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THE ROLE OF THE GRAN TELESCOPIO MILIMÉTRICO IN STUDIES OF STAR FORMATION

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RESUMEN

El Gran Telescopio Milimétrico (*GTM*) es un nuevo telescopio desarrollado por las comunidades astronómicas internacionales mexicana y norteamericana, para investigar el universo milimétrico. El gran tamaño de su apertura y la instrumentación científica con la que cuenta ofrece una excepcional capacidad para dilucidar algunas de las cuestiones más fundamentales asociadas a la producción de estrellas muy jóvenes en el medio magneto-turbulento interestelar.

ABSTRACT

The Gran Telescopio Milimétrico (*GTM*) is a new facility for the Mexican, U.S., and international astronomical communities to investigate the millimeter universe. The aperture size and science instrumentation offer unprecedented capabilities to study the star formation process in the Milky Way and nearby galaxies. In this review, I will describe these capabilities and how these can address some of the most fundamental questions associated with the production of newborn stars from the magneto-turbulent interstellar medium.

Key Words: ISM: clouds — stars: formation

1. INTRODUCTION

The transformation of interstellar gas into stars plays a key role throughout astrophysics – from the formation of the Solar System and extra-solar planets to the structure and evolution of galaxies. As a sensitive probe of the dense, molecular, star-forming phase of the interstellar medium in galaxies, spectral line and continuum emission at millimeter wavelengths provide critical information that guide and constrain descriptions of the star formation process. Since the initial detection of the CO line at 2.6mm by Wilson et al. (1970), ever more capable detectors and telescopes have been constructed that can now measure signatures of star formation in the distant universe (Hughes et al. 1998; Austermann et al. 2009; Scott et al. 2008) as well as circumnuclear disks about newborn stars (Andrews & Williams 2007).

The Gran Telescopio Milimétrico is a powerful new facility to carry out measurements of the millimeter sky and investigations of star formation. It is a 50 meter telescope located at the 4600 meter summit of Sierra Negra in the state of Puebla, Mexico. Its design includes an active surface to account for deformations caused by gravity and thermal effects to enable precise measurements within the millimeter band with angular resolutions of 5–15″. Radiometric conditions at the site are excellent over the year as demonstrated by 225 GHz opacity measurements gathered between 1999 and 2007 (see Figure 1). The water opacity is sufficiently low to allow 3mm observations throughout the year and 1mm observations from November through March.

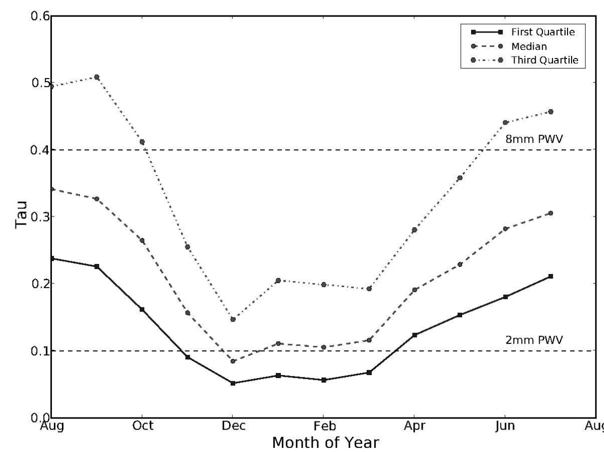

Fig. 1. Variation of water opacity over the course of the year at the Sierra Negra site based on 225 GHz measurements taken between 1997 and 2007.

The initial set of science instrumentation is a powerful complement to the collecting area and high resolution afforded by the 50 meter aperture of the *GTM*. These emphasize imaging of low surface brightness emission as afforded by a filled aperture and point source sensitivity owing to the collect-

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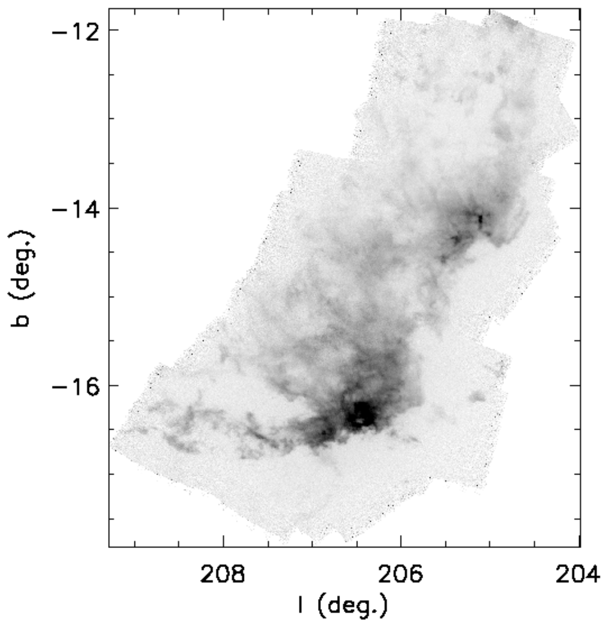

Fig. 2. Image of CO J=1-0 emission from the Orion B molecular cloud taken with *SEQUOIA* on the FCRAO 14 meter telescope.

ing area. Several of these instruments have been completed and have carried out science programs on other telescopes.

SEQUOIA is a 32 pixel heterodyne focal plane array covering frequencies 85.3–115.3 GHz. It had been deployed on the FCRAO 14 m telescope between 1998 and 2006 as a key instrument in critical surveys of molecular line emission along the Galactic Plane (Jackson et al. 2006), individual molecular clouds (Heyer et al. 2006; Ridge et al. 2006; Goldsmith et al. 2008; Narayanan et al. 2008), and nearby galaxies (Heyer et al. 2004). Figure 2 shows an example of wide field imaging of ^{12}CO J=1-0 emission from the Orion B molecular cloud that locates the star forming sites while also revealing the intricate texture of the molecular gas distribution in the low column density envelope. *SEQUOIA* and the other heterodyne instruments are supported by an array of digital autocorrelation spectrometers that provide bandwidths up to 800 MHz to cover the full velocity range expected for galaxies while offering modes with high spectral resolution over narrower bandwidths with multiple I.F.s to study the chemistry and kinematics of cold, dense molecular cores.

AzTEC is a 144 element bolometer focal plane array to image the thermal dust continuum emission from interstellar dust or the Sunyaev-Zeldovich Effect. It has had successful runs on the *James Clerk Maxwell Telescope* in Hawaii and the *Atacama Submillimeter Telescope Experiment* in Chile to investigate the population of submillimeter galaxies, nearby galaxies, and Galactic star forming regions.

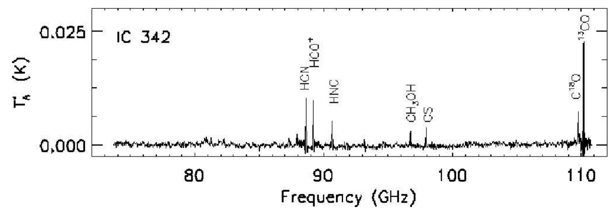

Fig. 3. 3mm spectrum of IC 342 taken with the *Redshift Search Receiver* on the FCRAO 14 m telescope.

The *Redshift Search Receiver* is a unique, wideband, heterodyne, 2 pixel, dual polarization frontend simultaneously covering frequencies 74–110 GHz. The backend is comprised of analog autocorrelation spectrometers that process the 4×36 GHz bandwidth output. A key feature of the *Redshift Search Receiver* is a rapid polarization switching system that provides excellent baseline stability. Such stability enables high sensitivity measurements to determine spectroscopic redshifts of galaxies from one or more molecular or atomic lines that are shifted into the band. Figure 3 shows the 3mm spectrum of the nearby galaxy IC 342 taken with the *Redshift Search Receiver* on the FCRAO 14 m telescope in Spring 2008.

The development of two additional instruments (*SPEED*, a 4 pixel, 4 band bolometer array, and a 1mm dual, polarization, single pixel heterodyne receiver) has been delayed owing to limited funding. However, conceptual designs are already in place for the next generation of instruments to exploit the advances in technology while addressing critical scientific requirements of future programs. These include a 10^4 pixel bolometer camera and a 16 element, dual polarization heterodyne array for the 1mm band. The next set of instruments will further augment the mapping speed to enable experiments and investigations not currently possible. Both the initial and future sets of instrumentation will keep the LMT scientifically competitive even within the era of the *Atacama Millimeter Array* (ALMA) in Chile, while also providing a valuable complement to ALMA capabilities.

2. STUDIES OF STAR FORMATION

The value of the millimeter band in studies of galaxy formation and evolution has only been recognized over the last 15 years (Solomon & vanden Bout 2005). The millimeter/submillimeter population of galaxies are stunning examples of intense star formation activity (rates $10^2 - 10^3\ M_\odot\ \mathrm{yr}^{-1}$) that generates copious amounts of rest-frame far infrared radiation from UV-heated dust grains. For distant galaxies (z > 2), this far infrared radiation is redshifted into the millimeter and submillimeter bands. Spectroscopic redshifts derived from millimeter and submillimeter molecular and atomic lines can link a submillimeter continuum source to a galaxy identified from optical/infrared imaging and spectroscopy. For galaxies with high extinctions, as might be expected for systems with large star formation rates, millimeter spectroscopy may be the only means to determine the redshift. With its collecting area and imaging and spectral instrumentation, the *GTM* is equipped to make fundamental contributions to this emerging field.

While *GTM* observations of galaxies at high redshift offer an exciting opportunity, studies of star formation in the Milky Way and nearby (< 20 Mpc) galaxies are also a necessary step in the development of accurate descriptions of galaxy evolution. The spatial resolution afforded by nearby systems allow one to investigate the physical processes that affect the production of newborn stars. While such production may be quite different in the early universe owing to lower metallicities, the two epochs share common questions. What processes regulate the yield of newborn stars in galaxies? What processes define the mass distribution of newborn stars? Answers to these questions in the local universe provide physical context to systems where the star formation is not resolved.

Star formation is a process that occurs within molecular clouds while affected over kpc scales within galaxies. There are two critical rate-limiting steps in this process:

- *formation of GMCs from the diffuse, atomic medium*

The transition to the molecular gas phase is critical as the efficient cooling provided by molecular line radiation allows for the development of dense, cool configurations of the gas. This is a large scale, top-down process involving thermal, gravitational, and possibly magneto-rotational instabilities as the gas responds to large scale dynamics and perturbations (spiral density waves, bar potentials, expanding supernova remnants (Balbus 1988; Kim et al. 2002; Mac Low et al. 2005). Such large scale processes are also responsible for injecting energy into interstellar clouds that drives the supersonic motions.

- *formation of gravitationally unstable protostellar cores*

Only a small fraction of the mass of a GMC is converted into stars. The stars ultimately condense from localized, high density regions with insufficient internal pressure to support against self-gravity. Many studies have consistently found that the Core Mass Function (CMF) has a similar shape but larger amplitude than the Initial Mass Function (IMF) (Motte et al. 1998; Testi & Sargent 1998; Johnstone & Bally 2006; Enoch et al. 2007). These results suggest the efficiency of converting a core mass to a star is constant for all masses. More significantly, these imply that the stellar mass, and ultimately, the IMF, are defined by the top-down processes within a cloud that are responsible for configuring the protostellar cores.

The competing theories of star formation and cloud evolution assign very different gas dynamics to the low density substrate of clouds and the role these dynamics play in the formation of protostellar cores. In one view, molecular clouds are supported against self-gravity by the interstellar magnetic field (Mouschovias 1976; Shu, Adams, & Lizano 1987; Adams & Shu 2007). Star formation is ultimately regulated by the rate of ambipolar diffusion that generates magnetically supercritical cores susceptible to gravitational collapse. In contrast, turbulent fragmentation poses that molecular clouds rapidly evolve due to super-Alfvenic turbulence. Star forming cores within the cloud result from the inevitable shocks that compress localized parcels of gas that decouple from the overlying turbulent flow (Padoan & Nordlund 2002; Mac Low & Klessen 2004; Krumholz & McKee 2005). The star formation activity is related to the properties of the turbulent velocity field of the low density substrate. These properties include the turbulent driving scale (Klessen, Heitsch, & Mac Low 2000), the sonic scale (Vazquez-Semadeni, Ballesteros-Paredes, & Klessen 2003), and Mach number (Mac Low & Klessen 2004; Nakamura & Li 2005).

To distinguish these descriptions with observations requires a census of protostellar and protocluster cores and measurements of the gas dynamics in both the low and high density regimes of molecular clouds. Does the star formation efficiency and core mass function with molecular clouds depend on the turbulent flow properties or the magnetic state of the cloud?

With its imaging instrumentation and sensitivity to both point sources and extended emission, the *GTM* will play a major role in studies of star formation. As described in more detail in the following sections, spectral line imaging of molecular line emission with *SEQUOIA* and *AzTEC* imaging of thermal dust continuum emission from star forming regions offers a powerful combination to compile the necessary information to evaluate and define descriptions of star formation. Future continuum and heterodyne instrumentation will further enhance these capabilities.

2.1. *Dynamics of Molecular Clouds*

Descriptions of the gas dynamics within the molecular interstellar medium are central to the understanding of star formation and the broader galactic environment. Are molecular clouds supported against self-gravity? If so, is such support provided by the interstellar magnetic field or turbulent pressure?

For turbulent fragmentation, two spatial scales have been proposed as key parameters to regulate star formation in molecular clouds (Krumholz & McKee 2005). The Jeans' Length,

$$\lambda_{J0} = (\pi k T/\mu m_H G \rho_\circ)^{1/2} \, ,$$

sets the scale for which gravity is important relative to thermal pressure. The sonic scale, λ_S, is the scale at which velocity fluctuations due to turbulence are equal to the sound speed. Below the sonic scale, non-thermal motions are subsonic and do not shock to produce density compressions that ultimately develop into protostellar cores. It depends on the kinetic temperature, T, the spectral index, γ, and amplitude, $v_\circ$, of the velocity structure function,

$$\lambda_S = (kT/v_\circ^2 \mu m_{H_2})^{1/2\gamma} \, .$$

Krumholz & McKee (2005) define a critical overdensity, $x_{\mathrm{crit}} = (\lambda_{J0}/\lambda_S)^2$ that tunes the formation rate of gravitationally unstable cores with a dependence on the Mach number (see Figure 4).

Wide field, spectroscopic imaging data of rotational lines of the ^{12}CO and ^{13}CO offer critical information to these key dynamical properties of molecular clouds. The cloud Jeans' length requires the cloud temperature and density. The kinetic temperature is derived from the observed ^{12}CO brightness temperature assuming the line is optically thick and thermalized. The mean density of the cloud, $\rho_\circ$, is estimated from the mass and dimensions of the cloud as determined from the optically thin ^{13}CO line. Furthermore, the spectral information resident within these data cubes can be leveraged by various methods to derive the power law parameters of the velocity structure function, $v_\circ, \gamma$ to determine the sonic scale, λ_S (Brunt & Heyer 2002a,b; Brunt et al. 2003; Heyer et al. 2006; Ossenkopf et al. 2006). If the sonic scale is not resolved by the observations, one must rely on an extrapolation of the structure function to smaller spatial scales that assumes no variations in its functional form. A more reliable and preferred estimate of these scales requires that these be fully resolved. Figure 5 shows the Galactic coverage of the *GTM* at 3mm for which these scales are resolved for typical cloud conditions, λ_{J0}=0.7 pc and λ_S=0.1 pc. The *GTM* can readily resolve the Jeans' Length beyond the Galactic Center at 3mm and throughout the Milky Way at 1mm. The sonic scale is resolved out to the Scutum-Crux spiral arm at 3mm with the *GTM*. This range allows one to sample a fairly broad range of environments within the Galaxy that may further impact the structure of clouds.

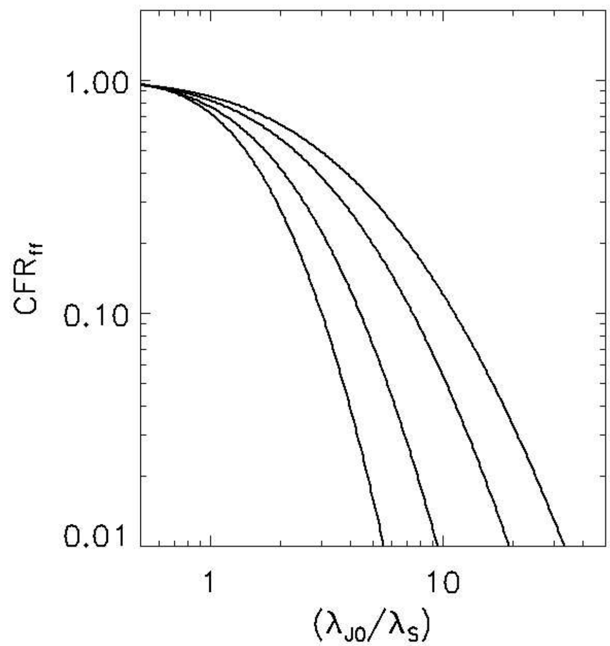

Fig. 4. The variation of the formation rate of gravitationally unstable cores over a free-fall time with λ_{J0}/λ_S for Mach numbers 2, 3.2, 6, 10 (bottom to top) as predicted by Krumholz & McKee (2005). The *GTM* can directly assess this model, and others, with its continuum and spectral line imaging capabilities at millimeter wavelengths.

Measurements of the interstellar magnetic field in molecular clouds have long posed a challenge to observers yet, establishing the role of the field, or lack thereof, is a fundamental goal to describe the molecular ISM and star formation (Heiles & Crutcher 2005). Zeeman observations of the OH 1667 MHz doublet line have been used as a direct tracer of

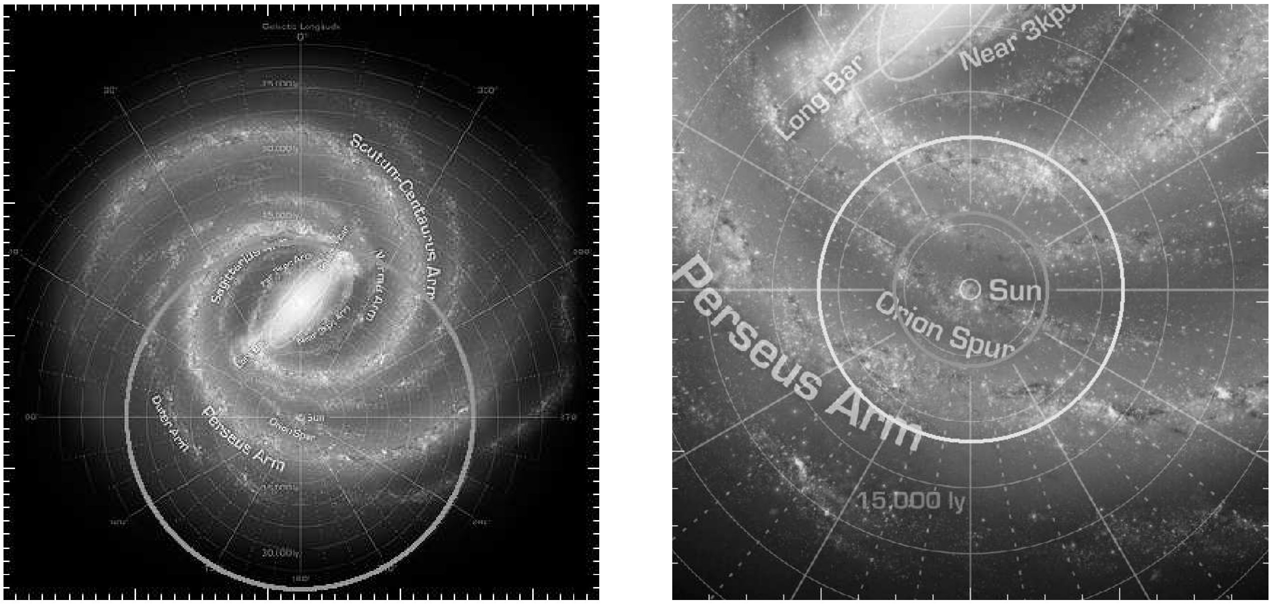

Fig. 5. The radial extent (circle centered on the Sun) at which the *GTM* at 3mm wavelength can resolve a Jeans' Length equal to 0.7 pc (left) and sonic scale of 0.1 pc (right) with respect to major features in the Galaxy. The overlay is an annotated image of the Milky Way produced by JPL/NASA.

the field strength within the low to moderate density regime (10^3-10^4 cm^{-3}) of molecular clouds (Troland & Crutcher 2008). At millimeter wavelengths, the CN hyperfine lines at a frequency of 113 GHz offer a tool to probe the field strength at higher densities ($\sim 10^5$ cm^{-3}) (see Crutcher et al. 1999; Falgarone et al. 2008). With its rapid polarization switching system, the *Redshift Search Receiver* could be a unique polarimeter system, but at present, it's bandwidth does not cover these frequencies. However, given a demand for such Zeeman measurements of the CN line, the design of the *Redshift Search Receiver* could be applied to the development of a customized polarization instrument at 113 GHz.

While providing a direct measure of the magnetic field strength, Zeeman measurements are operationally expensive owing to the required time to make a detection or to set meaningful upper limits. With current instruments, it is simply not possible to image the magnetic field strength with Zeeman measurements over the projected area of a single molecular cloud or many star forming regions that are necessary to derive general conclusions of the role of the magnetic field. Despite valiant efforts by several research groups, the role of the magnetic field in interstellar clouds remains observationally undefined.

There are several indirect measures of the field strength in interstellar clouds that rely on predicted behavior of the magnetic field under the assumption that the neutral and ion gas components are well coupled. Chandrasekhar & Fermi (1953) assumed that any variation of the polarization direction of background stars is due to the propagation of Alfvén waves through the cloud that distorts the magnetic field geometry. The magnetic field strength can then be estimated from the dispersion of measured polarization angles, the velocity dispersion of the gas, and the mean density. The utility of the Chandrasekhar-Fermi (C-F) method has been verified by MHD simulations (Ostriker et al. 2001; Padoan et al. 2001). It is important to emphasize that the polarization vectors must be well sampled to reliably derive field strengths from the C-F method. For selective absorption at optical/IR wavelengths, this sampling is limited to the positions of background stars. However, polarized far infrared or millimeter continuum emission from dust grains can be imaged at the diffraction limit of the telescope (Vaillancourt et al. 2008). The *GTM* could provide a powerful facility to mount a dedicated polarimeter-continuum imaging system to characterize the magnetic field geometry and C-F derived field strengths.

Li & Houde (2008) have developed a novel method to derive the magnetic field strength based on the measured relative velocity dispersions of a neutral (HCN) and ion (HCO^+) molecule. These molecules have similar excitation requirements and therefore, are presumed to arise from the same emitting volume. Differences in the amplitude of the velocity power spectra or structure functions are related to ion-neutral velocity drifts and the scale at which these decouple. For M17, they extrapolate a decoupling scale of 0.002 pc that corresponds to a field strength of 1 mG. The *GTM* can explore the method of Li & Houde (2008) in both the 1mm and 3mm bands for this same pair of molecules. The advantages of the *GTM* in the application of this method are its focal plane array instrumentation to derive the respective ion and neutral structure functions and higher angular resolution to directly resolve the decoupling scale or to reduce the errors due to extrapolation.

Strong MHD turbulence is expected to induce anisotropy of the velocity field with respect to the orientation of the mean magnetic field (Goldreich & Sridhar 1995). The theory predicts that the structure function of velocities parallel to the magnetic field should be steeper (more spatially coherent) than the structure function for velocities perpendicular to the field owing to the efficiency of Alfvén waves to transport energy. Such anisotropy is absent in the case of weak fields (Vestuto et al. 2003). Heyer et al. (2008) describe a method to determine the structure function along two orthogonal axes from molecular line observations. Applying their method to $45''$ ^{12}CO observations of the Taurus cloud envelope, they found velocity anisotropy aligned with the magnetic field as expected for a moderately strong magnetic field. From the degree of anisotropy, they estimated a field strength of 14μG that is consistent with the value derived using the C-F method for the same area. With its higher angular resolution and imaging instrumentation of line emission, the *GTM* can examine the degree of velocity anisotropy for more distant clouds in the Milky Way to quantitatively assess the dynamical relevance of magnetic fields.

2.2. *Protostellar and Protocluster Cores*

The pre-protostellar and proto-cluster cores that emerge from the magneto-turbulence of the overlying cloud are the precise sites of star formation within the ISM. These cores strongly radiate in the 1mm band owing to the resident cold dust. This continuum emission provides a reliable tracer of molecular hydrogen column density that requires few assumptions. The emission can be used to derive radial profiles of density for individual cores that can be compared to theoretical predictions and compile the core mass distribution function (Motte et al. 1998; Enoch et al. 2007). It is especially critical to define the CMF over the full range of expected masses. The disk and young cluster IMF is described by a log-normal distribution with a characteristic mass for stellar masses less than 1 $M_\odot$ and a power law for M> $M_\odot$ (Chabrier 2003). The CMF is predicted to vary with the prevailing dynamics of the parent molecular cloud (Padoan & Nordlund 2002).

To date, most continuum surveys do not have the sensitivity or resolution to accurately define the CMF at the low mass end. To fully sample the mass spectrum of protostellar cores, one requires mass sensitivity of 0.1 $M_\odot$ corresponding to the mass of brown dwarfs. Such a core would have a 1.1mm flux density of 20.5 (500 pc/d)^2 mJy, where d is the distance to the molecular cloud in parsecs and the assumed dust temperature is 15 K. A 4σ detection of such a low mass core in the Perseus spiral arm of the Galaxy (d=2.5 kpc) requires a target sensitivity of 0.2 mJy.

Imaging the millimeter thermal emission from dust grains with *AzTEC* and *SPEED* over the extent of a molecular cloud provides a direct census of active or potential sites of star formation that are characterized by high volume and column densities. A GMC at this distance subtending 1 deg^2 could be imaged by AzTEC in 45 hours to this sensitivity limit. Such imagery would provide invaluable information on the angular distribution of cores within the cloud and define the composite mass function to much lower mass limits than is available from current instruments and telescope facilities. The Core Formation rate over a free-fall time is derived from the mass resident within high density cores identified from 1mm continuum imaging and the total cloud mass derived from ^{12}CO and ^{13}CO observations.

Insight to the star formation process is further revealed by observations that probe the chemistry and kinematics of dense gas, as these trace the initial conditions prior to protostellar collapse. Excitation conditions (density and temperature) of the dense gas are derived from multiple transitions of key molecular species (CS, HCN, HCO^+, N_2H^+, CH_3OH, CH_3C_2H) and related isotopologues distributed within the 1 and 3mm bands. These spectral line measurements also define the motions of the dense material due to turbulence, outflow, infall, and rotation. High resolution and extended mapping of the dense gas is necessary to reliably separate these motions (Narayanan & Walker 1998). To effectively use these molecular constituents as probes of physical conditions, it is imperative to understand the chemical processes leading to a given chemical composition, so that differences in chemistry are not confused with variations of physical conditions (Bergin et al. 1997). With its heterodyne frontends that cover the 1 and 3mm bands and digital autocorrelation spectrometers that provide high spectral resolution, the LMT is well equipped to investigate the dense gas in GMCs using molecular spectroscopy.

2.3. *Summary*

The *GTM* and its instrumenation enable both detailed studies of individual star forming regions as well as wide field reconnaisance of millimeter continuum and spectral line emission in the Milky Way. Such reconnaissance allow astronomers to define the dynamical properties of clouds and cores to challenge current and future descriptions of the star formation process. The next generation of *GTM* instruments will further augment our understanding of the complex interstellar medium in order to place physical context to measurements of galaxy evolution in the early universe.

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