Astro2020 Science White Paper

Imaging molecular gas in high redshift galaxies at ≤ 1 kpc resolution

Thematic Areas: ☐ Galaxy Evolution

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Abstract

We discuss the importance of high resolution imaging of the cool molecular gas in distant galaxies, as a cardinal tool for studies of galaxy formation and the cosmic baryon cycle. Cool molecular gas represents the fuel for star formation in galaxies. Observations with ~ 1 kpc resolution are a prerequisite for future precision studies of the physical conditions of the ISM in early galaxies. Acting in concert with pan-chromatic, high resolution observations of other galaxy constituents, such as the stars and ionized gas, molecular imaging is needed to answer some of the most fundamental questions in galaxy formation, including: (i) is there a Universal relationship between cold gas and star formation through cosmic time?, (i) how does feedback from star formation and/or AGN affect star forming clouds?, (iii) what are the physical conditions in star forming clouds in the first galaxies?, (iv) what is the dynamics of the cold gas (rotation, infall, outflows), and how does this affect the galaxy formation process? While current facilities operating in the 10 GHz to 100 GHz range are capable of determing the integrated properties of main sequence star forming galaxies in the low order molecular transitions, and imaging the most massive systems at a few to 10 kpc resolution with long integrations, imaging with ~ 1 kpc resolution of typical main sequence galaxies at high redshift requires an order of magnitude increase in collecting area. Such molecular gas imaging, coupled with the capabilities of future optical, near-IR, and submm facilities, will usher-in the era of 'precision galaxy formation', providing information on the cosmic baryon cycle in early galaxies at a level of detail approaching what is now currently possible only for nearby galaxies and the Milky Way.

Precision Galaxy Formation

The next decade will usher-in the era of 'Precision Galaxy Formation Studies': with the advent of new, large facilities, such as the JWST, the ELTs, and the ever improving ALMA, studies of early galaxies will evolve from volumetric demographics, to detailed imaging studies of the internal physical processes of galaxies at resolutions of 1 kpc, or better, approaching the size of giant molecular clouds – the base unit for star formation in galaxies. Capabilities will span the electromagetic spectrum, from Far-IR studies of the warm dust with ORIGINS, to near-IR and optical studies of the ionized gas and stars with JWST and the ELTs, to submm studies of the cool dust, atomic fine structure lines, and high-order molecular gas transitions with ALMA. We are on the cusp of having a complete picture of the baryon cycle in galaxies throughout cosmic time, at a level of detail in early galaxies comparable to that now possible in the nearby Universe.

In this white paper, we discuss the importance of imaging the cooler molecular gas in galaxies – the fundamental fuel for star formation. The molecular gas is most commonly probed through observations of emission from low order rotational transitions of the trace element, CO. CO is the most abundant molecule after H_2, and CO rotational transitions are easily excited at low temperatures (Carilli & Walter 2013). Observations of low order CO provide one of the primary tools for deriving total molecular gas masses in galaxies (Bolatto et al. 2013). In particular, the Kennicutt-Schmidt, or gas mass-to-star formation rate, correlation has been calibrated in the nearby Universe using CO 1-0 observations (Leroy et al. 2008; Bigiel et al. 2008). Hence, low order CO observations across cosmic time are paramount to galaxy formation studies.

Current state of the art surveys with the VLA, ALMA, and NOEMA have made great progress in determining the evolution of the total molecular gas content of galaxies through cosmic time. Two ground-breaking results from these studies are: (i) the evolution of the cosmic molecular gas density parallels the rise and fall with redshift of the cosmic star formation rate density (Decarli et al. 2016, 2018; Riechers et al. 2019), and, (ii) the typical molecular gas fraction (gas mass/stellar mass) of star forming galaxies increases by an order of magnitude from $z = 0$ to $z \sim 2$, such that star forming galaxies become gas-dominated in the early Universe (Daddi et al. 2010; Geach et al. 2011; Genzel et al. 2015, Tacconi et al. 2018). Both of these results suggest that the cool molecular gas content of galaxies drives the cosmic star formation rate evolution, thereby highlighting the importance of studies of this key fuel for star formation (see Walter et al. 2019).

The next major step in understanding ISM physics, and the interplay between the gas content and star formation activity, in early galaxies will be through high resolution imaging (1 kpc or better). Such imaging is required to address the most fundamental questions in galaxy formation:

- **Comparison of the spatial distribution of ISM gas and dust phases, with the stars and star formation:** Spatially resolving observations are required for a detailed understanding of how the cool molecular gas fuels star formation, and how star formation then affects the ISM through feed-back processes. A key result will be determining a spatially resolved star formation law in early galaxies on scales down to GMCs.

- **Physical conditions in star forming clouds:** Our understanding of the detail physical conditions in star forming clouds in early galaxies remains rudimentary. Current inferences are made typically using observations of the integrated properties of galaxies. Only high resolution imaging can determine such basic quantities as ISM density, temperature, chemistry, ratiation field, etc... on scales relevant to star formation. The low order CO observations are a foundational requirement for such studies.

- **Kinematics of early galaxies**: High resolution spectral line observations reveal internal gas dispersions, to understand gas stability to collapse, as well as probe tidal features due to galaxy interactions, and gas inflows and outflows around early galaxies. Line observations can be used to determine the rotation curves of galaxies, as one probe of the dark-matter content.

Studies of our own Galaxy, and nearby galaxies have demonstrated clearly that understanding the physics of the ISM, and its relationship to star formation, requires a pan-chromatic approach, including eg. high resolution studies of the neutral atomic and molecular gas, optical and near-IR IFU observations of the ionized gas, submm and far-IR imaging of the fine structure cooling lines and dust, and X-ray imaging of the hot gas. The cool molecular gas plays an anchoring role in such studies, as the basic fuel for star formation.

High Resolution Imaging of CO 1-0

Figure 1 shows the current state-of-the-art of imaging CO 1-0 molecular gas emission from high redshift main sequence galaxies. The image shows VLA observations of CO 1-0 emission from two massive star forming main-sequence galaxies at $z \sim 2$ (Bolatto et al. 2013), with star formation rates ~ 250 M$_\odot$ year^{-1} and molecular gas masses $\sim 1 \times 10^{11}$ M$_\odot$. While the total CO 1-0 luminosity can be determined, high resolution imaging remains prohibitive with current facilities.

Major improvements in the study of cool molecular gas in early galaxies require a major increase in collecting area in the 10 GHz to 100 GHz range. Currently under design is the Next Generation Very Large Array, with 10x the VLA collecting area, and 10x the VLA resolution, operating between 1 GHz and 115 GHz (Selina et al. 2019; Murphy et al. 2019). We adopt the parameters for the ngVLA as representative of the potential for future large radio arrays in imaging molecular gas in distant galaxies.

Figure 2 shows a simulation of the capabilities of a telescope like the ngVLA for imaging the CO 1-0 in $z \sim 2$ galaxies. The input model is a numerical zoom simulation of a massive main sequence disk galaxy by Narayanan et al (2015, 2018), scaled to be comparable in size and gas mass to the galaxies shown in Fig. 1.

At 0.21" resolution (1.7 kpc), this deep image shows the CO distribution over the full 10 kpc disk of the main galaxy, as well as revealing the brighter filaments and satellite galaxies, with a sensitivity to an intrinsic brightness temperature of 0.4 K. At 0.075" resolution (0.6 kpc), the brighter clumps are delineated, as well as filaments in the inner few kpc of the galaxy, and the brightest emission from satellite galaxies. Scaling the sensitivity to a 10 km s^{-1} channel implies a 2σ mass detection limit for clumps of 3.3×10^8 M$_\odot$.

Figure 1c shows a simulated observation of different transitions of CO emission from a main sequence at $z = 4.5$, using parameters for an array such as the ngVLA for CO 1-0 and 2-1, and ALMA for CO 4-3 (Fig. 3; from Casey et al. 2019). This model is also from the zoom simulations of Narayanan et al., with characteristics comparable to the galaxy in Fig. 2.

Figure 1cd emphasizes a critical point: low and high order CO transitions trace gas of very different densities, and hence can show significantly different spatial structure. The high order transitions trace dense gas ($\geq 10^4$ cm^{-3}), directly associated with star forming clouds on

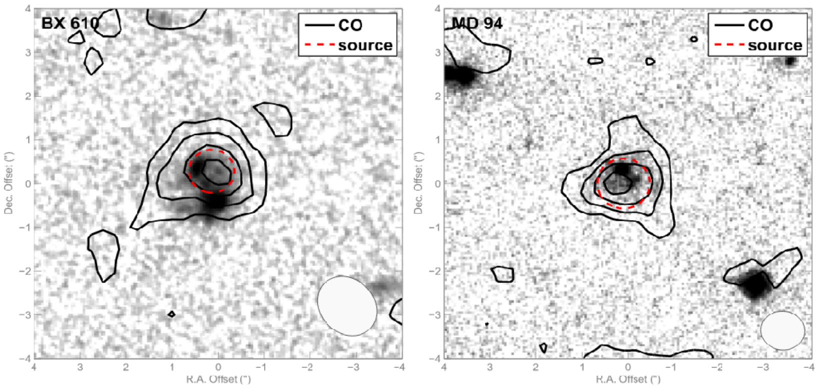

Figure 1: Images of the velocity integrated CO 1-0 emission (contours) for two massive main sequence galaxies at $z \sim 2$, with a resolution of 1", made with a 12hr observation with the VLA, overlayed on the HST images (Bolatto et al. 2013, ApJ, 809, 175).

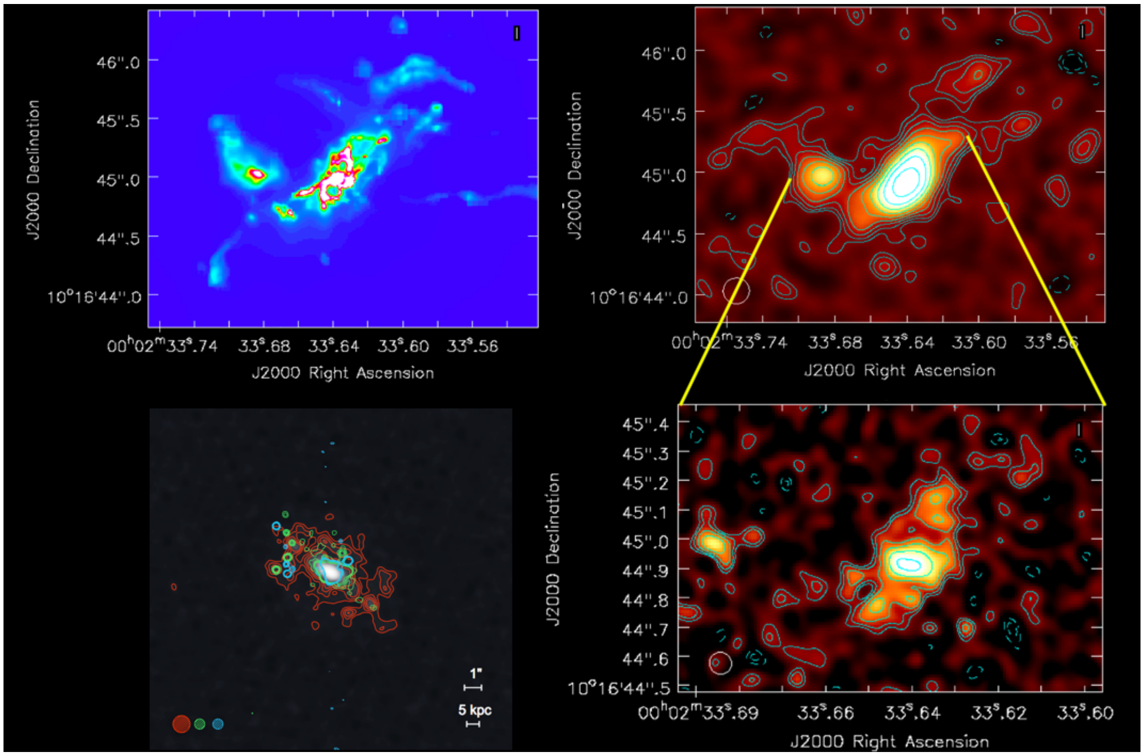

Figure 2: Top left: Input model for the velocity integrated CO 1-0 emission from a massive main sequence galaxy at $z = 2$ (Narayanan et al (2015). Top right: Simulated observation for 12hrs at a resolution of 0.21", with a future large array radio array, such as the next generation VLA, observed at 38 GHz. Contour levels start at $2\sigma = \pm 4.0\mu$Jy beam^{-1}, and increase with factors of square root two. Bottom right: ngVLA simulated observation for 12hrs at a resolution of 0.075". Contour levels start at $2\sigma = \pm 4.2\mu$Jy beam^{-1}, and increase with factors of square root two. Bottom left: Simulated observations of the velocity integrated CO(1-0) emission for a $z = 4.5$, massive main sequence galaxy shown in greyscale and red contours (Casey et al. 2019). The green contours are ngVLA CO(2-1) simulated observations, and blue contours the CO(4-3) emission from an ALMA.

pc-scales. The low order transitions, particularly, CO 1-0, trace lower density envelops (densities of a few hundred to 1000 cm^{-3}), and hence provide a more complete picture of the gas distribution over the disk of the galaxy, and the total fuel available for star formation. Hence, while ALMA can observe high order CO transitions from high redshift galaxies, it obtains a highly biased view of only the densest regions in the galaxies.

Resolved gas dynamics

Extensive efforts have been made to image the dynamics of the molecular gas in distant galaxies over the last decade or more (see Carilli & Walter 2013 for a review). These observations require tens to hundreds of hours per galaxy, even for the most luminous galaxies. The first conclusions are now being made about the shapes of rotation curves based on CO observations, and potentially the dark matter content of early galaxies (see, for example, Ubler et al. 2018; Hodge et al. ; Tacconi et al. 2008). However, imaging of the molecular gas dynamics typically remains limited to resolutions ~ 0.6" to 1", implying only a few resolution elements across the galaxy. We note that near-IR IFU observations have made great strides in imaging the dynamics of the ionized gas in distant galaxies using the Hα line (see Forster-Schreiber et al. 2018; Genzel et al. 2017, and references therein), while ALMA is opening the window of high resolution imaging of the atomic gas through the fine structure lines in very high redshift galaxies ($z > 4$; see de Breuck et al. 2014, A&A, 565, 59, Jones et al. 2017, and references therein).

Fig. 3 shows the capabilities of a large area radio telescope, such as the ngVLA, to image the dynamics of the CO emission from high redshift galaxies. The model in this case is CO 2-1 emission from a $z = 2$ galaxy, with a star formation rate of 25 M$_\odot$ year^{-1} and a molecular gas mass of 2×10^{10} M$_\odot$, substantially below the galaxies in Fig. 1. The underlying gas dynamics was set by the CO dynamics in the well studied nearby galaxy, M51 (Helfer et al. 2003; Schinnerer et al. 2013). Fig. 3 shows the velocity integrated CO emission (moment 0), intensity weighted mean velocity (moment 1), for a 30 hour observation with the ngVLA at 0.2" resolution (Carilli & Shao 2019). Also shown is the rotation curve derived from standard tilted ring model fitting, as well as the underlying velocity field of the model. The major axis position angle, and the sky-plane inclination angle, are determined to within 5% from model fitting, and a good measurement is made of the flat part of the rotation curve out to 7kpc[1]. What will remain difficult is delineating the inner fast rise of the rotation curve on scales ≤ 1 kpc.

For comparison, to obtain a similar observation with ALMA would require 3000 hours of integration time. Hence, existing facilities can detect the integrated CO emission from main sequence galaxies at $z = 2$, imaging at ~ 1 kpc resolution remains prohibitive. A major increase in collecting area is required to trace out both the gas distribution and dynamics on 1 kpc-scales across the disks of high redshift main sequency galaxies.

Summary

There are myriad scientific imperatives for obtaining high resolution (1 kpc or better) images of the low order molecular gas emission from typical star forming galaxies in the early Universe. High resolution CO observations represent a prerequisite for future precision studies of the physical conditions of the ISM in early galaxies. Acting in concert with pan-chromatic observations of other galaxy constituents, such as the stars and ionized gas, the molecular

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[1] Note that beyond 7kpc, M51 is known to have a strong warp in the velocity field (Oikawa & Sofue 2014

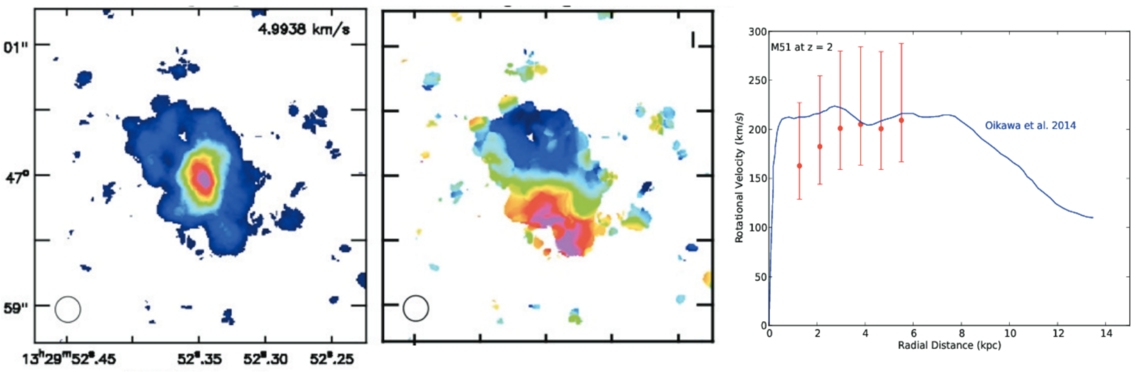

Figure 3: Simulated observation of CO 2-1 from a typical main sequence galaxy at $z = 2$ (gas mass = 2×10^{10} $M_\odot$), at 0.2" resolution, with a future large array radio array, such as the next generation VLA. Left: the velocity integated CO emission. Center: the intensity weighted mean velocity, with a velocity range of ± 80 km s^{-1}. Right: the derived rotation curver using tilted ring fitting (red points), and the input model rotation curve in blue (Carilli & Shao 2018).

observations are required to determine the relationship between molecular gas and star formation, and to determining the dynamics of the cool molecular gas – the gas fueling star formation – in the first galaxies.

Current facilities operating in the 10 GHz to 100 GHz range can detect the integrated CO 1-0 and 2-1 emission from main sequence star forming galaxies at high redshift, and image the gas distribution in the most massive systems at resolutions of a few to 10 kpc. However, to obtain images of main sequence galaxies with ~ 1 kpc resolution, requires a $10\times$ larger collecting area facility, such as the next generation Very Large Array.

References

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