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EXPLORING THE HIGH-REDSHIFT UNIVERSE WITH ALMA

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Abstract. The Atacama Large Millimeter Array (ALMA) is now observing the (sub-)millimeter sky for more than half a decade. Thanks to its unprecedented sensitivity, it has dramatically improved our understanding of the high-z dusty Universe. In this review, I present a short summary of the main ALMA results about z>3 galaxies. I will first discuss the star formation history with a focus on the contribution of the early massive and dusty systems. I will then explain how we obtained first constraints on their interstellar medium using (sub-)millimeter lines. Finally, I will present some of the most spectacular objects that ALMA has identified.

Keywords: ALMA, galaxy formation and evolution, high-redshift galaxies, star formation, dust, gas, interstellar medium

1 Why is ALMA important to understand the formation of massive galaxies at high redshift?

Understanding the early assembly of massive galaxies remains a challenge for modern astrophysics. We still do not well know how gas is accreted by galaxies, cool down, and is finally used as fuel for star formation. For instance, very massive galaxies have been found extremely early in the Universe (e.g., Riechers et al. 2013). Some of these objects are an order of magnitude more massive than the Milky Way less than a gigayear after the recombination and the mechanisms leading to their incredibly fast assembly are poorly known. Of course, the bulk of stars at high redshift are not form in these monsters. However, at these early times (z>3), a significant fraction of the stars were formed in already massive galaxies ($>10^{10}\,M_\odot$) hosting very high star formation rates (SFR>10 $M_\odot$/yr and even >100 $M_\odot$/yr for the most massive ones, e.g., Schreiber et al. 2015).

How can we explain that the stellar mass of these galaxies was assembled so early and so fast? The major mergers were the first explanation proposed. Indeed, in the local Universe, the highest SFRs are found in major mergers (Sanders & Mirabel 1996; Di Matteo et al. 2007) and the merger rate increases with redshift (e.g., Le Fèvre et al. 2000). However, the discovery of a correlation between the assembled stellar mass and the SFR (e.g., Noeske et al. 2007; Elbaz et al. 2011) and the quickly increasing gas fraction from z=0 to z=3 (e.g., Magdis et al. 2012; Tacconi et al. 2013; Dessauges-Zavadsky et al. 2015) contributed to the emergence of a new scenarii, where the intense star formation in these objects is driven mainly by cosmic accretion of cold gas onto early-assembled dark matter halos (e.g., Dekel & Birnboim 2006). This scenario is compatible with the strong clustering (typical of host halo mass of a few $10^{12}\,M_\odot$) of the dusty star formation measured up to z$\sim$3 using the anisotropies of the cosmic infrared background, i.e. the relic emission of the dust from all galaxies across cosmic times (e.g., Béthermin et al. 2013; Maniyar et al. 2018). Recently, zoom-in hydrodynamical simulation found that high-redshift star-forming structures could be even more complex with a strong contribution from both accretion, minor, and major mergers (e.g., Narayanan et al. 2015).

Until recent years, most of our constraints on the star formation at z>3 were essentially coming from the UV light from young stars escaping the galaxies (e.g., Madau & Dickinson 2014) and we had very few information on the UV light absorbed by dust and re-emitted at long wavelength or the galaxy gas content, except in bright lensed quasars and extreme starbursts. However, the stacking of *Herschel* data showed us that the most massive galaxies had a very high dust attenuation (Heinis et al. 2014). Having access to long-wavelength observations

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at z>3 is thus one of the keys to understand the formation of the early massive galaxies.

ALMA is a (sub-)millimeter array of 66 antennae built on the Chajnantor plateau at an elevation of 5 000m in one of the driest places on Earth (Fig. 1). It contains 50 12-meter antennae in the main array used to observe the compact sources and/or trace the small scales, 12 7-meter antennae used to reconstruct the intermediate scales, and 4 12-meter total power antennae used measure the large scales. Since ALMA has reached its final unprecedented capabilities, a new era is opening, and we can finally detect the dust emission of dusty star-forming galaxies and their cold gas reservoirs at these early times.

Fig. 1. ALMA antennae on the Chajnantor plateau (private picture).

2 ALMA and the obscured star formation history

The star formation history in the Universe, usually defined as the evolution of the sum of all the star formation per unit of comoving volume (SFR density or $\rho_{\rm SFR}$), can be measured by combining the UV light from young stars both escaping the galaxies and absorbed by dust reprocessed in the infrared (8-1000 μm rest-frame).

One of the best ways to measure this SFR density is to use deep fields data. However, they need to be sufficiently deep to detect the galaxy populations responsible for the bulk of the star formation activity and sufficiently wide to detect a statistically significant number of objects. Unfortunately, despite its incredible sensitivity, the small field of view of ALMA (only one antenna beam) does not allow us to map efficiently large area. The 4.5 $\rm arcmin^2$ of Dunlop et al. (2017) in the *Hubble* ultra deep field detected only one source at z> 4, while the ALMA-GOODS survey (69 $\rm arcmin^2$ but shallower, Franco et al. 2018) detected two z>4 objects. Due to scheduling problems, these surveys were not observed in slightly extended configuration and their sensitivity to extended galaxies was limited. Better results should be obtained in the future from deep fields observed in compact configuration only (re-observation of ALMA-GOODS has been completed). However, it shows how hard it is even at ALMA era to probe the high-z dusty Universe in a volume-complete way.

Another possible approach is to target with ALMA galaxy samples selected at shorter wavelength. For instance, the ALPINE large program targeted 122 4<z<6 objects selected using optical spectroscopy (PI: Le Fèvre et al.). Only 23 of these objects are detected in continuum (Béthermin et al. in prep.), but we can use stacking to estimate the properties of the fainter ones as a function of various proxies (UV luminosity, stellar mass...) and reconstruct the contribution of known galaxy populations to the SFRD at z>4. This analysis shows that at least half of the SFR density is still dust obscured at z∼5.5 (Khusanova et al. in prep.).*

In extended configuration, ALMA can spatially resolve the dust emission. These observations revealed important differences between the UV and dust morphologies (Elbaz et al. 2018), suggesting that the dust attenuation and probably the presence of dust and metals can dramatically vary inside an object. One of the most extreme case is the Jekyll&Hyde systems, where a component is bright with *Hubble* and invisible with ALMA, while it is the exact opposite for the other one (Schreiber et al. 2018).

*Note also the work of Wang et al. (2019) published after the oral presentation, which shows an important contribution of massive dusty galaxies not seen by *Hubble*.

3 ALMA to probe the cold interstellar medium in the teenager Universe

The mass of the cold gas reservoirs of high-z galaxies is a crucial constraint to understand their impressive star formation rate. Observations at intermediate redshifts (1<z<2) showed that normal star-forming galaxies follow a correlation between gas mass (or gas surface density) and SFR (or SFR surface density), while the starbursting systems have a significantly higher SFR for the same gas mass (Daddi et al. 2010; Genzel et al. 2010). Where does z> 3 systems lies in this diagram? *Herschel* stacking suggested that massive systems have in average large gas reservoirs and tend to follow the "normal" relation (Béthermin et al. 2015). Using the Rayleigh-Jeans dust continuum, Schinnerer et al. (2016) and Scoville et al. (2017) confirmed this results with ALMA by measuring individual gas masses and found that most of the objects were on the "normal" gas mass-SFR relation.

At z>3, it is really hard to detect lines in normal star-forming systems. However, the 158 μm [CII] line is particularly bright and is conveniently redshifted to the atmospheric sub-millimeter windows at z>3. Paradoxically, the higher the redshift, the easier its detection is. Initially, [CII] was not detected in some of the first targeted high-redshift systems (e.g., Ouchi et al. 2013). Models suggested that high-redshift galaxies could have a lower [CII] luminosity than what could be expected from the local [CII]-L_{IR}. This would be caused by a lower metallicity and/or higher interstellar radiation field (Vallini et al. 2015; Lagache et al. 2018). No [CII]-deficit has been found for the statistical ALPINE sample (see previous section, Schaerer et al. in prep.). The faint [CII] observed in the first targeted systems could be explained by a bias towards particularly metal-poor Lyman α-emitters or a quick transition above z=6.

To perform finer diagnostics of the interstellar medium (ISM) of z>3 galaxies, we need much more lines, but their detection usually request tens of hours of integration times. However, we can use the assistance of gravitational lensing magnifying the flux of some high-z galaxies. For instance, the South Pole Telescope (SPT) identified ∼70 high-redshift dusty star-forming galaxies magnified by intermediate-z elliptical galaxies and their spectroscopic redshifts were measured by ALMA (Vieira et al. 2013; Strandet et al. 2016). ALMA and NOEMA detected a large variety of lines in this type of systems: CO (e.g., Aravena et al. 2016; Yang et al. 2017), H_2O (e.g., Yang et al. 2016; Jarugula et al. 2019), [NII] (e.g., Béthermin et al. 2016; Cunningham et al. 2019), [CI] (e.g., Bothwell et al. 2016; Nesvadba et al. 2019), HCN/HNC/HCO^+ (e.g., Béthermin et al. 2018), CH^+ (Falgarone et al. 2017)...

Each of these lines probes a different phase of the ISM (Fig. 2) and provides much more powerful diagnostic than just the total gas mass. For instance, using tracers of the dense molecular gas (HCN and HCO^+), we can show that the most extreme star-forming systems (SFR>1000 $M_\odot$/yr) have both a high dense-gas fraction and a high star-formation efficiency. Combined with their large gas reservoirs, this could explain the impressive star formation they host. However, Zhang et al. (2018) suggest using CO isotopes that their actual SFR could be lower because of a top-heavy initial mass function. Using several lines and ISM models, various studies showed that the lensed dusty star-forming galaxies contain dense gas excited by an intense radiation field (e.g. Bothwell et al. 2016; Yang et al. 2017). The [NII]/[CII] ratio can also be used to obtain a rough estimate of their metallicity and we found lots of systems compatible with solar abundances (e.g., Nagao et al. 2012; Béthermin et al. 2016), suggesting a very quick enrichment in these early-assembled massive objects.

4 ALMA: a powerful tool to find the most extremes galaxies and (proto)cluster in the young Universe

Thanks to its incredible sensitivity in spectroscopy, ALMA is perfectly suited to determine the redshift of very dusty objects, which could not be measured with optical spectroscopy. SPT0311-58 was one of the reddest objects of the SPT SMG sample. The ALMA spectral scan campaign confirmed a redshift of 6.9 (Strandet et al. 2017). This is the record for an object selected purely in the millimeter, which could have never been found using lower-wavelength data because of its dustiness. SPT0311-58 has a SFR of ∼2900 $M_\odot$/yr, which is fueled by $\sim 2.7 \times 10^{11}\,M_\odot$ gas reservoir. ALMA follow-up at higher resolution revealed its kinematics. It has two distinct components, including one possibly rotation dominated (Marrone et al. 2018). The dark-matter halo mass of such a system can be estimated to be a few $10^{12}\,M_\odot$ and is probably the progenitor of a cluster.

ALMA can also measure spectroscopic redshift of even higher redshift candidates selected using the Lyman break technique. The bright 158 μm [CII] and 88 μm [OIII] fine-structure lines are particularly suited for this

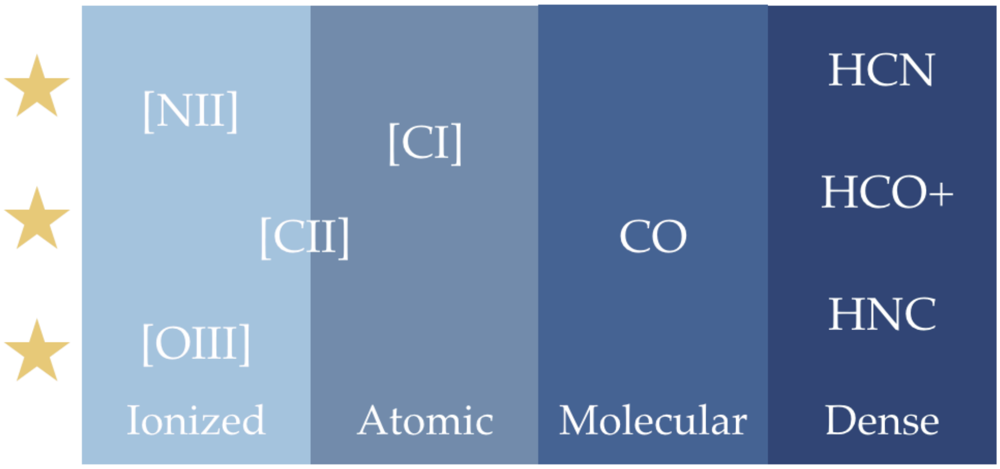

Fig. 2. (Very) simplified cartoon showing in which phase of the interstellar medium the various lines detected by ALMA are emitted.

task, since their observed frequency is lower at higher redshift and the atmosphere is thus more transparent. In addition, according to models, [OIII] has the convenient property to be bright in early low-metallicity systems (Inoue et al. 2014). This approach leads to the discovery of two consecutive record holders for spectroscopically-confirmed redshift: z=8.38 by Laporte et al. (2017) and z=9.11 by Hashimoto et al. (2018). Before the launch of JWST, ALMA is probably the best tool to determine spectroscopic redshifts at z>8.

ALMA is also particularly suited to detect the early stage of cluster formation, when their most massive galaxies were still star forming. As for field galaxies, massive cluster galaxies produced early an impressive amount of dust and are very bright in the (sub-)millimeter. Wang et al. (2016) confirmed the membership of 11 objects in a z=2.5 X-ray cluster by detecting CO with ALMA. At higher redshift, progenitors of even more massive structures can be found. Miller et al. (2018) found an overdensity of 17 galaxies with SFR>100 $M_\odot$/yr at the same spectroscopic redshift of z=4.3. The mass of such a system was estimated to be $\sim 10^{13}\,M_\odot$/yr, which corresponds to a progenitor of a Coma-like cluster. Another similar system was also identified by Oteo et al. (2018). A more systematic search for these overdensities of high-z dusty galaxies using the *Planck* is on-going (Planck Collaboration et al. 2015; Martinache et al. 2018; Kneissl et al. 2019).

5 Conclusions

Since its first observations, ALMA has dramatically changed our understanding of the high-redshift Universe. It is now clear that very dusty systems exist up to very high redshifts. These systems are already very massive, contain gigantic gas reservoirs fueling an intense star formation, and have already produced a large amount of metals and dust. They are probably the progenitor of the most massive galaxies.

However, many questions remain open and ALMA should be able to address them during the next decade:

- When were the very first massive and dusty systems assembled?
- Which fraction of these systems are in clusters or collapsing massive structures?
- Do we still miss a fraction of the star formation because of dust at very high redshift?
- How different is the physics of the star formation in high-z gas-rich galaxies fed by an intense accretion and affected by mergers compared to the local Universe?
- What is the metallicity of these early massive systems? How have they produced so quickly metals and dust?

This review is only a short summary of ALMA results, since cycle 0. It is thus highly incomplete and voluntarily biased towards the contribution of the french community.

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