The Formation and Evolution of the Cold Gas Component and the Baryonic Mass Build-up History in Galaxies

M. Yun† (UMass), A. Bolatto (U. Maryland), D. Calzetti (UMass), C. Carilli (NRAO), M. Dickinson (NOAO), A. Evans (Univ. Virginia/NRAO), D. Frayer (Caltech/SSC), S. Jogee (Univ. Texas), A. Pope (NOAO), N. Scoville (Caltech), K. Sheth (Caltech/SSC), G. Wilson (UMass), A. Wootten (NRAO)

† contact author: Min S. Yun (myun@astro.umass.edu)
University of Massachusetts
(tel) 413-545-2215

ABSTRACT. New spectroscopic measurements obtained in the millimeter and submillimeter wavelengths, spurred by the dramatically improved sensitivity and spectral coverage of the new instruments and facilities during the 2010-2020 decade, will provide a new avenue for exploring the galaxy baryonic mass assembly history through the determination of cold gas content evolution. Large-field surveys with existing and upcoming facilities (LMT, CARMA, CSO, etc.) combined with the high-angular resolution imaging capability of ALMA will provide a detailed insight on the gas accretion process and the internal dynamics of early galaxies.

1 Introduction

The success of the WMAP and other recent advances in observations and theory have ushered in the era of *precision* cosmology. Details of the initial conditions of the Big Bang are constrained to $\lesssim 10\%$, and the growth of dark matter (DM) halos and large scale structure driven by gravity is now considered by many to be a "solved problem", at least in the frame of the Lambda Cold Dark Matter (LCDM) cosmology. Despite the considerable success of the LCDM cosmological paradigm, a few notable problems remain, however. For example, the observed luminosity function of galaxies in general do not match the predicted DM halo mass spectrum very well, coming short on both high and low mass ends (Klypin et al. 1999, ApJ, 522, 82; Moore et al. 1999, ApJ, 524, 19). This discrepancy is not completely surprising since galaxies and other baryonic components of the universe are highly biased tracers of mass, subject to non-linear processes such as shocks and radiative cooling.

The baryonic history of galaxy formation is a process of transformation from gas to stars, dust, and metals. In this white paper, we argue that the determination of cold gas content evolution in galaxies offers important constraints on the physical processes that determine the mapping between dark matter and baryonic matter distribution and the details of this mass bias. We review and demonstrate that the cold gas content evolution can be mapped using the facilities that will become available during the 2010-2020 decade and will also be able to fill in potentially significant gaps in our understanding of the cosmic star formation history.

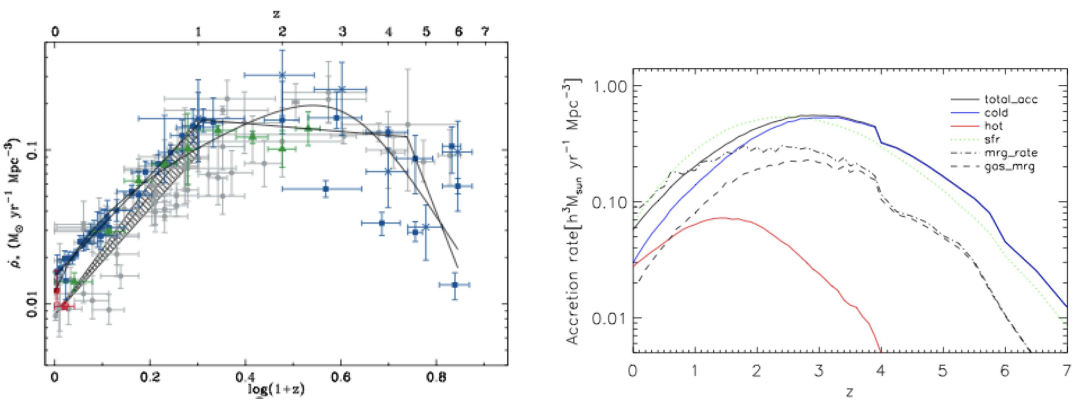

Figure 1: **(LEFT)** The cosmic star formation density evolution by Hopkins & Beacom (2006, ApJ, 651, 142). **(RIGHT)** The gas accretion rate as a function of redshift derived from a high resolution numerical simulation by Keres et al. (2009, MNRAS, submitted).

2 Cosmic star formation history as a test of galaxy mass assembly scenarios

At large scales where gravity dominates, baryonic matter should follow dark matter, and a prescription of the nature of dark matter and the initial perturbation power spectrum should then determine the formation and growth of DM halos and associated large scale structure. As shown in cosmological simulations of the growth of large scale structure by Keres et al. (2005, MNRAS, 363, 2) and others, the response of baryons can also be incorporated using a numerical prescription of relevant gas physics, and a gas accretion rate and accretion history for each DM halo can be derived.

A rapid rise in star formation rate density between z=0 and z=1 reported by Lilly et al. (1996, ApJ, 460, 1) and Madau et al. (1996, MNRAS, 283, 1388) has raised the possibility that measured cosmic evolution of star formation density can be used as a direct test of galaxy and structure formation scenarios, in terms of the gas accretion rate onto DM halos. The apparent similarity between the cosmic star formation history (CSFH) and gas accretion rate computed from a cosmological simulation, shown in Figure 1, suggests that our understanding of the galaxy mass assembly history has matured enough to confront theoretical scenarios.

In recent years, CSFH's have been measured both in the UV/optical and far-IR, to account for the effects of dust extinction. Many of these attempts, however,

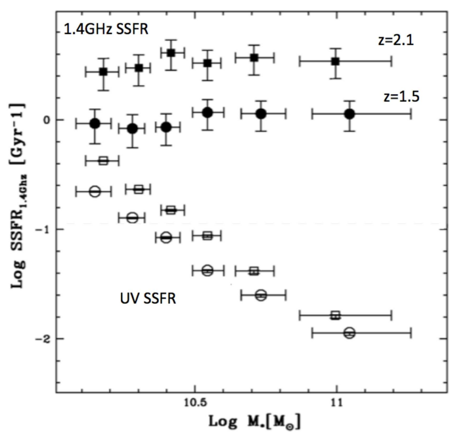

Figure 2: A comparison of the specific star formation rate (SSFR) derived from the radio continuum luminosity at 1.4 GHz for a large sample of galaxies in the COSMOS survey (Pannella et al., in prep). The SSFR at $z = 1.5$ and $z = 2.1$ are constant with the host stellar mass M_*, unlike the UV-derived SSFR that shows a strong differential extinction effect as a function of SFR and M_*.

do not yet merge those independently-determined CSFH's, and the heavily dust obscured starburst systems may still be missing in many of the current analysis (see Blain et al. 2002, Phys. Review, 369, 111). The contribution by dusty starburst galaxies rapidly rises with redshift and dominates the CSFH by $z \sim$ 1-2 (Le Floc'h et al. 2005, ApJ, 632, 169; Caputi et al. 2007, ApJ, 660, 97). The specific star formation rate (SSFR) derived for the COSMOS survey galaxies using 20cm radio continuum as a star formation tracer shows little evidence for redshift dependence among the $z = 1 - 2$ galaxies, in contrast to a strong dependence on stellar mass in the UV-derived SSFR (Pannella et al., in prep.).

Another major uncertainty associated with the derived cosmic star formation history is the highly uncertain assumption on the initial mass function (IMF). The faint end mass spectrum is the main difference among competing IMF models. The choice of an IMF can lead to a factor of a few difference in the inferred total stellar mass production rate, for the identical bolometric luminosity. For example, the steep faint-end slope of the Salpeter IMF can over-predict the stellar mass by a factor of ~ 2 (e.g., Bell et al. 2003, ApJS, 149, 289), and revised IMF by Kroupa (2001, MNRAS, 322, 231) or Chabrier (2003, PASP, 115, 763) may offer a better estimate. The IMF may vary within the same galaxy if the IMF depends on the star formation mode (e.g, quiescent vs. starburst). Readers are referred to the white paper on the IMF question by D. Calzetti.

3 Cold Gas Content in galaxies as a test of galaxy mass assembly scenarios

3.1 Rational

The fact that the Milky Way (MW) galaxy has $5 \times 10^9 M_\odot$ of cold gas and thus can sustain the present star formation rate of ~ 1 $M_\odot$/yr over nearly a Hubble time may have contributed to a likely incorrect notion that late type galaxies like the MW have undergone a steady-state evolution. The present mass accretion rate for the MW cannot sustain the present star formation rate, i.e. $\dot{M}_{acc} \neq \dot{M}_{sf}$ (see Putman 2006, ApJ, 645, 1164). We also know that a steady-state evolution is inconsistent with the basic idea of hierarchical paradigm and the observed trend of "downsizing" (Cowie et al. 1996, AJ, 112, 839).

Since stars form out of cold, dense molecular gas, the most relevant term in tracking the gas mass balance should be the evolution of molecular gas content, especially if indeed the star formation density and the gas accretion rate evolution track each other as seen in Figure 1. If $< \dot{M}_{acc} >$ and $< \dot{M}_{sf} >$ track each other *exactly*, then this would lead to $< \dot{M}_{gas} >= 0$ or no change in M_{H_2} over the cosmic time! This makes an interesting contrast to the gas mass fractions of up to 40% at $z \sim 2$ inferred using the SFR derived from optical tracers, measured source sizes, and the Schmidt-Kennicutt "law" (Bouche et al. 2007, ApJ, 671, 303). Making similar assumptions, Erb et al. (2006, ApJ, 646, 107) also estimated an average gas mass of $2 \times 10^{10} M_\odot$ (on average comparable to the stellar mass and $\sim 30\%$ of dynamical mass) for the rest-frame UV-selected star-forming galaxies at $z \sim 2$. Models of galaxy chemical evolution predict that the maximum amount of gaseous metals occurs when the baryonic gas fraction is 0.4–0.5 (see Frayer & Brown 1997, ApJS, 113, 221).

In the present epoch, the cold gas content of late-type galaxies is $\sim 20\%$ of the stellar mass content and only $\sim 2\%$ of the total baryonic content (Keres et al. 2003, ApJ, 582, 659). This may indicate that cold gas content in galaxies have undergone a *strong* evolution since $z \sim 2$, with a possibility of an even larger gas mass fraction during the earlier epoch of galaxy formation. A cold gas disk with such a large gas mass fraction is expected to be unstable and may undergo a rapid fragmentation and dynamical evolution. Direct molecular gas mass measurements should offer an interesting direct test to these remarkable inferences and an important new insight on the process by which stellar mass has assembled in galaxies.

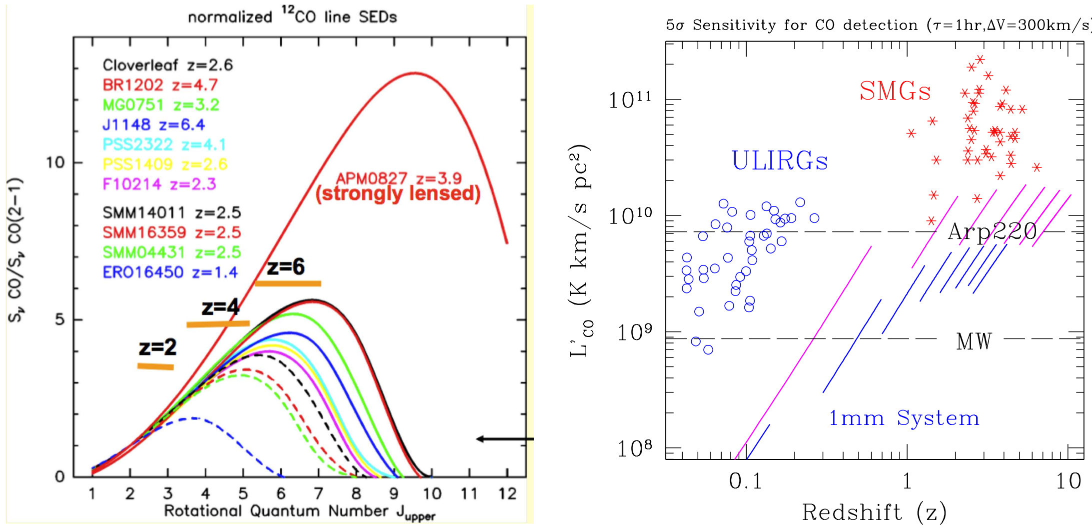

Figure 3: **(LEFT)** Relative strengths of different rotational CO transitions measured for different submillimeter bright galaxies (Weiss et al. 2007, ASP Conf. Series, 375, 25). For the low J transitions, thermalized line flux increases roughly as ν^2. The ranges of CO transitions occurring in the 3mm window at $z = 2$, 4, & 6 are shown with thick yellow lines. **(RIGHT)** Measured CO luminosity of local ULIRGs and high-z SMGs and QSOs are shown using different symbols. The 5σ detection sensitivities of the LMT Redshift Search Receiver after 1 hr of integration are shown in magenta (3mm band RSR) and blue (1mm system) lines.

3.2 Measuring Cold Gas Content Evolution

Poor sensitivity and extremely narrow bandwidth ($\Delta z < 0.01$) of the present and past millimeter and submillimeter wavelength facilities have been a particularly unfortunate combination that resulted in an extremely limited understanding of cold molecular gas content in external galaxies. The *total* number of extragalactic sources with a measured CO (the most commonly used tracer of molecular gas mass M_{H_2}) luminosity is ≤ 500, and *fewer than 50 CO measurements* are available at $z > 1$ (see review by Solomon & Vanden Bout 2005, ARAA, 43, 677). Equipped with new broadband spectrometers that no longer require a prior accurate redshift information and a drastically improved sensitivity from a larger collecting area, some of the present and future US mm/submm facilities listed in Table 1 will drastically improve the situation. **New studies will be able to target normal, MW-like galaxies, not just the "monsters", in the early epochs.** New tracers of higher density gas such as CS, HCN, and HCO^+ should

Table 1: Present and future US millimeter/submillimeter facilities[a]

Telescope	Collecting Area (m^2)	Frequency Range	Status
GBT,EVLA[b]	7850	$1-100$ GHz	in operation
CARMA[b]	730	$85-300$ GHz	in operation
ARO	79	$85-500$ GHz	in operation
CSO	79	$200-800$ GHz	in operation
SPT	79	$200-800$ GHz	in operation
SMA[b]	38	$200-800$ GHz	in operation
LMT	1960	$70-400$ GHz	under construction
ALMA[b]	5650	$85-900$ GHz	under construction
CCAT	490	$200-900$ GHz	in development

[a] based on the Radio, Millimeter and Submillimeter Planning Group report for the NSF 2005 Senior Review.

[b] Diameter given is effective size derived from the total geometric area.

also become accessible, offering new insights on the physical and chemical status of dense molecular gas as a function of redshift.

The measured CO luminosity of ultraluminous infrared galaxies (ULIRGs) and submillimeter bright galaxies (SMGs) and QSOs are shown on the right panel of Figure 3 along with 5σ detection sensitivities of the Redshift Search Receiver (RSR) on the Large Millimeter Telescope (LMT) as an example of the expected improvements in sensitivity. The LMT can detect CO emission from an Arp220-like ULIRG to $z \geq 6$ in just 1 hr of integration and a MW-like source to $z \sim 0.5$ using its 1mm receiver system. In addition to the RSR on the LMT, Zpectrometer on GBT and ZSPEC on CSO are instruments specifically designed with up to 10 times larger bandwidth than the earlier generation systems, for blind CO redshift surveys. Interferometers like CARMA, SMA, as well as ALMA can measure CO luminosity of distant galaxies efficiently if their redshifts are already known. The number of CO detected sources should expand to $> 10^{3-4}$ in just a few years, allowing a full characterization of CO emission and molecular gas content among sources at high redshifts. The rotational transition of CO occurs at integer multiples of 115.27 GHz. Their relative line brightness ("SED") reflects the excitation conditions of the gas (T=20-100K, n=10^{3-5} cm^{-3}; see Fig. 3), and multi-transition studies will become an important and essential research tool for studies of ISM at early epochs.

4 Prospects and Discovery Potential

Broadband mm/submm spectrometer systems such as RSR, Zpectrometer, and ZSPEC are inspired by the fact that some of the massive starburst systems discovered by mm/smm continuum bolometer (SCUBA, MAMBO, Bolocam, AzTEC) are exceedingly faint in optical bands and are beyond the reach of even the 10-meter class telescopes like the Geminis and the Kecks. Therefore, the current estimate of the cosmic star formation history is missing the contribution by these heavily obscured systems. The missing contribution by these high-z dusty starburst systems may be significant, as the Spitzer survey by Le Floc'h et al. (2005, ApJ, 632, 169) and Caputi et al. (2007, ApJ, 660, 97) have shown that sources with $L_{IR} \geq 10^{11} L_\odot$ dominate the cosmic star formation history by $z \sim 1$ and $L_{IR} \geq 10^{12} L_\odot$ sources at $z \sim 2$, respectively. Cosmic downsizing suggests an even larger fraction at higher redshift. Therefore, future CO surveys of high-z galaxies will not only provide an independent measure of galaxy mass assembly history, it will also complete the missing contribution by the dust obscured population that accounts for the 50% of the extragalactic background light (Gispert et al. 2000, A&A, 360, 1).

Atomic fine structure lines [C II] ($\lambda_r = 157.74$ μm) and [N II] ($\lambda_r = 205.18$ μm) may also prove to be extremely powerful tools for measuring SFR among high-z sources. In massive high-z galaxies, dust-obscured AGNs may contribute significantly to the IR luminosity, which is often used as the primary SFR indicator. These fine structure lines serve as the key coolant in photon-dominated regions (PDRs; warm atomic and ionized gas) and thus are less prone to the presence of an AGN. While less bright of the two, the ionization of [N II] is sensitive to the hardness of the ionizing photons, making it a potentially more robust tracer of SFR (Bennett et al. 1994, ApJ, 434, 587).

We also note that ALMA's ability to map the distribution and kinematics of cold gas in the early universe will be particularly important in understanding the processes governing gas accretion and gas dynamics that in turn govern the star formation activities. Mergers of two gas-rich galaxies are known to drive a rapid inflow of gas and fueling extreme starburst activities in the local universe (e.g., Mihos & Hernquist 1996, ApJ, 462, 576). High resolution numerical simulations of gas accretion during the galaxy mass build-up (Agertz et al. 2009, MNRAS, submitted; Keres et al. 2009, MNRAS, submitted) show cold streams entering DM halos and driving clumpy density and metallicity structures, dictating both the fate of the gas and their irregular appearance. Detailed information on the gas kinematics and morphology provided by ALMA will be essential in discerning the processes driving the gas accretion, fragmentation, and subsequent star formation.