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Galaxy gas fractions at high redshift: the tension between observations and cosmological simulations

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ABSTRACT

CO measurements of $z \sim 1$–4 galaxies have found that their baryonic gas fractions are significantly higher than those for galaxies at $z = 0$, with values ranging from 20 to 80 per cent. Here, we suggest that the gas fractions inferred from observations of star-forming galaxies at high-z are overestimated, owing to the adoption of locally calibrated CO–H_2 conversion factors ($\alpha_{\rm CO}$). Evidence from both observations and numerical models suggests that $\alpha_{\rm CO}$ varies smoothly with the physical properties of galaxies, and that $\alpha_{\rm CO}$ can be parametrized simply as a function of both gas-phase metallicity and observed CO surface brightness. When applying this functional form, we find $f_{\rm gas} \approx 10$–40 per cent in galaxies with $M_* = 10^{10}$–10^{12} M$_\odot$. Moreover, the scatter in the observed $f_{\rm gas}$–M_* relation is lowered by a factor of 2. The lower inferred gas fractions arise physically because the interstellar media of high-z galaxies have higher velocity dispersions and gas temperatures than their local counterparts, which results in an $\alpha_{\rm CO}$ that is lower than the $z = 0$ value for both quiescent discs and starbursts. We further compare these gas fractions to those predicted by cosmological galaxy formation models. We show that while the canonically inferred gas fractions from observations are a factor of 2–3 larger at a given stellar mass than predicted by models, our rederived $\alpha_{\rm CO}$ values for $z = 1$–4 galaxies result in revised gas fractions that agree significantly better with the simulations.

Key words: ISM: molecules – galaxies: formation – galaxies: high-redshift – galaxies: ISM – galaxies: starburst.

1 INTRODUCTION

Recent technological advances in (sub)millimetre-wave telescope facilities have allowed for the detection of star-forming H_2 gas in large numbers of galaxies at high redshift via the proxy molecule ^{12}CO (hereafter CO; Greve et al. 2005; Tacconi et al. 2006; Coppin et al. 2008; Tacconi et al. 2008; Dannerbauer et al. 2009; Wagg, Kanekar & Carilli 2009; Bothwell et al. 2010; Carilli et al. 2010; Daddi et al. 2010a,b; Genzel et al. 2010; Riechers et al. 2010, 2011a,b; Riechers 2010; Tacconi et al. 2010; Casey et al. 2011; Geach et al. 2011; Wang et al. 2011, see Solomon & Vanden Bout 2005 for a summary of pre-2005 references).

A major finding from these studies is that, at a given stellar mass, early Universe galaxies tend to be significantly more gas rich than their present-day counterparts, with baryonic gas fractions[1] [hereafter defined as $f_{\rm gas} = M_{\rm H2}/(M_{\rm H2} + M_*)$] ranging from ∼20 to 80 per cent (e.g. Daddi et al. 2010b; Tacconi et al. 2010). This is consistent with both observational and theoretical results that suggest that even gas-rich disc galaxies at $z \sim 2$ are able to form stars rapidly enough that they are comparable to the most extreme merger-driven starburst events in the local Universe (Daddi et al. 2005; Davé et al. 2010; Hopkins et al. 2010).

However, there is a tension between the inferred gas fractions of high-z galaxies and galaxy formation models. Hydrodynamic cosmological simulations typically account for the simultaneous growth of galaxies via the accretion of gas from the intergalactic medium (e.g. Keres, Yun & Young 2003) as well as the consumption of gas by star formation. A generic feature of these simulations is that the star formation rate (SFR) of 'main-sequence galaxies' (galaxies not undergoing a starburst event) is roughly proportional to the accretion rate and that galaxies tend to have weakly declining gas fractions as their stellar masses increase. Broadly, at a given stellar mass, galaxies in simulations have baryonic gas fractions a factor of 2–3 less than observed gas fractions. This is seen in both hydrodynamic simulations and semi-analytic models (SAMs; Lagos et al. 2011). As an example, Davé et al. (2010) find very few galaxies in a simulated ∼150 Mpc (comoving) volume with stellar mass $M_* \sim 10^{11}$ M$_\odot$ with gas fractions greater than

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[1] This includes a 36 per cent correction for helium.

30 per cent. This is in contrast to observations which infer gas fractions in comparable mass galaxies of up to 80 per cent.

One potential solution is that the inferred gas masses from high-z galaxies are systematically too large. H_2 masses are typically calculated using the luminosity of the CO ($J = 1$–0) emission line,[2] and then converted to an H_2 mass via a CO–H_2 conversion factor $\alpha_{\rm CO}$.[3] In the literature, $\alpha_{\rm CO}$ is typically used bimodally with one value for 'quiescent/disc mode' star formation and a lower value for 'starburst/merger mode' star formation. In the Galaxy and Local Group, $\alpha_{\rm CO}$ is observed to be relatively constant with an average $\alpha_{\rm CO} \approx 6$ (Blitz et al. 2007; Fukui & Kawamura 2010). In contrast, dynamical mass modelling of local galaxy mergers suggests that $\alpha_{\rm CO}$ should be lower in these galaxies by a factor of 2–10 (Downes & Solomon 1998; Narayanan 2011). Despite an observed dispersion in inferred $\alpha_{\rm CO}$ values from local mergers, a value of $\alpha_{\rm CO} \approx 0.8$ is typically uniformly applied to these starbursts.

At higher redshifts, it is more unclear which of the two bimodal values of $\alpha_{\rm CO}$ to use. For example, for a star-forming disc galaxy that may be undergoing rapid collapse in ∼kpc-scale clumps and forming stars at rates >100 M$_\odot$ yr^{-1} (i.e. comparable to local galaxy mergers), is the appropriate $\alpha_{\rm CO}$ the locally calibrated 'quiescent/disc' value or the 'starburst/merger' value? Similarly, should high-redshift submillimetre galaxies (SMGs), which are potentially forming stars up to an order of magnitude faster than local mergers, utilize the locally calibrated 'starburst/merger' value? Typically, observational studies use the locally calibrated quiescent/disc value for high-z discs and the local starburst/merger value for high-z SMGs.

Recent observational evidence by Tacconi et al. (2008), Bolatto et al. (2008), Leroy et al. (2011), Genzel et al. (2012), Schruba et al. (2012) and Papadopoulos et al. (2012), as well as theoretical work by Ostriker & Shetty (2011), Narayanan et al. (2011b), Shetty et al. (2011a,b) and Feldmann, Gnedin & Kravtsov (2012) have suggested that perhaps the picture of a bimodal $\alpha_{\rm CO}$ is too simplistic and that $\alpha_{\rm CO}$ may depend on the physical environment of the interstellar medium (ISM). This picture was expanded upon by Narayanan et al. (2012) who developed a functional form for the dependence of $\alpha_{\rm CO}$ on the CO surface brightness and gas-phase metallicity of a galaxy. When applying this model to observations of high-z galaxies, Narayanan et al. (2012) found that, on average, high-z disc galaxies have $\alpha_{\rm CO}$ values a factor of a few lower than those for present-epoch discs, and high-z SMGs have $\alpha_{\rm CO}$ values lower than those for present-day ultraluminous infrared galaxies (ULIRGs), with some dispersion. Physically, this means that for a given observed CO luminosity, the inferred H_2 gas mass should be systematically less than what one would derive using $\alpha_{\rm CO}$ values calibrated to local galaxies. This owes to warmer and higher velocity dispersion molecular gas in high-z galaxies which gives rise to more CO intensity at a given H_2 column density. The model form for $\alpha_{\rm CO}$ presented by Narayanan et al. (2012) finds success in matching local observations of discs and ULIRGs (Narayanan et al. 2011b), as well as observed CO–H_2 conversion factors for low-metallicity systems.

Based on these results, in this paper, we re-examine CO detections from high-z galaxies utilizing the physically motivated functional form for $\alpha_{\rm CO}$ presented in Narayanan et al. (2012), rather than the traditional bimodal form. We compare our results to those of cosmological hydrodynamic simulations and show that while the inferred gas fractions derived from the traditional $\alpha_{\rm CO}$ conversion factor are much larger than those predicted by models, the Narayanan et al. (2012) model form for $\alpha_{\rm CO}$ brings these values down, and in reasonable agreement with simulations. A principal result of the work we will present is that the typical gas fraction of a high-z galaxy is typically ∼10–40 per cent, rather than ∼40–80 per cent as is inferred when utilizing traditional $\alpha_{\rm CO}$ values. In Section 2, we describe the literature data utilized here; in Section 3, we present our main results and in Section 4, we summarize.

2 METHODOLOGY

2.1 Literature data

We examine CO detections of both inferred high-z disc galaxies and SMGs with masses ranging from $\sim 10^{10}$ to 10^{12} M$_\odot$ in stellar mass.[4] A large number of literature SMGs are compiled by Bothwell et al. (2012) and include 16 new detections presented in that paper. The compilation by Bothwell et al. includes detections from Neri et al. (2003), Greve et al. (2005), Tacconi et al. (2006), Casey et al. (2009), Bothwell et al. (2010) and Engel et al. (2010). Other SMGs included in our work are compiled in Genzel et al. (2010). The inferred disc galaxies are taken primarily from the compilation of Genzel et al. (2010) and Daddi et al. (2010b). These include galaxies from the Spectroscopic Imaging Survey in the Near-infrared with SINFONI (SINS) sample (Förster Schreiber et al. 2009), as well as *BzK*-selected galaxies (Daddi et al. 2004). Finally, we include optically faint radio galaxies (OFRGs) with CO detections from the Casey et al. (2011) sample.

In our sample, a large number of the *BzK* and SINS galaxies have been imaged and found to have rotationally dominated gas, consistent with a disc-like morphology. The SMGs are oftentimes assumed to be mergers, though there is some debate over this (Narayanan et al. 2009, 2010b; Davé et al. 2010; Hayward et al. 2011, 2012). The OFRGs are of unknown origin. As we will discuss in Section 3, the global morphology is irrelevant for our model form for $\alpha_{\rm CO}$ and the general results in this paper.

The observational papers that we draw from had to make a number of assumptions. Our philosophy is to simply utilize these assumptions in this paper and not make any adjustments to assumed numbers. The reason for this is to isolate the effects of applying our model $\alpha_{\rm CO}$ on the inferred gas fractions. For example, as we will discuss, CO surface brightnesses are required in order to employ the Narayanan et al. (2012) model for $\alpha_{\rm CO}$. When direct measurements are reported, we utilize them. Otherwise, we make the same size assumption that is made in the paper we draw from. Similarly, a number of the detections presented in the aforementioned papers utilized millimetre-wave telescopes, meaning that the observed transition is of higher lying CO lines in the rest frame. Conversion to the ground-state CO ($J = 1$–0) line then occurs via an assumption of CO excitation. Again, we simply utilize the conversion from excited CO lines to CO ($J = 1$–0) as presented in the paper we draw the data from. This said, the assumed excitation ladders in the literature are all relatively similar.

It is worth a quick word on the stellar masses of the SMGs in our sample. There is an ongoing literature debate regarding the stellar

[2] In fact, only a few studies directly observe CO ($J = 1$–0) at high z. Typically, higher rotational states are observed, and then down-converted to the ground state via an assumption about the CO excitation.

[3] $\alpha_{\rm CO}$ is alternatively monikered $X_{\rm CO}$ or the X factor. The two are related via $X_{\rm CO}$ (cm^{-2} (K km s^{-1})$^{-1}$) $= 6.3 \times 10^{19} \alpha_{\rm CO}$ (M$_\odot$ pc^{-2} (K km s^{-1})$^{-1}$). In this paper, we utilize $\alpha_{\rm CO}$ as notation for the CO–H_2 conversion factor.

[4] The limits on stellar masses are highly dependent on which literature stellar masses for SMGs we use (Michałowski et al. 2009; Hainline et al. 2011).

masses of high-redshift SMGs. Specifically, for the *same* SMGs, Michałowski et al. (2009) and Hainline et al. (2011) find differing stellar masses by up to an order of magnitude (with the Hainline masses being lower). Some attempts to understand the origin of the discrepancy have been reported by Michałowski et al. (2012). In this work, we remain agnostic as to which stellar masses are 'correct' and present our results in terms of both sets of observations when relevant.

2.2 Revised CO–H_2 conversion factors for observed galaxies

As discussed in Section 1, we utilize the functional form of α_{CO} derived in Narayanan et al. (2012) to recalculate the H_2 gas masses from the high-z galaxies in our sample. In this model, the CO–H_2 conversion factor can be expressed as

$$\alpha_{CO} = \frac{10.7 \times \langle W_{CO} \rangle^{-0.32}}{Z'^{0.65}}, \tag{1}$$

where α_{CO} has units of $M_\odot$ pc^{-2} (K km s^{-1})$^{-1}$, Z' is the gas-phase metallicity in units of solar and $\langle W_{CO} \rangle$ is the luminosity-weighted CO intensity over all Giant Molecular Clouds (GMCs) in a galaxy. While $\langle W_{CO} \rangle$ is a difficult quantity to observe, in the limit of uniform distribution of luminosity from the ISM in a galaxy, this reduces to L'_{CO}/A, where A is the area observed (L'_{CO}/A is the CO surface brightness). If the light distribution is actually rather concentrated (and most of the area observed is in dim pixels), the true surface brightness of the pixels which emit most of the light will increase, and the true α_{CO} will be even lower than what is calculated by equation (1). This will cause the gas fractions to decrease even further from what utilizing the Narayanan et al. (2012) model for α_{CO} derives, thus enhancing our results. The CO surface brightness ($\langle W_{CO} \rangle$) serves as a physical parametrization for the H_2 gas temperature and velocity dispersion, both of which affect the velocity-integrated CO line intensity[5] at a given H_2 gas mass.

The functional form for α_{CO} also depends on gas-phase metallicity. Physically, α_{CO} varies with the gas-phase metallicity due to the growth of CO dark molecular clouds in low-metallicity gas. In this regime, the required dust to protect CO from photodissociating radiation is not present, but the H_2 is abundant enough to self-shield for survival. For the galaxies in question, metallicity measurements are typically not available. Hence, we assume a solar metallicity ($Z' = 1$) for all galaxies. Based on the $z \sim 2$ mass–metallicity relation, galaxies of mass $M_* \sim 10^{11}$ $M_\odot$ typically have metallicities of the order of solar (Erb et al. 2006). Thus, an assumption of $Z' = 1$ is likely reasonable. We test the validity of this assumption by examining the effect of including a stellar mass–metallicity relation. Following Erb et al. (2006), we assume that all galaxies above $M_* = 10^{11}$ $M_\odot$ have $Z' = 1$ and that the metallicity evolves as $(M_*)^{0.3}$ for lower mass galaxies. The gas fractions in this test do not deviate by more than 10 per cent compared to our assumption that $Z' = 1$.[6] This is because of the weak dependence of metallicity on stellar mass, the weak dependence of α_{CO} on metallicity and the fact that gas fractions depend on stellar mass and gas mass.

It is worth noting that the results in this paper are not entirely dependent on the model for α_{CO} given in equation (1). A compilation of observations results in a very similar relation. Ostriker & Shetty (2011) showed that α_{CO} and Σ_{H2} are related via a power law in observed galaxies; a conversion of Σ_{H2} to W_{CO} via the relation $X_{CO} = \Sigma_{H2}/W_{CO}$ (and a linear relationship between X_{CO} and α_{CO}) gives an α_{CO}–W_{CO} relation that is nearly identical to the model form in equation (1). Similarly, while we assume $Z' = 1$ for the observed galaxies analysed in this work, we note that the model power-law relation between α_{CO} and Z' is very similar to what has been observed in samples of low-metallicity galaxies (Bolatto et al. 2008; Leroy et al. 2011; Genzel et al. 2012). In this sense, the forthcoming results in this paper could be derived entirely from empirical observational evidence.

In Fig. 1, we plot histograms of the literature α_{CO} values used in the observations of the galaxies analysed in this work (black), as well as our rederived α_{CO} values based on equation (1) (red). We divide the lines into high-z mergers (where SMGs are assumed to be mergers in this figure and hereafter) and high-z discs so that the reader can see the relative difference between our derived α_{CO} values and the original ones. While the range of α_{CO} values is similar in both cases, there is significantly more power towards low α_{CO} values when utilizing our model for both high-z discs and high-z mergers.

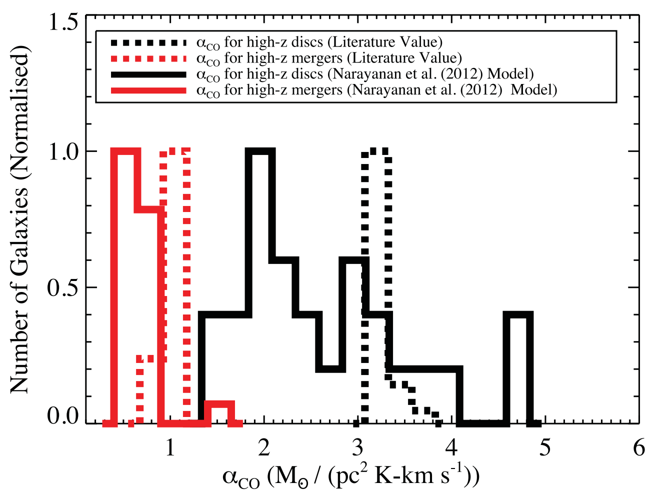

Figure 1. Histograms of literature values for α_{CO} for high-z galaxies, as well as those rederived via equation (1). The dashed lines denote the literature values and the solid lines the theoretical α_{CO} values. The black lines are for high-z discs and the red lines for inferred high-z mergers (SMGs). On average, the theoretical α_{CO} values are lower than the locally calibrated (traditional literature values) values for discs and mergers. This owes to higher velocity dispersion and warmer gas in high-z galaxies which drive more CO emission per unit H_2 gas mass than in local galaxies.

3 RESULTS AND DISCUSSION

We first examine the effect of modifying α_{CO} from the traditional bimodal values to the Narayanan et al. (2012) model on the f_{gas}–M_* relation in high-z galaxies. In Fig. 2, we show the f_{gas}–M_* relation for all galaxies in our sample utilizing both the Michałowski et al. (2009) and Hainline et al. (2011) stellar masses. The left-hand panels show the relationship for the observed galaxies when using the traditional bimodal α_{CO} and the right-hand panels when applying equation (1). In order to compare with galaxy formation simulations, we overlay the mean f_{gas}–M_* relation from the cosmological hydrodynamic calculations of Davé et al. (2010) denoted by stars. The error bars in the stars denote the range of possible f_{gas} values for the simulated galaxies in a given stellar mass bin. The simulated

[5] For optically thick gas.

[6] We note that there is one galaxy which varies by ∼22 per cent. This is the lowest mass galaxy in the Hainline et al. (2011) stellar mass determinations.

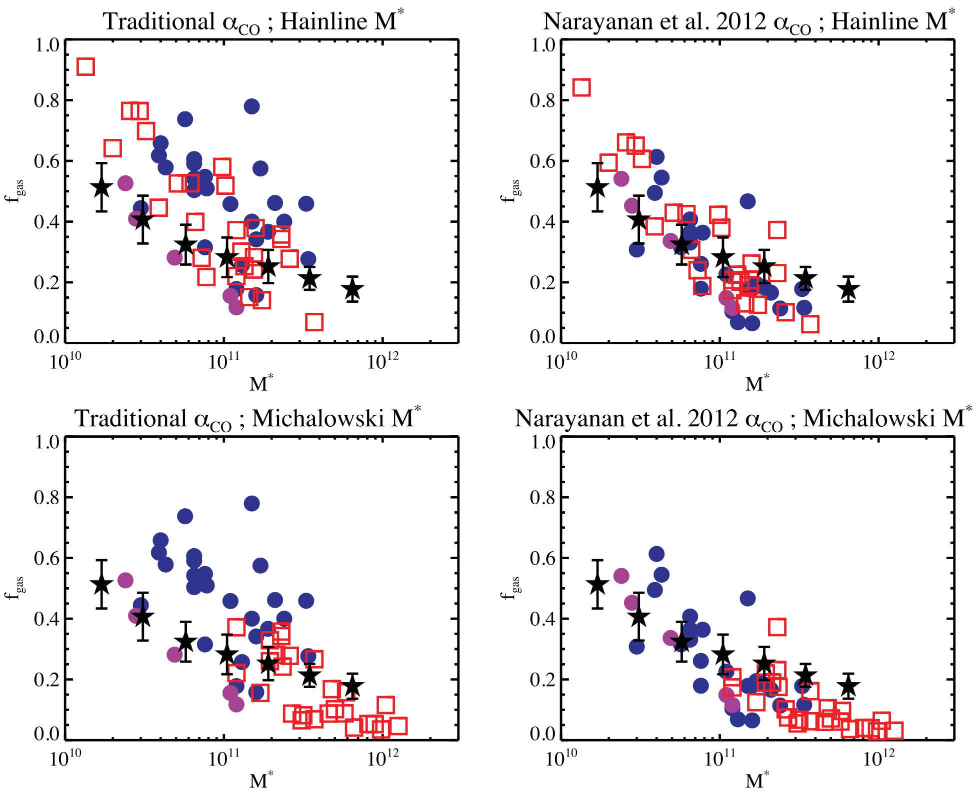

Figure 2. Comparison of $f_{\rm gas}$ against stellar mass (M_*) for discs and mergers at high z. The blue filled circles are observed high-z discs, the red open squares are observed SMGs (assumed to be mergers) and the purple filled circles are OFRGs (which are of unknown physical form). The black stars show results from main-sequence galaxies from the cosmological hydrodynamic simulations of Davé et al. (2010), with dispersion noted by the error bars. The top panels show the results when utilizing the Hainline et al. (2011) stellar masses and the bottom panels when utilizing the Michałowski, Hjorth & Watson (2009) masses (which are larger by a factor of a few). The left-hand panels show the $f_{\rm gas}$–M_* relation when utilizing the traditional locally calibrated literature $\alpha_{\rm CO}$ values, and the right-hand panel shows the effect of our model $\alpha_{\rm CO}$ (equation 1). When using the locally calibrated $\alpha_{\rm CO}$ values, the observed gas fractions are a factor of 2–3 larger than the theoretical gas fractions at a given stellar mass. Because the theoretical $\alpha_{\rm CO}$ values are typically lower than the locally calibrated values (Fig. 1), the inferred gas mass for a given CO luminosity decreases and brings the gas fractions into better agreement with galaxy formation simulations.

galaxies mostly represent 'main-sequence' galaxies which are not typically undergoing a starburst event.

When examining the left-hand panels in Fig. 2, it is evident that the observed galaxies all have substantially higher gas fractions at a given stellar mass than the simulations. While lower mass systems can be biased to somewhat higher gas fractions because they are (in part) selected by far-infrared luminosity, we have tried applying similar cuts to simulations and found that this cannot explain the difference. In contrast, when applying a CO–H_2 conversion factor which varies smoothly with physical environment, the inferred H_2 gas masses from the CO line measurements drop and come into better agreement with the simulations. Depending on the stellar mass adopted for the SMGs, the gas fractions can drop by up to a factor of 3 for a given galaxy.

The reason for the drop in gas fraction when using the Narayanan et al. (2012) model for $\alpha_{\rm CO}$ versus the traditional bimodal value is the typical environments of high-z galaxies. The gas fractions of high-z discs are typically large enough that, absent substantial internal feedback, large ∼kpc-scale clumps of gas become unstable and fragmented (Springel, Di Matteo & Hernquist 2005; Ceverino, Dekel & Bournaud 2010; Hopkins et al. 2011). These clumps can have large internal velocity dispersions (∼50–100 km s^{-1}) and warm gas temperatures owing to high SFRs ($\gtrsim$100 M$_\odot$ yr^{-1}; Narayanan et al. 2011a). High velocity dispersions and warm gas cause increased CO line luminosity for a given H_2 gas mass, and reduces $\alpha_{\rm CO}$ (Narayanan et al. 2011b). Because of this, in our model, high-z disc galaxies tend to have lower[7] $\alpha_{\rm CO}$ values than the traditional present-epoch 'quiescent/disc' value (though larger than the traditional present-epoch 'starburst/merger' value; Fig. 1). The mean derived $\alpha_{\rm CO}$ for high-z discs is 2.5, approximately half that of the Daddi et al. (2010b) and Magdis et al. (2011) measurements of high-z *BzK* galaxies.

A similar effect is true for high-z starburst galaxies. Owing to extreme SFRs (potentially up to a thousand M$_\odot$ yr^{-1}; Narayanan & Davé 2012), the gas temperatures and velocity dispersions in violent $z \sim 2$ mergers exceed those of even present-day ULIRGs. Hence, the average $\alpha_{\rm CO}$ is lower than the average ULIRG value today. Our average derived value for the high-z galaxies in our sample is $\alpha_{\rm CO} \approx 0.5$. Magdis et al. (2011) find an upper limit of the $\alpha_{\rm CO}$ for a $z = 4$ SMG of 1, and Tacconi et al. (2008) find a reasonable fit to their observed SMGs with an $\alpha_{\rm CO}$ of unity.

The combined effect of our modelling is that $\alpha_{\rm CO}$ for high-z discs is typically lower than that of the traditional $z = 0$ 'quiescent/disc' value, and $\alpha_{\rm CO}$ for high-z starbursts is lower than that of the traditional $z = 0$ 'starburst/merger' value (Fig. 1). Employing our model

[7] Increased ultraviolet photons produced in high-SFR galaxies do have the potential to photodissociate CO. However, these galaxies tend to have large dust-to-gas ratios. Increased dust columns allow GMCs to reach $A_V \approx 1$ quickly and shield CO from photodissociation throughout the bulk of the GMC (Narayanan et al. 2012).

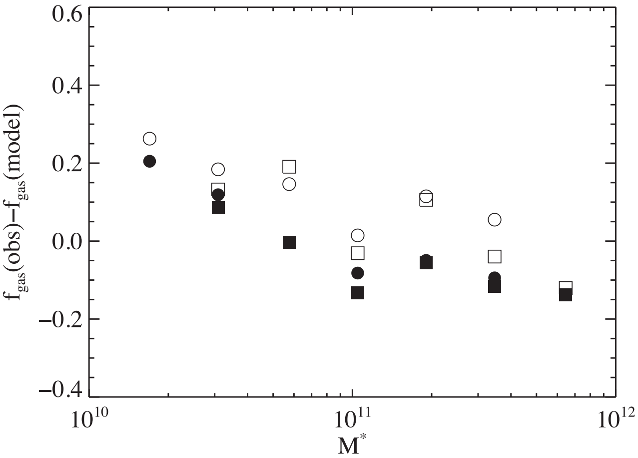

Figure 3. Difference between observed gas fractions and cosmological simulation gas fractions as a function of stellar mass. The squares denote the results when utilizing the Michałowski et al. (2009) data and the circles those from the Hainline et al. (2011) data. The open symbols denote the results when the observed gas fractions are calculated utilizing traditional α_{CO} values, and the filled symbols correspond to values calculated from the Narayanan et al. (2012) form for α_{CO}. Our functional form for α_{CO} results in lower gas fractions and, generally, better agreement between the simulations and observations.

α_{CO} consequently lowers gas masses and brings gas fractions into better agreement with cosmological galaxy formation models. This is quantitatively shown in Fig. 3, where we plot the residuals between the observed data and models for both the traditional $\alpha_{CO}$and that derived from the Narayanan et al. (2012) functional form.

The usage of our model form of α_{CO} reduces the scatter in the f_{gas}–M_* relation in observed galaxies by a factor of ∼2 at a given M_*. To calculate the reduction in scatter, we compare the standard deviation in galaxy gas fractions within a limited range of stellar masses ($M_* = [5 \times 10^{10}, 10^{11}]$ M$_\odot$). Much of the scatter in the original f_{gas}–M_* relation arises from using the bimodal α_{CO} values. In contrast, our model form of α_{CO} varies smoothly with the physical conditions in the ISM in a galaxy and has no knowledge as to whether or not the global morphology of a galaxy is a merger or a disc. So, if some high-z disc galaxies actually have physical conditions in their ISM comparable to starbursts, then their α_{CO} values will be lower than the canonical 'quiescent/disc' α_{CO} (Fig. 1). The vice versa is true for high-z SMGs and OFRGs. When accounting for the continuum in physical properties in the ISM of high-z galaxies (rather than binning them bimodally), the scatter in the observed f_{gas}–M_* relation reduces substantially. The correlation coefficient between the observed gas fractions and the modelled ones increases by ∼10 per cent (from ∼0.9 to 0.98) for both the Michalowski and Hainline masses.

The usage of the Michałowski et al. (2009) masses results in observed f_{gas} below the simulations for the highest mass galaxies. This could reflect either an overestimate of masses or perhaps physical processes that are neglected in the Davé et al. (2011) simulations where most SMGs (the most massive galaxies) are quiescent, main-sequence objects. Potential neglected physical processes include starbursts which may deplete gas (e.g. Narayanan et al. 2009, 2010a,b; Hayward et al. 2011) or a stage of gas consumption without replenishment (that ultimately ends in passive galaxies).

Utilizing our model α_{CO} additionally results in better agreement between the observed cosmic evolution of the gas fraction of galaxies with redshift and the modelled evolution. In Fig. 4, we plot the observed gas fractions of the galaxies in our literature sample against their redshifts. To guide the eye, we overplot the mean. We show the predicted values from the analytic model of Davé et al. (2011) for haloes of masses (at $z = 0$) 10^{13} and 10^{14} M$_\odot$ by the solid and dashed lines, respectively, and the simulated points from Davé et al. (2010) by the stars.

When comparing the mean observed values to the predictions from analytic arguments and cosmological simulations, we again see that when using the traditional α_{CO} calibrated to local values, the inferred gas fractions are significantly higher than the predictions from models. When applying the Narayanan et al. (2012) model for α_{CO}, the mean values come into better agreement with simulations. The scatter (measured as the standard deviation in gas fractions between $z = 0$ and 3) decreases by ∼25 per cent when utilizing our model form for α_{CO} as compared to the traditional values.[8]

It is important to note that it is the normal star-forming galaxies (e.g. the *BzK* galaxies represented by the filled blue circles) that come into better agreement with the simulations. On the other hand, SMGs, represented by the open red squares in Fig. 4, have lower gas fractions than the models predict. This is because SMGs are not typical galaxies at high z, but rather rare massive outliers, and therefore not reflected in the predictions for an average galaxy at high z.

Comparing the results of this paper to other galaxy formation models is nontrivial. For example, when compared to galaxies above $L_{bol} > 10^{11}$ L$_\odot$, the gas fractions returned from our model are significantly lower than those predicted by recent SAMs. Lagos et al. (2011) utilized the Durham SAM to predict the H_2 content in galaxies over cosmic time. As shown by Bothwell et al. (2012), these models substantially overpredict the H_2 gas fraction as a function of redshift. However, comparing to galaxies above $L_{bol} > 10^{12}$ L$_\odot$ produces better agreement (Lagos, private communication). Popping et al. (2012) utilized an indirect methodology to derive the H_2 content in observed galaxies. By inverting the Schmidt relation and using the Blitz & Rosolowsky (2006) pressure-based prescription for deriving the H_2/H I ratio, these authors found a gas fraction–stellar mass relation in good agreement with those derived from CO measurements. Implicit in this model, however, is an assumption of an α_{CO} conversion factor in setting the normalization of the observed Schmidt relation. In this sense, the measurement is not entirely independent of the methods used in CO-derived gas fractions.

4 SUMMARY

Observed baryonic gas fractions from high-redshift galaxies as inferred from CO measurements are typically higher at a given stellar mass or redshift than cosmological galaxy formation models would predict. These differences can amount to a factor of 2–3 in gas fraction.

[8] We note that to properly evaluate the evolution of the gas fraction of galaxies with redshift, one should ideally examine the same limited stellar mass range at each redshift interval. Given the limited number of CO detections at high z, however, this is currently infeasible. An examination of the galaxies in Fig. 2 shows that the majority of our galaxies reside in a stellar mass range of $\log(M_*) = 10.5$–11.5. The lack of clean sample selection is evident in the marginal increase in the already weak correlation coefficients: the correlation coefficient increases from 0.08 to 0.14 for the Hainline masses and remains roughly constant at ∼0.15 for the Michalowski masses. Forthcoming work will address the cosmic evolution of galaxy gas fractions in more detail.

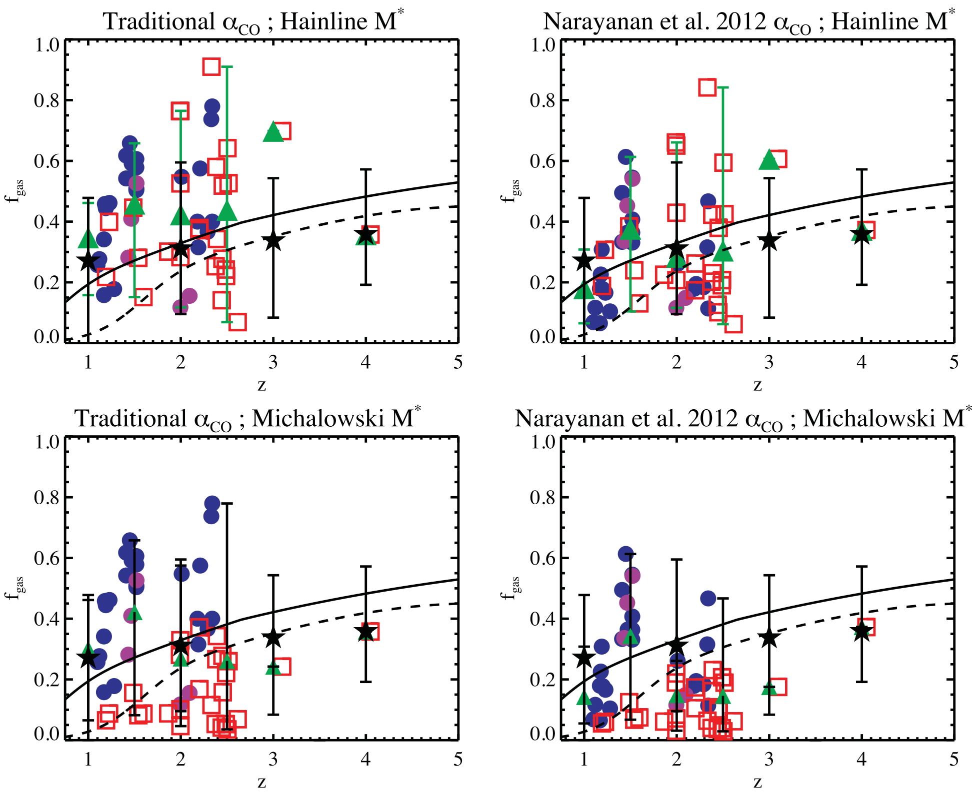

Figure 4. Comparison of $f_{\rm gas}$ against redshift. The filled circles and open squares are the same as in Fig. 2. The green triangles are median and range of data binned in bins of $\Delta z = 0.5$, and are presented to highlight the trends of $f_{\rm gas}$ with redshift. The solid line and dashed line denote predicted evolution for galaxies in ($z = 0$) haloes of $M = 10^{13}$ and 10^{14} $M_{\odot}$, respectively (Davé, Finlator & Oppenheimer 2011). The stars show the mean value and 1σ scatter for all simulated galaxies with $10.5 < \log(M_*) < 11.5$. Both observations and model predict that the mean gas fractions of galaxies should rise with redshift, though utilizing our model $\alpha_{\rm CO}$ (right-hand panels) versus the traditional literature values (left-hand panels) brings the normalization of the observed and theoretical $f_{\rm gas}$–z relations in better agreement.

We suggest that the observed gas fractions are overestimated due to the usage of locally calibrated CO–H_2 conversion factors ($\alpha_{\rm CO}$). If $\alpha_{\rm CO}$ scales inversely with the CO surface brightness from a galaxy (as both numerical models and empirical observational evidence suggest), then both high-z disc galaxies and high-z mergers will have lower average $\alpha_{\rm CO}$ values than their $z = 0$ analogues. This means that for a given CO luminosity, there will be less underlying H_2 gas mass.

Applying a functional form for $\alpha_{\rm CO}$ (equation 1) decreases the inferred H_2 gas masses by a factor of $\sim 2-3$ and brings them into agreement with cosmological galaxy formation models. Similarly, the usage of our model $\alpha_{\rm CO}$ reduces the scatter in the observed $f_{\rm gas}$–M_* relation by a comparable amount. Galaxy gas fractions decrease monotonically with increasing stellar mass, while the average gas fraction of galaxies in a given stellar mass range increases with redshift.

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