to the mass of gas available to form stars. These equations analytically lead to

$$Z = \frac{y_Z}{f_i} (1 - [(f_i - f_o) - (f_i - f_o - 1)\mu^{-1}]^{\frac{f_i}{f_i - f_o - 1}}), \quad (5.3)$$

and μ is written as,

$$\mu = \frac{M_{\text{gas}}^0 + (f_i - f_o - 1)M_*}{M_{\text{gas}}^0 + (f_i - f_o)M_*}, \quad (5.4)$$

where M_{gas}^0 is the initial mass of primordial gas in a galaxy.

To constrain the inflow (f_i) and outflow (f_o) rates, the analytic solutions are fitted to the observational data in each diagram of Figure 5.1. As shown in these equations,

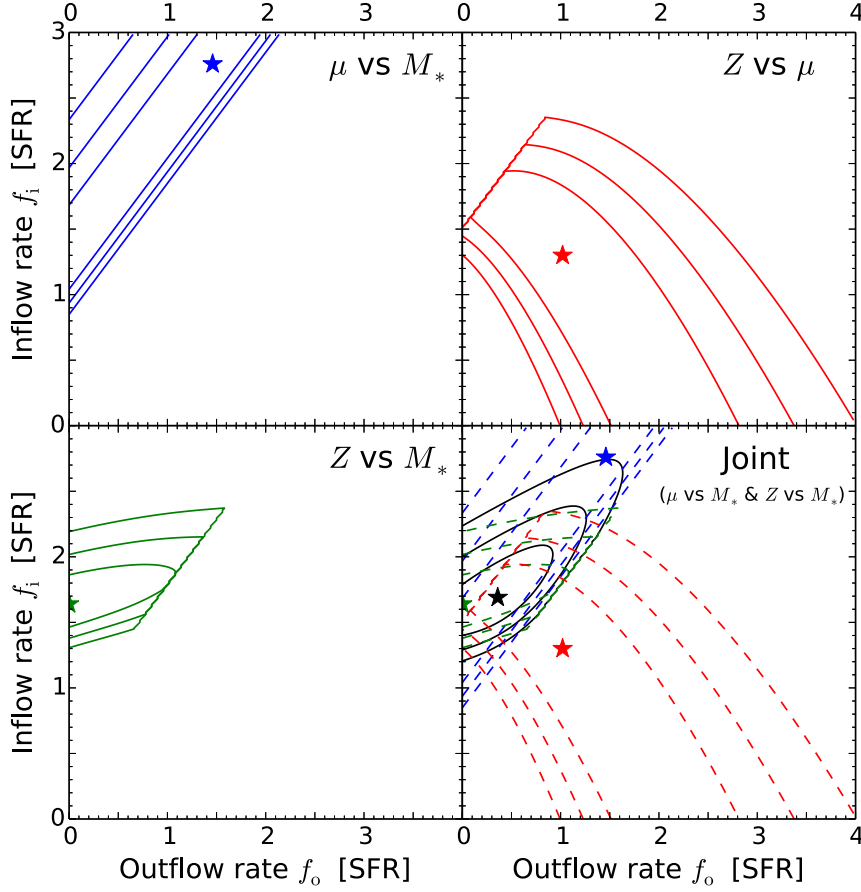


Figure 5.2: χ^2 contour maps of the fits for the diagrams of gas mass fraction vs. stellar mass (top left), metallicity vs. gas mass fraction (top right), metallicity vs. stellar mass (bottom left), and the joint fit with the diagrams of gas mass fraction vs. stellar mass and metallicity vs. stellar mass (bottom right). Stars show the best-fit value in each panel. Contours represent 1σ , 2σ , and 3σ .

f_i , f_o , and M_{gas}^0 are free parameters. From the least chi-square fitting in the diagram of μ versus M_* , we obtain a value of $M_{\text{gas}}^0 = 10.24 M_\odot$. The ranges of the parameters examined are $\log(M_{\text{gas}}^0/M_\odot) = 9.0 - 11.0$, $f_i = 0.0 - 3.0$, and $f_o = 0.0 - 4.0$ with 50 grids for each parameter. Then, we fixed the initial gas mass and fit each diagram of Figure 5.1 in the parameter ranges of $f_i = 0.0 - 3.0$, and $f_o = 0.0 - 4.0$ with 200 grids.

5.3 Results

In Figure 5.2, the χ^2 contour maps of the inflow and outflow rates are shown; the top left, top right, and bottom left panels show the fits for μ versus M_* , Z versus μ , and Z versus M_* , respectively. The best-fit combinations of inflow and outflow rates (f_i, f_o) are $(2.76^{+0.23}_{-1.71}, 1.46^{+0.48}_{-1.46})$, $(1.30^{+0.65}_{-1.30}, 1.02^{+1.80}_{-0.94})$, and $(1.64^{+0.33}_{-0.18}, 0.00^{+1.14}_{-0.00})$ for the μ versus M_* , Z versus μ , and Z versus M_* diagrams, respectively. The best-fit model is plotted with a black dashed line in each panel of Figure 5.1 and the best-fit combination of inflow and outflow rates is represented with a colored star in each panel of Figure 5.2. Although the degeneracy between the inflow and outflow rates is severe in the fitting of each diagram, since the directions of the degeneracy in each diagram are different, the inflow and outflow rates can be constrained with a joint fit. Since the three relations shown in Figure 5.1 are not independent, in this paper, we adopt the inflow and outflow rates from the joint fit from μ versus M_* and Z versus M_* , as done by Yabe et al. (2015a). The results of joint fitting of μ versus M_* and Z versus μ , and Z versus μ and Z versus M_* are almost the same as that for μ versus M_* and Z versus M_* . We explore the combination of inflow and outflow rates which minimizes the joint chi-square. The best-fit values are $(f_i, f_o) = (1.69^{+0.44}_{-0.30}, 0.36^{+0.60}_{-0.36})$ which are shown with a black star in the bottom right panel of Figure 5.2. The fit result is shown with a red solid line in Figure 5.1.

5.4 Discussion

As mentioned above, Yabe et al. (2015a) constrain the inflow and outflow rates at the same redshift. Our result is consistent with that of Yabe et al. (2015a) ($(f_i, f_o) = (1.84^{+0.14}_{-0.14}, 0.60^{+0.18}_{-0.22})$) to within errors. Although the uncertainty of the inflow and outflow rates is large, the best-fit model shows that the inflow rate is roughly equal to the sum of the outflow rate and effective SFR $((1 - R)\psi)$, which supports the equilibrium model for galaxy evolution. It should be noted that the inflow and outflow rates are $1.47^{+0.45}_{-0.23}$ and $0.04^{+0.76}_{-0.04}$, respectively, if we adopt the Chabrier IMF (Chabrier 2003) (the fit results and χ^2 contour maps are given in Figure 5.3). The stellar mass

with the Chabrier IMF is converted from that with the Salpeter IMF by dividing by 1.7 (e.g., Speagle et al. 2014). While the outflow rate is smaller than that derived with the Salpeter IMF, the equilibrium model for galaxy evolution is still supported.

We also examine the inflow and outflow rates by using the subsamples with lower (< 8.5) and higher (> 8.5) metallicity. The average stellar masses are $1.7 \times 10^{10} M_{\odot}$ and $6.6 \times 10^{10} M_{\odot}$ for the subsamples with lower and higher metallicity, respectively. The stacked molecular gas mass fractions for the subsamples with lower and higher metallicity are 0.65 ± 0.07 and 0.32 ± 0.09 , respectively. The stacked metallicities for the subsamples with lower and higher metallicity are $0.55 \pm 0.05 Z_{\odot}$ and $0.95 \pm 0.07 Z_{\odot}$, respectively. The joint fit gives an inflow rate of $1.50^{+0.41}_{-0.34}$ and outflow rate of $0.54^{+0.58}_{-0.54}$ (the fit results and χ^2 contour maps are given in Figure 5.4), which are consistent with the result derived by using the subsamples based on stellar mass, to within errors. The result also supports the equilibrium model for galaxy evolution.

According to the study of CO luminosity ratios for main-sequence galaxies at $z \sim 1.5$ by Daddi et al. (2015), the uncertainty of the luminosity ratio ($L'_{\text{CO}(5-4)}/L'_{\text{CO}(1-0)}$) is about a factor of 2. If we adopt the luminosity ratio of 0.12, the inflow and outflow rates are $1.40^{+0.46}_{-0.21}$ and $0.00^{+0.74}_{-0.00}$ ($M_{\text{gas}}^0 = 10^{10.56} M_{\odot}$), respectively (the fit results and χ^2 contour maps are given in Figure 5.5). If we adopt the luminosity ratio of 0.46, the inflow and outflow rates are $1.92^{+0.40}_{-0.30}$ and $0.76^{+0.50}_{-0.56}$ ($M_{\text{gas}}^0 = 10^{9.96} M_{\odot}$), respectively (the fit results and χ^2 contour maps are given in Figure 5.6). As the luminosity ratio is larger (i.e., molecular gas mass fraction is smaller), the inflow and outflow rates become large but the initial gas mass becomes small.

If we adopt the Galactic CO-to- H_2 conversion factor ($4.36 M_{\odot} (\text{km s}^{-1} \text{ pc}^2)^{-1}$) to derive the molecular gas mass, the inflow and outflow rates are $1.86^{+0.42}_{-0.30}$ and $0.40^{+0.60}_{-0.40}$ for the subsamples with smaller and larger stellar mass (the fit results and χ^2 contour maps are given in Figure 5.7), and $1.88^{+0.46}_{-0.34}$ and $0.42^{+0.72}_{-0.42}$ for the subsamples with lower and higher metallicity (the fit results and χ^2 contour maps are given in Figure 5.8). These best-fit values are consistent with those derived with the metallicity-dependent CO-to- H_2 conversion factor. However, the χ^2 of the joint fit is worse, and the best-fit models do not reproduce the observational data well in the diagram of Z versus μ which is not used for the joint fit.

Although the gas mass in the chemical evolution model includes the HI mass, the gas mass fraction of observational data used in this paper does not include it. According to a semi-empirical model by Popping et al. (2015), the HI mass in a galaxy at $z \sim 1.4$ with a halo mass of $10^{12-14} M_{\odot}$ is half or comparable to the H_2 mass. We examine the inflow and outflow rate assuming two cases that the HI mass in a galaxy is half of the H_2 mass and the same amount of the H_2 mass in a galaxy for the subsample with smaller/larger stellar mass. In these cases, the gas mass fraction is defined as $\mu = (M(H_2) + M(HI)) / (M(H_2) + M(HI) + M_*)$. The best-fit inflow and outflow rates for the case of $M(HI) = 0.5M(H_2)$ and the case of $M(HI) = M(H_2)$ are $1.51^{+0.44}_{-0.25}$ and $0.14^{+0.68}_{-0.14}$ ($M_{\text{gas}}^0 = 10^{10.44} M_{\odot}$) (the fit results and χ^2 contour maps are given in Figure 5.9) and $1.40^{+0.46}_{-0.21}$ and $0.00^{+0.74}_{-0.00}$ ($M_{\text{gas}}^0 = 10^{10.56} M_{\odot}$) (the fit results and χ^2 contour maps are given in Figure 5.10), respectively. The inflow and outflow rates are smaller and the initial gas mass is larger than those without HI mass. If we assume a larger HI mass than these (i.e., $M(HI) \geq 2M(H_2)$), the large amount of the initial gas mass causes a lower metallicity and the best-fit models in these cases are unable to reproduce the observed stacked values of metallicity (the fit results and χ^2 contour maps are given in Figure 5.11 and 5.12).

While the outflow rate value is consistent with zero to within error, the small number of stacked data points leads to large uncertainty. Heckman (2002) showed galactic-scale superwinds exist in galaxies with a global SFR surface density exceeding $0.1 M_{\odot} \text{ yr}^{-1} \text{ kpc}^{-2}$ from observations of local starburst galaxies. Because the SFR surface density in all of our sample, whose size is derived from B -band images, exceeds the threshold, the outflow rates of our sample may not be zero.

The uncertainty of inflow and outflow rates is large due to the small number of stacked data points. To obtain more reliable constraints of inflow and outflow rates, we need to increase the number of CO observations toward main-sequence galaxies with known metallicity covering wide ranges of stellar mass and metallicity.

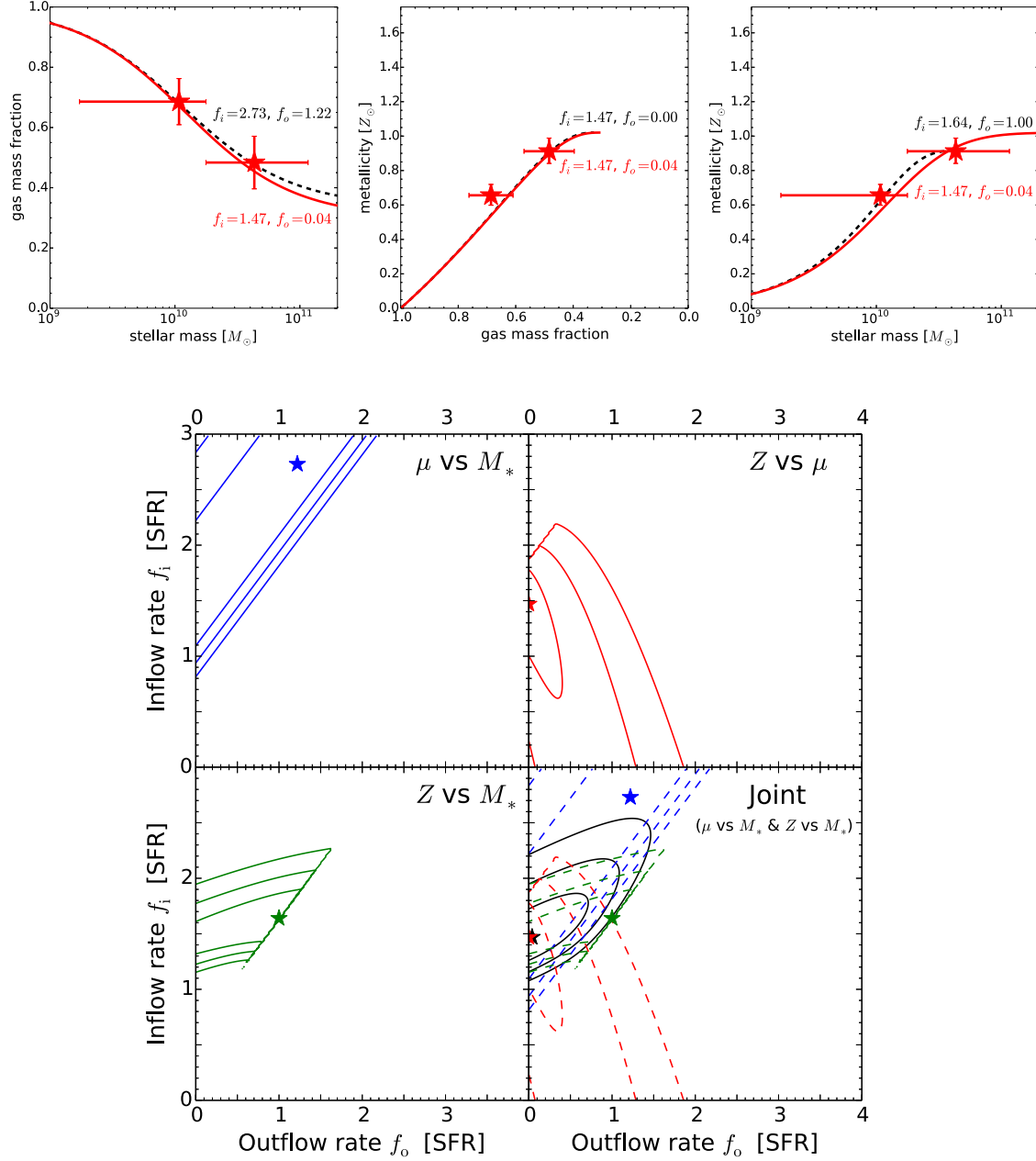


Figure 5.3: Same as Figure 5.1 (top) and 5.2 (bottom) but the stellar masses are derived with the Chabrier IMF.

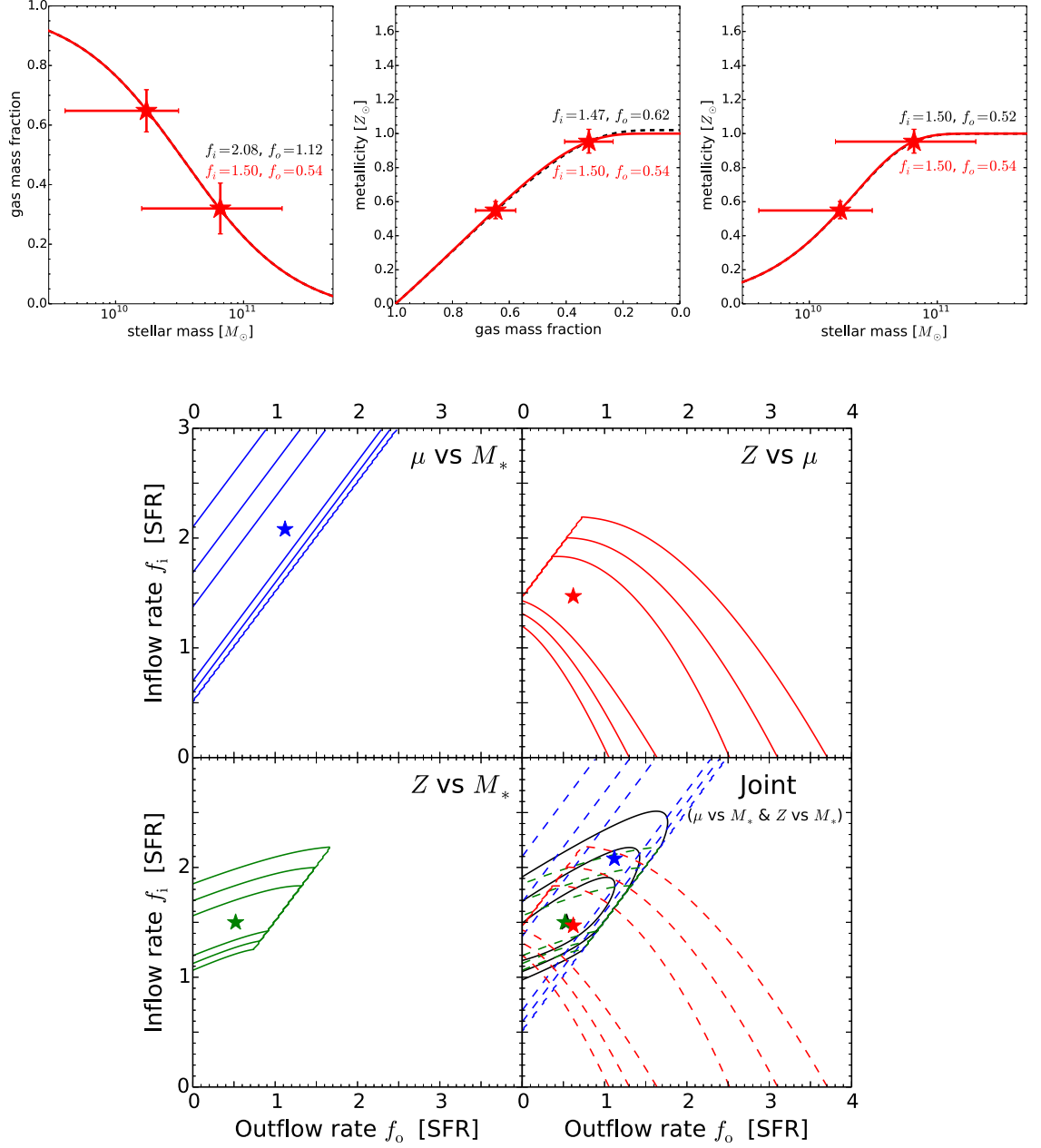


Figure 5.4: Same as Figure 5.1 (top) and 5.2 (bottom) but for the subsamples with lower and higher metallicity.

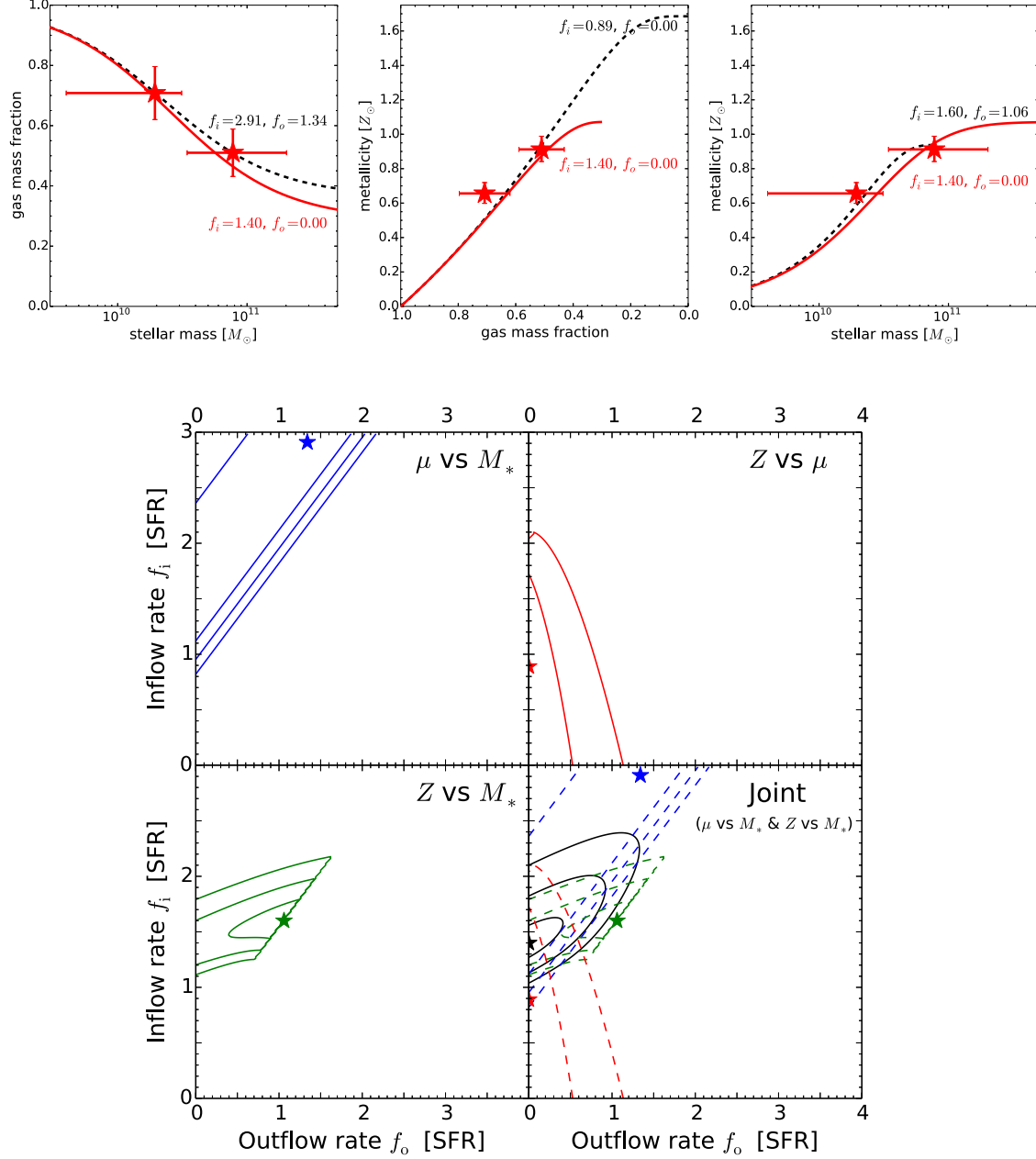


Figure 5.5: Same as Figure 5.1 (top) and 5.2 (bottom) but with the CO luminosity ratio of 0.12.

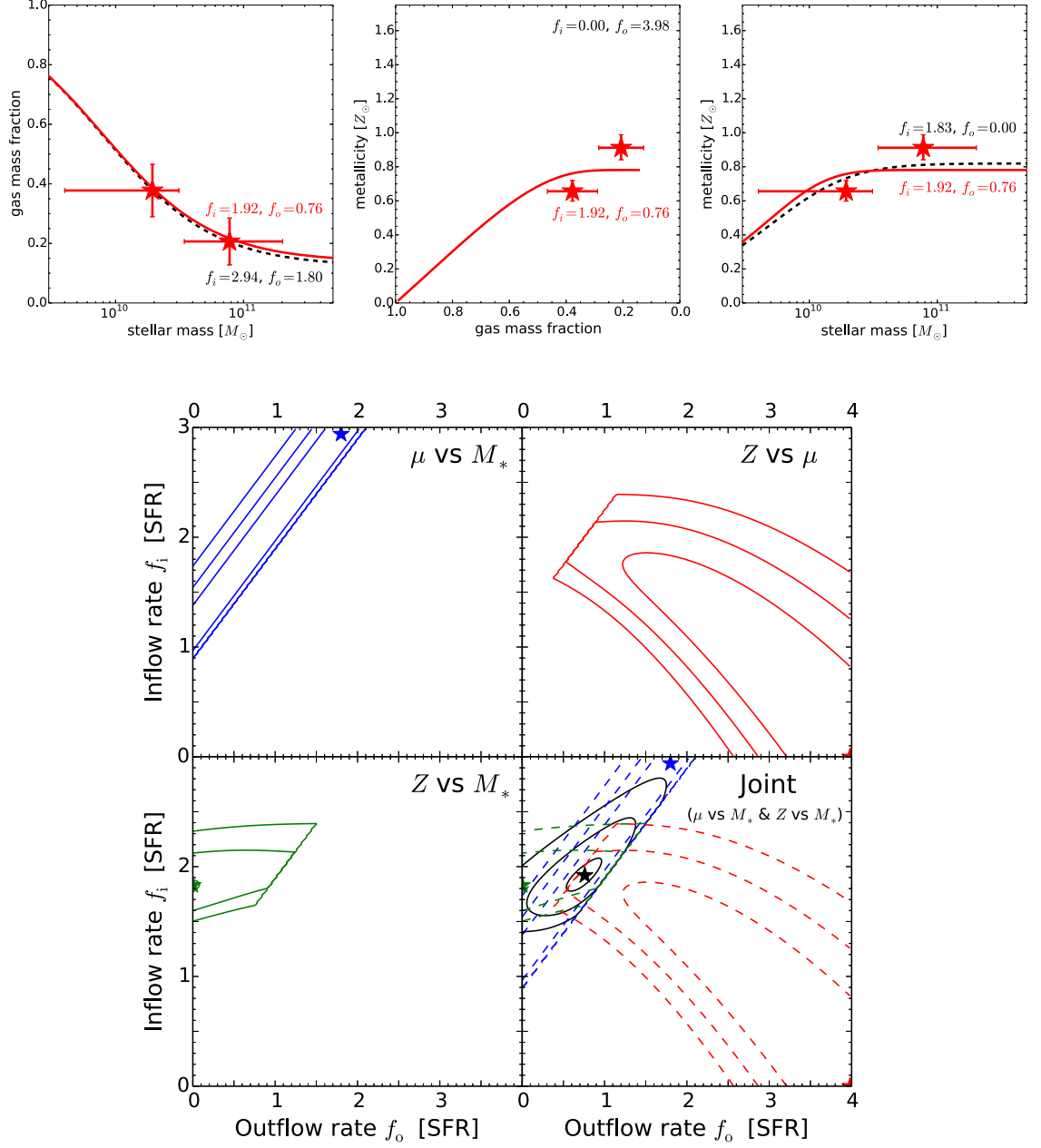


Figure 5.6: Same as Figure 5.1 (top) and 5.2 (bottom) but with the CO luminosity ratio of 0.46.

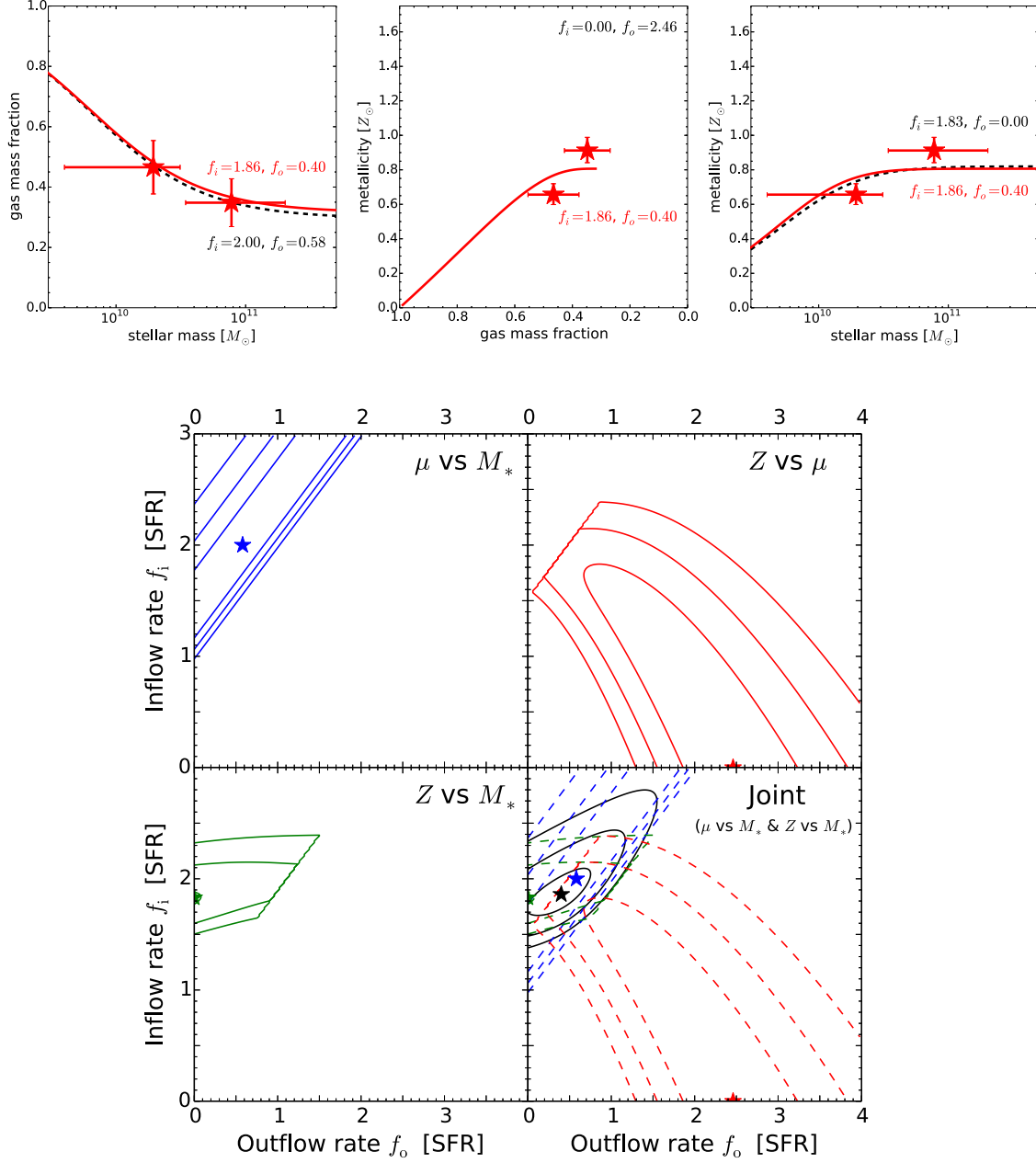


Figure 5.7: Same as Figure 5.1 (top) and 5.2 (bottom) but with the Galactic CO-to-H₂ conversion factor for the derivation of molecular gas masses.

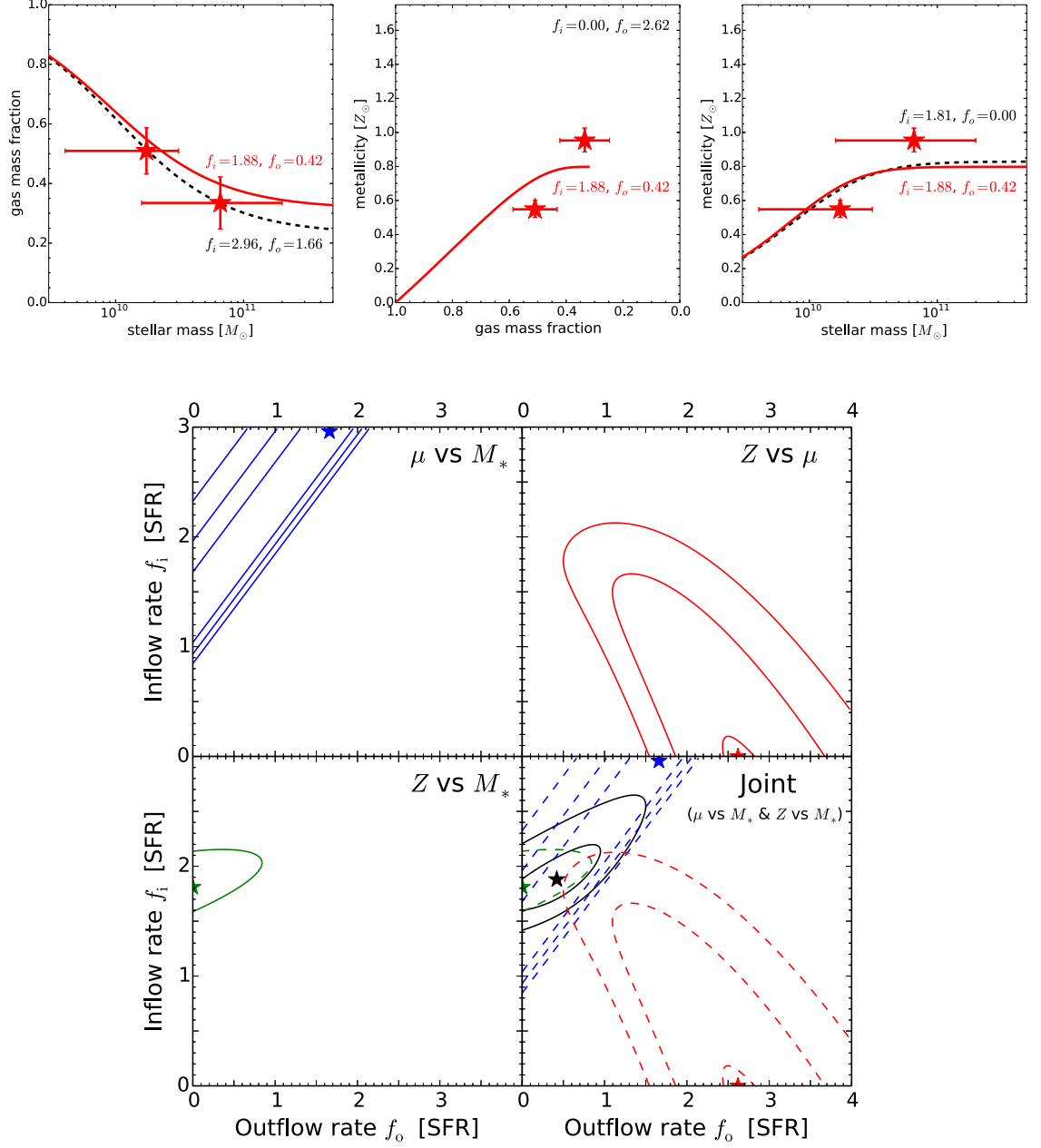


Figure 5.8: Same as Figure 5.1 (top) and 5.2 (bottom) but for the subsamples with lower and higher metallicity and using the Galactic CO-to-H₂ conversion factor for the derivation of molecular gas masses.

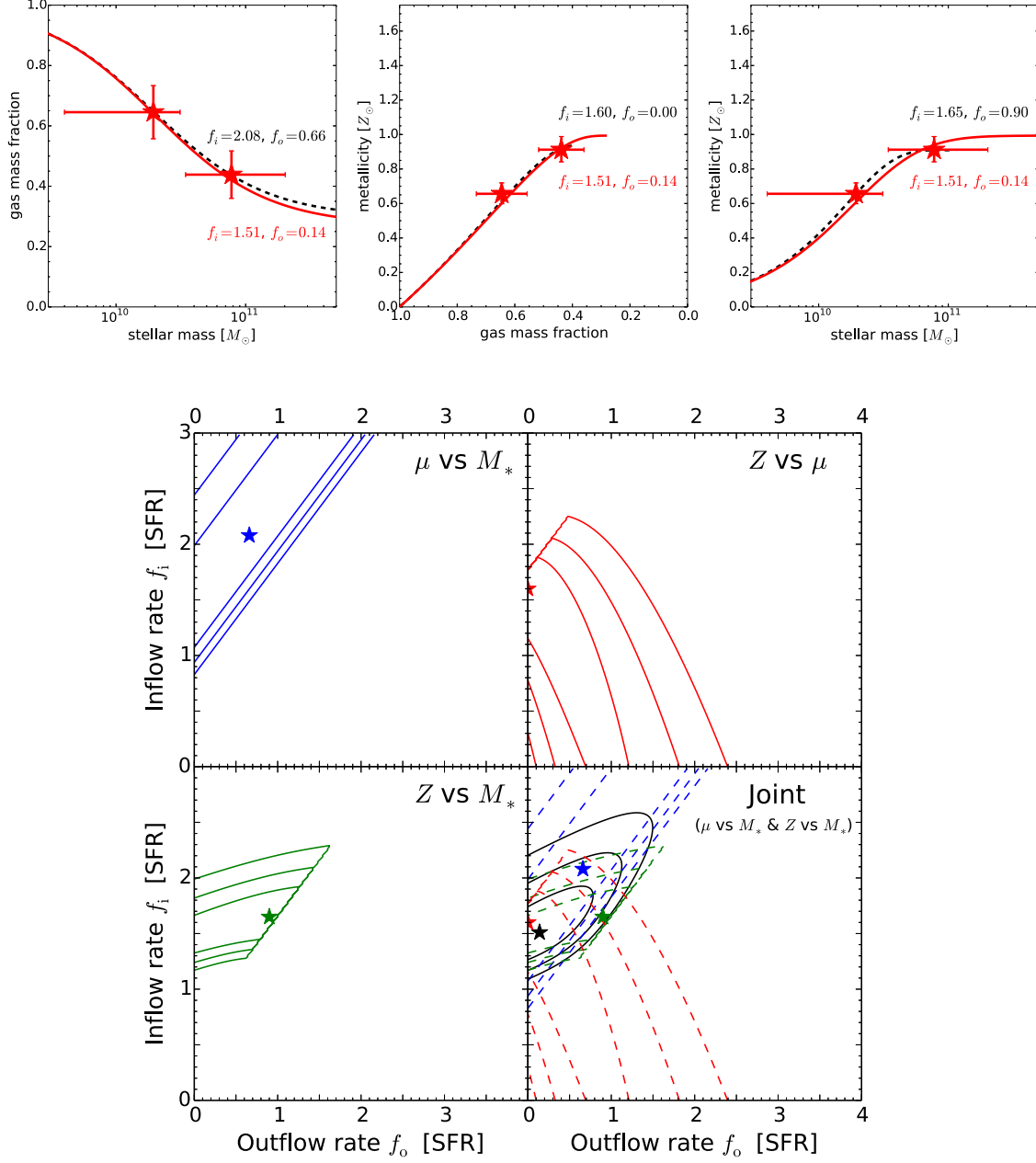


Figure 5.9: Same as Figure 5.1 (top) and 5.2 (bottom) but including HI mass by assuming $M(\text{HI}) = 0.5M(\text{H}_2)$.

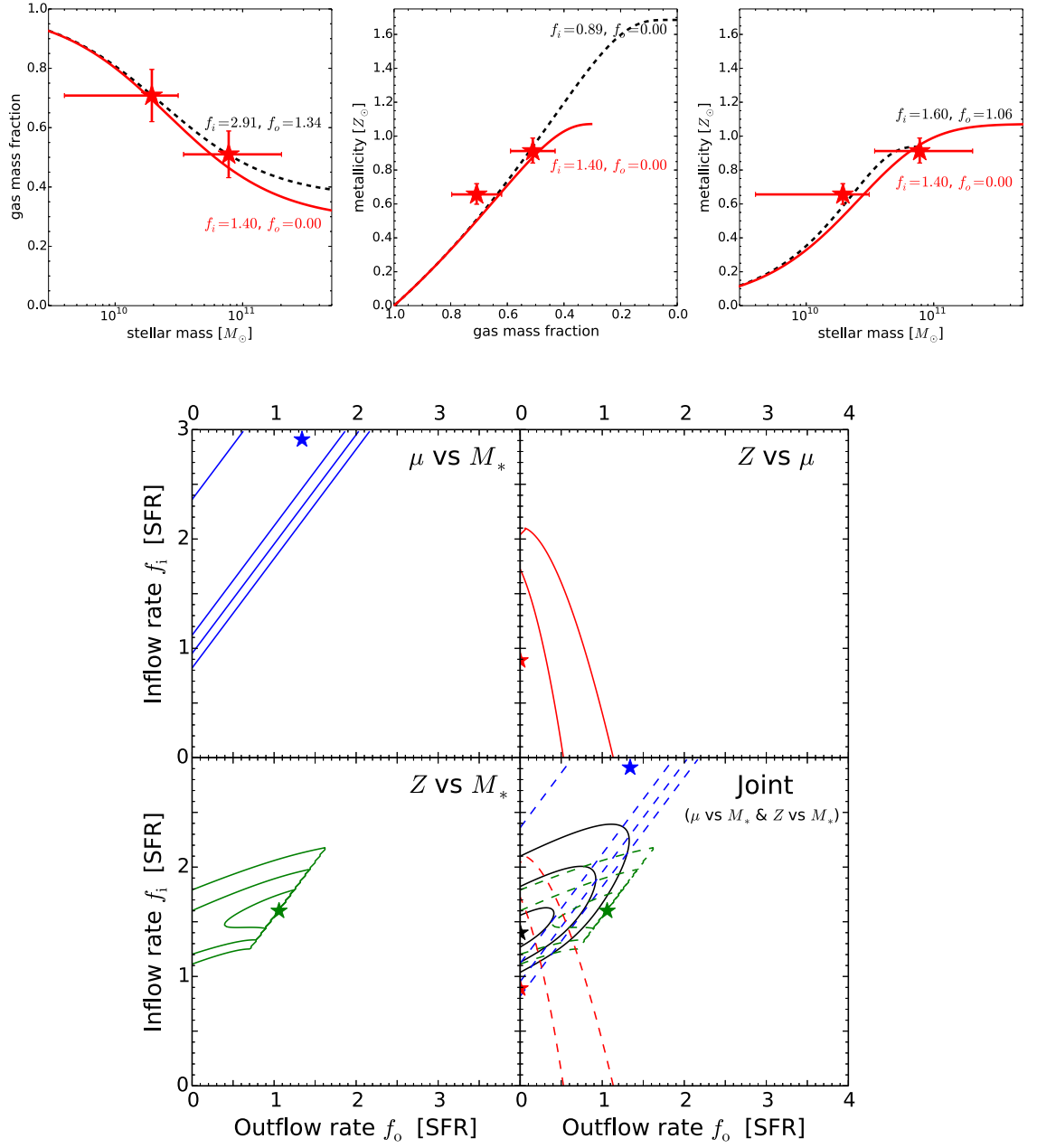


Figure 5.10: Same as Figure 5.1 (top) and 5.2 (bottom) by assuming $M(\text{HI}) = M(\text{H}_2)$.

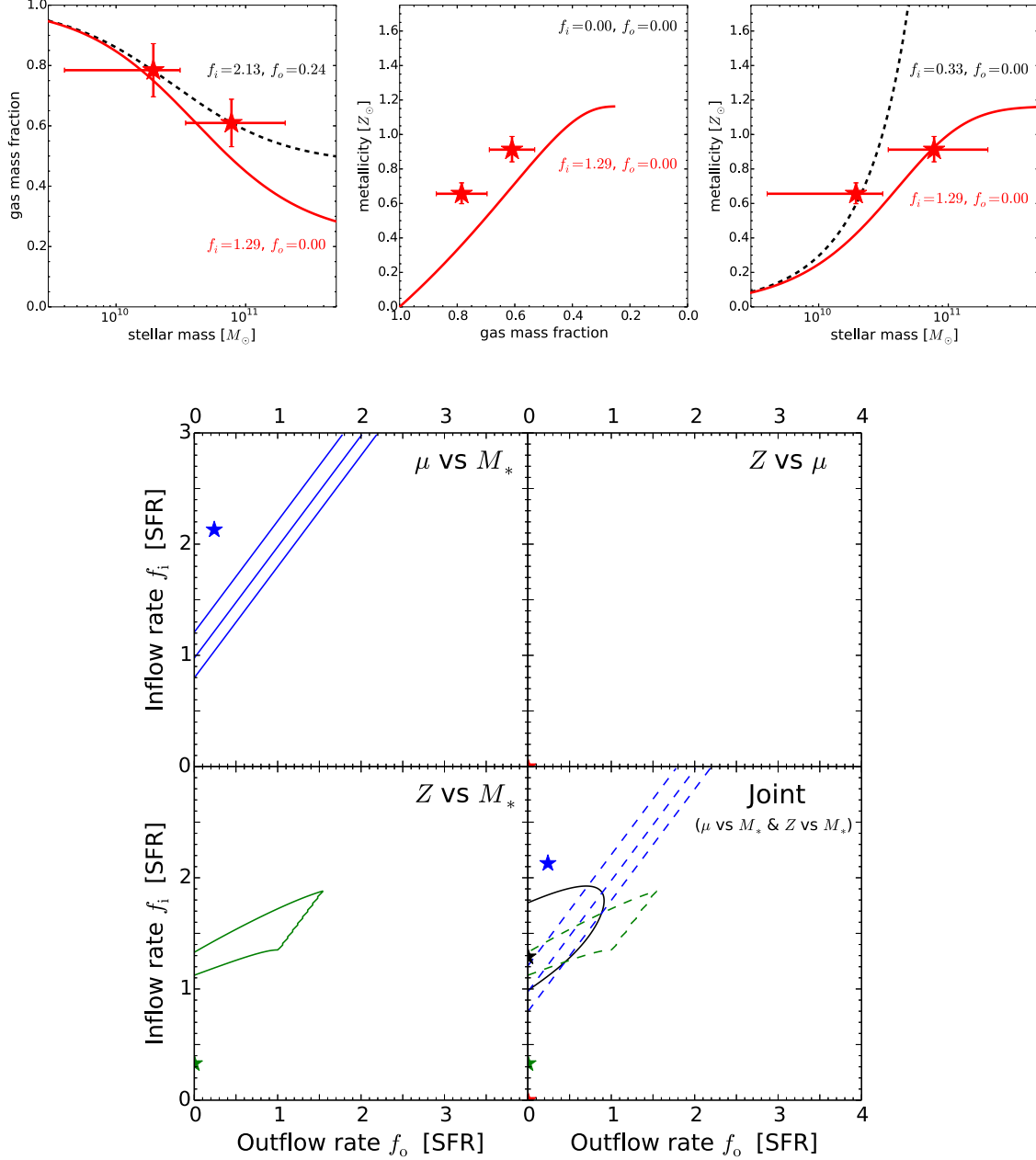


Figure 5.11: Same as Figure 5.1 (top) and 5.2 (bottom) but including HI mass by assuming $M(\text{HI}) = 2M(\text{H}_2)$.

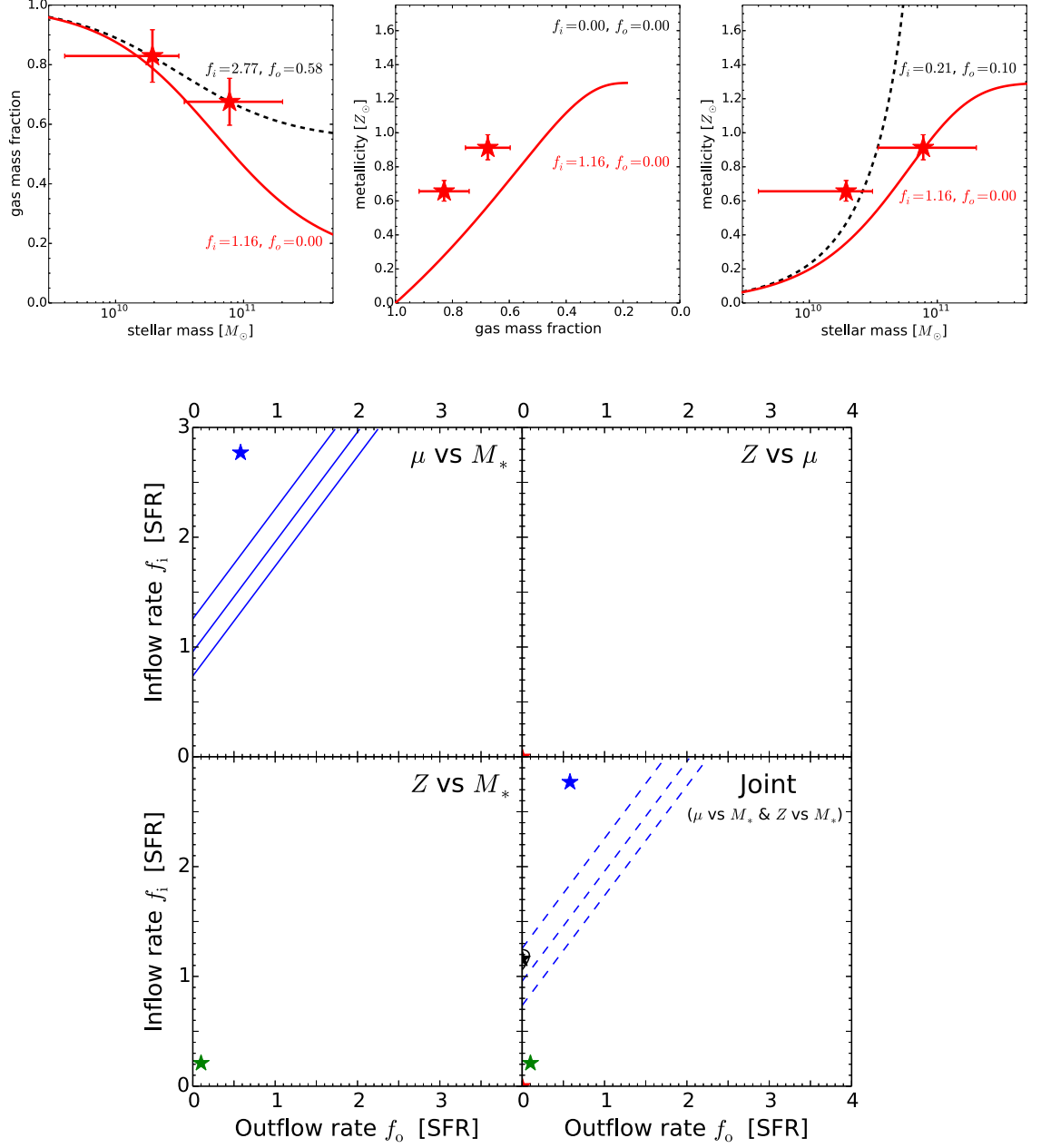


Figure 5.12: Same as Figure 5.1 (top) and 5.2 (bottom) but including HI mass by assuming $M(\text{HI}) = 3M(\text{H}_2)$.

Chapter 6

Concluding remarks

6.1 Summary

The studies of ISM in star-forming galaxies at the violent epoch of galaxy evolution is inevitable for the understanding of galaxy evolution. In this thesis, we investigated the properties of ISM in star-forming galaxies at $z \sim 1.4$ from the observations of ^{12}CO emission and dust thermal continuum emission. We conducted $\text{CO}(J = 5 - 4)$ and dust thermal continuum observations toward 20 galaxies using ALMA. We also carried out $\text{CO}(J = 2 - 1)$ observations of 6 galaxies using the Nobeyama 45 m radio telescope. The sample galaxies were selected from the $\text{H}\alpha$ detected galaxy samples which came originally from K_s -band selected galaxies in the SXDS field and 24 μm selected galaxies in the COSMOS field and were constructed by near-infrared spectroscopy with the FMOS on the Subaru telescope. The gas-phase metallicity was derived with the N2 method by using the $\text{H}\alpha$ and $[\text{NII}]\lambda 6584$ emission lines for each galaxy. The galaxy sample for ALMA was selected from the $\text{H}\alpha$ sample in the SXDS field to cover a wide range of stellar mass ($4 \times 10^9 - 4 \times 10^{11} M_\odot$) and metallicity ($12 + \log(\text{O}/\text{H}) = 8.2 - 8.9$) and to trace these distributions rather uniformly. The galaxy sample for the Nobeyama radio telescope was selected from the $\text{H}\alpha$ sample with a metallicity of $12 + \log(\text{O}/\text{H}) > 8.6$ to reduce the uncertainty of the CO-to- H_2 conversion factor and detected in the 24, 250, and 350 μm images in the both SXDS and COSMOS fields.

The CO emissions were detected from 11 galaxies in the ALMA observations and 3 galaxies in the Nobeyama observations. Masses of molecular gas and its fractions for the detected galaxies are in the ranges of $(3.9 - 35) \times 10^{10} M_{\odot}$ and $0.25 - 0.94$, respectively; these values are significantly larger than those in local spiral galaxies. For the ALMA sample, since the CO emission lines from about half of our sample galaxies are not detected, we performed stacking analyses to examine the relations of the molecular gas mass and its fraction against stellar mass and metallicity. The molecular gas mass increases with increasing stellar mass, but does not depend on metallicity. The molecular gas mass fraction decreases with both increasing stellar mass and metallicity. Due to the mass-metallicity relation, the dependences on stellar mass and metallicity are not separated clearly. To avoid the metallicity effect, we performed stacking analyses for subsamples with smaller and larger stellar mass at almost the same metallicity. The molecular gas mass increases with increasing stellar mass. Its fraction seems to decrease with increasing stellar mass, but the trend is not so significant. To avoid the stellar mass effect, we made stacking analyses for subsamples with lower and higher metallicity at almost same stellar mass. Both the molecular gas mass and its fraction decrease with increasing metallicity. CO-detected galaxies are located around the sequence of normal star-forming galaxies in the diagram of molecular gas mass versus SFR. The results of stacking analysis show that the depletion time of molecular gas is $\sim 3 \times 10^8$ yr, which is smaller than that in local galaxies. Although the uncertainty of depletion time is large, the timescale tends to decrease with increasing stellar mass and metallicity. These trends contrast with those in local star-forming galaxies.

From the ALMA observations, we detected significant continuum emissions from 2 galaxies with marginal detections from a further 5 galaxies. Continuum emissions tend to be detected for galaxies with larger stellar mass and with higher metallicity. Dust masses were derived with a modified blackbody model by adopting a dust temperature of 30 K for the ALMA sample and 35 K for the Nobeyama sample and adopting a dust emissivity index of 1.5. The derived dust masses of the detected galaxies are $(3.9 - 67) \times 10^7 M_{\odot}$. For the ALMA sample, we used stacking analyses to examine the relations of the dust mass against stellar mass and metallicity. The dust mass increases

with increasing stellar mass and seems to increase with increasing metallicity. We also derived the gas-to-dust ratio. The result of stacking the subsamples with lower and higher metallicity shows that the gas-to-dust ratios are ~ 500 , which is 3 – 4 times larger than those in local galaxies in the same metallicity range. The result of Nobeyama observations agrees with this result. The gas-to-dust ratio at $z \sim 1.4$ seems to decrease with increasing metallicity. The dependence of the gas-to-dust ratio on the far-infrared luminosity density is not clearly seen.

We constrained the inflow and outflow rates in star-forming galaxies at $z \sim 1.4$ by comparing the analytic model for the chemical evolution in a galaxy and the results of ALMA observations. The joint least χ^2 fit of the analytic model to the result of stacking analysis for the subsample with smaller/larger stellar mass shows the inflow and outflow rates in units of SFR are $1.69^{+0.44}_{-0.30}$ and $0.36^{+0.60}_{-0.36}$, respectively. The result is consistent with that from a previous study in which the gas mass was derived from extinction corrected $H\alpha$ luminosity and galaxy size by assuming the Kennicutt-Schmidt law. The inflow rate is roughly comparable to the sum of outflow rate and effective SFR, which supports the equilibrium model for galaxy evolution. The result is also consistent with that derived from stacking analysis for subsamples with lower/ higher metallicity. If we include the HI mass which is proportional to molecular gas mass, then lower inflow and outflow rates and larger initial gas masses are needed to explain the data. However, if we assume the amount of HI mass is larger than H_2 mass, the chemical evolution model used in this paper produces much lower metallicity, and does not reproduce the stacked metallicity. The uncertainty of inflow and outflow rates is large due to the small number of stacked data points. To obtain more reliable constraints of inflow and outflow rates, we need to increase the number of CO observations toward main-sequence galaxies with known metallicity covering wide ranges of stellar mass and metallicity.

6.2 Future prospects

6.2.1 CO observations with wider range of stellar mass and metallicity at the violent epoch of galaxy evolution

In this work, we showed the general trends of the ISM properties in star-forming galaxies at $z \sim 1.4$ against stellar mass and metallicity. However, the numbers of galaxies we observed and of stacked data points are small and the details of the trends are still not so clear. As mentioned in Section 5.4, the uncertainty of inflow and outflow rates constrained with the chemical evolution model is large due to the same reason. In addition to this, the ranges of stellar mass and metallicity of galaxy samples in this work and the previous studies are still not wide enough. Several semi-analytic models for the cosmological evolution of gas mass show that the slope of gas mass fraction against stellar mass at $M_* < 10^{10} M_\odot$ is flatter than that at $M_* > 10^{10} M_\odot$ (e.g., Fu et al. 2012; Popping et al. 2014, 2015). Cosmological simulations including star-formation, inflow, and outflow by Davé et al. (2011) also predict the relations between the gas mass fraction and stellar mass for the four outflow models: no winds, constant winds, slow winds, and momentum-conserving winds. These models except for no winds model also predict a flatter slope of gas mass fraction against stellar mass below $M_* \sim 10^{10} M_\odot$. The cause for this trend is the longer timescale of winds recycling, i.e., the return of the previously ejected material back into a galaxy, for galaxies with lower stellar mass (Oppenheimer et al. 2010). The stellar mass of the Milky Way (representative of present spiral galaxies) progenitor at $z \sim 2$ which is estimated by using an abundance-matching technique or by inferring the stellar mass growth along the evolution of the main sequence is $10^{9.5-10} M_\odot$ (e.g., van Dokkum et al. 2013; Patel et al. 2013; Papovich et al. 2015; Morishita et al. 2015). Therefore, the molecular gas observations of such lower stellar mass galaxies are inevitable for revealing galaxy evolution. The completion of ALMA last year enables us to conduct CO observations toward much more star-forming galaxies covering much wider ranges of stellar mass and metallicity at the violent epoch of galaxy evolution.

6.2.2 Properties of ISM in star-forming galaxies at $z = 0.1 - 1$

This work shows that the general trends of ISM properties in star-forming galaxies at $z \sim 1.4$ are different from those in local galaxies. To investigate the properties of ISM at each redshift from $z \sim 1.4$ to $z = 0$ leads to reveal how the trends at $z \sim 1.4$ change into those in local universe and to unveil galaxy evolution from $z \sim 1.4$ to 0. As described in Section 1.5.1, the number of CO observations toward main-sequence galaxies at $z = 0.1 - 1$ is so small and the observed galaxies in this redshift range are biased to objects with larger stellar mass and higher specific SFR. Therefore, we have not been able to connect the violent epoch of galaxy evolution and present universe yet. In this redshift range, the cosmic SFR density gradually decreases (e.g., Madau & Dickinson 2014:Figure 1.2). The decrease of molecular gas mass in galaxies and/or decline of the star-formation efficiency in galaxies can cause the decrease of the cosmic SFR density. Hence, the studies of ISM in main-sequence galaxies in this redshift range are very important to answer “what causes the decrease of cosmic SFR density?” and to unveil galaxy evolution. The advent of low-noise receivers on the Nobeyama 45 m telescope and the IRAM 30 m telescope and a new receiver on ALMA which allows us to observe in a frequency range of 125 – 163 GHz enables us to carry out CO observations toward main-sequence galaxies at $z = 0.1 - 1$ with wide range of stellar mass and metallicity.

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