**ALMA Observations of Gas-rich Galaxies in z ~ 1.6 Galaxy Clusters: Evidence for Higher Gas Fractions in High-density Environments**

The MIT Faculty has made this article openly available. Please share how this access benefits you. Your story matters.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.3847/2041-8213/AA77F3">http://dx.doi.org/10.3847/2041-8213/AA77F3</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>IOP Publishing</td>
</tr>
<tr>
<td>Version</td>
<td>Final published version</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sat Feb 02 20:18:16 EST 2019</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/114149">http://hdl.handle.net/1721.1/114149</a></td>
</tr>
<tr>
<td>Terms of Use</td>
<td>Article is made available in accordance with the publisher’s policy and may be subject to US copyright law. Please refer to the publisher’s site for terms of use.</td>
</tr>
<tr>
<td>Detailed Terms</td>
<td></td>
</tr>
</tbody>
</table>
ALMA Observations of Gas-rich Galaxies in $z \sim 1.6$ Galaxy Clusters: Evidence for Higher Gas Fractions in High-density Environments


$^1$Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA  
$^2$Department of Physics and Astronomy, York University, 4700 Keele Street, Toronto, ON M3J 1P3, Canada  
$^3$Departamento de Ciencias Físicas, Universidad Andres Bello, Fernandez Concha 700, Las Condes 7591538, Santiago, Región Metropolitana, Chile  
$^4$The University of Kansas, Department of Physics and Astronomy, 1251 Wescoe Hall Drive, Lawrence, KS 66045, USA  
$^5$European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-85748 Garching bei München, Germany  
$^6$Department of Physics, McGill University, 3600 rue University, Montréal, QC H3A 2T8, Canada  
$^7$Department of Physics and Astronomy, University of California, Riverside, CA 92521, USA  
$^8$Department of Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto, ON M5S 3H4, Canada  
$^9$Department of Physics, University of California Berkeley, 366 LeConte Hall, MC 7300, Berkeley, CA 94720-7300, USA  
$^{10}$Department of Physics and Astronomy, University of California, Irvine, 4129 Frederick Reines Hall, Irvine, CA 92697, USA  
$^{11}$Departamento de Astronomía, Universidad de Concepción, Casilla 160-C, Concepción, Región del Biobío, Chile  
$^{12}$Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA  
$^{13}$Australian Astronomical Observatory, 105 Delhi Road, North Ryde, NSW 2113, Australia

Received 2017 May 8; revised 2017 June 5; accepted 2017 June 6; published 2017 June 21

Abstract

We present ALMA CO (2–1) detections in 11 gas-rich cluster galaxies at $z \sim 1.6$, constituting the largest sample of molecular gas measurements in $z > 1.5$ clusters to date. The observations span three galaxy clusters, derived from the Spitzer Adaptation of the Red-sequence Cluster Survey. We augment the >3$\sigma$ detections of the CO (2–1) fluxes with multi-band photometry, yielding stellar masses and infrared-derived star formation rates, to place some of the first constraints on molecular gas properties in $z \sim 1.6$ cluster environments. We measure sizable gas reservoirs of $0.5–2 \times 10^{11} M_\odot$ in these objects, with high gas fractions ($f_{\text{gas}}$) and long depletion timescales ($\tau$), averaging 62% and 1.4 Gyr, respectively. We compare our cluster galaxies to the scaling relations of the coeval field, in the context of how gas fractions and depletion timescales vary with respect to the star-forming main sequence. We find that our cluster galaxies lie systematically off the field scaling relations at $z = 1.6$ toward enhanced gas fractions, at a level of $\sim 4\sigma$, but have consistent depletion timescales. Exploiting CO detections in lower-redshift clusters from the literature, we investigate the evolution of the gas fraction in cluster galaxies, finding it to mimic the strong rise with redshift in the field. We emphasize the utility of detecting abundant gas-rich galaxies in high-redshift clusters, deeming them as crucial laboratories for future statistical studies.

Key words: galaxies: clusters – general – galaxies: evolution – galaxies: high-redshift – galaxies: ISM – galaxies: star formation – infrared: galaxies

1. Introduction

Galaxy cluster evolution is intertwined with that of its constituent galaxies. Therefore, in order to understand the former, we must explore the baryonic processes that shape the latter. In particular, this requires a solid understanding of the molecular gas content in cluster galaxies, as this provides the necessary raw material to fuel star formation. Within these dense environments, cluster galaxies face hostile conditions, as substantiated by morphological and physical transformations. Various mechanisms have been invoked to explain the differences between cluster and field galaxies, many of which involve interactions with the intracluster medium (ICM). For example, ram-pressure stripping has been directly observed in low-redshift ($z \lesssim 0.3$) cluster galaxies via H I deficiencies (Jaffé et al. 2015), extraplanar H I gas (Chung et al. 2009), and long “jellyfish” gas tails (Owers et al. 2012).

The environmental effect of the ICM on molecular gas, however, is more ambiguous. It is thought that this denser gas is less susceptible to removal and can therefore survive the effects of ram-pressure stripping. Indeed, many studies have found no difference in the molecular gas content between field and cluster environments, as traced by the emission lines of $^{12}$CO (e.g., Stark et al. 1986; Kenney & Young 1989). However, more recent work has reported molecular gas deficiencies in cluster galaxies (e.g., Fumagalli et al. 2009; Jablonka et al. 2013; Scott et al. 2013; Boselli et al. 2014).

Technological advances in radio interferometers have enabled statistical samples of CO in the field out to $z \approx 3$ (e.g., Saintonge et al. 2011; Tacconi et al. 2013, 2017). Cluster samples, however, have primarily focused on low-redshift systems. A missing key component of molecular gas studies are observations within high-redshift cluster cores.

Observations (Tran et al. 2010; Brodwin et al. 2013) suggest that $z \gtrsim 1.5$ is the peak assembly time for galaxy clusters, and it is thus likely that many of the environmental effects on cluster galaxies occur at these early times in dense regions. While there have been some molecular gas observations in the dense regions of $z > 1$ clusters, these have been limited to only a handful of detections (Aravena et al. 2012; Wagg et al. 2012; Casasola et al. 2013; Hayashi et al. 2017; Rudnick et al. 2017).

Thus, whether high-redshift clusters typically harbor gas-rich galaxies, or whether they are analogous to some of their
lower-redshift counterparts, displaying signs of molecular gas deficiencies has yet to be determined conclusively.

Here, we present Cycle 3 ALMA observations of three massive galaxy clusters at z \approx 1.6 from the Spitzer Adaptation of the Red-Sequence Cluster Survey (SpARCS). With a total of 11 CO (2–1) detections at >5σ, we are filling in this CO redshift desert and enabling the first statistical constraints on gas properties in high-redshift cluster galaxies. Stellar masses and star formation rates (SFRs) are based on a Chabrier initial mass function (Chabrier 2003).

### 2. Observations and Analysis

#### 2.1. z \approx 1.6 SpARCS Clusters

SpARCS J022426–032330 (J0224), J033057–284300 (J0330), and J022546–035517 (J0225) were discovered within the 42 deg² SpARCS fields (Muzzin et al. 2009; Wilson et al. 2009; Demarco et al. 2010; see Table 1 in Nantais et al. 2016). They were initially identified using a technique that detects the 1.6 μm stellar bump feature as it spans 3.6 and 4.5 μm from 1.3 < z < 1.8 (Papovich et al. 2010; Muzzin et al. 2013). These three clusters are spectrscopically confirmed at z = 1.633, z = 1.626, and z = 1.59 (Lidman et al. 2012; Muzzin et al. 2013; Nantais et al. 2016), respectively, with 115 confirmed members in total. Richness-based estimates suggest cluster masses \textgreater 10^{14} M_☉, placing them among the most massive systems at z \approx 1.6 (e.g., Stanford et al. 2012; Bayliss et al. 2014; Tozzi et al. 2015; Webb et al. 2015).

Additional 11-band imaging exists from optical/near-infrared (ugrizYKs) to infrared (3.6/4.5/5.8/8.0 μm), allowing for accurate photometric redshifts and stellar masses. Imaging details and analysis are presented in Nantais et al. (2016). The central cluster regions have deep HST imaging from the “See Change” program (GO-13677 and GO-14327) in F160W on the WFC3-IR camera, with additional observations in the F105W and F140W filters for J0224 and J0330.

#### 2.2. ALMA Observations

The ALMA Cycle 3 data were taken between 2016 January 13 and January 20 over 12 execution blocks, with 8.4 hr of total integration time. Each cluster contains two separate pointings in Band 3, encompassing a total of 49 spectroscopically confirmed cluster members. We used the frequency division correlator mode in a single baseband to provide a total bandwidth of 1.875 GHz.

The maps were calibrated using ALMA reduction pipeline scripts in CASA version 4.6.0. We chose 0″3 pixels and a spectral resolution of 100 km s⁻¹. We performed minimal cleaning with natural weighting, generating continuum-subtracted and primary-beam-corrected maps with a field of view of \approx 110″ across. The resulting data cubes have synthesized beams of \approx 4″ × 3″ with a central rms of \approx 0.17 mJy beam⁻¹ per channel.

#### 2.3. CO (2–1) Detections

We blindly search the primary-beam-corrected image cubes for CO (2–1) detections, requiring a peak S/N \geq 5, and resulting in a final catalog of 11 CO detections over all 3 clusters. High-resolution HST imaging, in conjunction with optical spectroscopy and 11-band photometry, allows for unambiguous counterpart identification of the ALMA detections (Figure 1). Seven of the 11 CO detections represent individual cluster members, and the remaining 4 detections are associated with galaxy pairs. The “pair” systems (J0224–3680/3624 and J0224–396/424) are slightly blended in ALMA (and completely blended in the far-infrared imaging). We therefore treat all the pair detections as single combined systems, measuring total gas masses, stellar masses, and SFRs for each pair. This yields nine separate flux measurements.
To measure CO fluxes, we first create integrated-intensity maps by collapsing the image cube over the velocity channels with significant emission for each source. We then perform a two-dimensional Gaussian fit on their respective map and use the best-fit major and minor FWHM to create a 4σ region for spectral profile extraction on the full image cube. Within each of these regions, we model the spectral profile with a Gaussian function, determining rms errors from the line-free channels for each source. The area under the Gaussian spectral profile corresponds to the full integrated CO flux. These fluxes are subsequently converted into line luminosities (L_CO) using Equation (3) in Solomon & Vanden Bout (2005). To estimate the total molecular gas mass we use M_gas = α_CO(L'_CO/r21). We assume sub-thermalized emission with r21 = 0.77, which is empirically derived in Daddi et al. (2015) and consistent with the value used in Genzel et al. (2015), and a α_CO conversion factor of 4.36 (M_⊙(K km s⁻¹ pc⁻²)⁻¹), commonly used for the Milky Way and in normal star-forming galaxies with solar metallicities (Bolatto et al. 2013; Genzel et al. 2015). We note that all but one of the cluster galaxies lie within 2σ of the main sequence of star formation at z = 1.6. Table 1 displays our final CO (2–1) measurements, along with corresponding derived quantities.

### 2.4. Infrared Star Formation Rates

To obtain SFRs, we utilize infrared/far-infrared data from Spitzer and Herschel. All three clusters are within the SWIRE Legacy Survey (Lonsdale et al. 2003) and the Herschel Mid-infrared Extragalactic Survey (Oliver et al. 2012), providing MIPS-24 μm and SPIRE-250/350/500 μm imaging. MIPS counterparts to the ALMA detections are identified directly on the images, and fluxes are measured with aperture photometry. Measurement of SPIRE fluxes is less straightforward due to source confusion in the maps. We attempt to reduce the blending of SPIRE fluxes by using MIPS positional priors and employing a simultaneous stacking technique (SIMSTACK; Viero et al. 2013).

As in Webb et al. (2015), we use a Bayesian approach to fit spectral energy distributions to the infrared fluxes. We first form a two-dimensional parameter space consisting of 105 templates from Chary & Elbaz (2001), each scaled by 10⁴ amplitudes, ranging from 0 to 100. For each template and amplitude combination, we compute the χ² value from the observed infrared fluxes, creating a two-dimensional probability distribution. Assuming flat priors on both the amplitude and template, we calculate the weighted mean over the posterior to determine the infrared luminosity and its uncertainty. This is converted to a SFR using Kennicut (1998). The infrared-derived SFRs place the cluster galaxies around the main sequence at z = 1.6 from Whitaker et al. (2012). All but one galaxy (J0224−3656) fall within 2σ of the main sequence.

### 3. Results

With the first significant sample of CO detections in cluster galaxies at z ≈ 1.6, we can begin to investigate how the cluster environment might impact the molecular gas reservoirs. We present our main results below.

#### 3.1. Gas Properties Scaled to the Star-forming Main Sequence

The tightness of the main sequence of star formation (SFR–Mₜ) is thought to reflect the gas regulator model, in which galaxies grow through an influx of fresh gas that fuels star formation and is subsequently balanced by feedback (Bouché et al. 2010). The dependence of gas properties on the galaxy’s location on the SFR–Mₜ plane is therefore expected and has been observed in the field (e.g., Saintonge et al. 2011, 2016; Genzel et al. 2015).

We investigate the spread of depletion timescales and gas fractions as a function of relative offset from the main sequence in Figure 2. We show the field scaling relations from Genzel et al. (2015), calculated at z = 1.6 and normalized to the average stellar mass in our cluster sample. The gas fraction scaling relation has a steep dependence on stellar mass; we therefore also include tracks using the mass range of the cluster sample. From these scaling relations, it is evident that field galaxies further above the main sequence display higher gas fractions and shorter depletion timescales.

For a given mass, the z ≈ 1.6 cluster galaxies lie at systematically higher gas fractions than the scaling relation.
We compare the distribution of gas properties to coeval field galaxies from $1.2 < z < 1.6$ (Daddi et al. 2010; Tacconi et al. 2013; Decarli et al. 2016; Papovich et al. 2016) in the upper panel histograms. We restrict the field sample to galaxies within a similar range of offsets from the main sequence as the cluster CO-detected sample, from $-1$ to $2$. We note the cluster and field comparison samples are evenly distributed on the SFR–$M_\odot$ plane. The tendency toward higher gas fractions in cluster galaxies is again conspicuous. To evaluate the differences, we restrict the analogous field sample to values of $f_{\text{gas}}$ and $\tau$ above our nominal $3\sigma$ detection limit in the cluster sample. This is estimated using the typical rms in the center of the ALMA maps and the average FWHM, stellar mass, and SFR of our detected sample, yielding a gas fraction and depletion timescale limit of 32% and 0.33 Gyr. Comparing the two distributions above our nominal detection limits, we perform a Kolmogorov–Smirnov test, rejecting the null hypotheses in both cases with 99% confidence. We find an average gas fraction of $62 \pm 3.7\%$ and average depletion timescale of $1.4 \pm 0.2$ Gyr for our CO-detected cluster galaxies.

### 3.2. Evolution of the Gas Fraction in Clusters

In Figure 3, we plot the evolution of the gas fraction. We compile a subset of 19 additional CO detections in clusters from the literature from $0.2 < z < 1.5$ (Geach et al. 2011; Aravena et al. 2012; Wagg et al. 2012; Jablonka et al. 2013; Cybulski et al. 2016) to compare to our $z \sim 1.6$ detections. We similarly restrict the literature detections to $>10^{10} M_\odot$ galaxies that fall within a relative offset from $-1$ to $2$ of the main sequence at their respective redshift, yielding 15 cluster galaxies. Including galaxies markedly above the main sequence, for example, would...
fractions than the coeval redshifts. On average, limited to a narrow range around the main sequence at their respective redshifts. Genzel et al. 2015

inherently bias the literature detections to higher gas fractions given the aforementioned correlation in Section 3.1. We include the rise in the gas fraction for main-sequence field galaxies from the Genzel et al. (2015) scaling relations, normalized to the average mass of our cluster galaxies. The gas fraction in cluster galaxies mimics the strong evolution in the field. Notably, almost all the $z > 1$ cluster galaxies lie above the gas fractions in main-sequence field galaxies, despite half the galaxies lying slightly below the main sequence. Conversely, gas-rich galaxies in low-redshift clusters are on average closer to the field gas fractions. This is suggestive of a steeper evolution in gas fractions for cluster galaxies than the field, consistent with semi-analytical (Lagos et al. 2011) and semi-empirical (Popping et al. 2015) models that predict a stronger evolution in more massive halos. However, this warrants caution owing to the heterogeneous nature of the cluster and field samples, making interpretation difficult. For example, this could be dominated by systematic offsets in SFR measurements and/or selection biases. 

4. Discussion
We find that star-forming main-sequence cluster galaxies are systematically concentrated toward higher gas fractions compared to the field scaling relations at $z \sim 1.6$.

This could partially be a selection effect—we cannot fully exclude the possibility that with deeper data we would detect more galaxies on or below the scaling relations. However, it is unlikely the sole cause of the offset as more of our confirmed cluster members have CO detections as opposed to non-detections consistent with the scaling relations. Barring a selection effect, we propose three other plausible explanations for the offset in gas properties of cluster galaxies relative to the field.

5. Conclusion
We present the largest study of molecular gas in $z > 1.5$ cluster galaxies to date. Using ALMA Band 3, we detect CO
(2–1) in 11 galaxies over 3 massive SpARCS galaxy clusters. We summarize our results as follows:

1. The $z \sim 1.6$ cluster galaxies have consistent depletion timescales ($\tau = 1.4 \pm 0.2$ Gyr), but ∼4σ higher gas fractions ($f_{\text{gas}} = 62 \pm 3.7\%$) for a given offset from the main sequence compared to the scaling relations of coeval field galaxies.

2. Cluster galaxies on or around the main sequence mimic the strong evolution in the gas fraction in the field, with the trend continuing in clusters up to $z \sim 1.6$.

The origin of the gas fraction excess is not clear—whether it is a selection effect or stems from a cluster environmental bias. Based on observations made with the NASA HST, the Joint ALMA Observatory is operated by ESO, and KASI together with NRC representing its member states.

We thank the referee for providing feedback that improved this Letter, and H. Russell for useful discussions. We acknowledge support from the following sources: NSF grants AST-1517815/AST-1211358/AST-1517863/AST-1518257; NASA programs AR-13410.001-A/GO-13306/GO-13677/GO-13747/Universidad Andres Bello grant DI-18-17/557, A103.

This Letter makes use of the following ALMA data: ADS/JAO. ALMA#2015.1.01151.S. ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. The NRAO is a facility of the NSF operated under cooperative agreement by Associated Universities, Inc. Based on observations made with the NASA/ESA HST (GO-13677/GO-14327), obtained at the STSI, which is operated by the AURA, Inc. NASA contract NAS 5-26555.

References


Papovich, C., Labbé, I., Glazebrook, K., et al. 2016, NatAs, 1, 0003