

Analyzing the Fuel of Star Formation in the Early Universe

Molecular gas is a fundamental building material for structure in our universe: its properties influence where and how many (and possibly what type of) stars will form, governing how galaxies evolve. Molecular gas is also the building material for chemical reactions: molecules in space are observed to form compounds of increasing complexity, including prebiotic molecules (Hollis et al. 2000), which may then be delivered to forming solar systems. Given observational limits, our best understanding of molecular gas is for the present-day environment of our own Galaxy. However, star formation (and thus likely planet formation, e.g. Howard et al. 2012) peaked around 10 billion years ago (Madau et al. 1998). If, as suggested, star formation at these epochs proceeds differently than star formation in the local universe (e.g., van Dokkum and Conroy 2010), then studying the detailed properties of molecular gas at high redshifts is critical to understanding how and why these processes occurred differently than in the the present-day.

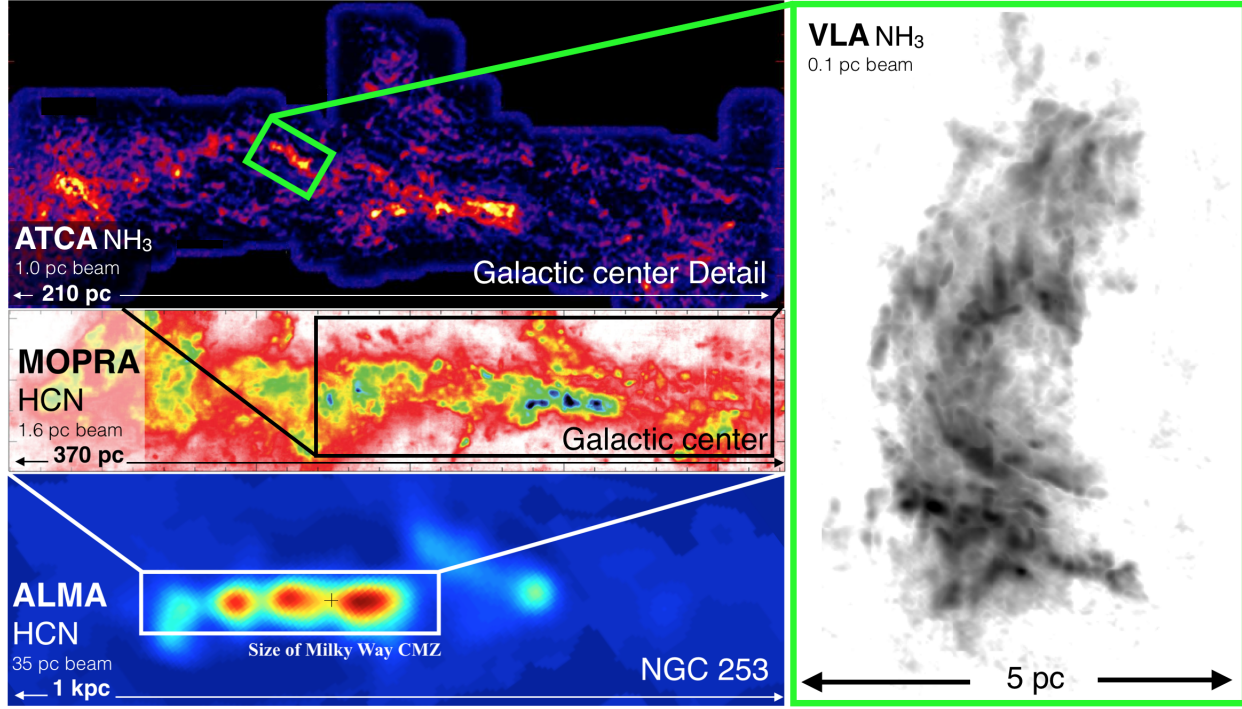
My research focuses on the best local analogue of high redshift systems (e.g., Kruijssen and Longmore 2013): the center of our Galaxy, the proximity of which allows for high-resolution probes of molecular gas properties that will never be possible for distant galaxies. I will use measurements of gas in this region as the first step in a process of comparison with gas in progressively more distant and extreme extragalactic environments, culminating in the first measurements of the variation of gas properties with cosmic time. **My work will provide accurate constraints on the range of chemical and physical conditions present in the molecular gas in the early universe, at the peak of star and planet formation, and galaxy assembly.**

1. The Need to Better Understand Molecular Gas Tracers

As molecular gas tracers are faint, much of our understanding of the gas in other galaxies is based just on observations of only one bright transition of a few common molecules (e.g., HCN 1-0 or CO 1-0 Kennicutt 1998; Gao and Solomon 2004a,b; Lada et al. 2012). However, relying on a single molecular line to trace physical quantities, such as the mass of gas present in a galaxy, can be subject to significant systematic errors due to variations in chemistry (Sandstrom et al. 2013) physical conditions (e.g., Gao and Solomon 2004a; Rosolowsky et al. 2015) or excitation mechanism (e.g., Ziurys and Turner 1986; Sakamoto et al. 2010; Mills et al. 2013). This problem is coming to a head with the advent of the highly sensitive Atacama Large Millimeter Array (ALMA), which is allowing molecular tracers to be used as probes of the more and more extreme environments of the luminous galaxies that are most commonly observed in the distant universe. To continue to employ the efficient approach of using a few bright lines to accurately derive physical conditions in such sources, new studies are necessary to determine whether tracers calibrated for use in the local universe are still valid for gas in the more extreme environments of high- z galaxies (e.g., Swinbank et al. 2011)

2. Testing Molecular Gas Tracers in Extreme Environments

I will conduct the first high-resolution observations of the molecular gas conditions in the extreme environment of extragalactic nuclei and directly compare them to studies of the molecular gas properties in our own Galactic center. Through this comparison I will calibrate the accuracy of individual molecular tracers for determining the molecular gas conditions in the extreme environments of galaxies in the early universe.



Clockwise from bottom left: Meier et al (2015) , Jones et al. (2011) , SWAG Survey (PI: Meier, Mills, Ott), Mills et al. (2015)

Fig. 1.— *Illustration of the steps I will use to calibrate tracers of molecular gas properties in distant galaxies based on those observed locally.* Clockwise from Bottom Left: (1): An ALMA map of the center of NGC 253 with 35 pc resolution, highlighting the current inability to pinpoint the scales on which extragalactic molecular emission occurs and the substructure of the emission. (2): A 1.5 pc resolution map of the Galactic center (GC) over a comparable area, showing the resolution that I will achieve with my ALMA observations of NGC 253 (3): A parsec-scale NH_3 map from the SWAG survey for which I am co-PI, used to measure gas temperatures. (4): VLA NH_3 observations of a GC cloud with 0.1 pc resolution, illustrating the detailed observations of extreme gas that can only be performed in the center of our Galaxy.

I will first use ALMA data to constrain gas temperatures and density in individual GC clouds on sub-parsec size scales which cannot be resolved outside of our Galaxy (Mills et al. 2013; Mills et al. 2014, 2015). I will follow this with comparison to parsec-scale surveys of gas properties that cover the entire Galactic center: for this I will continue to work with a network of European and Australian collaborators (Ginsburg et al. 2015; Ott et al. 2015). Finally, I will directly compare gas properties from these surveys with identical parsec-scale (milliarcsecond) ALMA observations of the nearby starburst galaxy NGC 253 (Leroy et al. 2014; Meier et al. 2015, See Figure 1, left). My observations will determine the range of conditions in some of the most extreme sources in the local universe, identifying the environments in which standard tracers are reliable probes of gas conditions, and alternative tracers for environments where they fail.

Using the molecular tracers calibrated by this work I will be able to accurately trace the quantity, temperature, and density of molecular gas in distant high-redshift systems as a function of cosmic time. This will allow the first comparison of these properties with studies of star formation rate as a function of redshift (e.g., Madau et al. 1998), determining the impact of gas conditions on the formation of stellar systems and the galaxies they make up. **By measuring the properties of the most extreme gas in the local universe, my research will lead to an unprecedented understanding of the relationship between gas conditions and star formation over the history of our universe.**

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