

# Dense Gas History of the Universe: From ASPECS to the ngVLA

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*Abstract* – We review the evolution of the cosmic average molecular gas density to large look-back times, using observations of rotational transitions of CO. Molecular gas is the fuel for star formation in galaxies. Deep searches for CO emission from distant galaxies have delineated the density of molecular gas back to  $z \sim 5$ , or within 1 Gyr of the Big Bang. The results show a rise and fall in the gas density that parallels and likely drives the rise and fall of the cosmic star formation rate density. We present the potential for the next generation Very Large Array to image the distribution and dynamics of the molecular gas in early galaxies and to make a precise measurement of the dense gas history of the universe.

## 1. Introduction

Radio astronomy plays key roles in studies of galaxy formation in the distant universe ( $z > 1$ , or  $t_{univ} < 6$  Gyr) in many ways.<sup>1</sup> As a function of observing frequency, the primary contributions in the past decade include the following

- At frequencies  $< 1$  GHz: Observations of HI 21 emission and absorption, using primarily the Giant Meterwave Radio Telescope<sup>2</sup> and more recently ASKAP<sup>3</sup> and MeerKAT<sup>4</sup> and in the

Manuscript received 27 December 2021.

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<sup>1</sup>This paper is synthesized from an invited review on radio observations of galaxy formation presented at the URSI General Assembly in Rome, 2021.

<sup>2</sup><https://www.gmrt.org>.

<sup>3</sup><https://www.atnf.csiro.au/projects/askap/index.html>.

<sup>4</sup><https://www.sarao.ac.za/gallery/meerkat>.

future the Square Kilometer Array (SKA),<sup>5</sup> determine the extent, temperature, and cosmic mass density of the neutral atomic gas across cosmic times [1].

- At 1 GHz–10 GHz: Observations of thermal Free-Free and nonthermal Synchrotron continuum emission with  $\mu$ Jy sensitivity surveys, using the Jansky Very Large Array (VLA),<sup>6</sup> ASKAP, MeerKat, and, in the future, the next-generation VLA (ngVLA)<sup>7</sup> and SKA, determine dust obscuration-free star formation rates and radio AGN demographics [2–4].
- At 30 GHz–300 GHz: Observations of cool molecular gas via the rotational transitions of CO, using the VLA, the Northern Extended Millimeter Array (NOEMA),<sup>8</sup> the Australia Telescope Compact Array,<sup>9</sup> and the Atacama Large Millimeter Array (ALMA)<sup>10</sup> [5, 6], determine the mass of the dense gas that acts as the immediate fuel for star formation in galaxies.
- At  $> 100$  GHz: Observations of thermal emission from warm dust, with ALMA and NOEMA and single-dish telescopes, reveal the dust-obscured star formation in early galaxies [7, 9].
- At  $> 250$  GHz: Observations of [CII] 158  $\mu$ m and other fine structure lines with ALMA at  $z = 310$  reveal the atomic gas and galaxy dynamics back to the first galaxies in the universe [10, 11].

In this short contribution, we focus on the latest results for the evolution of the molecular gas density, as measured in the 30 GHz–300 GHz range, particularly by ALMA with the ASPECS survey. We then discuss the potential for the ngVLA to advance these studies in the age of high-precision cosmology.

## 2. ASPECS Survey

Molecular gas is the immediate fuel for star formation in galaxies and hence constitutes a key constituent in models of galaxy formation [5, 6]. Only

<sup>5</sup><https://www.skatelescope.org>.

<sup>6</sup><https://science.nrao.edu/facilities/vla>.

<sup>7</sup><https://ngvla.nrao.edu>.

<sup>8</sup><https://www.iram-institute.org/EN/noema-project.php>.

<sup>9</sup><https://www.narrabri.atnf.csiro.au>.

<sup>10</sup><https://www.almaobservatory.org/en/home>.

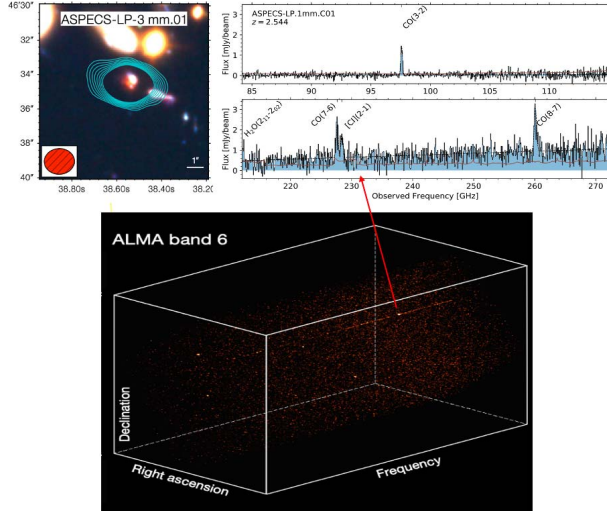


Figure 1. A 3D view of the ASPECS survey (RA, December frequency = distance) in the ALMA 240 GHz bands and an example image and spectra of one galaxy [8, 15, 17]. The bright knots are emission lines, and the broad streak indicates a thermal dust continuum signal.

recently, measurements of the cosmic volume average density of molecular gas have been made through the advent of large, wideband interferometers, such as VLA, ALMA, and NOEMA. While the molecular gas mass is dominated by  $H_2$ , for practical reasons, a primary (although not exclusive) method for tracing molecular gas mass entails observation of the rotational transitions of CO and adoption of calibrated conversion factors [12].

The ALMA Spectroscopic Survey (ASPECS) is the definitive deep blind search for molecular gas via CO emission in the distant universe [13]. The survey covered 5 arcmin<sup>2</sup> in the Hubble Ultra-Deep Field, scanning the full ALMA 90 GHz and 230 GHz bands at  $\sim 1''$  resolution, covering multiple CO transitions down to gas mass limits of a few  $10^9 M_\odot$ , and covering a comoving volume of 42,000 Mpc<sup>3</sup>. Figure 1 shows a three-dimensional view of the ASPECS field (two sky coordinates and frequency = redshift = distance), with an example of a CO detected galaxy [7, 8, 13]. A total of 32 CO emission lines were detected from galaxies at  $z = 0.5$ –3.6.

Properties of this unique galaxy sample selected by molecular gas mass include the following:

- 60% are detected in the dust continuum in the associated deep ALMA image, with star formation rates  $> 10 M_\odot \text{ year}^{-1}$  [7].
- 100% are detected in the deep optical and near-IR images of the UDF [7, 15].
- 70% are “main sequence” disk galaxies, and the rest are compact or irregular [15].
- Metallicities are typically solar or greater [15].
- Chandra X-ray observations imply that 20% of the galaxies host AGN [15].

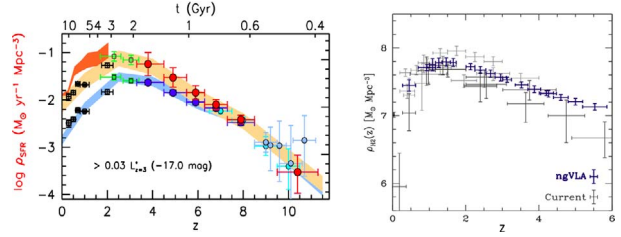


Figure 2. Left: Evolution of the cosmic volume average density of star formation rate [21]. The upper points, highlighted by the orange curve, include a correction for dust obscuration, while the lower blue-highlighted curve does not. Right: Evolution of the cosmic volume average molecular gas density [20, 24, 25, 27]. The black and gray points are current measurements, and the blue points and errors are predictions for the ngVLA deep fields.

- Multiline CO observations imply modest excitation [18].

A key result from ASPECS is the confirmation that the typical ratio of gas mass to stellar mass in massive disk galaxies increases from  $\sim 0.1$  in the nearby universe to  $\geq 1$  at  $z \sim 3$  [16]. Also, the deep 230 GHz continuum image from the survey implies a clear flattening of the source counts below 0.1 mJy, which has important implications for future submillimeter deep fields [19].

The ASPECS survey, along with other deep blind surveys, such as the VLA COLDZ large program [20], and targeted observations of known galaxies [6] have determined the evolution of the cosmic volume average density of molecular gas to within  $\sim 1$  Gyr of the Big Bang, or a look-back time of  $\sim 13$  Gyr. Figure 2 shows a compendium of molecular gas measurements along with the evolution of the cosmic star formation rate density [21]. Both quantities show a rise and fall with cosmic time, peaking in the range  $z \sim 1.5$ –2.5 ( $t_{univ} = 3.3$  Gyr). This peak in the cosmic star formation rate density, during which about half of the stars in the current universe form, has long been known [22, 23] but not fully explained. The parallel rise and fall in the molecular gas density provides strong circumstantial evidence that the evolution of the cosmic star formation rate density is a consequence of the evolution of the molecular gas content of galaxies.

The molecular gas measurements were the last piece in the puzzle of the evolution of the baryonic matter associated with galaxies. A consistent picture is emerging in which galaxies accrete ionized material from the intergalactic medium, which passes through a neutral atomic phase, then builds up as the molecular phase, which then collapses to form stars [25]. The need for gas replenishment to fuel continued star formation in early galaxies was pointed out in the early paper by [26]. The latest measurements confirm this requirement.

Unfortunately, the molecular gas measurements remain limited, with large errors at each redshift, and the ability to perform high-resolution imaging of the gas

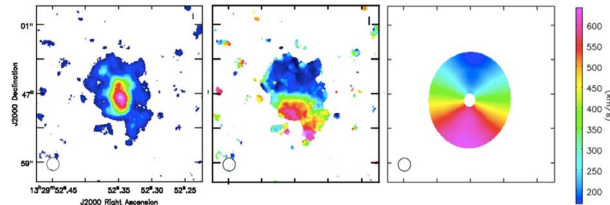


Figure 3. Simulation of an ngVLA observation at 44 GHz of a  $z = 4.2$  massive disk galaxy. Left: Total molecular gas column density; the center is the intensity-weighted mean velocity. Right: Best-fit model of a rotating disk galaxy [32].

in distant galaxies remains prohibitively expensive, even with the largest existing interferometers.

### 3. ngVLA

The ngVLA constitutes an order-of-magnitude increase in collecting area over the current VLA and ALMA, covering the frequency range from  $\sim 1$  GHz to 116 GHz, with baselines from tens of meters to thousands of kilometers [28, 29]. A precise measurement of the dense gas history and high-resolution imaging of molecular gas in distant galaxies are primary science drivers for the ngVLA [31, 32]. In just a few hours of integration, the ngVLA can detect a gas mass of  $\sim 10^9 M_{\odot}$  at  $z \sim 2$ , at a resolution of  $0.15''$ . The wide frequency range of the ngVLA also allows for multi-transition studies of molecular gas excitation, including the low-order transitions, which provide perhaps the best measure of total molecular gas mass [30].

In terms of the cosmic density of molecular gas, Figure 2 shows the capability of the ngVLA versus the best current measurements. The increased bandwidth and sensitivity of the ngVLA will increase the survey speed by almost two orders of magnitude, revealing thousands of galaxies in blind surveys (as opposed to the current tens). The results will provide a precise measurement of the evolution of the molecular mass density [31] to complement future measurements of the cosmic star formation rate density by James Webb Space Telescope and the Extremely Large Telescopes.

For CO imaging, Figure 3 shows a simulation of ngVLA observations (30 hours) of CO 2-1 emission from a massive disk galaxy at  $z = 4.2$  at a resolution of  $0.2''$  (total gas mass  $\sim \text{few} \times 10^{10} M_{\odot}$ ), including velocity-integrated CO emission (column density) and mean velocity. The gas can be easily traced over the 10 kpc disk, and the velocities are well determined. Also shown is a rotating disk model fit to the data, from which a rotational velocity and even a radial profile can be derived, potentially determining the dark matter content of the first galaxies. Such observations are well beyond the capability of existing facilities [32].

Figure 4 shows an ngVLA simulated observation of CO 1-0 emission of a forming massive cluster of galaxies at  $z = 2$ . A recent exciting discovery has been the detection of CO emission on tens to 100 kpc scales in forming clusters of galaxies [33]. The ngVLA has the ability to resolve the molecular gas distribution down to

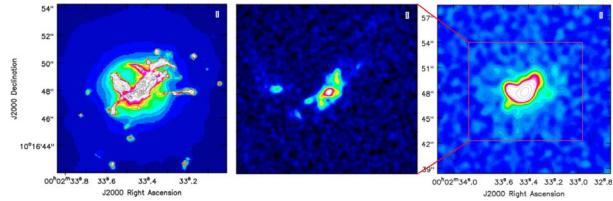


Figure 4. Simulation of an ngVLA observation at 38 GHz of CO 1-0 emission from a  $z = 2$  forming giant galaxy and proto-cluster. Left: The model. Center: Total molecular gas column density at  $0.13'' = 1$  kpc resolution for the simulated observations. Right: Column density at  $1''$  resolution (adapted from [35]).

1 kpc resolution and to delineate the extended CO emission out to  $\sim 100$  kpc [34].

### 4. Discussion: Future Context

We have reviewed the current status of measurements of the evolution of the molecular gas content of galaxies back to within  $\sim 1$  Gyr of the Big Bang and its relationship to the star formation history of the universe. We then present the capabilities of the ngVLA to advance these studies into the next decade to obtain a precise measurement of the dense gas history of the universe. We briefly discuss the broader radio astronomy landscape in the immediate future and beyond.

A number of telescopes arrays are either starting operation or expected to attain first light in the coming 5 years. These include the current operations of the  $\mu$ GMRT, MeerKAT, and ASKAP and the future operation of phase I of the SKA. Regardless of sensitivity, all of these facilities operate at frequencies below 15 GHz. Hence, while they are or will be powerful devices to study the HI 21 cm emission and radio continuum emission from distant galaxies, they will be unable to study the primary rotational molecular transitions, except for CO 1-0 at  $z > 7$ . At such high redshift, this transition is highly suppressed due to depopulation of the lower excitation states by the cosmic microwave background radiation and effectively undetectable. The SKA phase II may eventually go up to 30 GHz, still being limited to only CO 1-0 at high redshift ( $z > 3$ ).

Study of the rotational molecular transitions remains the territory of millimeter telescopes, such as the current NOEMA and ALMA and, toward the end of the decade, the ngVLA. We have shown that, in terms of measuring the total gas masses and imaging of the molecular gas on kpc scales, the ngVLA, with its order-of-magnitude improvement in collecting area, will open unique parameter space critical for advancing our understanding of galaxy formation.

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