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Science Case for the GBT 3 mm Focal Plane Array

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ABSTRACT

We propose to build a large element (∼100) spectroscopic focal-plane array at 3mm (W′-FPA) for the GBT. The primary scientific goals of the instrument are studying the physical properties, processes, and astrochemistry of the ISM and star-forming regions within our Galaxy and nearby galaxies. The W′-FPA will be designed to cover the 84–116 GHz frequency range (ALMA Band-3) and will have sufficient sensitivity and wide-area mapping capabilities that will enable complementary science programs with ALMA. Considering the telescope performance and key science applications, the W′-FPA will be optimized at about 90 GHz to enable efficient observations of the dense molecular gas tracers that probe the cloud cores of star-formation regions.

1. Introduction

The combination of the large collecting area, unblocked aperture and wide field-of-view of the Robert C. Byrd Green Bank Telescope (GBT) is well-suited to focal-plane array receivers. A large spectroscopic focal-plane array (FPA) at 3mm (W-band)[1] will enable a powerful new set of scientific capabilities with the GBT, both as a stand-alone instrument and in combination with interferometers such as ALMA. The GBT is unique among 100-meter class radio telescopes in operating efficiently at wavelengths as short as 3 mm (30–35% aperture efficiency at 90 GHz). The ability of the GBT to detect low surface brightness emission and to map wide areas is complementary to the capabilities of interferometers which are sensitive to small-scale structures.

The GBT's sensitivity and unmatched signal-dish spatial resolution ($\sim 8''$) with a large spectroscopic focal plane array will provide unprecedented mapping ability at 3 mm. A 100 element array with pixel spacing of 2.5 beamwidths has an array footprint of about $3' \times 3'$. This footprint is well matched to the size scales needed to map Galactic infrared dark clouds

[1]Traditionally W-band corresponds to 75–110 GHz; we define W′ as the frequency range associated with the W′-FPA instrument.

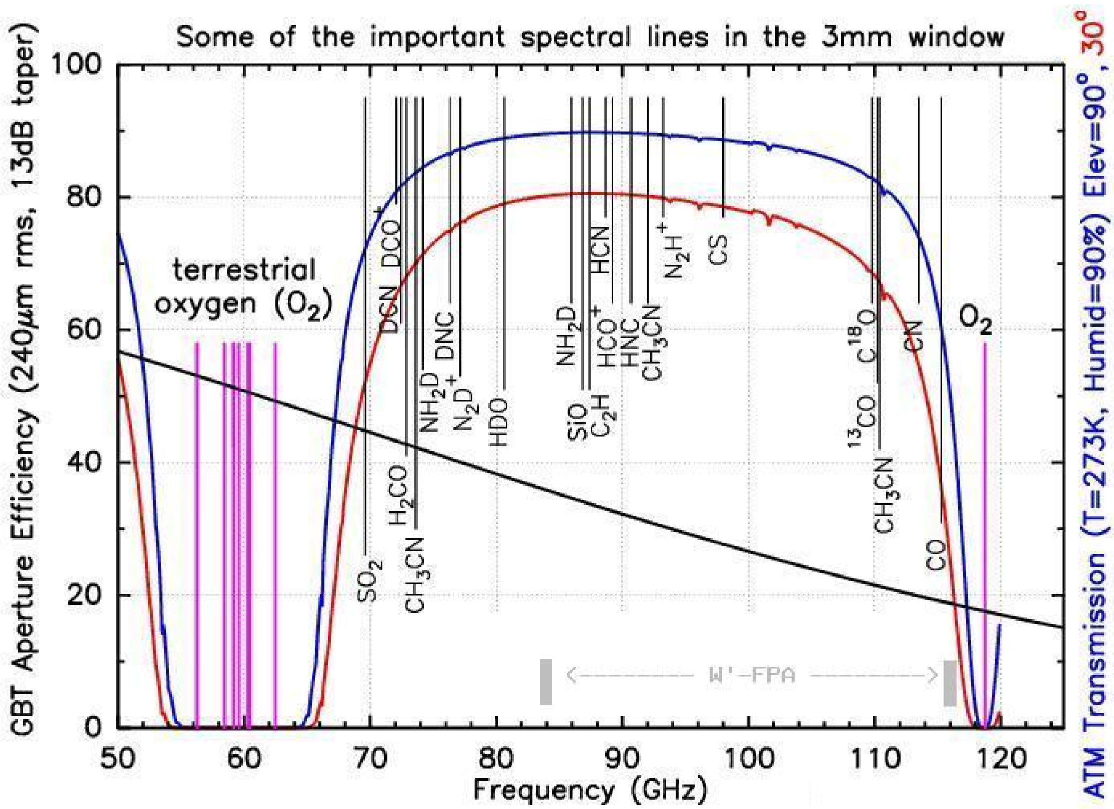

Fig. 1.— The 3 mm atmospheric window and important astronomical spectral line transitions. The atmospheric transmission in percent for Green Bank is given by the blue curve for an elevation of 90° and the red curve at 30°. The solid black curve systematically decreasing with frequency represents the aperture efficiency of the GBT assuming the current surface performance of 240μm rms. Important astronomical lines are labeled. The proposed W′-FPA receiver would cover frequency range from 84–116 GHz which includes the important dense gas tracers of HCN, HCO+, HNC, and N2H+ at around 90 GHz as well as the bright CO lines at 110–115 GHz.

(the progenitors of star clusters) and nearby galaxies. The spatial resolution of $\sim 8''$ is also well matched to the Spitzer mid-infrared 24μm data and the Herschel far-infrared data. Both of these infrared space telescopes have carried out large-area Galactic imaging surveys, as well as mapping significant samples of nearby galaxies. The GBT W′-FPA will be able to survey several 100 square degrees of the regions mapped by Spitzer and Herschel, which will permit detailed studies of the molecular gas on the same spatial scales as the dust emission observed by Spitzer and Herschel. The W′-FPA will be a key instrument for the investigation of the astrochemistry, properties, and processes associated with molecular clouds and star formation within our Galaxy and nearby galaxies.

2. Science Justification

Molecular gas and dust are the main ingredients out of which stars, planets, and galaxies form. The electromagnetic spectrum in the 3 mm atmospheric window ($\sim$ 67 – 116 GHz) is exceptionally rich in molecular lines (Fig. 1), with more than 2000 detected lines (Lovas, Johnson, & Snyder 1979 and updates given in online databases, e.g., NIST). Due to its symmetry, molecular hydrogen is undetectable in its rotational transitions. Thus, other molecular species are used to probe the molecular gas within the cold ISM. In particular, CO which is the most abundant molecule after H_2 is key for detecting molecular gas in faint sources, and its transitions (110–115 GHz) are used to study the overall structure and dynamics of molecular clouds. At frequencies of 86–98 GHz, the astronomical spectrum is dominated by the bright lines of SiO, HCN, HCO+, HNC, N2H+, and CS. Compared to CO, these transitions require higher densities to be collisionally excited, and therefore they are better tracers of the compact condensations of molecular material from which stars are actively forming.

Based on the ASTRO-2010 Survey, four key research areas have been identified for the GBT. The GBT W′-FPA would greatly enhance the science capabilities in all of these areas.

- **Fundamental Physics** – The GBT W′-FPA will enable studies of fundamental chemistry of molecular species under the physical conditions and time scales not achievable in terrestrial laboratories.
- **Origin of Life** – The GBT W′-FPA will carry out molecular spectroscopy of complex organic molecules and pre-biotic molecules in the ISM and comets which are key for studying the conditions from which life eventually forms.
- **The Context of Star Formation** – The GBT W′-FPA will provide efficient wide-area mapping of star-forming regions of many important molecular transitions which is key for understanding the dependencies between the large-scale processes within the ISM and the formation cold proto-stellar cores from which stars form.
- **Galaxies Across Cosmic Time** – The GBT W′-FPA will provide mapping studies of CO and the dense gas tracers, such as HCN and HCO+, of significant samples of nearby galaxies, as well as for the measurements galaxies and clusters in CO(1-0) at intermediate redshifts which is a key cosmological period over which galaxies evolve.

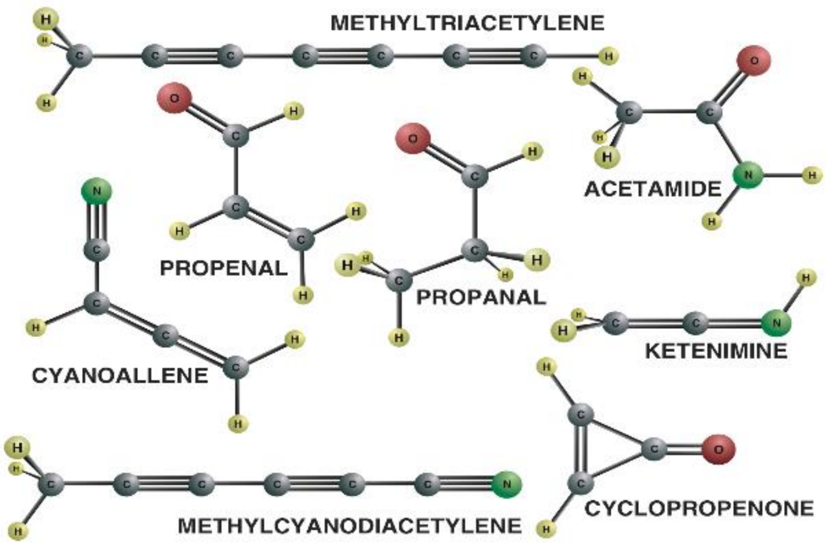

Fig. 2.— Several biologically important species have been recently discovered at the GBT (Hollis et al. 2004a,b, 2006a,b). Opening up the 3mm window will allow searches for new transitions that are key for understanding fundamental astrochemistry and their possible associated with the formation and evolution of life.

2.1. Fundamental Physics

2.1.1. Astrochemistry

The GBT has helped to revolutionize the study of astrochemistry. Recently, 13 new organic molecules including $CH6^-$, which is the first interstellar anion, have been found using the GBT. Contrary to prior expectations, many of these new species are not concentrated in compact hot cores, but are found in extended cool clouds. These discoveries have caused chemists to re-evaluate the chemical pathways and reaction rates in interstellar gas (e.g., Quan & Herbst 2007).

Given the recent observational results, there is a new paradigm arising from the chemistry community. Instead of using chemistry to understand astronomical phenomena, chemists are now using the unique conditions afforded by the interstellar clouds for the study of chemistry itself. Terrestrial laboratories are largely limited to reactions in liquids or high-density gases. The ISM enables the study of chemical pathways in low density gas, weakly ionized gas, and gas in the presence of weak magnetic fields. These studies cross traditional disciplinary boundaries and only can be addressed by astronomical observations in conjunction with theoretical and laboratory studies. The newly established Center for Chemistry in the Universe at the University of Virginia has be formed for this purpose, and the GBT W′-FPA will play a central role in these efforts.

2.1.2. The Galactic Center

One of the prime astronomical targets for the study of astrochemistry will be the Galactic Center. The physical environments in the Galactic Center 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 super-massive black hole Sgr A*. The nearby massive star forming region Sgr B2 has proved to be a bonanza for the search of molecular lines of organic species and of molecular lines in general. Due to the large extend of the Central Molecular Zone around the Galactic Center (about 5 by 1 degrees), 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. For line ratio studies it is essential to recover the flux on all spatial scales, and given the large spatial extent of the Central Molecular Zone, interferometric measurements have had only limited value. Due to the southern declination of the Galactic center ($\sim -29^{\circ}$), the GBT visibility of the region will be relatively short for each observation. Therefore, a large element W′-FPA is imperative to permit efficient mapping of the Galactic Center with the GBT.

2.2. Origin of Life

2.2.1. The ISM

Transitions of complex organic molecules exist throughout the 3 mm band. Given the importance of finding the precursors to biological molecules within the ISM and within comets for our understanding of the formation and evolution of life, it is important to maximize the available frequency coverage. Several transitions are available in the 3 mm window, including those from the simple-sugar species glycolaldehyde (CH2OHCHO) and ethylene glycol (HOCH2CH2OH). The existence of these species in significant quantities has been shown recently from transitions below 50 GHz with the GBT (Hollis et al. 2004a, b).

The GBT results also indicate that the distribution of many organic species are not confined to hot molecular cores. Instead, many organic species, including interstellar aldehydes have spatial scales on the order of $1' - 2'$. The current arrays are not sensitive enough to map the spatial distribution of these large organic bio-molecules in a reasonable amount of time. The GBT W′-FPA would be able to map the distribution of interstellar bio-molecules to locate the regions with the highest abundance, which is key to constraining the formation chemistry of these species.

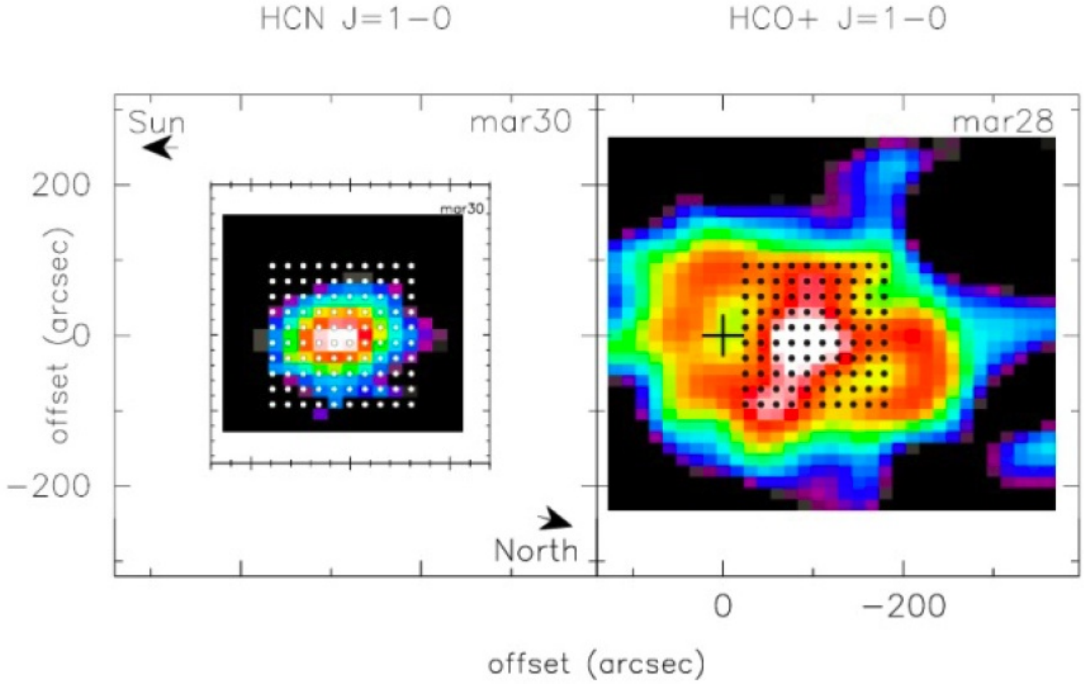

Fig. 3.— The W′-FPA footprint (100 pixel) superimposed on the HCN(1-0) (left) and HCO+(1-0) (right) images of comet Hale Bopp, as observed with the FCRAO 14m telescope whose resolution is given by the cross in the HCO+ image. Images are courtesy of A. Lovell. Comets allow us to study the primitive material left over from the formation of the solar system.

2.2.2. Comets

Observations of comets are particularly important for our understanding of the formation of the solar system and the origin of life on Earth. Comets contain the primitive material left over from the formation of the solar system, and as such, their study provides key insight into the early formation life (Irvine et al. 2000). Currently, there is a serious lack of data on the possible chemical variations among comets, which is important to understand since comets are thought to have formed over a wide range of heliocentric distances. Studies of comets provides constraints on the degree of processing of in-falling material and the amount of radial mixing in the early solar nebula, setting boundary conditions for solar system chemistry, and conceivably influencing theories of the origin of life on Earth.

Mapping of the cometary atmosphere ("coma") emission is key since the composition and physical parameters such as temperature, density, and outflow velocity all strongly depend on location within the coma. High-spatial resolution mapping ($\lesssim 10''$) allows the possibility of distinguishing among various possible chemistry mechanisms for different molecular species, such as sublimation from the nuclear ices versus chemical or photochemical production in the coma itself. The coma is extended over spatial scales of order 1×10^5 km, which is about $5'$ at 0.5 AU. Given that the structure within comets can change within hours over various spatial scales, studies of comets require rapid measurements over a wide field of view with high sensitivity to low surface-brightness lines and with good spatial resolution ($\lesssim 10''$). Since all of these needs are uniquely met by the specifications of the GBT W′-FPA , cometary research as been coined as the “killer application” for the instrument.

Researchers now depend on the occasional spectacular bright comet such as Hale-Bopp for studies (Fig. 3), but with the vastly improved sensitivity provided by the W′-FPA on the GBT, several comets every year will be detectable over periods of 3–4 weeks. Hence, the W′-FPA on the GBT will be a unique tool that will transform cometary research by detecting comets at much great distance and by providing the ability to make quasi-realtime movies of spectral images of multiple molecular species.

2.3. The Context of Star Formation

It is becoming increasingly apparent that stars do not form in isolation, but rather form within stellar groups/clusters embedded in molecular clouds (Lada & Lada 2003). While theoretically the formation of isolated low-mass stars has a well-developed “standard model” (Shu, Adams, & Lizano 1987), there is no consensus model of how stars form within groups/clusters within the real complex environment of the galaxy. In one picture, “turbulent fragmentation” produces the structures which develop under self-gravity into orbiting and interacting cores and stars (Mac Low & Klessen 2004). Another view holds that initial conditions are more important than interactions: gas with star-forming density $> 10^4\mathrm{cm}^{-3}$ is structured as a cloud forms, and the distribution of such gas determines the number and distribution of stellar masses (Adams & Myers 2001; McKee & Tan 2003; Shu, Li, & Allen 2004). The W′-FPA instrument on the GBT will enable observations of molecular gas over a wide range of spatial scales which is key to understanding the processes associated with star-formation.

2.3.1. Cloud Cores

Infrared dark clouds (IRDCs, Simon et al. 2006) are the suspected birth sites of young star-clusters (Fig. 4). Spectroscopic imaging of sufficiently large sample of IRDCs will answer key questions about cluster formation and to discriminate between various 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 proto-stellar cores move through their clusters? To answer these questions it is necessary to image cluster-sized fields of order 1 pc^2 or larger, since this is the size scale over which dense gas is organized to make

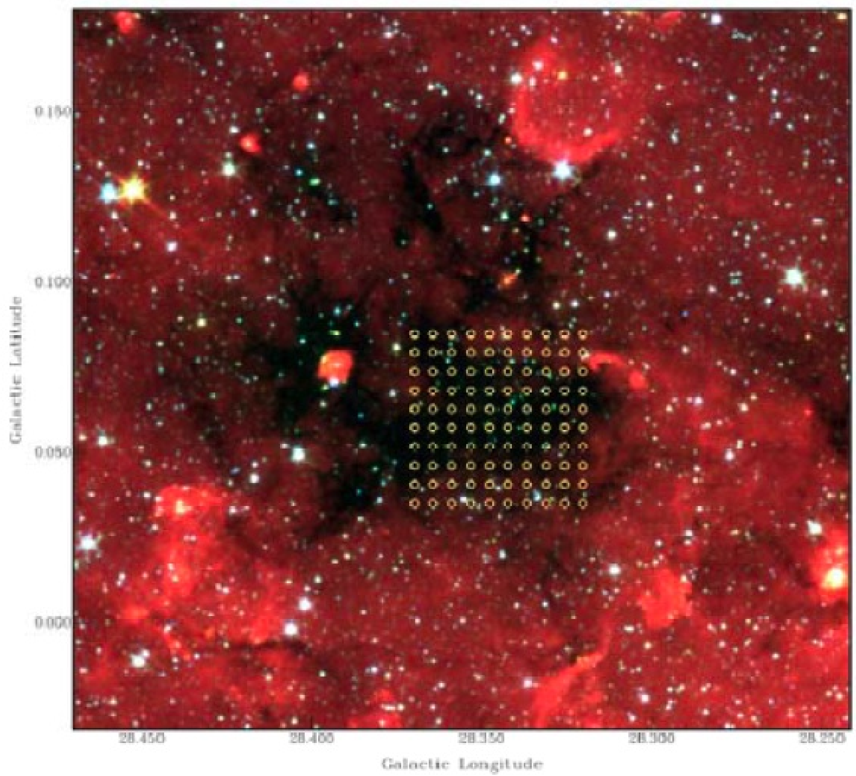

Fig. 4.— The W′-FPA footprint (100 pixel) superimposed on an infrared dark cloud which are the birth sites of clusters of stars. The W′-FPA will be able to map large molecular cloud structures and uncover the positions of proto-stellar cores.

clusters (Lada & Lada 2003).

The GBT W′-FPA will be able to map large areas (many patches of 1–10 square degrees) of the sky in the brighter dense gas line tracers, such as HCN and N_2H^+ 1-0 (e.g., Di Francesco, Anré, & Myers 2004) which will uncover thousands star-forming cores. These wide-area surveys with the GBT W′-FPA will provide the locations of proto-stellar regions that will enable detailed follow-up ultra-high resolution studies with ALMA. Even without the sub-arcsec imaging that ALMA could provide, the 8″ resolution of the GBT is sufficient to address many important science questions. Pre-stellar cores have a typical size of order 0.1 pc, which at the distances to nearest star-forming regions corresponds to angular sizes of $\sim 2.5'$ in Taurus and 40″ in Orion. For these large nearby cores, current interferometer observations have resolved out a majority of the flux (e.g., Olmi et al. 2005; Schnee et al., in prep), and the GBT W′-FPA would have sufficient spatial resolution to study the sub-structure within the cores. Fortunately, many of the brightest northern hemisphere large molecular cloud structures (e.g., Taurus, Perseus, Auriga and Orion) are up during the low opacity winter season for the GBT.

The 1-0 lines of N_2H^+, HCN, and HCO^+ (and their isotopologues) will be used to trace high-density (10^5 cm^{-3}) star-forming cores and infall onto them. Currently, only two starless cores have had their infall velocity mapped at high resolution (Williams, Lee & Myers 2006), and this took many hours of observing time. Myers (2005) showed that measuring the velocity profile is a good way to determine the initial geometries and collapse ages of starless cores. In addition, surveys of SiO(2-1) can be used to find well-collimated bipolar jets from the protostars. All four of these species (N2H+, HCN, HCO+, and SiO) are in the 86-93 GHz part of the spectrum, so their images will have essentially the same linear resolution. These data will reveal whether clumps are self-gravitating, how fast the clumps are moving, and which clumps have evidence of infall and outflow. In addition, high resolution maps could be used to to estimate their magnetic field strengths; e.g., Martin Houde and collaborators have derived magnetic field strengths by comparing the line widths of neutral and ion species (Li & Houde, 2008; Houde et al. 2000).

In short, observations of the dense molecular line species are key for our understanding of proto-stellar cores. These lines provide information that cannot be obtained from continuum observations or from maps of molecular lines tracing lower density, such as CO. The GBT W′-FPA observations will recover all the flux, in contrast to interferometer observations which do not have complementary short-spacing information. The GBT W′-FPA will provide mapping capabilities with a large dynamical range of spatial scales and will permit blind surveys of wide areas to uncover large samples of pre-stellar cores.

2.3.2. Stellar Outflows

Bipolar, jet-driven molecular outflows associated with star-formation are common within star-forming regions. Nearly all young stellar objects may go through a phase of collimated molecular outflows. The collimated jets can shock and sweep up the ambient molecular material. Outflows are studied in the bright CO line tracers and extend over several arcmin to larger than 15′ (Bourke et al. 1997; Lopez-Sepulcre et al. 2009). The lobes show signs of shock-excitation from SiO and other shock tracers. Recent observations also show the presence of complex organic molecules such as COCH3, CH3CN, HCOOH, and C2H5OH (Arce, et al. 2008). The large outflows are difficult to study with interformeters and will be challenging even with ALMA given the large number of required pointings (Shepard 2008). These studies would benefit greatly from the GBT W′-FPA .

2.3.3. Galactic Molecular Clouds and Complexes

Observations of CO and its isotopomers (^{13}CO, $C^{18}O$ and $C^{17}O$ have been used over the past 40 years to infer the excitation conditions and physical conditions of the Galactic

ISM. Although molecular "clouds" are considered self-gravitating and are approximated as "spherical" clouds in many theoretical treatments. Large area (several square degrees) surveys data have show rich, complex structures such large-scale filaments, arcs, rings, bubbles, and clumps (e.g., Carpenter, Snell & Schloerb 1995). To date, large areas surveys have been done with only modest size telescopes (e.g., CfA 1.2 m whole-Galaxy survey at $30'$ resolution (Dame et al. 1987) and various surveys with the FCRAO instrument at $45''$ resolution and the NRAO 12m at about $1'$ resolution). CO surveys carried out with the GBT would improve the spatial resolution by factors of 7 or better over the previous surveys. This will allow for detailed analysis of the molecular gas complexes that will provide insight into the conditions and formation of the dense condensations of gas which become the stellar-birth sites.

2.3.4. Galactic Structure

CO observations also permit the study of galactic structure and the Galactic bar (e.g., Liszt 2006). CO surveys have shown that the majority of molecular gas in the Galaxy exists within the "molecular ring" between Galactic radii of 3 – 7 kpc. With CO imaging and kinematic studies over large areas, Galactic hydrodynamical models of the gas can be constrained.

2.4. Galaxies Across Cosmic Time

2.4.1. Nearby Galaxies

The GBT W′-FPA would be able to efficiently map large nearby galaxies at much higher resolution than available from the previous single-dish surveys. The improved resolution would enable the study the molecular bars within many spirals, spiral arms and their kinematics, and inter-arm spurs. The inter-arm spurs are large-scale (hundreds of parsecs), low surface density structures which are especially difficult to observe with interferometers. With the GBT W′-FPA , one can determine the morphology and kinematics of the spurs for comparison with the model predictions (e.g., Kim & Ostriker 2002, 2006).

The nearby infrared-bright galaxies will be key extragalactic targets for the GBT W′-FPA . Solomon et al. (1997) demonstrated the strong correlation between IR-emission and CO(1-0) emission for infrared-bright galaxies. However, Gao & Solomon (2004) have demonstrated that the HCN is a far better tracer of the star-formation activity in galaxies than CO, given its associated with dense gas. Hence, the dense gas traces of HCN, HCO+, and HNC are important in studying the material associated with the ongoing star-formation and AGN activity. The amount dense gas traced by HCN compared to the total molecular gas traced

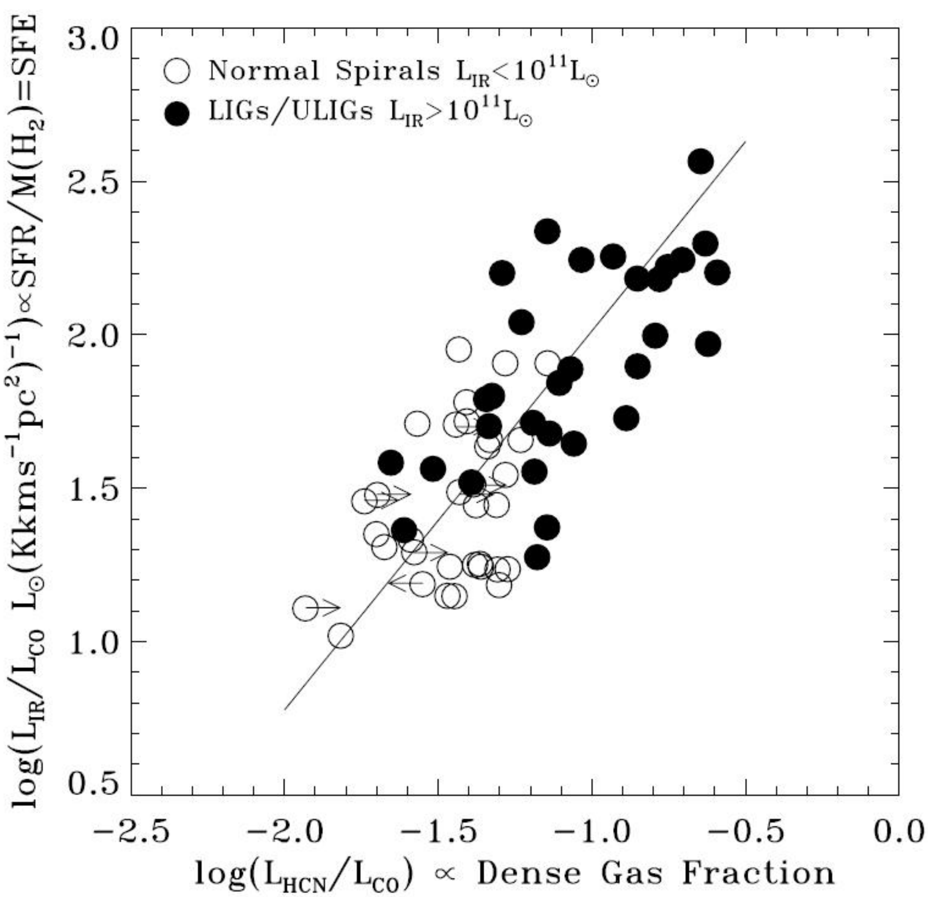

Fig. 5.— The fraction of dense gas traced by HCN has been shown to be correlated with the total star-formation efficiency (Gao & Solomon 2004). Tracers of dense gas, such as HCN are better probes of the ongoing star-formation activity than CO.

by CO is a proxy for the star-formation efficiency. The the GBT W′-FPA will enable mapping of the CO and dense gas lines for large samples of galaxies and ultraluminous infrared galaxies. These observations will constrain the level of enhanced star-formation efficiencies (e.g., measured from the HCN/CO ratios) for extreme starburst regions in comparison to the "normal-mode" of star formation found in the disks of spiral galaxies.

Observations of line ratios of the dense gas tracers and CO show significant variations between galaxies and within galaxies. For example in the galaxy IC342 (Fig. 6), Meier & Turner (2005) have found large differences among the density sensitive tracers such as C2H, CS, N2H+, CH3OH, HNCO, HNC, HC3N, and SO on the spatial scales of tens of parsecs. 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. Shock traces such as SiO and thermal CH3OH can be used to map the location and strength of

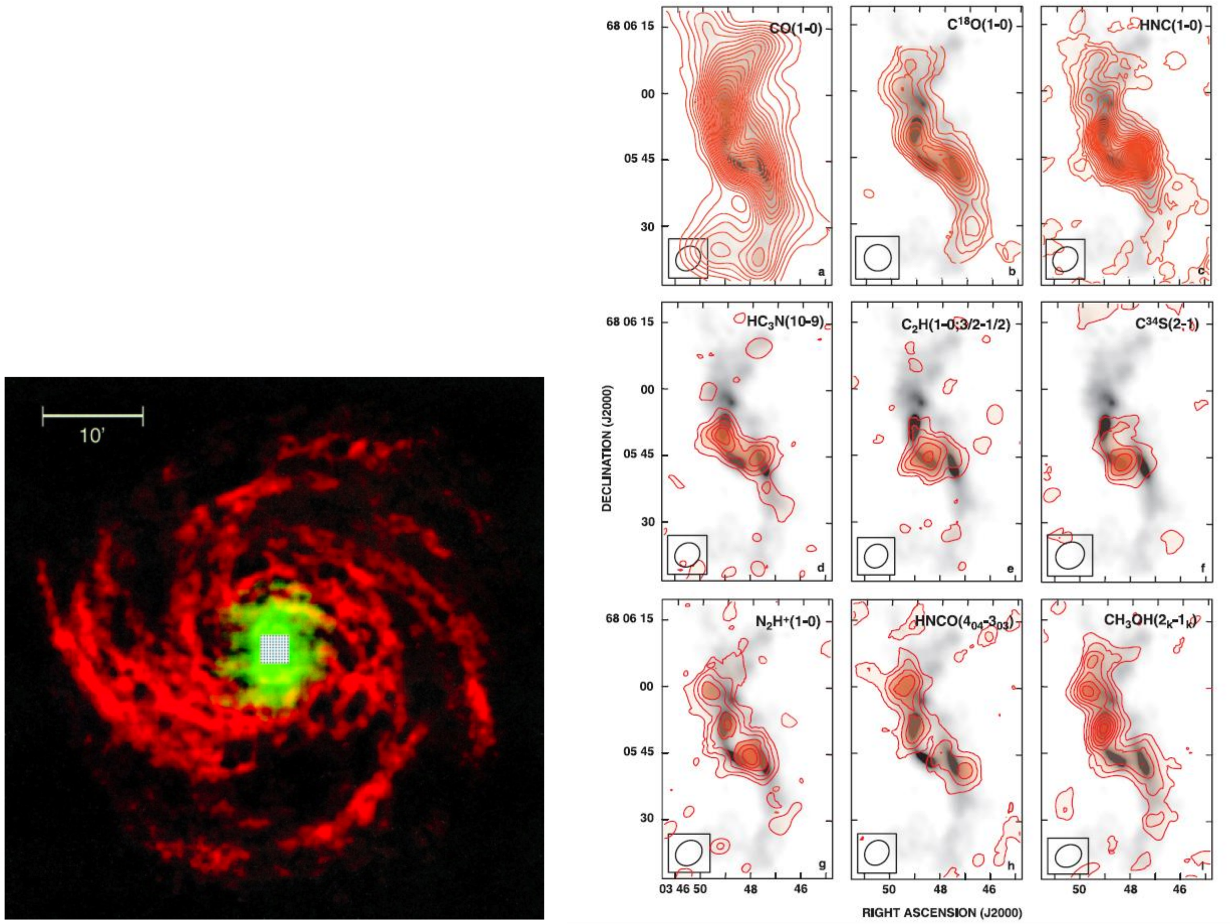

Fig. 6.— (Left) An image of the nearby starburst galaxy IC342 in ^{12}CO (green) and HI (red) with the footprint of the 100 element W′-FPA shown in white. (Right) The integrated intensities of nine tracer molecules observed within the central regions at a resolution of 5″ (Meier & Turner 2005). The GBT would have sufficient resolution to study the large-scale molecular variations in nearby galaxies.

shocks induced by internal galaxy dynamics (bars, spiral arms) and external interactions. Photo-dissociated region (PDR) tracers can identify massive star formation/molecular gas interaction sites, and many other quiescent and ionization tracers (such as HCN, HNC, HCO+ and N2H+) can be used to characterize the ambient dense gas properties away from shocks and massive star forming regions.

A large inventory of mapped species will allow several important questions to be addressed 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 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?

For nearby galaxies (D $<$ 5 Mpc), the $8''$ beam ($<$ 100 pc) of the GBT will be sufficient to separate individual GMCs. The resolution of GBT is well matched to the ongoing VLA HI surveys at $6''$ resolution (THINGS, ANGST, and the local volume "LITTLE THINGS" survey) and the $\sim 6''$ CO interferometric SONG survey. In addition, th resolution of the GBT is well matched to the SINGS survey of local galaxies in the mid-infrared with the Spitzer 24μm band and the Herschel KINGFISH survey of local galaxies in the the far-infrared bands (70, 100μm at 6–$8''$ resolution). The combination of these data will not only provide a basic inventory of the gas and dust at different densities and temperatures as a function of galaxy type and environment, the matched-resolution data will provide insight into the mechanisms whereby the gas and dust is transferred between the neutral and molecular gas phases of the ISM and provide estimates of the lifetimes of molecular clouds and star formation efficiency.

2.4.2. Galaxy Clusters

Cold molecular gas has been detected in several cooling flow clusters containing large optical H-alpha filaments and structures (Edge 2001; Salome & Combes 2003). The early interferometer observations suggest peculiar CO morphology and dynamics (Edge & Frayer 2003; Salome & Combes 2004), and the derived CO gas masses are consistent with the amount of mass expected from the X-ray data. Salome et al. 2006 have mapped the Perseus cluster in CO(2-1) with the HERA multi-beam array on the IRAM 30m. These observations show molecular gas extended over $2'$, which is ideally suited for W$'$-FPA observations. By mapping large areas of clusters with the GBT, we can study the cold ISM/IGM and the associated star formation within cluster environments. Studies of galaxies in groups and clusters suggest that frequent collisions and ram pressure stripping 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, revealing the recent mass accretion history and cooling flows within the clusters. Studies at moderate redshifts will provide insight into the evolution and formation of clusters.

2.4.3. Low Surface Brightness Galaxies and Low Metallicity Galaxies

Given their diffuse nature, low surface brightness galaxies (LSB) are difficult to study in CO and would benefit greatly from very sensitive single-dish observations (e.g., O'Neil, Chinnerer, & Hofner 2003). 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 spiral galaxies. The typical HI sizes of the LSBs are of order a few arcminutes which would be well matched to the GBT W′-FPA .

In contrast to the LSB galaxies which seem to lack significant ongoing star formation, many dwarf galaxies contain active starbursts, but they appear under-evolved in comparison to local spiral galaxies given their low metallicity. Dwarf irreglar galaxies have typical metallicities of about 10% solar and are local templates for studying chemically young galaxies whose properties are thought to be similar to galaxies forming in the early Universe. Although CO is "under-luminous" in metal-poor systems (Wilson 1995), the ^{12}CO line still provides the best constraints on amount of molecular gas in these systems.

2.4.4. Distant Galaxies

Large samples ULIRGs and LIRGS have been uncovered by the Spitzer and Herschel surveys over a wide-range of redshifts and could be targeted in the bright CO and HCN transitions with the GBT W′-FPA . Sources at $z < 0.37$ could be observed in fundamental CO(1-0) transition which measures the total amount of molecular gas. Studying sources at these intermediate redshifts is crucial in understanding the strong evolution of the galaxies from today to $z = 1$ (e.g., Magnelli et al. 2009). Objects at higher redshifts could also be studied using the higher-J CO transitions to help constrain the evolution of molecular gas in galaxies across cosmic time. In practice, the GBT W′-FPA contribution to the study of molecular gas in high-redshift galaxies may be limited. The detection of faint broad lines from high-redshift galaxies may require a nutating tertiary which is currently not available for the GBT.

3. Discussion

The specifications of the instrument are provided in FPA Memo #F0002 (Frayer & O'Neil 2011). We discuss some of the key items related to these specifications here.

3.1. High-Frequency Coverage

Although the performance of the GBT and the atmosphere degrades significantly above above 110 GHz, the high end of the band is crucial for traditional ISM studies within our Galaxy and nearby galaxies. The CO lines (C^{18}0 at 109.782 GHZ, ^{13}CO at 110.201 GHz, C^{17}O at 112.359 GHz, and ^{12}CO at 115.271 GHz) are key for molecular gas studies.

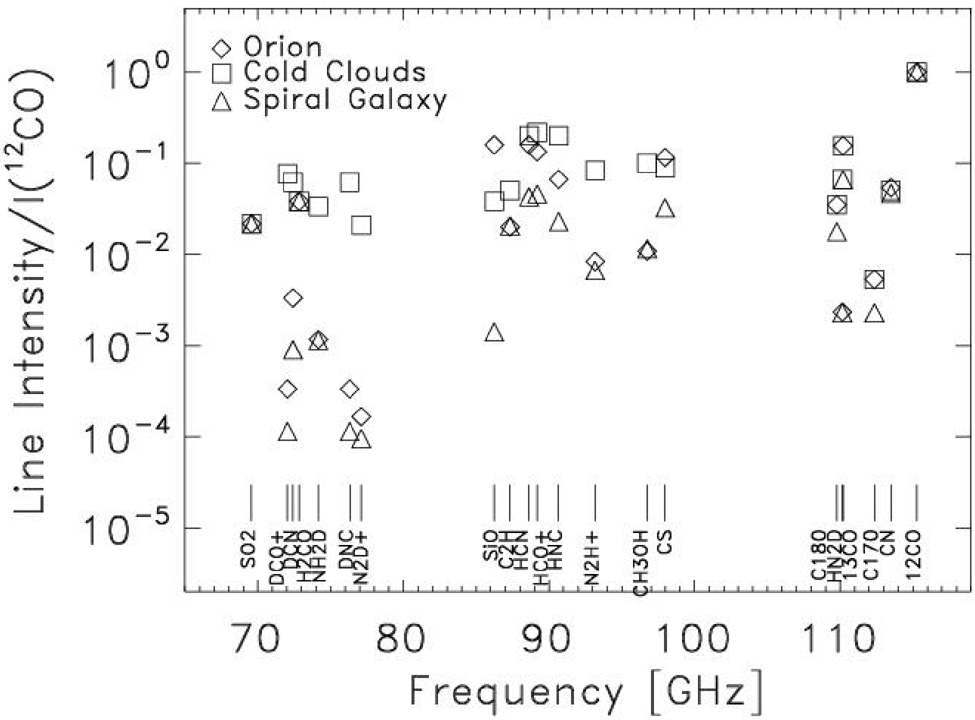

Fig. 7.— Estimated line strengths of Orion, cold cloud cores, and normal spiral galaxies normalized to ^{12}CO(1-0). Although the deuterium species and the N2H+ transitions are greatly enhanced in cold cloud cores, the CO, HCN, and HCO+ transitions are among the brightest lines over a wide-range of astronomical conditions.

The ^{12}CO line is by far the strongest line, and observers use the CO isotopes to probe deeper into complex regions which allow for radiative transfer calculations that provide better measurements on the total amount of molecular gas. Given the relative brightness of ^{12}CO is typically at least 5 times brighter than any other molecular line (Fig. 7), ^{12}CO is by far the most sensitive tracer for detecting faint levels of molecular gas in emission. Hence, it is important to at least provide the opportunity for ^{12}CO observations with the instrument.

3.2. Size of the W′-FPA

The science targets, both galactic and extragalactic, are well suited for mapping with a W′-FPA footprint of a few arcmin in size. The baseline plan of 100 elements would be about 2.5–4′ on the sky (depending on horn spacing). Smaller arrays would take longer to map the typical targets and much larger arrays would be inefficient for mapping sources smaller than the array.

3.3. Optimization at 90 GHz

The brightest key dense gas traces are located near 90 GHz (HCN, HCO+, HNC, and N2H+). These lines are crucial for studying the dense condensations of molecular gas associated with star formation within our Galaxy and nearby galaxies. The performance of the telescope is best at 90 GHz and below, so optimization is planned for about 90 GHz.

3.4. Matching the ALMA Band-3 Frequency Range

It is not a coincident that ALMA Band-3 as well as nearly all other 3 mm facilities cover the 84–116 GHz frequency range. This window contains the brightest astronomical lines from SiO(2-1) at 86.243 GHz to CO(1-0) at 115.271 GHz; this window also includes the important HCN, HCO+, N2H+, CS(2-1), $C^{18}O$, ^{13}CO, and CN lines. By matching the ALMA Band-3 frequency range, the GBT W′-FPA can provide complementary single-dish maps for any transition available with ALMA and help guide ALMA follow-up high-resolution imaging of interesting targets/species uncovered by wide-area imaging with the GBT W′-FPA .

There are several lines of astronomical interest below 80 GHz, in particular the deuterium species in cold cloud cores, which will not be observable with the W′-FPA , but these lines are generally fainter than other species. The W′-FPA will be used for wide-area mapping of the brightest astronomical lines. The fainter transitions at lower frequencies can be observed in deep targeted surveys with the GBT 4 mm receiver. If ultra-wide bandwidth front-end components become feasible (e.g., ALMA Band-2+3, 70–115 GHz), then the W′-FPA could be designed to work at lower frequencies.

4. The Weather

Based on the weather statistics at Green Bank over the last 5 years, there are 1000 hours available per year at Green Bank with excellent conditions ($\tau < 0.1$ at 90 GHz and with low winds; Lockman & Maddalena 2010, GBT Memo#267). With the planned upgrades in the servo system and using the quadrant corrections for the feed-arm motions, we expect to achieve about 1–1.5″ pointing reconstruction errors even in moderate winds, which will be sufficient for 3 mm mapping experiments. In principle, up to about 3000 hours of acceptable 3 mm conditions ($\tau < 0.2$ at 90 GHz) exist on average every year at Green Bank (i.e., about 30% of the total year).

The weather predictions based on R. Maddalena's modeled calculations have proven very robust, and the Dynamical Scheduling System (DSS) makes use of these predictions to successfully schedule high-frequency programs in periods of good weather. In 2009, the DSS scheduled 2000 hours of projects at 18 GHz or higher frequency out of a possible 3000 hours with good weather. In 2009, the DSS was limited in scheduling high frequency observations due to the numerous fixed-time programs carried out GBT (e.g., VLB, pulsar monitoring, targets of opportunity).

5. Concluding Remarks

The W′-FPA on the GBT will be a transformational instrument for the investigation of the properties, processes, and astrochemistry associated with molecular clouds and star formation within our Galaxy and nearby galaxies. The wide-area surveys enabled by the W′-FPA will probe the key large-scale processes associated with star formation in the Galaxy and will uncover the locations of thousands of proto-stellar cores. The GBT W′-FPA will provide complementary single-dish maps for any transition available with ALMA Band-3 and will guide follow-up ALMA high-resolution imaging of interesting targets discovered by the wide-area imaging with the GBT. Studies of comets and searches of organic molecules within the ISM with the W′-FPA will address important issues related to the origin of life. Extragalactic observations of CO and the dense gas tracers of HCN and HCO+ will constrain the evolution of galaxies, and detailed imaging of various molecular transitions within nearby galaxies will provide a baseline of knowledge that may be applied to our understanding of young galaxies in the early Universe.

We acknowledge the significant efforts that have gone into the previous 3 mm receiver NRAO proposals. Significant portions of the W′-FPA science case is taken from the science cases presented previously by Jewell et al. (2000), Ott et al. (2007), O'Neil et al. (2010), & Frayer et al. (2010).

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