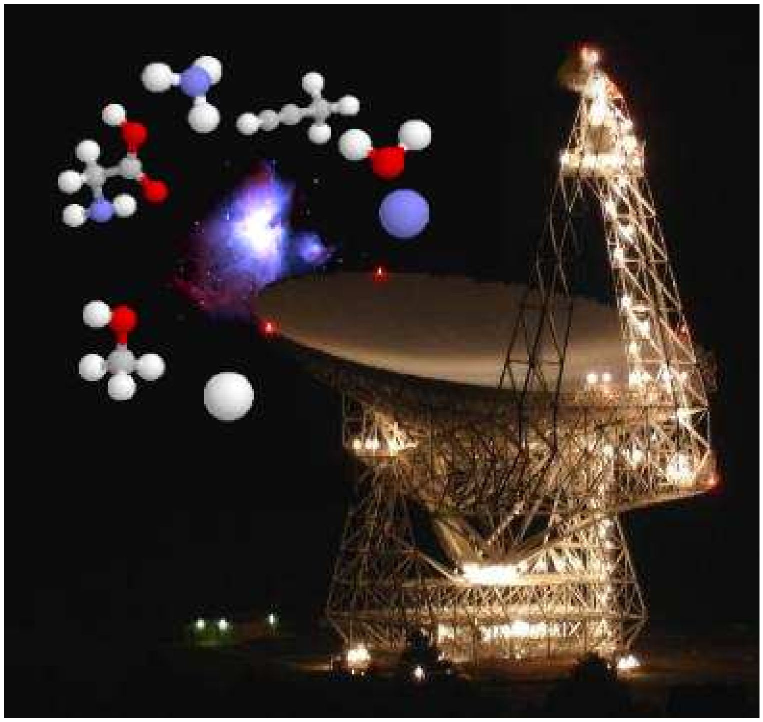
A 3 mm Heterodyne Focal Plane Array for the GBT



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Abstract

The Green Bank Telescope (GBT) will be the only 100 m class radio telescope to operate at 3 mm wavelengths for the foreseeable future. We propose that the expected exceptional high sensitivity and resolution ($\sim 7''$) of the GBT in this frequency window be exploited with a state-of–the–art wide–field focal plane heterodyne receiver array (FPA). This will be a uniquely capable instrument for the investigation of astrochemistry, molecular cloud and star formation processes in the Galaxy, in nearby galaxies of all morphological types, and in objects of the distant Universe.

Science Case

Molecular Lines in the 3 mm Atmospheric Window

Molecular gas and dust are the main ingredients that form stars. The electromagnetic spectrum in the atmospheric window at a wavelength of ~ 3 mm ($\sim 65 - 116$ GHz) is exceptionally rich in molecular lines – to date, more than 2000 have been detected in the interstellar medium within this frequency band (Lovas, Johnson, & Snyder 1979 and updates[1]). Due to the symmetry of the most abundant molecule, molecular hydrogen, cold H_2 remains undetectable in its electric dipole transitions. Thus, observations of molecular gas need to target lines of other molecular species. The most abundant molecule after H_2 is carbon monoxide ($^{12}C^{16}O$, or simply CO). The rest frequency of its fundamental rotational transition, J=1-0, is at the upper frequency end of the 3 mm band at ~ 115 GHz (which implies a continuous redshift coverage up to $z \approx 0.7$ for CO (1-0) in the 3 mm atmospheric window). This bright transition has a low critical density of $\sim 3000\,\mathrm{cm}^{-3}$ which makes it the best tracer for detecting molecular gas in the near and far Universe and allows one to study the overall structure and dynamics of giant molecular clouds (GMCs). The lowest rotational lines of its isotopologues, ^{13}CO, $C^{18}O$, and $C^{17}O$ are in the range of $109 - 112$ GHz and combinations of observations of those tracers allows one to perform proper radiative transfer analysis and determine optical depths in GMCs.

At lower frequencies, the 3 mm spectrum is dominated by the bright fundamental (J=1-0) rotational lines of molecules such as HCN, HCO^+, HNC, N_2H^+, and at somewhat higher frequency, CN. Higher J lines of other common molecules are also present, including CS (2-1) and SiO (2-1). Compared to CO (1-0), all of these transitions require higher densities to be collisionally excited and therefore they are better tracers of the more compact condensations of molecular material, the sites where stars are actively forming.

Located at the low frequency end of the 3 mm band, 65 to ~ 80 GHz, the ground state lines of important deuterated molecules, such as DCO^+, DCN, and HDO can be utilized to probe the physical conditions and chemical networks within interstellar clouds, the baryon density in the early Universe, and the formation and destruction of icy grains.

A 3 mm band receiver on the GBT will permit the study of a rich collection of molecular lines arising from objects ranging from our own Solar System to the edge of the Universe. Whereas some excellent science could be done with a dual beam receiver (see the science case for such an instrument at *https://wikio.nrao.edu/bin/view/GBT/GbtScienceCase/science_wband.pdf* for some examples), a 3 mm focal plane array (FPA) of heterodyne receivers would help the GBT meet its full potential. What follows is a sampling of some of the major science goals that could be achieved with this instrument[2]. Note that we are omitting continuum science as we consider this to be an area that will be covered by the MUSTANG project.

Solar System Astronomy

Comets

In recent years it has become evident that millimeter and sub–millimeter observations offer a unique tool for the investigation of the chemistry and physics of comets. Such observations provide the possibility of determining their chemical composition and measuring such physical parameters as temperature, density and outflow velocity in the cometary atmosphere ("coma"). Mapping the emission is particularly important, since all of the above quantities typically depend strongly on position in the coma, and mapping allows the possibility of distinguishing among possible sources of a given molecular species (e.g. sublimation from the nuclear ices versus chemical or photochemical production in the coma itself), since the resulting spatial distributions are different. Cometary lines can also be weak; the emission region is generally limited to the region between where the molecule is produced and where it is photo–dissociated. This region is smaller when the comet is closer to the Sun but, in general, much of the flux is lost to interferometers. The small GBT beam coupled with the large areal coverage of an FPA would be excellent for comet studies at millimeter wavelengths. The GBT will be able to study the properties of large populations

[1] see *http://physics.nist.gov/cgi-bin/micro/table5/start.pl*
[2] More details are available at *https://wikio.nrao.edu/bin/view/GBT/ScienceCaseWbandFpa*

of comets with superior sensitivity and resolution compared to past single-dish studies (e.g. Lovell et al. 1998).

There are many important molecular lines observed in comets in the 3 mm band, including HCN, CN, CO, CH_3OH, H_2CO, C_2H, HCO^+. Of particular interest are deuterated molecules. The very high deuterium fractionation observed in some cometary volatiles, more than an order of magnitude relative to the cosmic D/H ratio for water and 2 orders of magnitude for HCN, seems to require chemical processes similar to those in the interstellar medium (ISM). Indeed, the large ratios of HDO/H_2O and DCN/HCN provide the strongest evidence that comets preserve interstellar molecular material (e.g. Irvine et al. 2000). Such a conclusion has many important ramifications, including constraining the degree of processing of infalling material and the amount of radial mixing in the solar nebula, setting boundary conditions for solar system chemistry, and conceivably influencing theories of the origin of the oceans and life on Earth.

Galactic Astronomy

Interstellar Medium and Star Formation

Millimeter-wavelength observations provide us with a nearly complete view of the cold, dense interstellar medium that is responsible for forming stars within our galaxy. The low temperature, high density ISM is largely molecular, and the 3 mm band is especially rich in molecular species (see discussion above). Molecular line observations with a FPA on the GBT will provide important diagnostics to characterize the motions, physical conditions, and chemical state of the ISM. Progress in addressing the evolution of the molecular ISM involves understanding a complex of interrelated issues such as turbulence, collapse, angular momentum evolution, interstellar shocks, interstellar chemistry, all of which span a large range of spatial scales. Data are required both at high spatial resolution as well as on large angular extent to adequately understand problems at such scales. With a 3mm FPA, the GBT will be able to efficiently map entire Infrared Dark Clouds with sizes of $> 3.5'$(Simon et al. 2006), while nearly resolving massive cores (on scales of a few arcseconds). The GBT's sensitivity and angular resolution make it an ideal instrument for the study of star formation.

Cold Pre-Stellar Cores

When a cold, starless core begins to collapse to form a low mass protostar, most of the traditional molecular gas tracers (like CO and CS) have already frozen out onto dust grains. These molecules and their isotopologues show central holes at the position of the dust emission peak. However, there are a few species that continue to trace the dust peak and do not show a hole. These are N_2H^+ and N_2D^+, and quite often NH_3 (e.g. Tafalla et al. 2002). As a measure of the amount of deuterium fractionation that has occurred, the ratio of N_2D^+ to N_2H^+ is believed to reflect the evolutionary state of the core. With the sensitivity to detect these lines at 3 mm and with a beamsize well-matched to the core size, a FPA on the GBT will be able to quickly locate and image a large number of these objects and more closely trace the evolutionary chemical sequence from pre–stellar core to protostar.

The detection of complex molecules in cold dark clouds like TMC-1 has led to much examination of their formation pathways. The fact that they peak at locations distinct from more common molecular peaks (such as NH_3 and DCO^+) must also be explained. Traditionally, the possible routes include gas-phase neutral-neutral reactions, ion-molecule reactions, and grain surface chemistry. At present, neutral-neutral reactions are believed to be important, with complex molecule abundance peaks determined by evolutionary phase (Ehrenfreund & Charnley 2000). However, this remains an active area of research. The GBT can provide a higher angular resolution view of the spatial abundance gradients of carbon chain molecules, especially when equipped with a focal plane array. This combination of resolution and sky coverage can also be directed toward the study of more distant, more massive counterparts to TMC-1, such as the population of Infrared Dark Clouds identified by *MSX* and *Spitzer*.

Hot Cores

Hot molecular cores are often found in the vicinity of ultracompact H II (UCH II) regions and are thought to be driven by massive protostars in an evolutionary phase prior to the development of an UCH II region. Hot cores show strong emission in high-density tracers such as CH_3CN, HCN and HC_3N. Complex organics such as methanol, methyl formate and dimethyl ether typically show a forest of lines in these objects. Millimeter interferometers have demonstrated that the emission is generally quite compact, on arc-second scales at 1 kpc (and proportionally less in the more distant regions). In the nearest hot cores, in Orion, the $3'' - 6''$ beamsizes of the BIMA interferometer was sufficient to resolve hot cores (Wright et al. 1996). The GBT will marginally under-resolve these cores, but will not miss any of the flux.

Although similar in their general properties, hot cores often differ in their details. For example, some show strong emission in shock tracers like SO and SiO while others do not. Some show strong ethanol (C_2H_5OH) while others do not. Whereas some of these differences may arise from geometry and interaction of outflows with surrounding material, others may reflect a common chemical evolution. It has long been speculated that a chemical census of hot cores could someday provide the relative ages of these objects. Because most of these objects are quite distant (several kpc), high sensitivity is needed to detect them quickly, particularly at their early stages. In contrast to longer wavelength bands, the 3 mm band provides the necessary variety of tracers to perform a survey of hot cores that can address these goals.

The Formation of Stellar Clusters

Spectroscopic imaging of the star-forming gas in a sufficiently large sample of young stellar clusters will answer key questions about cluster formation and to discriminate between models: (1) What is the mass distribution of self-gravitating clumps? (2) What is the current rate of star formation in different clusters? (3) How fast do clumps and protostellar cores move through their clusters? To answer these questions it is necessary to image cluster-sized fields of order 1 pc^2, since that is the size over which dense gas is organized to make clusters (Lada & Lada 2003). It is also necessary to resolve the smallest star-forming cores, which extend over a few 0.01 pc in tracer lines such as N_2H^+ (1-0) (Di Francesco et al 2004). In the nearest young groups and clusters, which lie within a few hundred pc, these dimensions are well-matched by the mapping capabilities of a 3 mm FPA on the GBT.

One could use this instrument to study nearest embedded groups and clusters visible from GBT in the J=1-0 lines of N_2H^+ (1-0), tracing star-forming gas with densities 10^5 cm^{-3}, HCN (1-0) and HCO^+ (1-0) (and their isotopologues) tracing cores and infall onto them, and SiO (2-1) tracing the well-collimated bipolar jets from protostars. These four lines are in the 86-93 GHz part of the spectrum, and so their images will have essentially the same linear resolution. They will reveal whether clumps are self-gravitating, how fast the clumps are moving, and which clumps have evidence of infall and outflow - information which is necessary to understand cluster formation, but which cannot be obtained from continuum observations alone, or from maps of lines tracing lower density. Such filled-aperture observations will recover all the flux, in contrast to interferometer observations which do not have complementary short-spacing information.

Protoplanetary Disks

Single-dish surveys of protoplanetary disks (e.g. Thi, van Zadelhoff & van Dishoeck 2004) have found that some organic molecules are quite common (including CO, HCO^+, CN and HCN) while others are not (CS, CH_3OH, H_2CO). From these observations, it is now clear that protoplanetary disks contain an active, non-equilibrium chemistry (Bergin et al. 2007).

For example, the abundance ratios of some species, such as CN/HCN, are found to be powerful probes of the effect and extent of UV photo–dissociation. Images of the J=3-2 lines of these species with arcsecond resolution have been obtained with the Sub–Millimeter Array (SMA) which demonstrate that the ratio varies with radius (Qi et al., in prep). Like HCN (1-0), the CN (1-0) transition also lies in W band (at 113 GHz). Similarly, the DCO^+/HCO^+ ratio provides a measure of the level of deuterium fractionation in disks. The J=1-0 transitions of all four of these species lie within the 3 mm band. Surveys of these pairs of lines with the GBT could be performed in a large number of T Tauri stars, and provide a larger sample of targets for ALMA follow–up imaging.

Deuterium Chemistry

Singly deuterated molecules have been known to be abundant in cold molecular clouds with a very high abundance enhancement as a result of fractionation (Wootten 1987). The enhancement is preferred at cold temperatures and becomes strongest in cold dense clouds without internal sources. Knowledge of the distribution of deuterated molecules provides an excellent guide to the location of cores in their most primitive state for further characterization. Recently, multiply deuterated molecules have been observed in nearly every variety imaginable, including triply deuterated ammonia and methanol. Although the first thoughts to explain such high levels of deuteration focused on deuterium-rich grain mantles, a review of ion-molecule chemistry led astrochemists to understand that depletion of molecules which could destroy the dominant ion, H_3^+, could lead to enhancement of it and its deuterated isotopomeres. In fact, D_3^+ could well be the dominant deuterated ion in clouds. As a result, deuterated isotopomeres of many molecules may be abundant, becoming sources of 'unidentified' lines in many clouds (c.f. Marcelino et al. 2005).

As the chemistry of deuteration is an ion-molecule chemistry, the most important lines are those of the fundamental molecular ions, DCO^+ and N_2D^+. Images of a cloud in these lines immediately identify the coldest, densest cores, the sites of the next generation of star formation. As hydrogen is an abundant constituent of astrophysical molecules, the lines of deuterated isotopomeres may be used to probe the physics of these prestellar cores. Often, the lines of the deuterated molecules are optically thin, expediting interpretation. In addition to the cornerstone molecular ions DCO^+ (72 GHz) and N_2D^+ (77 GHz), several other important lines are available, including DCN (72 GHz), DNC (76 GHz), NH_2D (85 GHz), HDO (80 GHz) and NHD_2 (67.8 GHz).

Astrochemistry & Astrobiology

A primary focus of current astrobiology research is to investigate our prebiotic molecular origins. As such, over the last several years there have been significant advances in this field primarily due to dedicated searches for large molecules that are possible precursors to molecules of biological importance (biomolecules) in the interstellar medium and in the atmospheres of comets. Successful dedicated searches with the GBT below 50 GHz in the last two years have led to the detections of interstellar aldehydes namely propenal (CH_2CHCHO) and propanal (CH_3CH_2CHO) (Hollis et al. 2004a), simple aldehyde sugars like glycolaldehyde (CH_2OHCHO) (Hollis et al. 2004b), the first keto ring molecule to be found in an interstellar cloud, cyclopropenone (c-H_2C_3O) (Hollis et al. 2006a), the third organic imine to be detected in an interstellar cloud, ketenimine (CH_2CNH) (Lovas et al. 2006), and acetamide (CH_3CONH_2) (Hollis et al. 2006b), the largest interstellar molecule detected with a peptide bond. These searches and detections all took place in the direction of the Galactic center towards Sgr B2(N) in a region that has been named the "Large Molecule Heimat" (LMH) and have greatly enhanced our understanding of the distribution and abundance of these large organic molecules in interstellar clouds. However, dedicated searches are very limited in the identification for new interstellar species and transitions because they often cover only a restricted range of frequencies and bandwidth. What is needed is a more complete survey over a large frequency range and bandwidth to obtain as much information as possible. This includes expanding the frequency coverage into the 3 mm region.

For the last 10 years, the LMH has been the first source searched to identify and detect new large biomolecules since many of the large organic species have been found confined to its $\sim 5''$ diameter (Hollis 2006). These results were consistent with the conventional wisdom persisting for decades that the interesting complex molecules would be found and studied with high-resolution arrays able to couple well to the more compact molecular emission sources (Hollis 2006). However, the recent GBT results indicate that the distribution of at least a subset of these species are not confined to hot molecular cores. Instead, these species, including interstellar aldehydes, appear to have spatial scales on the order of $1' - 2'$. Currently, there is no array in the world sensitive enough that is able to map the spatial distribution of these large organic biomolecules in a reasonable amount of time. Thus, in order to obtain a better understanding of the distribution and formation of large interstellar molecules, including biomolecules, it is important to follow up the single dish detections with FPA observations that are able to match the spatial distribution of these species. The high sensitivity of a GBT focal plane array at 3 mm wavelengths of the distribution of interstellar biomolecules will help constrain the formation chemistry of these species and can help to point out where the highest abundance of these species are located.

The Galactic Center

The Galactic Center is obviously the most nearby core of a galaxy and therefore a unique object to study. The physical environments are more extreme than in the rest of the Galaxy in terms of star formation activity, tidal fields, high UV radiation field, and the influence of the central supermassive black hole Sgr A*.

The molecular gas in the Galactic Center is embedded in a high pressure, hot starburst environment which leads to broad lines and signatures of large scale outflows (e.g., Bland-Hawthorn & Cohen 2003). Albeit a unique region in the Milky Way, the center of the Galaxy appears to be a working template to be compared with the cores of other galaxies (e.g., Menten 2004). The region is home to the Sgr B2(N) LMH (discussed above) and is rich in wide–spread organic molecules. Due to the large extent of the Central Molecular Zone around the Galactic Center (about 5×1 degrees), however, large scale maps have been mostly restricted to relatively low spatial resolution of a few arcminutes (e.g., see the AST/RO maps, Martin et al. 2004) or to mapping of small regions. Due to the southern declination of Sgr A* ($\sim -29°$), the GBT visibility of the region will be relatively short for each observation. The sensitivity of the GBT combined with the large field of view of an FPA is therefore imperative for an efficient mapping of the Galactic Center and the associated Central Molecular Zone from the northern hemisphere. For line ratio studies it is essential to recover flux of all spatial scales and interferometric measurements are only of limited value for the investigation of the physical conditions and the chemistry of the Central Molecular Zone.

Magnetic Fields

In recent years it has become widely accepted that magnetic fields play an important and possibly crucial role in the process of star formation on both large and small scales (e.g. McKee 1999, Crutcher 2007). On large scales magnetic fields are thought to help support a cloud against overall collapse and on small scales help to carry away angular momentum through magnetic braking and bipolar outflows. Although removal of angular momentum is crucial for star formation, little is currently known about the magnetic field morphology on the relevant scales (typically a few arcseconds for nearby high mass regions). Indeed, detailed modeling suggests that the magnetic field should exhibit an hourglass morphology (with the protostar located at the "pinch"; e.g. Fiedler & Mouschovias 1993; Girart et al. 2006). In the past it has been very difficult to test these models observationally due to poor sensitivity and resolution. The GBT with a 3 mm band FPA provides the sensitivity, resolution, and areal coverage to study magnetic fields on both the molecular cloud and galaxy-wide scales. Unlike ALMA, the GBT is not able to resolve dense star forming cores, but it is well placed to investigate the magnetic interface between clouds and cores, and clouds and galaxies as a whole.

The Zeeman effect remains the only technique available to *quantitatively* measure the *strength* of magnetic fields (along the line of sight) in star-forming regions. Although studies of the Zeeman effect in centimeter wavelength H I and OH absorption lines provide important measurements of global magnetic field properties (e.g. Brogan & Troland 2001; Sarma et al. 2000), these lines do not trace the high density gas where stars actually form. There are a few molecules that do have strong Zeeman coefficients and trace high densities ($\gtrsim 10^5$ cm^{-3}) in the mm/sub-mm wavelength regime (see Bel & Leroy 1989; Bel & Leroy 1998). Of these, the CN, SO, and CCH molecules are particularly promising since they are relatively abundant $\sim 10^{-4}$ - 10^{-5} (compared to CO; Bergin et al. 1997), and have high Zeeman coefficients (~ 2 Hz μG^{-1}). However, because the Zeeman effect depends on the inverse of the line width (measured in frequency), millimeter wavelength Zeeman observations will require commensurately higher sensitivity than those at cm wavelengths.

A few attempts have been made to measure the Zeeman effect at millimeter wavelengths, for example with the IRAM 30m in CN at 3 mm (Crutcher et al. 1999) among others. However, these experiments have thus far produced disappointing results due to insufficient sensitivity and poor quality polarizers. Additionally, relatively little is currently known about the properties (strength, morphology, line width, and optical depth) of CN, SO, and CCH in star forming regions (c.f. Savage et al. 2002; Bergin et al. 1997). Thus, the outstanding collecting area, sensitivity, and unblocked aperture of the GBT are ideally suited to studying 3 mm transitions of these promising Zeeman molecules, and measure Zeeman magnetic field strengths on angular scales of ~ 7". This resolution is a factor of two better than, for example, 1.3 mm data from the James Clerk Maxwell Telescope, which has had a large impact in this field.

Linear polarimetry observations trace the magnetic field *direction* in the plane of the sky in contrast to the Zeeman effect which traces the line of sight component as well as its strength using circular polarization. Thus, both types of data are needed in order to understand the $3-D$ morphology and role of magnetic fields in star forming regions. Unfortunately, few sources have been the subject of both linear and circular polarization studies, because sources that are good Zeeman candidates are not necessarily good dust polarization candidates, and vice versa. Zeeman absorption observations require the presence of fairly dense ($\sim 10^4$ cm^{-3}) H I or OH gas in front of a star forming region that is also a strong radio continuum source, while dust polarization studies require strong infrared dust emission. Additionally, Zeeman studies can distinguish between magnetic field contributions from different velocity components along the line of sight, which are often complex in star forming regions, while dust polarization studies cannot. This means that even when both types of observations exist (i.e. M17; Dotson 1996; Brogan & Troland 2001; Houde et al. 2002), it is uncertain whether they sample the same kinematic region. An obvious solution for this dilemma is to obtain spectral line linear polarization data.

Goldreich & Kylafis (1981) predict that the emission from rotating molecules can be linearly polarized if the cloud in which the molecules reside is anisotropic. Deguchi & Watson (1984) further predict that this effect can result in polarized intensities of $\sim 1\%$ and is maximized when the observed species has $\tau \sim 1$ and the collision rate approximately equal to the radiative rate. This effect was detected for the first time by Greaves et al. (1999) using the JCMT and the CO(2−1) transition toward the "2 pc ring" at the Galactic Center and S140 (also see Crutcher & Lai 2002; Girart et al. 1999). The full power of this technique to distinguish between different velocity components is demonstrated in Greaves et al. (2002) where it is shown that one of the high velocity streamers falling into the circumnuclear disk (CND) around Sgr A* has a different magnetic field direction that that of the CND, in contrast to the dust polarization results that show a uniform field direction. A 3 mm FPA on the GBT would allow exploration of this important diagnostic using the J=1-0 transitions of CO. Since the ^{12}CO, C^{13}O, C^{18}O, and C^{17}O isotopologues all fall within the band, all four transitions can be used to probe successively deeper $\tau = 1$ surfaces within molecular clouds.

The Nearby Universe

Many problems of molecular cloud and star formation are best addressed by observing extragalactic objects. The Doppler shifts of molecular lines are often confused when observing molecular clouds in the Milky Way and the study of galactic structure is much easier in nearby galaxies due to their variety of inclination angles. In addition, the environments in other galaxies – elliptical, dwarf, active, starburst, or merging galaxies – are fundamentally different to those in large spirals such as the Galaxy. Problems of molecular cloud and star formation as well as galactic evolution can be studied in a much wider parameter space of physical and chemical conditions by studying galaxies in the nearby Universe. These studies also provide a vital link to the processes in the early Universe.

Molecular Cloud Formation in Spiral Galaxies

If we wish to understand galaxy evolution, it is essential to have an accurate description of the processes that regulate star formation. A long–standing question how do GMCs condense from the diffuse ISM. Theories of GMC formation generally fall into two broad categories: (1) gravitational instability of diffuse gas and (2) compression of the diffuse gas by large-scale, turbulent motions (e.g., driven by energy injected by cloud-cloud collisions, shells driven by supernovae, and compressible turbulence in the atomic gas layer). The formation of GMCs in the spiral arms of galaxies such as M 51 through gravitational instabilities has been studied in detail by Kim and Ostriker (2002, 2006). They showed that, in the presence of a moderately strong magnetic field, gravitational instabilities can produce dense, bound structures (massive GMCs) in the arm and more diffuse spurs that project from the main body of the arm into the interarm region; the spurs bear remarkable resemblance to the feather-like dark features apparent in the HST image of M 51 (Scoville et al. 2001). If correct, the model would have strong implications for the formation and evolution of GMCs. The GBT focal plane array is ideally suited for testing the Kim-Ostriker model. A firm prediction of the model is that the spurs will extend from the arms into the interarm region. These large-scale (hundreds of parsecs), low (surface) density structures would be difficult to observe with interferometers. With the GBT array, one can determine not only the morphology but also kinematics of the spurs for comparison with the model predictions. Together with information on the magnetic field structure from polarization measurements, the data would provide even tighter constraints.

The Chemistry of Molecular Clouds and Star Formation in Spiral Galaxies, Starburst, and AGN systems

On global scales, star formation in galaxies appears to be governed by the Schmidt law, an empirical correlation between the star formation rate and the average gas surface density on kiloparsec scales. On smaller scales, however, this relation brakes down and it is important to answer questions such as how are spiral density waves affecting the physical properties of molecular clouds that pass through a spiral arm and the relation to associated star formation (Rand et al. 1992, 1999, Lord and Kenney 1991). What is the radial distribution of molecular gas properties? How do the properties of molecular gas vary as a function of environment (for example in starbursts, AGNs, low metallicity galaxies, etc.). The millimeter wave transitions of CO and its isotopomeres are excellent probes of diffuse molecular gas (e.g. Young and Scoville 1991). However, CO is readily excited and is typically optically thick, and so it tends to favor the warmer, diffuse surface layers of clouds. Dense gas is highly correlated with indicators of star formation (e.g. Gao and Solomon 2004). It is therefore preferable to map density-sensitive trace molecules that are optically thin to understand how star formation varies in different galactic environments. Indeed, imaging observations of nearby galaxies with an angular resolution of $\sim 5''$ show that density sensitive tracers such as C_2H, CS, N_2H^+, CH_3OH, HNCO, HNC, HC_3N and SO are present in the centers of such galaxies and that they can show significant variation on scales of tens of parsecs (Meier and Turner 2005). These observations suggest that dense molecular clouds differ markedly in their chemical properties and, importantly, these differences correlate directly with galactic features such as large-scale shocks, dynamical resonances, and locations of intense radiation fields. For nearby galaxies ($D \lesssim 5\,$Mpc), the $7''$ beam, high sensitivity and large field of view of the proposed GBT instrument will cover $\sim 2\,$kpc of the disk at resolutions of $\sim 100\,$pc, the scale needed to separate individual GMCs. The 3 mm window provides access to shock tracers (such as thermal CH_3OH and SiO) which can be used to map the location and strength of shocks induced by internal galaxy dynamics (bars, spiral arms) and external interactions, photo–dissociated region (PDR) tracers (such as CN and C_2H) which delineate massive star formation/molecular gas interaction sites, as well as many other quiescent and ionization tracers (such as HNC, HCO^+ and N_2H^+), to help locate and characterize the ambient dense gas properties away from shocks and massive star forming regions. Of the above molecules only SiO has relevant transitions that are readily observable in any other band below 3 mm. With a wide bandwidth backend the GBT will be capable of observing many of these, generally broad lines of galaxies, simultaneously.

A large inventory of mapped species will permit the addressing of additional important questions such as: over what physical scale do AGN and massive star forming regions influence the chemical and physical conditions of their surroundings? What is the average molecular complexity reached for the bulk of galaxies' ISM and what constraint does this impose on basic chemical formation pathways? Does the average chemistry change with galactocentric distance? Does it change when the molecular material is transported along a bar toward the cores of starburst and active galaxies? What about the cosmic ray ionization rate? What is the ionization fraction at different galactocentric distances and is there evidence for its control of physical parameters such as cloud support and star formation? Can the chemical state of the gas be used to "clock" the age of molecular clouds with position in a galaxy? Detecting chemical molecules in a select few nearby low metallicity systems should be possible with the GBT providing important clues on the dependence of molecular abundances to abundances of the atomic pools. In particular, when combined with data from IR and optical wavelengths, such as the *Spitzer* Infrared Nearby Galaxies Survey (SINGS), these observations will shed new light on such key issues as the lifetimes of molecular clouds and star formation efficiency.

Dwarf Irregular Galaxies

Due to their low gravitational potential and the absence of density waves and galactic shear, dwarf irregular galaxies are unique laboratories to study the stochastic modes of molecular cloud and associated star formation. Those modes may be fundamentally different from the mechanism of the Kim & Ostriker model. For example, the dwarf irregular galaxy NGC 4214 (Walter et al. 2001) clearly shows the scattered presence of molecular clouds which are not solely correlated with tracers of active star formation like H α or to large column densities of the atomic gas. The observed properties are challenging common models of molecular gas and star formation. A combination of GBT CO observations with data from ongoing and approved programs at other wavelengths, for example the optical *HST* 'ACS Nearby Galaxies Survey Treasury' (ANGST; PI J. Dalcanton), its follow–up VLA large project to map HI at high angular resolution (PI: J. Ott), the complementary 'Little THINGS' VLA large project (PI: D. Hunter), and the '11 Mpc H-alpha and Ultraviolet Galaxy Survey' (11 HUGS, PI: R. Kennicutt), will be crucial for a detailed comparison between observations and increasingly sophisticated numerical simulations of the formation of GMCs (and eventually stars) out of turbulent H I gas (e.g., Glover & Mac Low 2007). In addition, dwarf galaxies are low–metallicity (typically 10% solar) 'building blocks' of large spirals, the properties of which may resemble hierarchically forming galaxies in the early Universe. Therefore, dwarf galaxies may be our best nearby templates to observationally study the formation of the first generations of stars.

Low Surface Brightness Galaxies

Despite more than a decade of study, it remains an enigma how star formation proceeds in low surface brightness (LSB) galaxies - galaxies with central surface brightnesses at least one magnitude fainter than the night sky. The global properties of LSB galaxies — blue colors, high gas mass-to-luminosity ratios, and low metallicities – lead to the conclusion that LSB systems are under-evolved compared to their high surface brightness (HSB) counterparts. Once their typically low gas surface densities ($\Sigma_{\rm H\,I} \leq 10^{21}\,{\rm cm}^{-2}$) and low baryonic-to-dark matter ratios are taken into account, the question becomes less why LSB galaxies are under-evolved than how they can form stars at all (O'Neil et al. 2003, and references therein). The average total gas and dynamical masses of LSB and HSB galaxies are very similar. However, the average gas mass-to-luminosity ratio $M_{\rm H\,I}/L_B$ is significantly higher for LSB galaxies ($2.4\,M_\odot/L_\odot$) than for their HSB counterparts ($0.4\,M_\odot/L_\odot$). Within a given mass bin, galaxies' gas-to-*light* ratios appear to increase with lower surface brightness, even as their gas-to-*mass* ratios stay the same. This perplexing result implies that star formation must follow different paths in the LSB and HSB populations. The study of LSB galaxies is extremely difficult, and determining their molecular gas properties even more so, for the simple reason that the gas, like the light in these galaxies, is extremely diffuse. As a result, studying LSB galaxies requires an extremely sensitive telescope, but one which has both a large field of view (to readily search the entire galaxy for gas) and which can cover the zero spacings, as much of this gas is extremely diffuse and could be missed by interferometers. The GBT with a 3 mm FPA will be ideal for detecting and mapping the molecular gas in LSBs.

Star Formation in Tidal Streamers and the Formation of New Galaxies

Interactions of galaxies can result in very extended tidal streamers of gas, well outside deep gravitational wells of the galaxies involved (e.g., the M 81 triplet, Yun et al. 1994). In some of these streamers, the strong tidal forces as well as stochastic and self–gravitation processes are leading to the conversion of atomic to molecular gas and the formation of stars (e.g., Lisenfeld et al. 2004; Walter at al. 2006, Hibbard et al. 2006). Other theories do not assume in–situ formation of the molecular gas but prefer a ballistic model where GMCs are torn out of the initial interacting galaxies. In some cases, parts of the tidal streamers are self–gravitating and ultimately from new dwarf galaxies in a top–down process. Studying molecular cloud and associated star formation in tidal streamers may be important for the element enrichment of the intergalactic medium which is observed in metal line absorption systems at all redshifts. The reason being the metals in tidal streamers are readily distributed into the intra–group medium and galaxy–galaxy interactions were very common in the past. A sensitive search of molecular material in tidal streamers with telescopes such as the GBT will be needed to address how widespread molecular cloud formation in tidal features is, how efficient the formation of stars can become in these systems, and how this is connected to the formation of proper tidal dwarf galaxies.

The Distant Universe

Bright lines of CO, but also of other molecules such as HCN, over a broad redshift range fall within the 3 mm window. The redshift range for CO [HCN] (J=1-0) is $0.0 \lesssim z \lesssim 0.7$ [$0.0 \lesssim z \lesssim 0.3$], $2.0 \lesssim z \lesssim 3.4$ [$1.5 \lesssim z \lesssim 2.7$] for CO [HCN] (J=2-1), $3.0 \lesssim z \lesssim 5.1$ [$2.3 \lesssim z \lesssim 4.1$] for CO [HCN] (J=3-2), and $4.0 \lesssim z \lesssim 6.8$ [$3.0 \lesssim z \lesssim 5.1$] for CO [HCN] (J=4-3). This implies a continuous redshift coverage with the only gap being between $0.7 \lesssim z \lesssim 2.0$ [$0.3 \lesssim z \lesssim 1.5$]. These gaps can be reduced by using the lower frequency receivers on the GBT. Some redshift ranges, for example, $4.0 \lesssim z \lesssim 5.1$ [$3.0 \lesssim z \lesssim 4.1$] actually provide the opportunity to observe two lines, the CO [HCN] (J=4-3) and CO [HCN] (J=3-2) lines, with the same receiver. A 3 mm receiver on the 100 m GBT dish will therefore be a vital tool to study properties of molecular gas in the distant Universe.

Galaxy Clusters at Moderate Redshifts

With the proposed FPA, imaging molecular gas distribution and kinematics in a sample of tens of galaxies with a reasonable amount of observing time becomes possible for the first time. This will allow one to systematically study of the impact of rich cluster environments on the evolution of galaxies at moderate distance ($z \lesssim 0.7$, a range which spans the last $\sim 6\,$Gyr), where evidence of the enhanced activity (the "Butcher-Oemler effect") is emerging. Observations of molecular gas with the GBT, combined with the superb H I and radio continuum data that can be obtained quickly and efficiently using the Expanded VLA (H I up to a redshift of ~ 0.4), the response of the cold ISM and its effects on star formation can be investigated in great detail (for recent CO observations, see, e.g., Salomé & Combes 2003, Salomé et al. 2006). Such observations will shed light on how molecular gas properties vary as a function of environment and redshift (e.g. Kenney & Young 1989, Nakanishi et al. 2006). At higher redshift these studies would be limited to the brightest galaxies. It is becoming increasingly clear that environment plays an important role in driving the evolution of galaxies and their star formation history. Studies of galaxies in groups and clusters suggest that frequent collisions and ram pressure stripping may play a significant role in the evolution of galaxies within such dense environments. Gas and galaxies in filamentary large scale structure that are newly accreted into the cluster potential can be identified by their cold gas content and morphology, in comparison with the X-ray images obtained with the *Chandra* or *XMM–Newton* observatories, revealing the recent mass accretion history of and cooling flows within the clusters. A study of molecular gas (CO and isotopomeres) distribution and gas mass for galaxies at low to moderate redshifts ($z \leq 0.7$) clusters is particularly well-suited for the GBT because of its superb surface brightness sensitivity and high angular resolution.

How Star Formation Calmed and Spirals Gained Their Shapes

Galaxies evolved strongly the last few Gyr – for instance the star formation density rises by an order of magnitude from z=0 to 1 (e.g. Takahashi et al 2007). The scale of a 7″ GBT beam varies from 21 kpc at z=0.2 to 45 kpc at z=0.7. The population of spirals at the distant end of the range is dominated by luminous infrared galaxies (LIRGs; Shi et al. 2006). However, as one proceeds further back in time, galaxy morphology increasingly dominated by heavily disturbed galaxies. By investigating CO over this range, the GBT can tell us how star formation and morphology changed over the last half of the age of the Universe and how spiral arms evolved from morphologically irregular shapes. The molecular lines of 'typical' ULIRGs are bright enough to permit observations of all two dozen ULIRGs in the Hubble Ultra–deep field (Shi et al. 2006) that fall in the redshift range of the 3 mm receiver, within a few hours of integration time per object. The spatial resolution of the GBT nicely matches the visible extent of these objects.

Molecular Surveys of Deep Fields

The studies of deep fields, such as the Hubble Deep Field (HDF; Williams et al. 1996) and others, have truly revolutionized our understanding of high redshift galaxies, particularly the multi-wavelength studies (see Ferguson et al. 2000 for a review). The bright sub-mm sources in these fields identified by SCUBA (e.g., Hughes et al. 1998, Serjeant et al. 2003, Borys et al. 2003) reveal galaxies that have extremely high star formation rates and are, therefore, good candidates for searches for CO emission (e.g., Wagg et al. 2007). There are about 8 sub-mm sources in the $6\,\square'$ HDF-North (Serjeant et al. 2003) and over 30 in a larger, $165\,\square'$ surrounding region (Borys et al. 2003). Traditionally, searches for CO, HCN, and/or HCO^+ from bright sub-mm or infrared sources have targeted individual galaxies, but a 3 mm FPA would allow more efficient observations of molecular emission from these galaxies by mapping the entire survey region, without a bias towards extremely dusty objects. Alternatively, where the number density of sources is lower, individual sources can be observed sequentially in a subset of beams providing many 'off' spectra for each 'on' (e.g. Zwaan et al. 2004). Note, however, that the bandwidth of the backend may restrict molecular line searches to narrower redshift ranges.

Synergies with Other Telescopes

The GBT is a single–dish telescope with a resolution of $\sim 7''$ at a wavelength of 3 mm. It will therefore be ideal to fill in the zero and short spacings of interferometric data such as obtained from CARMA and PdBI (note that it is planned that ALMA will record auto–correlations, which, combined with the ACA, will recover all missing spacings). Such a combination is essential for the understanding of molecular cloud structure on all scales and to derive reliable line intensities for studies of the physical properties and chemical networks of molecular clouds.

The resolution of the GBT in the 3 mm waveband will match that of many telescopes at all wavelengths. For example, the HERA FPA at the IRAM 30 m telescope is a nine–pixel receiver at 1 mm wavelength which matches exactly the GBT resolution at 3 mm and roughly of the LMT @ 1 mm. This will enable one to obtain multiple transitions of molecules at virtually the same resolution. At higher sub–mm frequencies, the SMA, APEX, and the upcoming *HERSCHEL* and *SOFIA* telescopes at various frequencies match the GBT resolution, and bolometers to image the same amount of detail are SHARC II on CSO, SCUBA-2 on the JCMT ($\sim 7.5''$ @ 450 μm), and LABOCA on APEX, and, of course, MUSTANG on the GBT. A comparison with the EVLA shows that H I observations in the B–array configuration almost exactly match the GBT beam at 3 mm; this is important for the comparison of molecular and atomic gas in star forming regions and across entire galaxies. The VLA also has a similar resolution when configured in A–array @ 90 cm or D–array @ 2 cm (and a possible E–array @ 1 cm). The far–infrared 24 μm MIPS detector of *Spitzer* also match the resolving power of the GBT instrument and *Spitzer's* legacy projects will be a valuable source for comparisons with GBT data. At high energies, the X–ray observatory *XMM–Newton* provides the same amount of detail. It is also worth mentioning that particular data analysis techniques of data obtained at higher resolutions derive properties of objects under study on the same spatial scales as observations with the GBT at 3 mm; notably, spatially resolved stellar populations as gained from the HST can be constructed on scales of $\sim 6''$ (e.g., Dohm–Palmer et al. 1997, 1998), i.e., the star formation history of nearby galaxies can be determined to the same level of detail as the resolving power of the GBT for molecular gas.

Technical and Site Considerations

PTCS and the GBT Site

Observing with the GBT above 50 GHz is currently limited by four things: aperture efficiency, thermal effects, winds, and atmospheric opacity. The atmospheric opacity is low enough for 3 mm observations for about 3000 hours per year (not just winter months). This is similar to the usable hours at other low altitude sites such as the FCRAO 14m.

The aperture efficiency of the GBT above 50 GHz is currently less than 20%, dropping to 2% at 115 GHz. This is limited by the panel-to-panel offsets and PTCS (Precision Telescope Control System) has the goal of improving the efficiency to 48% at 72 GHz and 27% at 115 GHz. This will dramatically improve the sensitivity of the GBT.

Winds and differential heating and cooling of the telescope both have adverse effects on the pointing of the telescope. Presently, high frequency observations are limited to nighttime and when the wind is low; for 3 mm observations would be limited to times when the wind speed is less than 5 mph. These two restrictions limit 3 mm observations to about 150 hours per year. With PTCS improvements, the usable number of hours could be increased to over 1000 hours per year with efficiencies 2-10 times higher. The success of PTCS is critical for making the GBT the premiere 3 mm single-dish telescope in the world.

Assuming that PTCS pointing and aperture efficiency improvements are successful, what are the median 3 mm observing conditions in Green Bank? Median opacities are better than 0.15 from 80-100 GHz, rising to 0.21 at 110 GHz and 0.5 at 115 GHz. On the low frequency end they rise to 0.26 at 72 GHz. Median system temperatures are between 115-130 K between 80-110 GHz. $T_{\rm sys}$ is higher at the edges of the band: $T_{\rm sys}$=140 K at 72 GHz and $T_{\rm sys}$=190 K at 115 GHz. When considering the required observing time to reach a given signal-to-noise, the effective system temperature $T_{\rm eff} = T_{\rm sys} e^{-\tau}$ should be used instead. $T_{\rm eff}$ ranges between 130-165 K over the 80-110 GHz range. It is 184 K at 72 GHz and 332 at 115 GHz. Even without PTCS improvements to the GBT's aperture efficiency, the GBT is more sensitive than many other telescopes operating at 3 mm, including Nobeyama, IRAM 30m, Plateau de Bure Interferometer, and the Combined Array for Research in Millimeter-wave Astronomy (CARMA). With PTCS improvements, it will be more sensitive than any 3 mm-capable radio telescope except ALMA. Its point source sensitivity will be 20% better than the Large Millimeter Telescope (LMT) and 5-10 times better than the IRAM 30m and other leading 3 mm telescopes. In terms of integration times, the GBT will reach equivalent signal-to-noise ratios 1.4-100 times faster than other telescopes. What the GBT lacks in $T_{\rm eff}$, it more than compensates for in collecting area. The GBT will also yield finer angular resolution than any of these telescopes, with a beam size of $\sim$ 7", roughly a factor of two finer than other 3 mm single-dish telescope. This combination of sensitivity and angular resolution makes the GBT and ideal complement to ALMA at 3 mm.

Focal Plane Array Technology

This proposal does not specify the exact technical layout of a focal plane array for the GBT. The size, frequency range, and technology used to build a 3 mm FPA for the GBT depends on a number of issues; budget and technological feasibility being the most obvious. In principle, the frontend could be either a 'conventional' multi–horn instrument with many pixels that undersample the focal plane; a technology that is in use at many telescopes and frequencies and is being proposed for a K-band FPA for the GBT. A second option would be the development of beam forming cluster arrays. The latter design would have various advantages, including a fully sampled field of view. It may also be a beneficial technical development for the SKA. On the other hand, since it is a novel approach, it is also a riskier path than building a conventional FPA. We would like to refer to the wiki page
https://wikio.nrao.edu/bin/view/GBT/ScienceCaseWbandFpa
for Neal Erickson's beam forming cluster feed proposal developed at UMass.

A new spectrometer to be used with a prototype K-band FPA has been proposed. This spectrometer will take advantage of the FPGA (Field Programmable Gate Array) based hardware being developed by the Berkeley CASPER[3] group. Such a spectrometer would have very flexible capabilities and would, hopefully, be expandable to work with a 3 mm FPA.

We propose to address the technical and budgetary constraints during the period of active PTCS upgrades at the GBT. A FPA at 3 mm will only make sense if enough observing time is available under suitable 3 mm atmospheric and telescope operating conditions and that issues such as the efficiency of the aperture at the high frequency end are in a range that is necessary to perform quantitative science. This project would be a natural extension to the PTCS upgrades, the development of a K-band FPA, and new spectrometer developments being proposed by Green Bank and CDL.

We strongly recommend that the development of a 3 mm FPA be a collaboration between NRAO and university groups. Interest has been raised by the engineering groups at UMass, Caltech/JPL, and Berkeley, but collaborations with other institutes would also be welcome.

[3] *http://seti.berkeley.edu/casper/*

References

Bel, N., & Leroy, B. 1989, A&A, 224, 206
Bel, N., & Leroy, B. 1998, A&A, 335, 1025
Bergin, E. A., Ungerechts, H., Goldsmith, P. F., Snell, R. L., Irvine, W. M., & Schloerb, F. P. 1997, ApJ, 482, 267
Bergin, E. A., Aikawa, Y., Blake, G. A., & van Dishoeck, E. F. 2007, Protostars and Planets V, 751
Bland-Hawthorn, J., & Cohen, M. 2003, ApJ, 582, 246
Boone, F., et al. 2005, A&A, 429, 129
Borys, C., Chapman, S., Halpern, M., & Scott, D. 2003, MNRAS, 344, 385
Brogan, C. L., & Troland, T. H. 2001, ApJ, 560, 821
Crutcher, R. M., Troland, T. H., Lazareff, B., Paubert, G., & Kazès, I. 1999, ApJ, 514, L121
Crutcher, R. M., & Lai, S.-P. 2002, Hot Star Workshop III: The Earliest Phases of Massive Star Birth, 267, 61 Crutcher, R. M. 2007, EAS Publications Series, 23, 37
Deguchi, S., & Watson, W. D. 1984, ApJ, 285, 126
Di Francesco, J., André, P., & Myers, P. C. 2004, ApJ, 617, 425
Dohm-Palmer, R. C., et al. 1997, AJ, 114, 2527
Dohm-Palmer, R. C., et al. 1998, AJ, 116, 1227
Dotson, J. L. 1996, ApJ, 470, 566
Duc, P.-A., & Mirabel, I. F. 1994, A&A, 289, 83
Ehrenfreund, P., & Charnley, S. B. 2000, ARA&A, 38, 427
Ferguson, H., & Murdin, P. 2000, Encyclopedia of Astronomy and Astrophysics
Fiedler, R. A., & Mouschovias, T. C. 1993, ApJ, 415, 680
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
Girart, J. M., Crutcher, R. M., & Rao, R. 1999, ApJ, 525, L109
Girart, J. M., Rao, R., & Marrone, D. P. 2006, Science, 313, 812
Glover, S. C. O., & Mac Low, M.-M. 2007, ApJS, 169, 239
Goldreich, P., & Kylafis, N. D. 1981, ApJ, 243, L75
Greaves, J. S., Holland, W. S., Friberg, P., & Dent, W. R. F. 1999, ApJ, 512, L139
Greaves, J. S., Holland, W. S., & Dent, W. R. F. 2002, ApJ, 578, 224
Hibbard, J. E., et al. 2005, ApJL, 619, L87
Hollis, J. M., Jewell, P. R., Lovas, F. J., Remijan, A., & Møllendal, H. 2004a, ApJ, 610, L21
Hollis, J. M., Jewell, P. R., Lovas, F. J., & Remijan, A. 2004b, ApJ, 613, L45
Hollis, J. M., Remijan, A. J., Jewell, P. R., & Lovas, F. J. 2006a, ApJ, 642, 933
Hollis, J. M., Lovas, F. J., Remijan, A. J., Jewell, P. R., Ilyushin, V. V., & Kleiner, I. 2006b, ApJ, 643, L25
Hollis, J. M., 2006, "The Lewis E. Snyder Astrochemistry Lectures"
Houde, M., et al. 2002, ApJ, 569, 803
Hughes, D. H., et al. 1998, Nature, 394, 241
Irvine, W. M., Schloerb, F. P., Crovisier, J., Fegley, B., Jr., & Mumma, M. J. 2000, Protostars and Planets IV, 1159
Kenney, J. D. P., & Young, J. S. 1989, ApJ, 344, 171
Kim, W.-T. & Ostriker, E. C. 2002, ApJ, 570, 132
Kim, W.-T. & Ostriker, E. C. 2006, ApJ, 646, 213
Lada, C. J., & Lada, E. A. 2003, ARA&A, 41, 57
Lisenfeld, U., Braine, J., Duc, P.-A., Brinks, E., Charmandaris, V., & Leon, S. 2004, A&A, 426, 471
Lord, S. D., & Kenney, J. D. P. 1991, ApJ, 381, 130
Lovas, F. J., Johnson, D. R., Snyder, L.E. 1979, ApJS, 41, 451
Lovas, F. J., Hollis, J. M., Remijan, A. J., & Jewell, P. R. 2006, ApJ, 645, L137
Lovell, A. J., Schloerb, F. P., Dickens, J. E., De Vries, C. H., Senay, M. C., & Irvine, W. M. 1998, ApJ, 497, L117
Marcelino, N., Cernicharo, J., Roueff, E., Gerin, M., & Mauersberger, R. 2005 ApJ 620, 308
Martin, C. L., Walsh, W. M., Xiao, K., Lane, A. P., Walker, C. K., & Stark, A. A. 2004, ApJS, 150, 239
Meier, D. S. & Turner, J. L. 2005, ApJ, 618, 259
Menten K. 2004, Symp. Dense ISM in Gals.
McKee, C. F. 1999, NATO ASIC Proc. 540: The Origin of Stars and Planetary Systems, 29
Nakanishi, H., et al. 2006, ApJ, 651, 804
O'Neil, K., Schinnerer, E., & Hofner, P. 2003, ApJ, 588, 230
Phillips, R. B., Straughn, A. H., Doeleman, S. S., & Lonsdale, C. J. 2003, ApJL, 588, L105
Rand, R. J., Kulkarni, S. R., & Rice, W. 1992, ApJ, 390, 66
Rand, R. J., Lord, S. D., & Higdon, J. L. 1999, ApJ, 513, 720
Salomé, P., & Combes, F. 2003, A&A, 412, 657
Salomé, P., et al. 2006, A&A, 454, 437
Sarma, A. P., Troland, T. H., Roberts, D. A., & Crutcher, R. M. 2000, ApJ, 533, 271
Savage, C., Apponi, A. J., Ziurys, L. M., & Wyckoff, S. 2002, ApJ, 578, 211
Scoville, N. Z., et al. 2001, AJ, 122, 3017
Serjeant, S., et al. 2003, MNRAS, 344, 887
Shi, Y., Rieke, G. H., Papovich, C., Pérez-González, P. G., & Le Floc'h, E. 2006, ApJ, 645, 199
Shu, F. H., Adams, F. C., & Lizano, S. 1987, ARA&A, 25, 23
Simon, R., Rathborne, J. M., Shah, R. Y., Jackson, J. M., & Chambers, E. T. 2006, ApJ, 653, 1325
Tafalla, M., Myers, P. C., Caselli, P., Walmsley, C. M., & Comito, C. 2002, ApJ, 569, 815
Thi, W.-F., van Zadelhoff, G.-J., & van Dishoeck, E. F. 2004, A&A, 425, 955
Wagg, J., Hughes, D. H., Aretxaga, I., Chapin, E. L., Dunlop, J. S., Gaztañaga, E., & Devlin, M. 2007, MNRAS, 375, 745
Walter, F., Taylor, C.L., Hüttemeister, S., Scoville, N., & McIntyre, V. 2001, AJ, 121, 727
Walter, F., Martin, C. L., & Ott, J. 2006, AJ, 132, 2289
Williams, R. E., et al. 1996, AJ, 112, 1335
Wootten, A. 1987, in IAU Symposium No. 120, 'Astrochemistry", ed. M. S. Vardya and S. P. Tarafdar. (Dordrecht: Reidel), p.311
Wright, M. C. H., Plambeck, R. L., & Wilner, D. J. 1996, ApJ, 469, 216
Yun, M. S., Ho, P. T. P., & Lo, K. Y. 1994, Nature, 372, 530
Zwaan, M. A., et al. 2004, MNRAS, 350, 1210