

Connecting Gas Properties from Low to High Redshift

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 the chemical and physical properties 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; Dressing and Charbonneau 2013) peaked around 10 billion years ago, at a redshift of ~ 1.5 , with the peak time for galaxy mass assembly occurring similarly long ago (Madau et al. 1998). If, as suggested, star formation at these epochs proceeds differently than star formation in the local universe (van Dokkum and Conroy 2010; Cappellari et al. 2012), 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 current research focuses on the best local analogue of high redshift systems (e.g, Kruijssen and Longmore 2013): the center of our Galaxy, which at a distance of only 8 kpc allows for detailed and sensitive probes of molecular gas properties that will never be possible at high redshift. My future research will use constraints on the chemical and physical properties of gas in this region as the first step in a process to compare them to gas in progressively more distant and extreme extragalactic environments, culminating in the first measurements of the variation of these properties with cosmic time. **As a professor at San Jose State University I will lead work to 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 Make Better Assumptions about Molecular Gas Excitation

Molecular gas is the fuel for the primary internal processes thought to control the growth and evolution of galaxies: star formation and black hole growth via AGN-related accretion. A full understanding of these processes is then dependent upon understanding molecular gas conditions and their evolution over cosmic time. However, probes of molecular gas outside of our Galaxy are limited by the weakness of molecular spectral lines, making the detection of this gas in extragalactic systems prior to ALMA (the Atacama Large Millimeter Array) a time-intensive process. As a result, much of our understanding of the molecular gas reservoirs in other galaxies, including the widely-used finding that star formation is closely correlated with the amount of (dense) gas in a galaxy, is based just on observations of only one 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).

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. Variations in the gas chemistry can change the relative abundance of a tracer, thus changing the conversion factor between the line brightness and inferred mass by an order of magnitude (Sandstrom et al. 2013). Changes in the temperature or density of the gas that alter the excitation of a molecule will change the relative strengths of its spectral lines (e.g., Gao and Solomon 2004a; Rosolowsky et al. 2015). Excitation

in some cases is not even dominated by the collisional processes sensitive to temperature and density, but can be dominated by the radiation field, if it has the right frequency to excite the molecule (e.g., Ziurys and Turner 1986; Sakamoto et al. 2010; Mills et al. 2013). Thus, even if a single line can be shown to be a reasonable tracer of some physical property, tracers calibrated for one environment— the Galactic disk— may not be more applicable over the suite of conditions that dominate in other galaxies or in the early universe.

The question of the range over which current tracers are reliable is becoming critical as telescopes like ALMA allow for molecular tracers to be used at greater cosmological distances (e.g., at a redshift of 3 in SDP.81 Rybak et al. 2015). These tracers are then being used as probes of the more and more extreme environments of the luminous sources that are most easily observed at large distances (e.g., submillimeter galaxies and ULIRGS). 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 the assumptions that have driven our understanding of the relationship between dense gas and star formation in the local universe are still valid for gas in the more extreme environments of high- z galaxies (e.g., Swinbank et al. 2011)

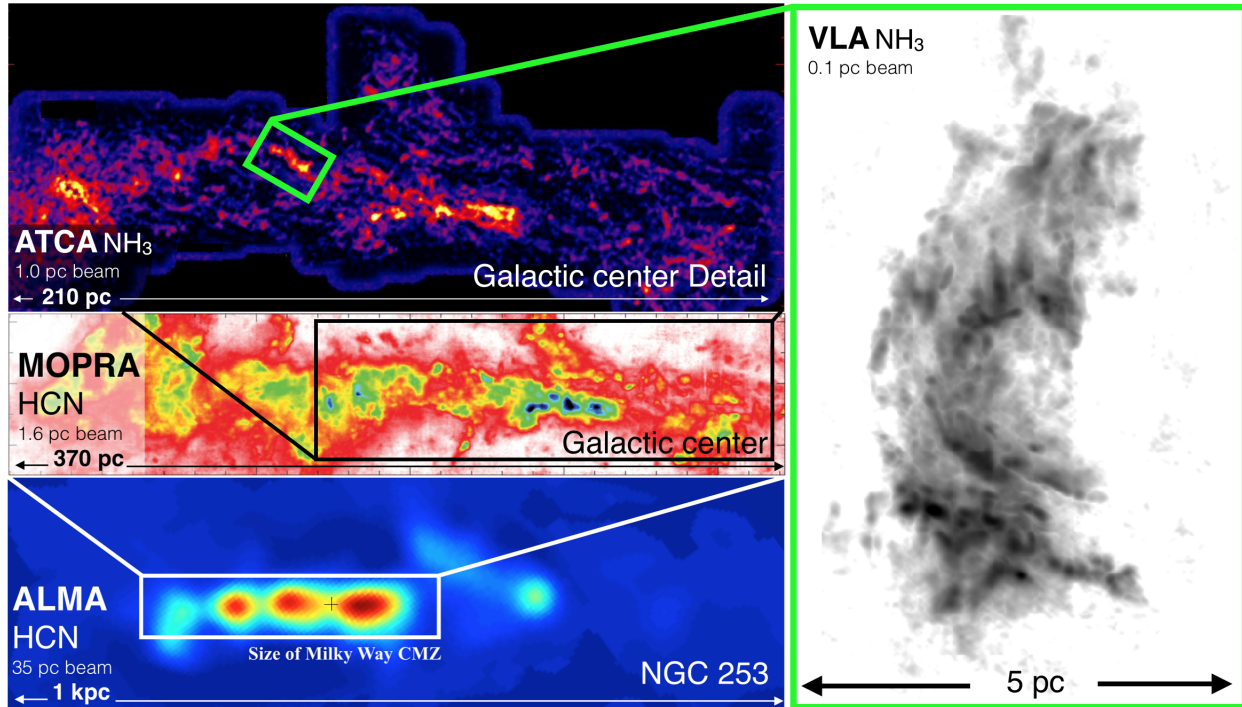


Fig. 1.— *Illustration of the steps I will use to calibrate tracers of molecular gas properties in distant galaxies based on those observed locally.* Clockwise from Bottom Left: (1): An ALMA map of the center of NGC 253 with 35 pc resolution, highlighting the current inability to pinpoint the scales 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 NH₃ map from the SWAG survey for which I am co-PI, used to measure gas temperatures. (4): VLA NH₃ 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.

2. Making Improved Measurements of Gas in Extreme Environments

As a faculty member at San Jose State I will constrain the range of chemical and excitation conditions present in the gas in extreme environments, thus allowing gas properties to be accurately inferred in the early universe. My research will utilize the cutting-edge capabilities of ALMA for efficiently observing multiple lines, including very faint lines that are both necessary to probe excitation, optical depth, and chemistry. In the past, detecting faint lines and the need to resolve local variations in gas conditions has limited a full analysis of excitation and chemistry to only the most nearby regions. This has been difficult to reconcile with a goal of constraining the environments typical of high-redshift galaxies: one is faced with the nearly contradictory need to be able to both make the highest sensitivity and resolution observations possible (typically, in our Galaxy) but also to sample the hottest, densest, and most highly irradiated gas conditions (typically, outside of it).

Luckily, the nucleus of our Galaxy is an excellent laboratory for studying extreme environments for molecular gas, and with ALMA it is now accessible at the resolutions and sensitivities necessary for a full census of the molecular gas conditions. The gas in the central 0.5 kpc of our Galaxy has an order of magnitude higher temperatures, densities and turbulence than in disk (e.g., Güsten et al. 1985; Bally et al. 1987; Mills and Morris 2013), which is suggested to be largely similar to what is known of high redshift galaxies (Kruijssen and Longmore 2013). The Galactic center (GC) is also already proving to be a region where many locally-calibrated observational relationships between the amount of dense gas and star formation are no longer valid (Longmore et al. 2013).

However, an open question is whether the processes that make our GC “extreme” are the same as those which dominate in more active galaxies. Even though the GC is an extreme environment compared to rest of our Galaxy, it is still quiet when compared to many other galaxies just in the local universe. It does not host an AGN, and its star formation rate is orders of magnitude below that seen in the starbursts of other galaxies like M82 and NGC 253. At present the fundamental missing step for accurately extrapolating the conditions inferred locally to those in the more distance universe is a dataset of identically-high-resolution local and extragalactic observations, as illustrated in Figure 1. **At San Jose State I would bridge this gap to conduct the first parsec-scale, multi-frequency observations of the molecular gas excitation in extragalactic nuclei and directly comparing them to studies of the molecular gas excitation in our own Galactic center, one of the most extreme environments in our own Galaxy.**

3. Calibrating Gas Properties Inferred from Excitation

By better characterizing the small-scale chemical and physical conditions of the hottest and densest gas observed in our Galaxy, and systematically comparing them to those measured at comparable resolutions in other galaxies, I will perform the first definitive analysis of the accuracy of individual molecular tracers for determining the molecular gas conditions in the extreme environments of distant galaxies.

I am currently leading studies that include a VLA NH_3 survey of GC clouds at 0.1 pc resolution which are finding deviations from prior lower-resolution results (e.g., Hüttemeister et al. 1993; Ott et al. 2014), illustrating the necessity of high-resolution observations to calibrate the intrinsic gas properties in an extreme environment (Mills et al. 2014, 2015, Mills in prep.). I also have

a large ALMA project to study gas within a few parsecs of the central supermassive black hole in our Galaxy to reassess gas densities inferred in the presence of strong radiation fields (Mills et al. 2013).

Moving forward, I will continue to quantify how accurately these true gas conditions revealed by sub-parsec scale investigation are reflected in properties inferred from the larger-scale surveys of the entire nucleus of our Galaxy. At San Jose State, I will continue to work with a network of European and Australian collaborators to survey the GC at multiple frequencies on parsec size scales, and I will perform the first uniform excitation studies of the molecular gas across the entire GC, measuring of the global variation and trends in molecular gas temperature, density, and turbulence in this environment.

I will directly compare these data with my approved Cycle 3 ALMA observations of the nearby starburst galaxy NGC 253 on subarcsecond size scales (Leroy et al. 2014; Meier et al. 2015, See Figure 1, left), allowing me to make the first analysis of a more extreme extragalactic environment on identical scales and with identical tracers as used in observations of our Galaxy. I will also observe other nearby galaxies amenable to similar study, to determine where the gas conditions are analogous to those in our own Galaxy (e.g., the chemically-rich star forming cloud Sgr B2, or highly-excited gas near our black hole) and where they are entirely dissimilar, e.g., forming globular clusters (e.g., Turner et al. 2003), or deeply buried AGN (e.g., Aalto 2008). My groundbreaking high-resolution observations will determine the range of excitation conditions in some of the most extreme sources in the local universe, identifying the environments in which standard tracers are reliable probes of the physical and chemical conditions in the gas.

The end goal of this work is the identification of molecular tracers that do not suffer from inaccuracy in tracing the chemical and physical conditions present in the molecular gas in extreme environments. These tracers will allow astronomers, with as few observations as possible, to constrain the molecular gas conditions in galaxies spanning a significant range of ages. For the first time studies of star formation rate as a function of redshift (e.g., Madau et al. 1998) can be compared to the gas conditions in the same eras: tracing the quantity, temperature, and density of molecular gas in these systems as a function of cosmic time, and determining their impact on the formation of stellar systems and the galaxies they make up. **By measuring the chemical and excitation properties of the most extreme gas in the local universe, the research I will do as a professor at San Jose State University will lead to an unprecedented understanding of the relationship between gas conditions and star formation over the history of our universe.**

Synergy with San Jose State Astronomers

As a professor at San Jose State I will complement the research interests of the department in the chemistry of interstellar medium while also significantly expanding the research expertise of the department in molecular gas and star formation over cosmic time. The focus of my research on gas conditions in the centers of galaxies is highly synergistic with ongoing research of Professor Michael Kaufman. At San Jose State I will lead research into the molecular gas conditions from the local ISM to high-redshift galaxies and will continue to PI successful proposals using ALMA. As one of few astronomers with more than 90 hours of ALMA time, I have a demonstrated ability to give students at San Jose State experience working with data from this world-class facility, giving them a unique and marketable expertise for their future careers. I will also further my collaboration with researchers at the Scientific Computing and Imaging (SCI) Institute at the

University of Utah to visualize the complex spectral line data cubes currently being generated by telescopes like ALMA and to address current computational challenges in big data analysis and visualization in radio and submillimeter astronomy.

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