Uncovering Early Galaxy Evolution in the ALMA and JWST Era
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ALMA Deep Field in the SSA22 proto-cluster at z = 3

Hideki Umehata[1,2]

[1]RIKEN Cluster for Pioneering Research, 2-1 Hirosawa, Wako-shi, Saitama 351-0198, Japan
email: hideki.umehata@riken.jp

[2]Institute of Astronomy, School of Science, The University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015, Japan

Abstract. Galaxies and nuclei in dense environment at high redshift provide a good laboratory to investigate accelerated, most extreme evolution of galaxies. The SSA22 proto-cluster at $z = 3.1$ is known to have a three-dimensional 50 (comoving) Mpc-scale filamentary structure, traced by Lyα emitters, which makes the field a suitable target in this regard. To identify dust-obscured star-formation, a contiguous 20 arcmin^2 region at the node of the cosmic structure was observed in ALMA band 6. In total 57 ALMA sources have been identified above 5σ, which makes the field one of the richest field in ALMA-identified (sub)millimeter galaxies. The follow-up spectroscopy confirmed about 20 sources as exact proto-cluster members so far. Together with high X-ray AGN fraction, our results suggest that the vigorous star formation activity and the growth of super massive black holes occurred simultaneously in the densest regions at $z \sim 3$.

Keywords. galaxies: evolution, galaxies: high-redshift

1. Introduction

Models of cosmological structure formation in a cold dark matter universe predict that the matter in the intergalactic medium (IGM) forms a "cosmic web" of sheets and filaments (e.g., Bond *et al.* 1996). The most massive dark matter halos lie at the intersections of filaments (e.g., Kauffmann *et al.* 1999), and high over densities in the dark matter distribution would make cradles in which galaxies form and thrive, eventually. Streams of cold gas flowing along the IGM filaments can provide fuel for the mass growth of galaxies and super massive black holes (SMBHs) through the circumgalactic medium (CGM, e.g., Dekel *et al.* 2009). Consequently galaxies and nuclei in the densest environments at high redshift are a nice laboratory for understanding of galaxy formation and evolution in their forming era.

In the last decades, such galaxy overdensities have been found preferentially tracing rest-UV-selected star-forming galaxies such as Lyα emitters (LAEs) and Lyman break galaxies (LBGs) (e.g., Steidel *et al.* 1998), (sometimes) in conjunction with 'beacons' of the over densities like high-redshift radio galaxies (HzRGs) (e.g., Venemans *et al.* 2002) (see Overzier *et al.* 2016 as a review). While such UV-bright populations indicates the existence of proto-clusters and give us some fundamental insights such as structures and overdensity, accumulating evidence now suggests that they are just part of star-forming galaxies and a complementary approach is essential to comprehend the formation of galaxies, especially for massive populations.

This is because actively star-forming galaxies generate significant amount of dust as they evolve and increase stellar mass, which absorbs the stellar lights significantly. Eventually their spectral energy distribution (SEDs) are dominated by rest-frame Far-IR to (sub)mm emission (for reviews; Blain *et al.* 2002; Casey *et al.* 2014). Therefore it is crucial to uncover not only the 'visible' part (i.e., UV/Optical views) but also the 'obscured' part (i.e., FIR views) of various galaxy populations (e.g., Dunlop *et al.* 2017).

Motivated by this, a number of extragalactic surveys were carried out at submm/mm using bolometer cameras onboard single-dish telescopes (e.g., SCUBA, SCUBA2/JCMT, AzTEC/ASTE) (e.g., Tamura *et al.* 2009; Umehata *et al.* 2014). Together with follow-up observations using an interferometer such as the SMA and (J)VLA, association between submillimeter galaxies (SMGs) and proto-clusters at high redshift was reported in some works (e.g., Tamura *et al.* 2010). However, the identification has been hard for years, and our knowledge had been limited to several exceptionally bright SMGs. As a reasonable successive step, astronomers have sought for an ALMA follow-up, which provide us with unprecedented sensitivity and angular resolution.

While snapshot surveys of single-dish selected submm/mm sources is one cost-effective way, such observations suffer from selection bias and completeness issue, which would result in a highly biased view. Therefore, ALMA deep surveys - mapping a significant area contiguously - are essential to obtain an unbiased submm/mm view. Such surveys are now on-going in general fields (e.g., Franco *et al.* 2018; Hatsukade *et al.* 2018), and a proto-cluster, which is the theme of this paper.

An ALMA deep survey is especially vital to understand massive galaxy formation, although it is helpful for understanding various aspects of galaxy formation. In the local Universe, the centers of cluster are known to be occupied by massive elliptical galaxies (Dressler *et al.* 1980). Simulations and galactic archeology suggest that such massive ellipticals experienced an episodic starburst phase at $z > 2-3$ in an ancestor of cluster - proto-cluster- (e.g., De Lucia *et al.* 2006). As we described above, the massive galaxies in the forming phase, possibly also forming a central SMBH, would be heavily obscured by dust. ALMA deep surveys are expected to identify and characterize such galaxies in the early Universe.

2. Survey Description

Our target field is a proto-cluster at $z \approx 3$. The SSA22 field is known to harbor a >100-Mpc-scale huge structure traced by $z \approx 3.09$ LAEs (Yamada *et al.* 2012), which includes a three-dimensionally-confirmed 50-Mpc-scale filamentary structure in the densest, proto-cluster region (Matsuda *et al.* 2005). This is the most spectacular known proto-cluster amongst all the known over-densities at $z > 2$ (Yamada *et al.* 2012), which provides a unique laboratory to investigate the co-evolution of galaxies and cosmic structures.

In ALMA Cycle-2, we have started a series of ALMA projects in the SSA22 proto-cluster field to uncover the cold regime - the universe of gas and dust-. The details of the observations are reported in previous papers (Umehata *et al.* 2015, 2017, 2018, 2019) and to be reported in an upcoming paper (H. Umehata *et al.*, in prep), and hence here we just briefly presented our observation. We mapped a central area of the proto-cluster contiguously and we name the project ALMA Deep Field in SSA22 or ADF22. So far we mapped 7 arcmin^2 area in band 6 down to 25 μJy Beam^{-1}. We also observed an adjacent 13 arcmin^2 field with 1σ sensitivity of 60 μJy Beam^{-1} (Umehata *et al.* 2018). The former 7 arcmin^2 area is also covered by band 3 observations which are designed to detect $z = 3.1$ CO(3-2) emission line (Umehata *et al.* 2019). The representative noise level per a 100 km s^{-1} channel is $\sigma = 90$ μJy beam^{-1} at around 84-86 GHz.

3. The ADF22 Results

Identification of SMGs in the proto-cluster: The deep and wide 1.1 mm map uncovers 57 SMGs above 5σ (note that the noise level is heterogenous within the map, as we explained

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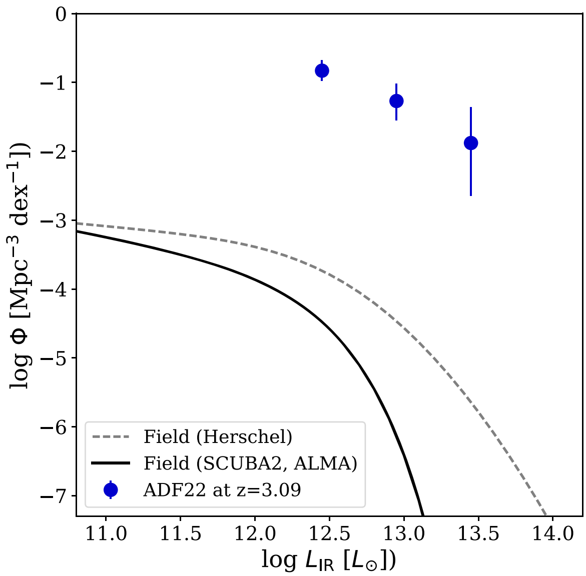

Figure 1. IR luminosity function of the ADF22 field and general fields. Blue points shows the ADF22 results. For comparison, the luminosity function at similar epoch, derived from *Herschel* (Gruppioni *et al.* 2013) and the combination of SCUBA2 and ALMA (Hatsukade *et al.* 2018) in general fields are shown. The excess in ADF22 is easily recognizable compared to both. The difference is larger for the SCUBA2 and ALMA results, which do not suffer from source confusion so much and hence more reliable. The excess shows that the dusty, intense star-formation seen in rapidly growing massive galaxies preferentially occurs in such a dense environment at $z \sim 3$.

above.) The negative map shows no *negative* 5σ peak, which demonstrates that our threshold is conservative enough not to count artificial peak due to noise fluctuations (e.g., Umehata *et al.* 2018). If we relax the criteria, the source number increases significantly. We perform various spectroscopic follow-up observations for the detected ALMA sources like NearIR spectroscopy using MOSFIRE on Keck and mm spectroscopy using ALMA as above (Umehata *et al.* 2019). So far 20 SMGs are confirmed to be the exact proto-cluster members through mult-wavelength spectroscopic follow-ups, which results in clear excess on 1 mm number counts (e.g., Umehata *et al.* 2018).

Luminosity Function at the proto-cluster: Here we further investigate the excess, focusing on the ADF22A (i.e., the deepest 7 arcmin2 region), which has the richest ancillary data. Among the top brightest 18 SMGs with $S_{1.1\mathrm{mm}} \geqslant 0.5$ mJy, 16 SMGs are found to be at $z = 3.09$ (2 SMGs are confirmed to be at $z = 3.991$ and $z = 2.05$, respectively; e.g., Umehata *et al.* 2018). Then the accurate redshifts allows us to perform SED fitting and derive total IR luminosity (rest-frame 8-1000 μm). Since the 16 SMGs are 'flux-limited' samples, then we can evaluate IR luminosity function at the core of the proto-cluster. The results are shown in Fig. 1). As shown in the figure, the excess is quite remarkable, showing more than 3 dex, while the excess of LBGs is ∼6 times than general field (Steidel *et al.* 1998). This further demonstrates that intense star-forming activity in massive galaxies is accelerated in the proto-cluster core.

High X-ray AGN fraction: The SSA22 proto-cluster has been observed by *Chandra* X-ray observatory (e.g., Lehmer *et al.* 2009a,b). Thanks to the relatively deep integration time (about 400 ks), 8 X-ray luminous AGNs at $z = 3.09$ with X-ray Luminosity $L_x \approx 10^{44}$ erg s^{-1} have been found in ADF22 (e.g., Umehata *et al.* 2015, 2019). Furthermore, six of the eight are also detected in ALMA and included in the 16 brightest SMGs in the field. The volume density of the X-ray AGN is three orders of magnitudes higher than the

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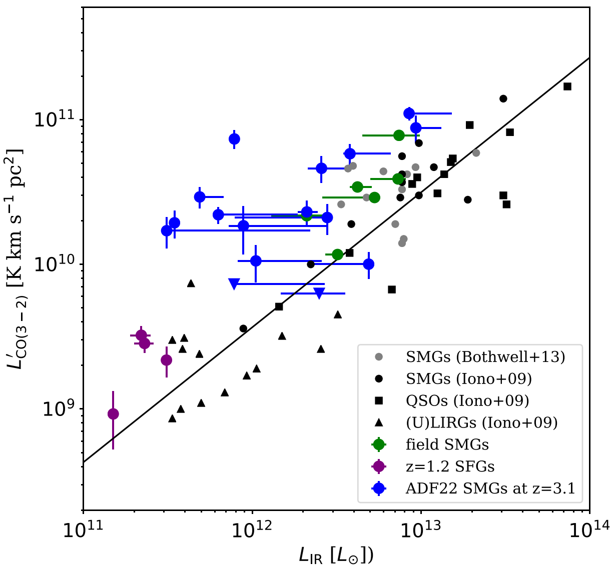

Figure 2. The relation between IR luminosity ($L_{\rm IR}$) and CO(3-2) line luminosity ($L'_{\rm CO(3-2)}$) for the ADF22 SMGs. For comparison, we plot the results for SMGs in general fields (e.g., Iono *et al.* 2009; Bothwell *et al.* 2013; Wardlow *et al.* 2018). The solid line shows best-fit function from Iono *et al.* (2009). The digram suggests that some of the ADF22 SMGs have relatively molecular gas-rich nature, compared to field SMGs.

general field (Umehata *et al.* 2019). Together with the high X-ray AGN fraction, this indicates that there is not only the star-bursting activity but also accelerated accretion activity at the node of the cosmic structure.

Molecular gas reservoirs The co-spatial band 3 survey provides a census of molecular gas for all the 16 SMGs at $z=3.09$ in ADF22A. We show the relation between the IR luminosity ($L_{\rm IR}$) and the CO(3-2) line luminosity ($L'_{\rm CO(3-2)}$) as a proxy of the SFR-$M_{\rm gas}$ relation (where SFR shows star-formation rate and $M_{\rm gas}$ shows molecular gas mass, Fig. 2). There is certain diversity among the ADF22 SMGs (as we can easily recognize it from the fact that some of SMGs are not detected in CO(3-2)), which would somehow reflect the evolutionary stage. Another interesting feature is that some of the SMGs show relatively large CO(3-2) line luminosity at a given IR luminosity, compared to field SMGs. The ADF22 SMGs are located at the proto-cluster core, where the potential well is expected to be deep. Hence one interpretation is that the SMGs are fueled by cosmic web filaments and abundant gas supply leads the starbursts and large molecular gas reservoir. But we also note that we assume a brightness temperature ratio which is derived for SMGs in general field (Bothwell *et al.* 2013), which may not be appropriate. More data are required to make a final conclusion.

4. Summary and Prospects

We present the background, survey strategy, and some key results of our ongoing ALMA survey towards the SSA22 proto-cluster at $z=3$. We have uncovered unusual active growth of massive galaxies and SMBHs at the center of the proto-cluster on the basis of a contiguous mm mapping, utilizing the unprecedented capability of ALMA. Further ALMA observations such as fine structure lines and/or very high angular resolution imaging would give us further insights. Moreover, synergy with other wavelengths, such as optical IFU (e.g., MUSE), would be of great importance to uncover various aspects of galaxy formation at the proto-cluster.

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