A CO Survey of SpARCS Star-forming Brightest Cluster Galaxies: Evidence for Uniformity in BCG Molecular Gas Processing across Cosmic Time

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Abstract

We present ALMA CO (2-1) detections of 24 star-forming brightest cluster galaxies (BCGs) over 0.2 < z < 1.2, constituting the largest and most distant sample of molecular gas measurements in BCGs to date. The BCGs are selected from the Spitzer Adaptation of the Red-Sequence Cluster Survey (SpARCS) to be IR-bright and therefore star-forming. We find that molecular gas is common in star-forming BCGs, detecting CO at a detection rate of 80% in our target sample of 30 objects. We additionally provide measurements of the star formation rate and stellar mass, calculated from existing MIPS 24 μm and IRAC 3.6 μm fluxes, respectively. We find these galaxies have molecular gas masses of 0.7–11.0 × 10¹⁰ M_☉, comparable to other BCGs in this redshift range, and specific star formation rates that are similar to the main sequence of Elbaz et al. We compare our BCGs to those of the lower-redshift, cooling-flow BCG sample assembled by Edge and find that at z ∼ 0.6 the two samples show very similar correlations between their gas masses and specific SFRs. We suggest that, in this redshift regime, the ~10% of BCGs that are star-forming process accreted molecular gas into stars through means that are agnostic to both their redshift and their cluster mass.

Unified Astronomy Thesaurus concepts: Galaxy clusters (584); Galactic and extragalactic astronomy (563); Brightest cluster galaxies (181); Galaxy evolution (594); Molecular gas (1073)

1. Introduction

Galaxy clusters are extreme examples of hierarchical structure formation, forming the largest overdensities in the primordial universe. Brightest cluster galaxies (BCGs), as massive galaxies residing in the dense, violent centers of galaxy clusters, evolve through pathways that are a direct result of this environment.

In the latter stage of their evolution (after z ∼ 1), the stellar mass of BCGs roughly doubles (Lidman et al. 2012). While this is expected to be mostly a dry process done primarily through gasless mergers of the BCGs with infalling cluster galaxies (De Lucia & Blaizot 2007), some (~10%), based on a 24 μm flux >100 μJy; Webb et al. 2015) BCGs do show star formation at these redshifts. The mechanism driving this star formation is not clear. Possible scenarios include mergers, either major or minor, of the BCG with gas-rich infalling cluster galaxies, or large-scale “cooling flows” of gas from the intracluster medium (ICM) onto the BCG.

Galaxy clusters themselves are not a homogeneous population, complicating the search for a star formation mechanism in their centers. Early X-ray observations revealed that some cluster cores contain an ICM dense enough to cool hydrostatically on timescales much shorter than the Hubble time (e.g., Fabian & Nulsen 1977). As the ICM cools and compresses, hot gas from outer regions of the cluster flows in to replace it, causing a cooling flow. Located at the center of the cluster, the BCG is often the recipient of gas from the cooling flow. Indeed, some star-forming BCGs seem to have star formation attributable to cooling flows. Examples include the Phoenix cluster at z = 0.596 (McDonald et al. 2012; Russell et al. 2017) and SpARCS104922.6+564032.5 (SpARCS1049; Webb et al. 2017; Hlavacek-Larrondo et al. 2020) at z = 1.709.

A key tool in deciphering star formation processes is cool molecular hydrogen (H_2) gas, which acts as the fuel for future star formation in galaxies, and is commonly traced by the rotational transitions of CO (Solomon & Vanden Bout 2005). However, few studies have systematically measured the molecular gas content in BCGs over a range of redshifts. We aim to constrain the processes driving BCG mass growth by studying molecular gas in a large sample of BCGs spanning 6 Gyr of cosmic time.

In this paper, we present new ALMA measurements of the CO (2-1) transition in 30 BCGs, selected from the SpARCS survey (described in Section 2.1). Our sample is large, containing 24 CO detections, and extends to much higher redshifts (z ∼ 1.2) than any previous statistical BCG survey. We introduce the SpARCS cluster sample, our ALMA observations, and our data reduction method in Section 2. In Section 3, we contextualize our BCGs’ molecular gas with other field and cluster measurements. Section 4 discusses the implications of these observations for BCG mass growth, and we present our conclusions in Section 5. We use standard cosmology (H_0 = 70 km s⁻¹ Mpc⁻¹, Ω_matter = 0.3; Ω_Λ = 0.7) throughout.

2. Observations and Data Reduction

2.1. The Parent SpARCS Sample

The BCGs studied here are drawn from clusters in the Spitzer Adaptation of the Red Sequence Cluster Survey (SpARCS;
2.3. Observations

Our observations were performed on the Atacama Large Millimeter Array (ALMA; Program ID 2019.1.01529.S, P.I. Webb) between 2019 November 22 and December 15. 30 BCGs were observed over a total of ～15 hr. Three BCGs were not observed because of the ALMA COVID-19 shutdown. We used ALMA bands 3, 4, and 5 (chosen to measure the CO (2–1) line) and configurations C43-1, C43-2, and C43-3. Data were calibrated using ALMA reduction pipeline scripts in CASA version 5.4.0. The nominal flux density calibration uncertainty for ALMA sources in these bands is ～5%–10% (Remijan et al. 2019). We cleaned the image cubes minimally with natural weighting and pixel sizes between 0′′/2 and 0′′/4, resulting in continuum-subtracted and primary beam-corrected images with 46″ to 90″ fields of view. We detected mostly unresolved CO emission at ～3σ in 24 of 30 pointings, or at a detection rate of 80%. We chose the spectral resolution of each image cube individually, based on the strength of the detection. We show examples of three BCGs from our sample, spanning the observed redshift range and the observed S/N range, in Figure 2. A single BCG (CDFS-CO3) was additionally detected in radio continuum.

These observations were designed to be complete to a constant gas mass depth of $M_{\text{gas}} \geq 10^{10} M_\odot$ at all redshifts. However, due to ALMA’s minimum on-source integration time for a single science goal, many of the lower-redshift objects ($z \lesssim 0.6$) were observed for longer than necessary to achieve this molecular gas mass limit, resulting in 3σ image RMS depths between 1.2 mJy beam$^{-1}$ ($z \sim 0.2$) and 0.6 mJy beam$^{-1}$ ($z \sim 1.2$) over 100 km s$^{-1}$ channels. The sensitivity to low gas masses thus increases at lower redshifts (see Figure 3).

2.4. CO (2–1) Molecular Gas Measurements

We determine galaxy gas masses in a three-step process. First, we generate first-pass spectral profiles by placing an elliptical aperture with semimajor and semiminor axes twice as large as those of the synthesized beam, and at the same orientation, at the center of each BCG. Spectra are fit with a single one-dimensional Gaussian profile. Second, we generate an integrated-intensity “Moment-0” map by collapsing the image cube over the velocity channels with significant emission as determined by this Gaussian fit to the spectral profile. We keep channels within 2σ (2 standard deviations) of the mean. We then fit potential signal in the Moment-0 map to a two-dimensional, elliptical Gaussian profile. Finally, we create a second one-dimensional spectral profile, extracted from an elliptical aperture with the parameters of the two-dimensional fitted profile; the new axis sizes are now three times the Gaussian full width at half maximum (FWHM).

We determine the mass of gas present in each galaxy by fitting the second-pass spectral profile to either single- or double-peaked Gaussians, depending on which gives the better fit according to its reduced $\chi^2$ statistic. We take the area under this fit as the total line flux, and we convert this flux to a CO luminosity using Solomon & Vanden Bout (2005) Equation (3). We use galactic CO-to-H$_2$ conversion factors ($\alpha_{\text{CO}} = 4.36 M_\odot (\text{K km s}^{-1} \text{pc}^2)^{-1}$, $r_2 = 0.8$), as these are typical of galaxies on the star-forming main sequence (see Solomon et al. 1997; Freundlich et al. 2019) and allow easy comparison with existing H$_2$ masses in BCGs, such as those of Edge (2001) and Castignani et al. (2020). We note, however, that using different CO-to-H$_2$ conversion factors (for
example, $\alpha_{\text{CO}} = 0.9$ and $r_{21} = 0.85$, typical of ultraluminous infrared galaxies; Bolatto et al. 2013) does not affect the results of this paper.

We treat the RMS noise in line-free channels ($\sim 7$σ from the mean) of the spectral profile as the uncertainty in each flux value, and account for it while performing the least-squares Gaussian fits. We also search for CO emission in our six nondetections by stacking their spectra, centering each around the expected position of the CO line using the OzDES redshifts. The stack shows no significant emission, down to 3σ.

We determine gas mass limits on the six nondetections by collapsing the image cubes over a bandwidth equivalent to the average FWHM of the detected CO peaks (356 km s$^{-1}$) and taking the 3σ RMS value as an upper limit to the flux.

2.5. Stellar Masses and Star Formation Rates

We calculate the stellar mass of each galaxy using existing IRAC 3.6 μm photometry from SWIRE (Lonsdale et al. 2003) to determine the rest-frame K-band luminosity. We use an SED template from Bruzual & Charlot (2003) to calculate the K-correction, adopting an 11 Gyr simple stellar population with solar metallicity and a Salpeter initial mass function (IMF; Salpeter 1955). We note that adopting a template with a younger stellar population changes the average stellar mass values by at most 8%. This is within uncertainty and does not affect our results significantly, as they are primarily comparative. We determine a mass-to-light ratio of 0.83 by comparing our sample of 3.6 μm based values to more accurate values from a griz/3.6 μm/4.5 μm (Abbott et al. 2018; Lonsdale et al. 2003) SED fit using FAST (Kriek et al. 2018). We take the scatter in this relation (0.3 dex) as the uncertainty in the stellar masses.

We also calculate star formation rates (SFRs) from SWIRE-MIPS 24 μm flux values (Lonsdale et al. 2003), using Kennicutt (1998) Equation 4 based on the luminosity at 24 μm ($L(24)$) from Chary & Elbaz (2001). We note that this
method is known to overestimate SFRs, particularly at high redshifts, but this generally occurs above the redshifts covered by our sample, at $z \sim 1.5$ (Elbaz et al. 2011). We achieve similar results with more modern SFR methods such as that of Rieke et al. (2009). We take the scatter of 0.15 dex described in Kennicutt (1998) to be the uncertainty in the SFRs. Because of SWIRE’s 100 μJy MIPS limit, our sample is not complete in SFR—we can detect galaxies significantly ($\sim 1\sigma$) below the Elbaz et al. (2011) MS only to $z \sim 0.6$, and only starbursting galaxies above $z \sim 1$.

We present the properties of our BCG sample, including $M_*$ and SFR values, in Table 1.

### 2.6. A Low-redshift BCG Comparison Sample

Edge (2001) introduces a sample of 34 BCGs at redshifts $\leq 0.45$ in clusters selected from ROSAT to have cooling flows. Of these, 16 galaxies are detected in CO, through a combination of CO(3-2) measurements made using the A3i receiver on JCMT, and CO(1-0) measurements made using the IRAM 30m telescope. Additionally, 12 BCGs have available 3.6 μm and 24 μm flux measurements. As the largest available sample of well-studied BCGs at low redshifts ($c_{\text{mean}} = 0.12 \pm 0.09$), belonging to clusters with known dynamical states, this is a convenient sample with which to compare our BCG detections.

We take the molecular gas masses from Edge (2001), correcting the values for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. Stellar masses and SFRs have been published for the Edge sample (O’Dea et al. 2008; Rawle et al. 2012); however, we choose to recalculate these values to allow for a homogeneous comparison between the Edge sample and our own. We therefore calculate both stellar masses and SFRs for these BCGs using the methods outlined in Section 2.5, including multiplying the SFR by the same FAST conversion factor, as the multiband photometry used in this SED conversion is not available for the Edge galaxies. We take 3.6 μm flux values from Quillen et al. (2008), Yamagishi et al. (2010), and Landt et al. (2010), and MIPS 24 μm photometry from Shi et al. (2005), Quillen et al. (2008), Yamagishi et al. (2010), and the Spitzer Science Source List (Teplitz et al. 2010).

### 2.7. AGN Contamination

To check for AGN contamination, we compare the IRAC colors of both our sample (from SWIRE; Lonsdale et al. 2003) and the Edge sample (Quillen et al. 2008; Landt et al. 2010; Yamagishi et al. 2010) to the criteria described in Donley et al. (2012). We find that one CO-detected galaxy from each sample falls into the Donley AGN wedge, as well as three nondetected galaxies at higher redshifts. These galaxies all show high sSFRs, and the 24 μm flux is likely dominated by the AGN; we thus exclude them from all further analysis but continue to show them on plots.

### 3. Results

The molecular gas properties of our BCG sample are presented in Table 1. With the largest and highest-$z$ sample of significant molecular gas detections in BCGs assembled, we can investigate the reservoirs fueling their in situ star formation.

#### 3.1. Gas Properties Compared to the Larger Galaxy Population

To place the gas in our BCGs in context, we compare in Figure 3 the molecular gas reservoirs found in our sample to those of a range of other galaxy types. We pick out the Edge (2001) sample described in Section 2.6 as our main comparison sample. We indicate also the two other BCGs selected from SpArCS with confident molecular gas detections—SpArCS1049 (Webb et al. 2017), whose gas has recently been shown to be fed by a massive cooling flow (Hlavacek-Larrondo et al. 2020), and J0225-303 (Noble et al. 2019), which possibly represents a merging BCG based on rest-frame optical HST imaging, but whose cluster dynamical state has not been conclusively determined. The gap in coverage visible at $0.8 \leq z \leq 1.0$ corresponds to the redshift range within which CO lines fall into the gap in the ALMA frequency coverage between bands 3 and 4.

Figure 3 makes it immediately obvious that our sample reaches much higher redshift ranges than all previous BCG surveys. Few large-scale studies of molecular gas in BCGs have been undertaken, and those that do exist have been limited in distance by both CO instrument quality and the availability of cluster surveys at high redshifts. Above $z \sim 0.3$, most existing BCG gas masses come from targeted observations of known exceptional objects. These include the BCGs in A1664 ($z = 0.128$; Russell et al. 2014), A1835 ($z = 0.252$; McNamara et al. 2014), the Phoenix cluster ($z = 0.596$; Russell et al. 2017), and SpArCS 1049 ($z = 1.709$; Webb et al. 2017). Previous BCG studies include Edge (2001; described in detail in Section 2.6), who detected 16 BCGs, Salomé & Combes (2003), who detected 6 non-BCG cluster galaxies are taken from Noble et al. (2019, 2017) and Jablonka et al. (2013). Field galaxies are taken from Aravena et al. (2020), Bauermeister et al. (2013), Boogaard et al. (2020), Braun et al. (2011), Brownson et al. (2020), Combes et al. (2013), Decarli et al. (2016), Freundlich et al. (2019), Geach et al. (2011), and Hatsukade et al. (2020). Other BCG detections are from Castignani et al. (2020), Fogarty et al. (2019), McNamara et al. (2014), Russell et al. (2014), Russell et al. (2017), Salomé & Combes (2003), Tremblay et al. (2016), and Vantyghem et al. (2016).
BGCs, with some overlap with the Edge (2001) sample, and Castignani et al. (2020), who detected five BGCs. Our sample of 24 BGCs is therefore large by comparison. Each of these studies had detection rates considerably lower than our own, likely because these studies either did not select their sample based on star formation (Edge 2001; Salomé & Combes 2003), or used a much weaker SFR criterion (Castignani et al. 2020).

3.2. Direct Comparison with Lower-redshift BCGs

In the field, tight correlations are known to exist between a galaxy’s SFR, \( M_\star \), and gas mass (e.g., Genzel et al. 2010), suggesting a uniformity in baryon processing by field galaxies. To test if similar correlations exist in BCGs, we compare the sSFRs and molecular gas masses of our sample to those BCGs detected by Edge (2001) in Figure 4. Due to the sSFR depth limitations discussed in Section 2.5, we first analyze only the BCGs in our sample with redshifts below 0.6 (left panel). To determine if the two samples exhibit the same sSFR/\( M_{\text{gas}} \) properties, we fit a straight line to each sample separately in logarithmic space, using orthogonal distance regression (ODR) to account for uncertainties existing in both axes. We show fits, and their 1σ confidence regions, in Figure 4. With (logarithmic) slopes of 0.9 ± 0.3 and 0.9 ± 0.2 and offsets of −10 ± 3 and −10 ± 2, respectively, our sample of BCGs and the Edge (2001) sample display the same correlation below \( z = 0.6 \). As the slope in this plot is slightly lower (log(\( SFR/M_\star \))/log(\( M_{\text{gas}} \))), a quantity related to the star formation efficiency (SFR/\( M_\star \)), this suggests the two samples are processing molecular gas through similar means.

In the right panel of Figure 4, we plot the complete sample over all redshifts. Much of our sample to \( z \approx 1.0 \) falls into the 1σ confidence region of the fit to the Edge (2001) BCGs, suggesting that this similarity in gas processing could persist to higher redshifts, but this is inconclusive due to the small sample size and potential selection effects from limited sensitivity. The BCGs at redshifts above \( z \approx 1.0 \) seem to fall above this relation, suggesting a possible change in gas processing, but this is again somewhat speculative due to the limits of the sample. In both panels the CO nondetections are included for comparison. We note the three nondetections that fall off the plotted correlation all have sSFRs that are likely inflated by the presence of AGN.

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While we have worked to control for all potential systematic sSFR/$M_\text{gas}$ differences between the two samples, there do remain several limitations. These include the CO line transitions used in the $M_\text{gas}$ values calculated by Edge (2001), the difficulty defining selection effects in this sample (which includes measurements from several different sources), and the incompleteness of our own sample. Additionally, while several large samples or field galaxies with molecular gas measurements do exist, such as ASPECS (Decarli et al. 2016), PHIBSS1 (Tacconi et al. 2013), and PHIBBS2 (Freundlich et al. 2019), few of these galaxies have both the 3.6 $\mu$m and 24 $\mu$m measurements necessary for rigorous comparison with the BCGs in this work, and those that do tend to fall above the MS. Ultimately, more CO data is required, for BCGs and field galaxies, particularly at high redshifts.

4. Discussion

We measure CO (2-1) in a sample of 30 star-forming BCGs, chosen from SpARCS. We find that 80% of our BCGs are detected in CO, suggesting that molecular gas is common in star-forming BCGs at high redshifts. While this is seemingly in contrast with the results of similar BCG surveys such as Castignani et al. (2020), we note that these previous studies imposed no SFR limit on their samples (see Section 3.1). We specifically target star-forming galaxies, and new stars cannot form without fuel.

Semi-analytic models suggest that strangulation, ram pressure stripping, and other cluster effects actively remove molecular gas from galaxies in dense environments (e.g., Gavazzi et al. 2006; De Lucia & Blaizot 2007), and therefore limit star formation. It is thus necessary to account for two different processes when analyzing BCG star formation—the process by which gas is deposited onto the BCG, and the mechanism by which the BCG converts that gas into stars. This distinction between gas feeding and processing in BCGs may have important implications, especially as similar theories have been proposed for the general galaxy population (see Behroozi et al. 2019).

In Figure 4, we show that our BCG sample at $z \lesssim 0.6$ has a remarkably similar correlation between $M_\text{gas}$ and sSFR to that of Edge (2001), with nearly identical slopes. This implies that the two BCG samples are both processing their in situ molecular gas into stars with the same efficiency for a given stellar mass. This correlation exists at $z \lesssim 0.6$, and possibly to higher redshifts ($z \sim 1.0$), although this is uncertain due to the limiting depth of the sample, suggesting that many star-forming BCGs at $0 < z \lesssim 0.6$ may regulate the formation of these stars from gas in the same way, independent of their redshift or cluster properties. This is a picture of galaxy star formation that has been proposed for non-BCGs (e.g., Bouché et al. 2010; Dekel & Mandelker 2014).

Similarities in star formation processes between the Edge (2001) sample and our own have the potential to be very interesting, as the two samples differ in both selection method and cluster mass, in addition to the redshift difference discussed in Section 2.6. The Edge (2001) sample contains only BCGs from known cool-core clusters. In fact, all previous large BCG studies have selected galaxies either explicitly from known cool-core clusters (Edge 2001; Salomé & Combes 2003), or from X-ray surveys (Castignani et al. 2020). The parent, red-sequence selected SpARCS sample does not select clusters based on ICM state, and should therefore exhibit no cool-core selection effects. While the cool-core fraction varies depending on the selection criteria used, it should be $\lesssim 0.3$ in the redshift range we study (McDonald et al. 2013).
We do note, however, that our BCG sample is selected on star formation, which may bias it toward cool-core clusters (e.g., Fogarty et al. 2015). If our galaxies are all cool-core cluster BCGs, and therefore fed by cooling flows, this is an interesting result on its own, as additional confirmation that the star formation we see in BCGs at $z \lesssim 0.6$ may be the result of those BCGs being fed molecular gas principally by cooling flows, instead of other possible scenarios such as gas-rich mergers. Unfortunately, we lack the X-ray measurements necessary to confirm the dynamical state of our clusters.

These speculations should not affect our main result—$M_{\text{gas}}$ is a measurement of the amount of gas already in the galaxy. However, the CO-to-H$_2$ conversion factor used to determine molecular gas mass depends, among other things, on gas density (e.g., Bolatto et al. 2013). If some of our BCGs are dynamically unrelaxed post-mergers, this conversion factor could be affected, changing the relation. It is possible that we see this effect in Figure 4 at high redshifts, where BCGs tend to appear above the relation. This is in line with past work such as McDonald et al. (2016), which suggests that the mechanism fueling star formation changes from primarily cooling gas to gas-rich mergers in BCGs at $z \gtrsim 0.6$.

We cannot compare the cluster halo masses of our sample to those of Edge (2001) in depth, as we have no equivalent measurements to compare. We do, however, have cluster richnesses ($N_{\text{gal}}$) measured from SpARCS (Webb et al. 2015) for our sample, and halo masses based on SDSS DR7 (Popesso et al. 2020; Yang et al. 2005) for the Edge (2001) BCGs. As $N_{\text{gal}} = 12$ is roughly equal to $M_{\text{gal}} \sim 1 \times 10^{14}$ (e.g., Andreon & Congdon 2014), our clusters have an average cluster mass $\sim (1.5 \pm 0.7) \times 10^{14} M_{\odot}$ compared to an average cluster mass of $\sim (1.3 \pm 0.9) \times 10^{15} M_{\odot}$ for the Edge (2001) sample. The clusters presented in Edge (2001) are therefore almost an order of magnitude more massive than ours.

It has been suggested that halo mass is directly related to central galaxy star formation, with the fraction of quenched central galaxies increasing with host halo mass (e.g., Behroozi et al. 2019). However, the star formation efficiency for galaxies at a given distance from the MS has been shown not to change with host halo mass (Popesso et al. 2020). We select only star-forming galaxies (i.e., galaxies at a fixed distance from the MS; Figure 1), so our values are unaffected by the fraction of quenched central galaxies at a given halo mass, and it is therefore unsurprising that the two BCG samples line up well despite their differing cluster masses.

5. Conclusions

We present the largest and highest-redshift study of molecular gas in BCGs to date. Using ALMA bands 3, 4, and 5, we study CO (2-1) in 30 SpARCS BCGs. We summarize our results as follows:

1. We find that molecular gas is common in star-forming BCGs at $0.2 \leq z \leq 1.2$, detecting gas reservoirs in 80% of our sample of 30 galaxies.

2. We note a clear $M_{\text{gas}}$-sSFR trend is apparent in our sample. Below $z = 0.6$ this trend is consistent to 1σ with the sample of BCGs presented in Edge (2001). We therefore propose a scenario by which most BCGs below $z \sim 0.6$ process molecular gas into stars at a rate dependent on stellar mass, through mechanisms independent of redshift, and likely independent of cluster mass and cluster dynamical state.

This scenario appears to persist to higher redshifts, but we require a larger and more complete sample to determine this conclusively.

The process by which these BCGs obtain molecular gas is still not clear. We require X-ray observations of our clusters to confirm both their dynamical state and their total mass. Still, as a large, high-$z$, collection of BCGs selected homogeneously and detected in CO, our sample offers an exciting means by which to study cluster evolution as a whole.

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