Uncovering Early Galaxy Evolution in the ALMA and JWST Era
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Molecular clouds in a Milky Way progenitor at $z = 1$

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Abstract. Thanks to the remarkable ALMA capabilities and the unique configuration of the Cosmic Snake galaxy behind a massive galaxy cluster, we could resolve molecular clouds down to 30 pc linear physical scales in a typical Milky Way progenitor at $z = 1.036$, through CO(4–3) observations performed at the $\sim 0.2''$ angular resolution. We identified 17 individual giant molecular clouds. These high-redshift molecular clouds are clearly different from their local analogues, with $10 - 100$ times higher masses, densities, and internal turbulence. They are offset from the Larson scaling relations. We argue that the molecular cloud physical properties are dependent on the ambient interstellar conditions particular to the host galaxy. We find these high-redshift clouds in virial equilibrium, and derive, for the first time, the CO-to-H_2 conversion factor from the kinematics of independent molecular clouds at $z = 1$. The measured large clouds gas masses demonstrate the existence of parent gas clouds with masses high enough to allow the in-situ formation of similarly massive stellar clumps seen in the Cosmic Snake galaxy in comparable numbers. Our results support the formation of molecular clouds by fragmentation of turbulent galactic gas disks, which then become the stellar clumps observed in distant galaxies.

Keywords. gravitational lensing, galaxies: high-redshift, galaxies: ISM, ISM: clouds

1. Introduction

The motivation to search for molecular clouds at high-redshift is two-fold. *First*, the molecular gas in present-day galaxies is known to be structured in discrete cloud complexes, the giant molecular clouds (GMCs). They are the seeds of star formation, as star clusters form by condensation of these GMCs. Typically, local GMCs have gas masses between 10^4 $M_\odot$ to 10^7 $M_\odot$ and radii as small as 5 pc to 100 pc (e.g., Bolatto *et al.* 2008; Columbo *et al.* 2014; Sun *et al.* 2018). Achieving such small scales at $z > 1$ is observationally challenging. The higher resolution ALMA observations of high-redshift galaxies were performed at $0.03'' - 0.04''$, that is still ~ 200 pc at $z = 1 - 2$. At this resolution, sub-mm galaxies do show structures in the rest-frame far-IR continuum emission (Hodge *et al.* 2019), but normal star-forming galaxies do not (Rujopakarn *et al.* 2019). The only way we may beat this spatial resolution limitation is with the help of gravitational lensing. Observations of a strongly lensed sub-mm galaxy at $z = 3.042$, reading down to $50 - 100$ pc, revealed massive CO clouds (Swinbank *et al.* 2015).

Second, about 60% of galaxies at the peak of the cosmic star formation have perturbed morphologies, characterized by UV-bright star-forming clumps (e.g., Cowie *et al.* 1995; Elmegreen *et al.* 2013; Guo *et al.* 2018). These clumps have stellar masses between 10^6 $M_\odot$ to 10^9 $M_\odot$, that is, they are, on average, two orders of magnitude more massive than the star cluster complexes found in nearby galaxies (Dessauges-Zavadsky *et al.* 2017). What is the origin of these stellar clumps? Are they accreted satellites following a merger event, or are they formed 'in situ' in host galaxies? In the latter case, we should see the molecular clouds which led to the formation of these stellar clumps. Currently, there is a number of observational findings which favour the in-situ clump origin: (i) the redshift evolution of the clumpy galaxy fraction is inconsistent with the evolutionary trends of minor and major mergers (Shibuya *et al.* 2016); (ii) clumpy galaxies are dominated by disk-like systems with Sersic indices of $n \sim 1$ (Shibuya *et al.* 2016); (iii) the kinematics of the majority of star-forming galaxies at $z = 1 - 2$, including clumpy galaxies, is dominated by ordered disk rotation (e.g., Wisnioski *et al.* 2015; Girard *et al.* 2018); (iv) edge-on clumpy galaxies (the dubbed chain-galaxies) have very comparable disk scale-height to edge-on spirals without UV-bright clumps (Elmegreen *et al.* 2017); and (v) the stellar mass function of high-redshift clumps follows a power law with a slope of -2, which is characteristic of local star clusters (Dessauges-Zavadsky & Adamo 2018). Based on numerical simulations, it has been proposed that the observed high-redshift turbulent disks are subject to violent gravitational instability, caused by intense cold gas accretion flows, which triggers their fragmentation, and then the formation of in-situ gravitationally bound gas clouds believed to be the progenitors of the observed stellar clumps (e.g., Dekel *et al.* 2009; Bournaud *et al.* 2014). State-of-the-art high-resolution simulations predict a stellar mass distribution of clumps formed via disk fragmentation in perfect agreement with the observed distribution of high-redshift stellar clumps (Tamburello *et al.* 2015; Behrendt *et al.* 2016; Dessauges-Zavadsky *et al.* 2017). If the proposed scenario is correct, the observed stellar clumps currently provide an important evidence of galaxy mass build-up via cosmic cold gas accretion flows rather than mergers. The detection of the associated molecular clouds will bring an even stronger support to this scenario.

2. Target and molecular cloud identification

We have undertaken the search for molecular clouds in the 'Cosmic Snake' galaxy at $z = 1.036$, strongly lensed by the massive galaxy cluster MACS J1206.2–0847. With a stellar mass of 2.4×10^{10} $M_\odot$, a star formation rate of 18 $M_\odot$ yr^{-1}, and a molecular gas fraction of 30%, it is a typical main-sequence galaxy in rotation, inclined by 70 degrees (Patricio *et al.* 2018; Girard *et al.* 2019). It is characterized by a clumpy morphology with 21 stellar clumps detected in the HST images (Cava *et al.* 2018). We obtained ALMA imaging in the CO(4–3) emission with a synthesized beam size of $0.22'' \times 0.18''$, comparable to the HST rest-frame UV to optical images. Together with the lens model accuracy of $0.15''$ and magnification factors between 10 and > 100, we achieve resolutions of $30 - 70$ pc, similar to those of local galaxy molecular gas studies.

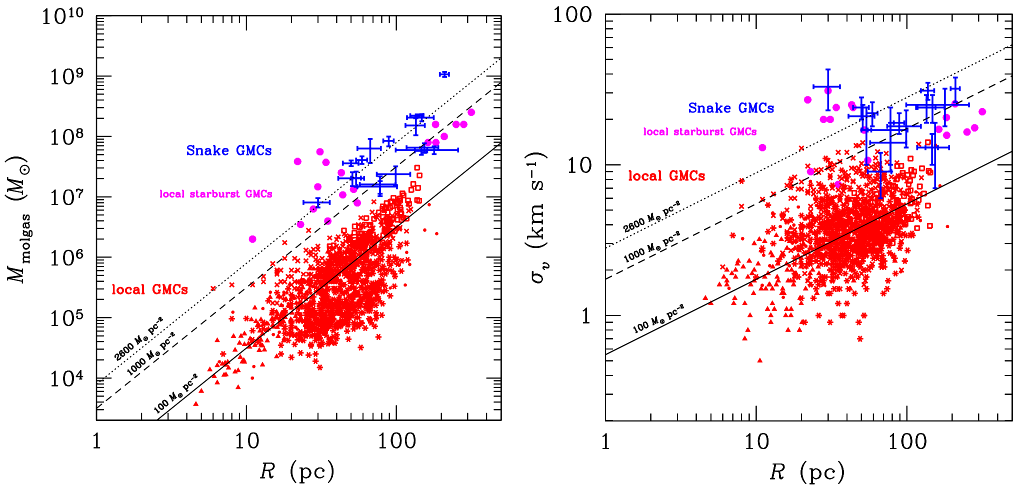

Figure 1. *Left.* Molecular gas masses as a function of radius for the GMCs identified in the Cosmic Snake galaxy (blue data points), the local quiescent galaxies (red symbols from a compilation of various publications), and the nearby starbursting galaxies (magenta filled circles from Wei *et al.* (2012) and Leroy *et al.* (2015)). The black lines show fixed molecular gas mass surface densities. *Right.* Internal velocity dispersions as a function of radius, plotted for the same GMC populations as in the left panel. The black lines show the $\sigma_v \propto R^{0.5}$ relation expected for virialized clouds with fixed gas mass surface density (same values as in the left panel).

We used individual CO(4–3) intensity channel maps of 10.343 km s^{-1} to search for molecular clouds. We first extracted all the emission peaks per channel above our detection threshold set to 100% fidelity (Walter *et al.* 2016), and ewe kept only the emissions detected over at least two adjacent channels. Using the lens model, we associated the emissions with 40 counter-images of 17 molecular clouds. The 17 identified molecular clouds are detected at a significance level $> 6 - 27\sigma$. For each cloud, we measured the radius, the internal velocity dispersion, and the CO(4–3) line-integrated flux, which we converted to the molecular gas mass assuming the CO luminosity correction factor $r_{4,1} = L'_{\rm CO(4-3)}/L'_{\rm CO(1-0)} = 0.33$ (extrapolated from our $r_{4,2}$ measurement in the Cosmic Snake and $r_{2,1}$ obtained in $z \sim 1.5$ BzK galaxies by Daddi *et al.* (2015)) and the Milky Way CO-to-H_2 conversion factor. All the Cosmic Snake molecular clouds are spatially resolved, with measured radii all larger than the equivalent circularised beam detection limit and measured molecular gas masses all larger than the molecular gas mass detection limit (for the 100% fidelity) at the magnification of a given cloud. The radii range between 30 pc to 210 pc, the molecular gas masses between 8×10^6 $M_\odot$ and 1×10^9 $M_\odot$, and the internal velocity dispersions between 9 km s^{-1} and 33 km s^{-1}.

3. Molecular cloud physical properties

To compare the derived physical properties of the Cosmic Snake GMCs with GMCs hosted in the Milky Way and nearby galaxies, we considered the Larson scaling relations used for a long time as the benchmark of local GMC populations and thought to reflect identical GMC physical properties in all galaxies at all times (Larson 1981). As shown in Fig. 1, the Cosmic Snake GMCs are offset from the Larson scaling relations: they have higher molecular gas masses by two orders of magnitude, higher gas mass surface densities by one order of magnitude with a median density as high as 2600 $M_\odot$ pc^{-2}, and larger internal velocity dispersions. This is not so surprising, as genuine variations in the physical properties of GMCs hosted in different interstellar environments have already

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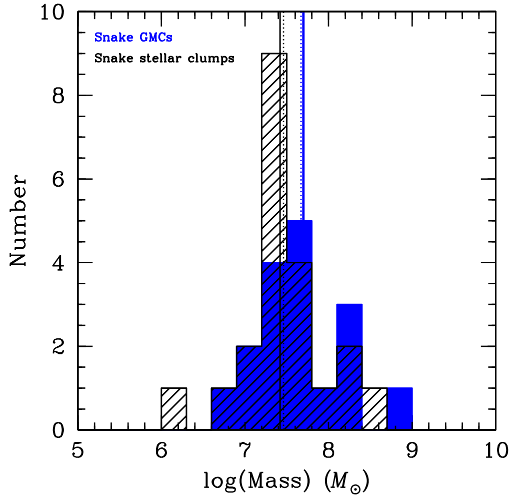

Figure 2. Comparison of the gas mass distribution of the Cosmic Snake molecular clouds (filled blue histogram) with the stellar mass distribution of the stellar clumps identified in the HST UV to near-IR images (hatched black histogram). The medians (solid lines; the dotted lines show the means) are 5.0×10^7 $M_\odot$ for the molecular clouds and 2.6×10^7 $M_\odot$ for the stellar clumps.

been reported in nearby mergers (the Antenna merger; Wei *et al.* 2012) and starbursting nuclear regions (NGC 235; Leroy *et al.* 2015). properties in fact very much resemble those of high-redshift Cosmic Snake GMCs. The universality of GMCs is definitely challenged, the environment must matter. There seems to be a link between the GMC properties and the interstellar medium conditions of the host galaxy, which are more extreme in distant objects in terms of the ambient turbulence and the disk hydrostatic pressure. In the Cosmic Snake disk we measured a 1000 times stronger hydrostatic pressure ($\sim 10^{7.7}$ cm^{-3} K) than in the Milky Way disk.

The enhanced surface density and turbulence of the Cosmic Snake GMCs guarantee their survival and equilibrium. Fourteen out of the 17 identified GMCs are indeed found in virial equilibrium. For the virialized GMCs, we can, for the first time, constrain the CO-to-H_2 conversion factor from the kinematics of individual GMCs at $z = 1$. The derived conversion factor of 3.8 ± 1.1 $M_\odot/(\mathrm{K\ km\ s^{-1}\ pc^2})$ is close to the Milky Way value, despite the stronger photodissociating radiation expected in the Cosmic Snake galaxy given its relatively high star formation rate. This implies that the measured gas mass surface densities are high enough to shield the clouds.

The Cosmic Snake GMCs are highly supersonic with 10 times higher Mach numbers than in local GMCs. Does this betray a higher efficiency of star formation? The fact that we have identified GMCs and stellar clumps at the same spatial resolution enables us to provide an estimate of the efficiency of star formation in a similar fashion as it has been done in the local Universe, from the comparison of the mass distributions of the molecular clouds and the stellar clumps (Evans *et al.* 2009). Under the hypothesis that the identified GMCs are representative of the parent gas clouds which gave rise to the observed massive star clusters, we obtained an efficiency of star formation of $26 - 34\%$, fairly much higher than the canonical values smaller than $\sim 10\%$ found in contemporary galaxies. The derived efficiency is, on the other hand, in very good agreement with the FIRE numerical simulations predicting a dependence of the star formation efficiency on the gas mass surface density of molecular clouds (Grudic *et al.* 2018).

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4. Conclusion

This is the first time that we detect molecular clouds and stellar clumps in comparable numbers in a high-redshift galaxy. The detection of the molecular clouds in the Cosmic Snake galaxy, moreover, demonstrates the existence of parent gas clouds with masses high enough to allow the in-situ formation of stellar clumps seen in the galaxy. Galactic disk fragmentation can therefore be proposed as the mechanism of formation of massive molecular clouds in distant galaxies.

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