5. Star Formation and the Interstellar Medium in the Milky Way

The matter and energy between the stars, the interstellar medium (ISM), is vitally important to the evolution of galaxies, since it is in this environment that stars are formed, and to this environment that both young and aging stars return matter enriched in the heavy elements that are essential for the formation of planets and the evolution of life.

5.1 Processes of Star Formation

Stars form within the dense, localized regions of giant molecular clouds (GMCs) within galaxies. While millimeter-wave studies of galaxies define the distribution of GMCs and large-scale processes that regulate star formation (see Chapter 4), high spatial resolution measurements are required to describe the relevant dynamics within the molecular clouds that set the initial conditions for protostellar evolution. Such resolution is only achieved by observations of star-forming regions within our own Milky Way Galaxy. The LMT offers a near complete set of instrumentation to investigate the many scales and processes related to star formation in molecular clouds. The capability of the LMT to rapidly image both molecular line and thermal dust continuum emission provides astronomers with powerful tools to study the global cloud dynamics, the development of massive cores and pre-protostellar condensations from the low density substrate, the gravitational collapse of material onto the central object and circumstellar disk, and the protostellar wind phenomenon. The low geographic latitude of the LMT site is also an advantage, offering an excellent view of the Milky Way. This opportune location enables studies of more distant star-forming regions within the molecular ring of the Galaxy and the Galactic Center region, where the interstellar gas conditions are more extreme that than those found in the solar neighborhood.

Accurate descriptions of the dynamics of molecular clouds are essential to our understanding of the star formation process. The dynamics of a cloud plays a pivotal role in setting the time interval over which the cloud can produce stars and the mode (clustered or distributed) in which stars are generated. A high-resolution view of a nearby molecular cloud (Figure 5.2) reveals a web of filaments, shells, and high density cores that attest to a complex dynamical state. The observed complexity is produced by expanding motions from HII regions and stellar winds, and the interplay between magneto-turbulent pressures and the self-gravity of the cloud. Determining the relative roles of the magnetic field, turbulence, and wind-driven shocks is a central goal of molecular cloud studies and the subject of a spirited debate amongst theorists within the astronomical community.

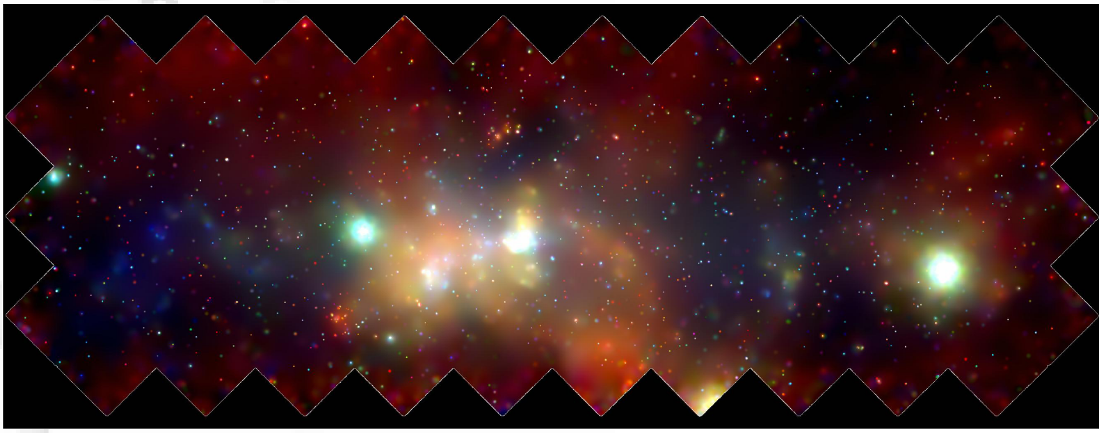


Figure 5.1 The center of our Milky Way Galaxy as imaged in X-rays with the Chandra satellite observatory by UMass Amherst astronomer D. Wang and colleagues[1]; colors indicate the energy of the X-rays, from red (low) to blue (high). This region is rich in molecular gas, including most of the known interstellar molecules.

The LMT is poised to resolve this debate with observations that set meaningful constraints to theoretical descriptions of the molecular ISM and star formation. Wide-field imaging of molecular line emission will provide a wealth of dynamical information beyond the capabilities of current mm-wave single dish telescopes and interferometers, since both small- and large-scale structure of the cloud will be recovered by the LMT. The spatial variations of velocity and column density are fossil records of the dynamics

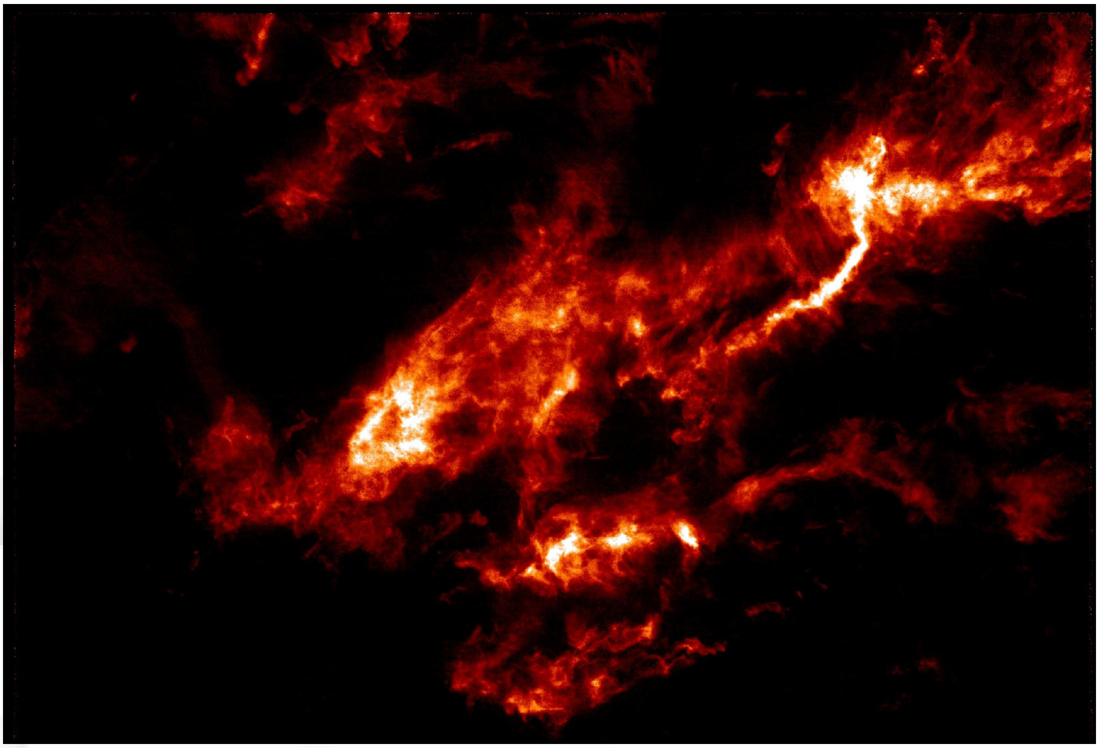
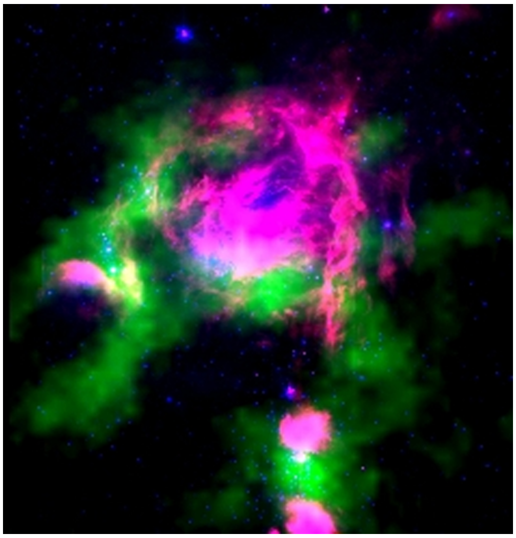


Figure 5.2 An image[2] of ^{13}CO $J = 1\text{-}0$ emission from the Taurus Molecular Cloud, a nearby star-forming region observed with the FCRAO 14 m telescope and the SEQUOIA receiver system (Section 8.3.1). The LMT can image similar but more distant star-forming systems to sample a broader range of interstellar environments.

that can be compared to model predictions of cloud structure. Moreover, with the dual polarization of the LMT heterodyne systems one can detect and image the Zeeman Effect in molecular clouds to examine the spatial variations of the magnetic field.

Figure 5.3 The Sharpless 235 star-forming region imaged with the Spitzer Space Telescope[3]. The blue image shows background and embedded stars and the red image reveals emission from polycyclic aromatic hydrocarbons excited by the UV radiation of the massive stars. The green image shows the distribution of ^{13}CO $J = 1\text{-}0$ emission from a selected region of the extended giant molecular cloud as observed with the FCRAO 14 m telescope[2].



Two distinct modes of star formation have been identified in molecular clouds. Distributed star formation occurs within small (0.1 pc), low mass (1-10 times the mass of the Sun), dense (10,000 molecules per cm^3), isolated cores that typically form a single star with low to moderate mass. The Taurus molecular cloud (Figure 5.2) is the prototypical example, and much of the observational and theoretical efforts to understand star formation have been focused on this basic mode. However, most stars within the Galaxy emerge from sites of clustered star formation that are less well understood or defined. The dense regions from which newborn stellar clusters emerge are larger (0.5-1pc), more massive (1,000 to 10,000 times the solar mass), denser (1 million molecules per cm^3), and more inhomogeneous than the core counterparts associated with distributed star-forming regions. Such regions have the capacity to produce 100 to 1,000 stars and are almost the only sites of massive star formation. These massive cores are bright both in spectral line and thermal dust continuum emission and are often associated with compact or evolved HII regions. However, there are few nearby examples that would provide insights into their origins within giant molecular clouds and the complex interactions that must occur between embedded protostellar objects.

The LMT will produce definitive descriptions of massive cores in the interstellar medium of the Milky Way. Mapping of the thermal dust continuum emission with the AzTEC and SPEED bolometer arrays will reveal the column density distribution of material and identify protostellar objects within the massive cores, complementing the mid-infrared measurements from the Spitzer Space Telescope. The local dynamics and chemistry of the massive core will be determined by imaging of spectral line emission that directly traces the dense gas. Such complementary measurements will define the coupling of the dynamics to the protostellar condensation.

The actual formation of a star results from the gravitational collapse of a dense parcel of gas within a molecular cloud. A study of protostars provides knowledge of the physics and initial conditions required for star formation, protostellar evolution, and the formation of solar systems like our own. In the earliest phases of star formation, protostellar objects are highly obscured in a cocoon of dust and gas, and hence, are not observable with optical or infrared telescopes. However, mm-wave observations can penetrate the dust and provide spectral evidence for infall motions in protostellar regions. Such measurements have placed important constraints on the infall velocity, angular momentum, and density profile of a protostellar core. However, the sensitivity of current systems limits one to the latest stages of protostellar collapse, when the infall radius is large and the velocities small. The larger collecting area of the LMT will enable astronomers to study the properties of protostellar collapse at earlier stages. Moreover, the resolution and imaging capability of the LMT can more readily distinguish motions associated with infall from the rotation and outflowing motions that may also be present.

The gas and dust disks around protostars, within which planets form, are discussed in Section 6.3.

5.2 Astrochemistry

Molecular clouds are the largest objects in the universe whose composition is subject to chemical bonding. Interstellar chemistry is thus scientifically important both in its own right, and in its application to astrophysical problems such as star formation, where the dynamical coupling to magnetic fields through the abundance of molecular ions and the cooling of clouds by trace molecular constituents are critically important. In addition, the low temperatures (often < 10 K) and densities make these clouds interesting laboratories where the spectra and structure of a number of molecular species have been studied before this was possible in the laboratory[5]. Finally, since interstellar organic molecules may well be incorporated into comets and hence brought to the early Earth, it is at least conceivable that such exogenous material may have played some role in the origin of life[6].

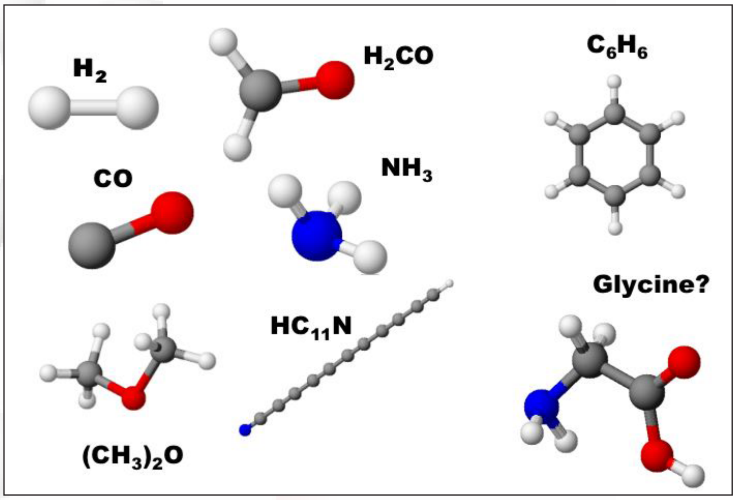


Figure 5.4 Some of the approximately 130 known interstellar and circumstellar molecules; the detection of the simplest amino acid, glycine, has been controversial and will be the subject of investigations with the LMT (white-hydrogen; grey-carbon; red-oxygen; blue-nitrogen)[4].

Although much is known about the chemistry of dense interstellar clouds, much also remains uncertain, as a result of the variety of different processes which may be important, including reactions in the gas phase, processes on grains, and the effects of radiation fields and cosmic rays. Absolute abundances are difficult to determine as a function of physical conditions; such conditions vary significantly among and within different environments; reaction rates and branching ratios in the gas phase may not be known at relevant temperatures; the nature of grain surfaces and hence processes on and in grains are poorly constrained; and the interchange of material between solid and gas phases is not well understood. Thus, the constraints on models supplied by the determination of the abundances of molecules under differing physical conditions and the identification of new molecular species remain very important. The increased sensitivity of infrared detectors and the necessity of such measurements for non-polar species and for solid-state features are increasing the importance of infrared observations of vibrational spectra for interstellar chemistry. Nonetheless, the great bulk of the relevant data come from heterodyne observations of rotational spectra at mm and sub-mm wavelengths. The high sensitivity, angular resolution, and mapping speed of the LMT will enable detailed investigations of the chemistry of interstellar molecular clouds, protoplanetary disks, and comets (Section 6.1.1).

The exceptional mapping speed of the LMT will allow detailed comparisons of the chemical content of a variety of molecular clouds in differing stages of evolution and with differing physical conditions and environments. Likewise, the high spectral resolution and sensitivity available with the LMT will produce data on isotopic fractionation and its dependence on cloud physical parameters and evolution. Together such new results will address such fundamental questions as the relative importance of purely gas phase versus grain surface synthesis of complex molecules in the ISM, and the relation between interstellar molecules, the chemistry of primitive solar system bodies such as comets, the delivery of organic molecules to the early Earth from space, and the role of such molecules in the origin of life.

5.3 Stellar Mass Loss: How Evolved Stars Return Mass to the Galaxy

As stars expand and ascend the Red Giant Branch, their surface gravity plummets, allowing copious stellar winds to return matter to the interstellar medium. This recycled gas is rich in the heavy elements required for life and provides key molecular tracers for density, temperature, and abundances throughout the interstellar medium. Estimates of mass loss rates and physical conditions in envelopes of evolved stars provide critical input to our understanding of stellar evolution and also to galactic structure as influenced by star formation. In molecularly rich stellar environments, compact and bright maser emission in a number of molecular species and transitions can be used to study gas dynamics and physical conditions on size scales much smaller than the stellar photosphere. High resolution 43 GHz VLBI movies of SiO (J = 1-0) maser emission surrounding the Mira variable TXCam show simultaneous infall and outflow of gas driven by stellar pulsations, with clear deviations from spherical symmetry[7]. Such VLBI results are vital elements in improving our understanding of the mass loss process, but typically observations of multiple maser transitions are required to determine physical conditions throughout the circumstellar envelope. The LMT provides a unique opportunity to expand the frequency range over which VLBI maser observations can be made. When coupled with the VLBA, the LMT will create an ultra-sensitive spectral line VLBI array near 86 GHz covering the SiO J=2-1 maser line. At higher frequencies, baselines from the LMT to other mm sites can be used to map maser transitions in the 86-230 GHz range from molecular species including water, methanol, HCN and SiO. Exploration of these transitions with VLBI will open a new window on gas dynamics, conditions, and abundances around this important class of stars.

5.4 References

1. Credit: Prof. Q. Daniel Wang, UMass Amherst.

2. Credit: M. Heyer, FCRAO, UMass Amherst.

3. Hora, J. L. et al. (2004), "The Role of Photodissociation Regions in Massive Star Formation," Amer. Ast. Soc. Meeting 204, #41.12.

4. Credit: P. Ehrenfreund, University of Leiden.

5. Bell, M.B. et al. (1987), "Deuterium Hyperfine Structure in Interstellar C_3HD," *Chem. Phys. Lett., 136*, 588.

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7. Diamond, P. & Kemball, A. (2003), "A Movie of a Star: Multiepoch Very Long Baseline Array Imaging of the SiO Masers toward the Mira Variable TX Cam," *Astrophys. J., 599*, 1372.