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CO LINE WIDTH DIFFERENCES IN EARLY UNIVERSE MOLECULAR EMISSION-LINE GALAXIES: SUBMILLIMETER GALAXIES VERSUS QSO HOSTS

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ABSTRACT

We investigate the CO line widths in early universe molecular emission-line galaxies. There is a clear difference in the CO line widths in QSO host galaxies compared to submillimeter galaxies, as first pointed out by Greve et al., with the QSO hosts' line widths typically a factor of 2.3 narrower in velocity. Powerful radio galaxies fall in between. At the same time, there is no major difference between the molecular gas mass distributions of the different galaxy types. We consider possible explanations for the narrower line widths in the QSO hosts and favor an explanation that the QSO hosts are systematically closer to the sky plane than the submillimeter galaxies, $\langle\theta\rangle_{\rm QSO} = 18°$, consistent with the lack of strong obscuration toward the active galactic nucleus. However, we cannot rule out other possible factors, such as different stages in a merger sequence or galaxy mass or size. Only high-resolution imaging of a large sample of sources can address this interesting dichotomy.

Key words: galaxies: evolution — galaxies: formation — galaxies: ISM — galaxies: kinematics and dynamics — radio lines: galaxies

Online material: color figures

1. INTRODUCTION

The study of galaxy formation has been revolutionized over the last 10 years through a number of critical observations. First, the census of the cosmic star formation rate density, including both normal and very dusty galaxies, shows a peak at $z \sim 2$–3 (Blain et al. 2002). This redshift range has been dubbed the "realm of galaxy formation." Second, observations of Gunn-Peterson absorption toward the highest redshift QSOs (Fan et al. 2006) imply that we are finally probing into the near edge of cosmic reionization, corresponding to the time of formation of the first galaxies and massive black holes. Third, it has been shown that most (all?) spheroidal galaxies host supermassive black holes (SMBHs), and that the black hole mass correlates with the velocity dispersion of the host spheroid. This $M_{\rm BH}$-σ_V relation suggests a "causal relation between the formation of SMBHs and spheroidal galaxies" (Gebhardt et al. 2000). And fourth, observations at short centimeter and millimeter wavelengths have revealed large molecular gas reservoirs ($\geq 10^{10}\ M_\odot$) in an increasing sample of high-z galaxies, spanning the realm of galaxy formation into the epoch of reionization (Solomon & vanden Bout [2005] and references therein). Molecular gas is the basic fuel for star formation, and these early universe molecular emission-line galaxies (EMGs) present ideal cases for studying galaxy formation to the highest redshifts.

Observations of molecular gas in high-z galaxies require long integration times on current telescopes. This requirement leads to some limitations on the statistical samples. First, the current sample (36 galaxies) is a mixed bag of sources, ranging from optically selected QSOs, to powerful radio galaxies, to massive starburst galaxies discovered in wide-field submillimeter surveys (the "submillimeter galaxies"). And second, the current generation of millimeter telescopes is limited to studying only the brightest (i.e., most massive) EMGs at high z, typically with molecular gas masses $>10^{10}\ M_\odot$, with a few exceptions in the fortuitous cases of strong gravitational lensing. For comparison, the molecular gas mass of a large spiral such as the Milky Way is 1 order of magnitude smaller. Still, these EMGs provide the first look into the process of conversion of gas mass to stars in the earliest galaxies.

In this short paper we explore one simple aspect of the EMG properties, namely, molecular line width as a function of galaxy type. The important point is that, given the observational limitations, the gas masses for the different galaxies types (QSOs, radio galaxies, and submillimeter galaxies) span similar ranges; i.e., most of the sources are very massive (again, with the exception of the strongly lensed sources). However, there is a clear difference of line widths for the different galaxy types, as first pointed out by Greve et al. (2005), with the QSO hosts having significantly smaller line widths than the submillimeter galaxies. We discuss possible causes for this line width difference.

2. THE CO LINE WIDTH DISTRIBUTION FOR EMGs

The sample includes all molecular gas detections at $z > 1$, taken from the compendium of Solomon & vanden Bout (2005). They designate sources as QSO, radio galaxy, or submillimeter galaxy based on the original selection and classification in the literature. In the large majority of cases the classification is straightforward and obvious, e.g., bright optical QSOs from the Sloan Digital Sky Survey (York et al. 2000) or the Digitized Palomar Sky Survey (Djorgovski et al. 2003), powerful radio galaxies from low-frequency radio surveys, or starburst galaxies from wide-field submillimeter surveys. Gas masses are derived from CO emission lines by Solomon & vanden Bout (2005) using the standard conversion factor of line luminosity to gas mass applicable to luminous starburst galaxies (Downes & Solomon 1998) and assuming a thermal distribution of line strengths to extrapolate to the 1–0 transition.

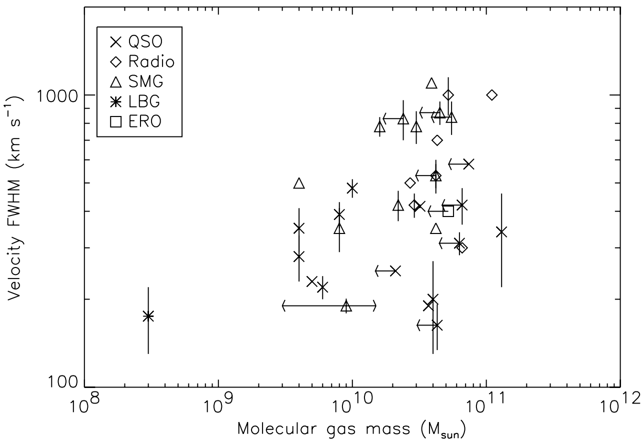

FIG. 1.—Molecular gas mass vs. CO line FWHM of the 36 EMGs, including 15 QSOs (*crosses*), 7 radio galaxies (*diamonds*), 12 SMGs (*triangles*), 1 ERO (*square*), and 1 LBG (*asterisk*). The data are taken from Solomon & vanden Bout (2005). An arrow denotes an upper limit to the gas mass in cases in which the lensing effect is not clear.

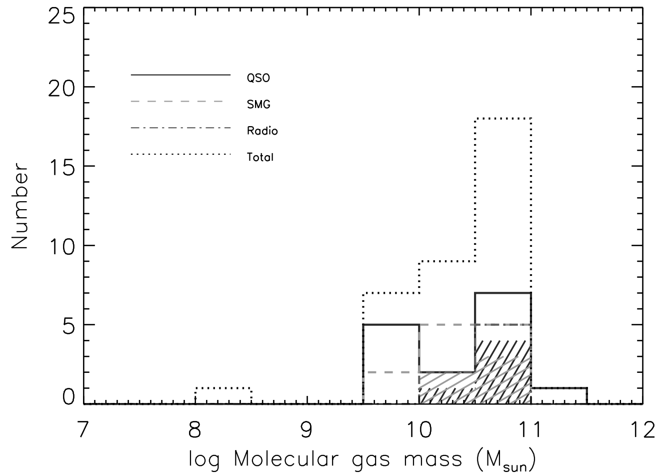

FIG. 3.—Histogram of gas masses in units of log solar mass. Lines are the same as in Fig. 2. Hatched areas denote upper limits to the gas masses for sources with uncertain lens corrections. [*See the electronic edition of the Journal for a color version of this figure.*]

Figure 1 shows the molecular gas mass versus CO line FWHM of the 36 EMGs, including 15 QSOs (*crosses*), 7 radio galaxies (*diamonds*), 12 submillimeter galaxies (SMGs; *triangles*), 1 extremely red object (ERO; *square*), and 1 Lyman break galaxy (LBG; *asterisk*). An arrow denotes an upper limit to the gas mass in cases in which the lensing effect is not clear. The different galaxy types show no clear differentiation in terms of the mass distribution, with both galaxies and QSOs distributed similarly over the range of a few $\times\, 10^9$–$10^{11}\ M_{\odot}$. However, in terms of line widths, the SMGs populate the upper part of the diagram, while the QSOs are typically in the lower half of the overall distribution.

This difference in line widths is shown more clearly in Figure 2, which shows the histogram of line widths for the different galaxy types. All but one of the QSOs have line widths <500 km s^{-1}, with a median value of 300 km s^{-1}. In comparison, two-thirds of the SMGs have FWHM values >500 km s^{-1}, with a median value of 700 km s^{-1}. The radio galaxies span an intermediate range, with a median value of 500 km s^{-1}. Figure 3 shows histograms for the gas mass distributions. While admittedly spanning a wider range (due to the lensed sources, necessitating a log analysis), the key point is that there is no obvious difference between the mass distribution of the SMGs and the QSOs.

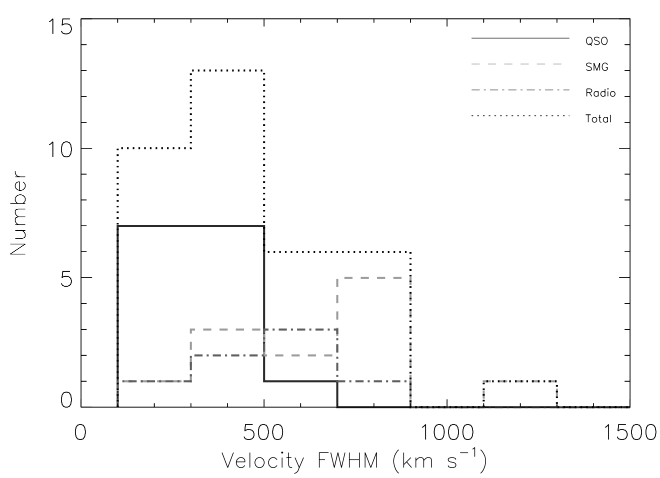

FIG. 2.—Histogram of CO emission-line widths. The histograms of QSOs (*solid line*), SMGs (*dashed line*), and radio galaxies (*dash-dotted line*) are plotted, as is the total gas mass distribution of the 36 EMGs (*dotted line*). [*See the electronic edition of the Journal for a color version of this figure.*]

We have quantified the difference in line widths using a standard Kolmogorov-Smirnov (K-S) test for the distributions. The results are shown in Table 1. We find that there is only a 0.9% chance that the line widths for the SMGs and the QSOs are drawn from the same parent population. For comparison, the mass distributions have a 72% chance of being drawn from a single parent population.

3. DISCUSSION

There is no clear difference between the various EMG types (QSO, radio galaxy, and submillimeter galaxy) in terms of their gas mass, as expected due to the limitations of current instrumentation. However, there is a clear difference between the CO line widths between the QSOs and the submillimeter galaxies (see also Greve et al. 2005), with the median QSO host line width a factor of 2.3 smaller than that for the submillimeter galaxies. We discuss briefly the possible origin of this difference.

The simplest model is for the molecular gas to be in a rotating disk on subkiloparsec scales, as has been seen in the majority of low-redshift ultraluminous infrared galaxies (ULIRGs; Downes & Solomon 1998). In this case the obvious parameter to consider is the angle of the disk relative to the sky plane, θ. The submillimeter galaxies are selected from wide-field submillimeter surveys, and hence their orientation with respect to the sky plane is likely random ($\langle\theta\rangle_{\rm submm} \sim 45°$). In this case the factor of 2.3 difference in line width for the QSO hosts implies a $\langle\theta\rangle_{\rm QSO} = 18°$. A molecular disk orientation close to the sky plane for the QSO host galaxies is consistent with the lack of strong obscuration toward the optical active galactic nucleus (AGN) and hence is a natural consequence of their original selection as optical QSOs.

TABLE 1
K-S TEST RESULTS

Distribution	$P_{\rm null}$ (Line Width)	$P_{\rm null}$ (Mass)
QSO-SMG..................	0.009	0.724
QSO-radio	0.106	0.061
SMG-radio	0.524	0.129

However, there are other factors that need to be considered. For example, Greve et al. (2005) propose either lower mass host galaxies or possibly smaller disk radii for this line width difference. In the few high-z cases imaged with high resolution, it has been shown that the dynamical mass that dictates the CO line width is comparable to the molecular gas mass (Walter et al. 2004; Carilli et al. 2002; Genzel et al. 2003; Greve et al. 2005; Tacconi et al. 2006). A similar conclusion has been reached for the low-z ULIRGs (Downes & Solomon 1998). If this is generally true for EMGs, then the different line widths cannot be the result of different dynamical mass, since the QSO hosts and submillimeter galaxies have similar molecular gas mass distributions. We also point out that consideration of space densities and other galaxy properties (e.g., the $M_{\rm BH}$-σ relation) suggests that both submillimeter galaxies (Greve et al. 2005) and luminous QSO hosts (Fan et al. 2004) are at the extreme high end of the halo mass distribution, with halo masses $\sim 10^{11}\ M_{\odot}$.

Another possibility is that the assumption of a rotationally supported disk may be incorrect. For instance, about 40% of the submillimeter galaxies show double-peaked CO line profiles (Greve et al. 2005). While this could be interpreted as a disk galaxy with a flat rotation curve, an alternative is a merging galaxy system. Optical and near-IR imaging of submillimeter galaxies show that $\geq$50% have optical morphologies consistent with merging galaxies, although complex dust distributions can mimic this effect (Smail et al. 2004), and a disk-type galaxy is often identified as at least one of the merger components. The high-z QSO line profiles are typically Gaussian, with a much smaller fraction ($\sim$10%) showing double peaks. It is possible that the submillimeter galaxies represent an earlier phase in a merging galaxy system, and the separation of the double peaks (which dominates the total line width) represents the full gravitational potential of the system. The QSOs could then be a later-stage merger, with the gas settled into a self-gravitating disk (Sanders & Mirabel 1996). High-resolution imaging of the gas distribution is required to test this idea.

Overall, we feel that the most plausible origin for the narrower CO line widths in QSO host galaxies relative to submillimeter galaxies is orientation, with the QSO host disks oriented close to the sky plane: $\langle\theta\rangle_{\rm QSO} = 18°$. A molecular gas disk close to the sky plane would also explain the lack of strong obscuration toward the AGN in obviously very dusty systems. However, we clearly cannot rule out other factors, such as nonrotational dynamics or galaxy mass or size. High-resolution imaging of the molecular gas distributions is required to address this interesting line width dichotomy. Unfortunately, such imaging is just at the limit of current instrumentation, such as the Very Large Array and the Plateau de Bure Interferometer, requiring major commitments of observing time for individual sources. Fortunately, the impending Atacama Large Millimeter Array telescope will have both the sensitivity and resolution to image large samples of these EMGs in reasonable integration times, thereby revealing the detailed gas dynamics in forming galaxies at the highest redshifts.

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ERRATUM: "CO LINE WIDTH DIFFERENCES IN EARLY UNIVERSE MOLECULAR EMISSION-LINE GALAXIES: SUBMILLIMETER GALAXIES VERSUS QSO HOSTS" (AJ, 131, 2763 [2006])

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It has been pointed out to us that in three dimensions the mean angle of randomly oriented disks with respect to the sky plane is $\langle\theta\rangle = 30^\circ$, and not the 45° assumed in the original paper. This lower angle for the (assumed) random distribution of submillimeter galaxies, coupled with the factor of 2.3 lower mean CO line width for high-*z*, far-IR-luminous QSO host galaxies relative to the submillimeter galaxies, implies a mean angle with respect to the sky plane for the QSO host galaxies of $\langle\theta\rangle_{\rm QSO} = 13^\circ$, as opposed to the 18° quoted in the original paper. We thank Pat Hall for bringing this to our attention.