Science Case for a K-Band Focal Plane Array for the Green Bank Telescope

Contributed to by Larry Morgan, D.J. Pisano, Jay Lockman, James Di Francesco, Jeff Wagg, & Jürgen Ott

9/24/2007

Executive Summary

A 7 pixel K-band focal plane array on the GBT will enhance its position as the premier telescope in the world operating between 18-26 GHz. It will provide the means to reveal both the masses and dynamics of starless cores in large samples, and thus give key insights into the origin of stellar mass, using temperatures and line velocities derived from NH_3 observations. A 7 pixel array will yield almost an order of magnitude increase in efficiency when mapping at K-band. This increase would, in turn, allow a large number of cores in nearby star-forming regions, already located from submillimeter continuum surveys, to be studied. The proposed array's angular extent is well matched to the sizes of core-bearing filaments in the Gould Belt clouds. The resolution of the GBT at 24 GHz is equivalent to the Jeans length of gas at 10 K and 10^6 cm^{-3} towards the nearest molecular clouds at 125 pc (i.e., Taurus and Ophiuchus), allowing turbulent fragmentation to be directly probed; more distant clouds can benefit from combination with EVLA data to reach such resolutions. Of all single-dish K-band telescopes in the world, only the GBT with a multi-pixel array has the resolution and sensitivity to make large-scale observations of NH_3 across populations of starless cores needed to understand the origins of stellar mass and dynamical motions. The array will also study the earliest stages of star formation in infrared dark clouds and starless cores. It will study bright-rimmed clouds, which may be examples of triggered star formation. And it will be useful for chemical studies of star-forming regions and the Galactic Center.

The proposed array will not just study star formation, it will study the molecular gas content of SMGs in galaxy clusters at z$\sim$4. Such observations will serve to confirm the association of the SMGs with the cluster and shed light on the role of mergers in driving activity in radio galaxies. The large bandwidth and areal coverage provided by the GBT make it ideal for such studies. This array will also make surveys of masers in Local Group galaxies far more efficient.

Equipping the GBT with a K-band focal plane array will complement the capabilities of the EVLA by providing the context for higher angular resolution studies with the latter. The GBT will also provide short spacing data for

EVLA observations to provide a complete picture of molecular emission at all spatial scales. The GBT is already the premier telescope at K-band and is vastly oversubscribed given the available time at these frequencies. By adding a focal plane array, we will increase the scientific output of the GBT and make it an ideal telescope for surveys at 18-26 GHz. With a full 61 pixel focal plane array, the GBT will be able to map the sky, at these frequencies, almost an order of magnitude faster than any other telescope in the world.

Background

The advent of focal plane arrays on single dish telescopes has opened up new areas of research, as demonstrated most recently with the Parkes 13-beam array at L-band, the FCRAO Sequoia 32-beam array at 85-116 GHz and SCUBA at the JCMT. A focal plane array for the GBT which covers the important, and heavily over-subscribed, 18-26 GHz band will likewise provide new capabilities. A K-band feed horn array could have many tens of elements in the GBT focal plane without any mechanical issues and a gain loss of roughly 10% at the outermost feeds. The HPBW of each pixel would be $30''$ and the beams would be spaced every $\sim$3 HPBW. For a prototype 7 pixel array, this would cover a 1.6 square arcminute area, while for a full 61 pixel array it will cover 14 square arcminutes. The GBT is already the premier telescope at this frequency, and operates at high efficiency, so an array could be put into operation without requiring improvements in telescope performance. This array would be the prototype for a series of GBT focal plane arrays at other wavelengths and could be a technological pathfinder useful to SKA development.

A K-band focal plane array would have an immediate impact on GBT science:

- It will speed up many observations by more than an order of magnitude, thus allowing experiments to be done which could never, in practice, be scheduled with a single pixel receiver.
- It will make the most efficient use of the restricted observing time available at low declinations, e.g., toward the Galactic center and inner Galaxy.
- It will make the most efficient use of good weather conditions at Green Bank.
- It will allow for more serendipitous discoveries by increasing the area of maps.
- It will improve the calibration of maps as the atmospheric conditions will be similar across the field at any instant.

For 2007, 767 hours were requested for K-band mapping projects in response to calls for GBT proposals; this is 300 hours more than in any other band and most could not be scheduled. With the proposed array in operation, more of this demand could be satisfied greatly improving the GBT's scientific output.

Three Key Projects

I. How are stars assembled?

The way in which stars are assembled from the interstellar medium and how their final masses are determined have been a long standing cause for debate. These questions remain among the major unsolved issues in modern astrophysics.

Stars have a regular, near-universal mass distribution. This distribution, also known as the Initial Mass Function (IMF), has a peak around $M \sim 0.3$ $M_\odot$ and at higher masses the distribution falls off as a power-law of $dN/dM \propto M^{-1.35}$ (Salpeter 1955). After more than 50 years of study, an observational clue to the origin of the IMF has finally come as large-format arrays like SCUBA have been able to map submillimeter emission at high resolution over large areas of nearby star-forming regions. These observations have uncovered populations of starless cores that appear to have mass distributions that are very similar to that of the IMF, suggesting a link between core formation and stellar mass. Only a few cores have been found in these clouds, so the similarity of the core mass distribution to the IMF remains formally uncertain. Furthermore, connections between potentially significant variations in the core mass distributions and the parent cloud properties have not yet been explored.

Next-generation submillimeter instruments will be able to detect large numbers of starless cores in nearby star forming clouds, given their larger fields and greater intrinsic sensitivities. These instruments include SCUBA-2 on the JCMT, which will map 850 μm and 450 μm emission at 10-15$''$ FWHM resolution, and SPIRE on the Herschel Space Observatory (HSO), which will map 250 μm, 360 μm, and 520 μm emission at 15-30$''$ resolution. Indeed, dedicated surveys have been approved on both the JCMT and the HSO that will observe all ~15 nearby star forming molecular clouds, revealing hundreds (if not thousands) of starless cores. These surveys, the "JCMT Nearby Star Formation Legacy Survey" and the HSO "The Origin of the IMF" Guaranteed Time Key Project, will likely begin in 2008 and 2009 and continue for 2-5 years and 1-2 years, respectively. These surveys are sometimes referred to as "Gould Belt" surveys after the location in the sky of most molecular clouds at distances < 500 pc. By uncovering statistically significant numbers of cores, the data from the Gould Belt surveys have the potential to settle the question of whether stellar mass is related to cloud properties.

A K-band focal plane array for the GBT will have unprecedented sky coverage, enabling the mapping of the regions pertinent to this problem. This has never before been possible due to the restrictively long observation times necessary. These maps will be at a higher resolution than that feasible with any other single-dish telescope (given the constraints of map size) and will probe the connection between core formation and stellar mass as suggested by, for example, Motte, André & Neri (1998), Johnstone et al. (2000) and Motte et al. (2001).

Despite the larger samples of cores expected from the Gould Belt surveys, uncertainties will remain that require complementary data. The temperatures of these cores will be poorly constrained, especially if they are cold and the peaks of their spectral energy distributions are poorly sampled by the continuum observations. Such temperatures are vital to determine mass accurately since submillimeter continuum emission depends not only on column density but also on temperature. NH_3 observations from the GBT can provide the means to determine the temperatures of these cores, allowing the origins of the IMF to be understood. Comparison of the (1,1) and (2,2) lines of NH_3 is an excellent means of directly measuring the kinetic temperatures of dense gas (Ho & Townes 1983), particularly in cold (< 20 K) regions. The proposed array will also be capable of observing lines up to the (6,6) rotational transition of NH_3, necessary for the determination of temperatures above $\sim$ 30 K. NH_3 will be the most relevant molecule for these array observations as it is a nitrogen bearing molecule, which is far less prone to depletion onto dust than CO (Aikawa, Ohashi and Herbst 2003). Present GBT capabilities, however, make NH_3 observations of such cores (which are more extended than the $33''$ beam size of the GBT at 24 GHz) prohibitively time consuming. A focal plane array will make such surveys feasible.

II. The Role of Turbulence in Star Formation

Dynamical theories of star-formation rest upon the relative importance of gravoturbulent motions and/or driven turbulence. The interplay between gravitational forces and supersonic turbulence potentially controls many stages of star-formation, providing stability on large scales and initiating collapse on small scales (e.g., Larson 2003 and Mac-Low & Klessen 2004). The internal dynamics of molecular clouds may be traced by molecular transitions observable with the K-band focal plane array. The relative importance of the different physical processes in cloud dynamics and star-formation is still highly contentious. Observations with the K-band focal plane array will establish the true importance of turbulence in these regions and determine the nature and origin of its effects.

Continuum observations do not satisfactorily probe the non-thermal, turbulent motions associated with dense gas. Such information can come from observations of molecular lines, but dense gas in cold cores (i.e., $n > 10^4$ cm^{-3} and $T < 20$ K) is difficult to trace with common molecules like CO or its isotopologues, like ^{13}CO, since these can be significantly depleted onto the surfaces of dust grains in such environments (see Tafalla et al. 2002). Ammonia, again, is the solution: the NH_3 lines provide an ideal probe of turbulence in dense, star-forming regions.

With temperatures determined directly from observations of NH_3 itself, the non-thermal, turbulent components of the NH_3 line widths can be immediately determined, yielding a direct probe of the role of turbulence in core formation (Friesen et al. 2007, in prep.). Comparison of the (1,1) and (2,2) transitions yield detailed temperature maps of large molecular clouds possible (see Fig.1). Once accurate temperature information has been gained then the degeneracy between high temperature - low density and low temperature - high density states as derived from linear molecules may be broken and density maps may

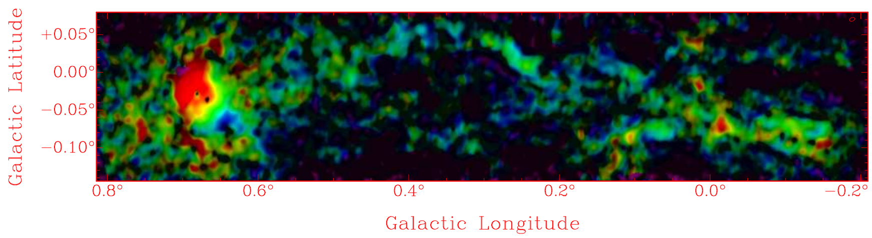

Figure 1: Kinetic temperature map of cold gas via NH_3 (1,1) and (2,2) transition observations in the Galactic Center Sgr A* to Sgr B2 region. Image courtesy J.Ott

be produced.

Non-LTE effects, turbulent bulk motions, and systematic motions such as infall and outflow may all be traced and even differentiated by careful analysis of the single (1,1) ammonia transition. The hyperfine structure evident in observations of the rotational transitions (Fig.2) shows, in its asymmetries, the prevailing physical processes (Park 2001;Longmore et al 2007). Besides tracing signatures of the dynamic processes occurring within the region, such direct measures of a molecular cloud's temperature and density may completely define the cloud's physical conditions.

III. Tracing the formation of galaxy clusters through observations of the molecular gas in cluster members

In order to study the first coherent large-scale structures in the Universe, many studies have focused on pointed sub-mm/mm-wavelength surveys toward 'signposts' of overdense regions, mainly those high-redshift radio galaxies suspected of being near the centers of early proto-clusters (e.g. Stevens et al. 2003; Greve et al. 2007). The 'negative K-correction' to the sub-mm/mm flux density of the sub-mm/mm galaxies (hereafter SMGs) identified in such surveys, results in a nearly constant flux density for a single object over redshifts z ∼1–10. Therefore, observations at sub-mm/mm wavelengths are ideally suited for identifying high-redshift clusters. Indeed, early imaging studies have identified an excess of SMGs within the central few square arcminutes of the radio galaxy fields, suggesting that some of these SMGs may be associated with the proto-cluster. Typically, redshifts for SMGs are obtained by optical spectroscopy of the proposed optical/infrared counterpart responsible for the sub-mm/mm emission, having been identified through radio-wavelength interferometry (e.g. Chapman et al. 2003, 2005). However, given the difficulty in using radio interferometry to identify optical/infrared counterparts, particularly for those objects at $z >> 3.5$, it is crucial that we explore alternative means of estimating redshifts for the sub-mm/mm luminous galaxies in these fields, and ultimately confirm their cluster membership.

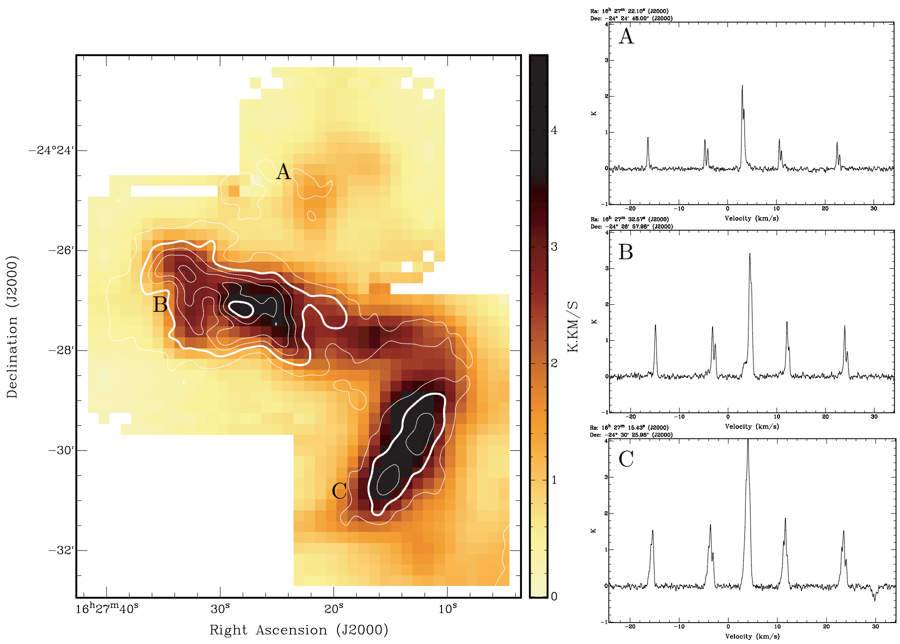

Figure 2: Map of NH3 (1,1) integrated line intensity (color scale) across the Ophiuchus B star- forming complex in L1688 by Friesen et al. (2007, in preparation), obtained with the current GBT K-band receiver system. Contours show levels of associated 850 micron thermal continuum emission from dust. The letters denote the cores associated with the respective examples of NH3 (1,1) spectra shown at right; the spectra were obtained at positions of maximum integrated line intensity. This map needed 31.5 hours of GBT time spread over 8-10 observing blocks with the current K-band system. A 7 pixel K-band array could observe a similar $8' \times 8'$ field in only $\sim$5 hours. Given that different parts of the core were observed during different nights in different atmospheric conditions, sensitivities vary by a factor of $\sim$1.5 across the map. A 7 pixel K-band array will map this region in one transit, reducing sensitivity variations. A 61-pixel K-band array would cover roughly a $10' \times 10'$ area in one footprint, slightly larger than the region shown. Such an array would reduce the observing time over this region to $\sim$1 hours, again assuming similar K-band receiver performance and single-pixel coverage per sky position. Note that the L1688 complex of cores is larger than the map shown here by a factor of $\sim$20, and would require 600 hours to be mapped with a single pixel receiver.

The low-J molecular CO line luminosity (J=2-1, 1-0) in star-forming galaxies is believed to be a good indicator of their total molecular gas masses, and is found to correlate weakly with their far-infrared luminosities out to high-redshift (e.g. Riechers et al. 2006). At redshifts, $z \gtrsim 3.5$, CO J=1-0 line emission has been detected only in extremely luminous quasars and radio galaxies, whose redshifts were measured previously using optical spectroscopy (e.g. Papadopoulos et al. 2001; Carilli et al. 2002; Greve et al. 2003; Klamer et al. 2005; Riechers et al. 2006). In such cases, single/dual-beam receivers on large single-dish cm-wavelength telescopes could be tuned to the correct frequency in order to ensure that the intensity in the CO line is constrained. Such a selection criteria for CO follow-up observations of $z \gtrsim 3.5$ objects could easily introduce a bias in our understanding of the molecular gas content in these young galaxies, and it is paramount that wide-area CO surveys of larger samples be conducted. A K-band focal plane array on the GBT would be ideally suited for such surveys.

The proposed 7-element K-band focal plane array used with the existing spectrometer would produce spectra covering 50 MHz if the signal from all 7 beams were processed. Given the broad widths of CO lines in high-redshift objects (∼300–600 km/s) and the typical velocity difference between the optical/infrared and molecular CO emission lines (∼500 km/s), larger bandwidths are better suited for studies of these objects, and so processing of only 4 beams with 800 MHz bandwidths is adopted for the following example.

Consider the case of 4c41.17, a radio galaxy at $z = 3.8$ which is believed to reside within a large galaxy overdensity indicated by observations at X-ray to radio wavelengths (Dey et al. 1997; Smail et al. 2003; Stevens et al. 2003; Scharf et al. 2003; Reuland et al. 2003; De Breuck et al. 2005; Greve et al. 2007). In particular, mm-wavelength surveys of this field have revealed a significant excess of SMGs over that expected from blank-field mm-wavelength surveys (Greve et al. 2007; Hughes et al. *in prep.*), suggesting that increased merger activity in the proto-cluster region is triggering higher star-formation rates (and hence higher far-infrared luminosities) in a fraction of the SMGs selected by these surveys. Indeed, Greve et al. (2007) find that while some of the SMGs in this field are confirmed (via optical spectroscopy) to be foreground objects, the mm-to-radio spectral indices for many are consistent with these being at $z \gtrsim 3$, and their optical/infrared counterparts are too faint for optical spectroscopic redshifts. Given the redshift of this proposed overdensity ($z \sim 3.8$), the CO J=1-0 line is redshifted to K-band frequencies (∼24 GHz), so that a survey of this field with the K-band focal plane array would have the potential to confirm an overdensity of far-infrared luminous starbursts in this proto-cluster, through detection of CO J=1-0 line emission in cluster SMGs.

In addition to obtaining redshifts, such observations would also provide estimates for the molecular gas masses, a crucial quantity in the study of the star-formation process at high-redshift, and also the dynamical masses of these systems derived from the CO line width. Figure 3 shows a simulation of a $4' \times 4'$ survey of the 4c41.17 field observed with the 7 pixel focal plane array. CO J=1-0 line emission is clearly detected in a number of SMGs associated with the 4c41.17 proto-cluster. Such a survey would require ∼120 hours of observing time. With the full 61 pixel array (which requires a new spectrometer as well), this map could be made in ∼10 hours.

The potential impact of a GBT K-band focal plane array on studies of high-redshift proto-clusters ($3.3 \leq z \leq 5.4$) would be enormous. A number of potential

SMG overdensities have already been identified in the fields of z $\gtrsim$ 3.5 quasars and radio galaxies, and redshift information for these proposed proto-cluster members is the crucial element needed before the field may advance.

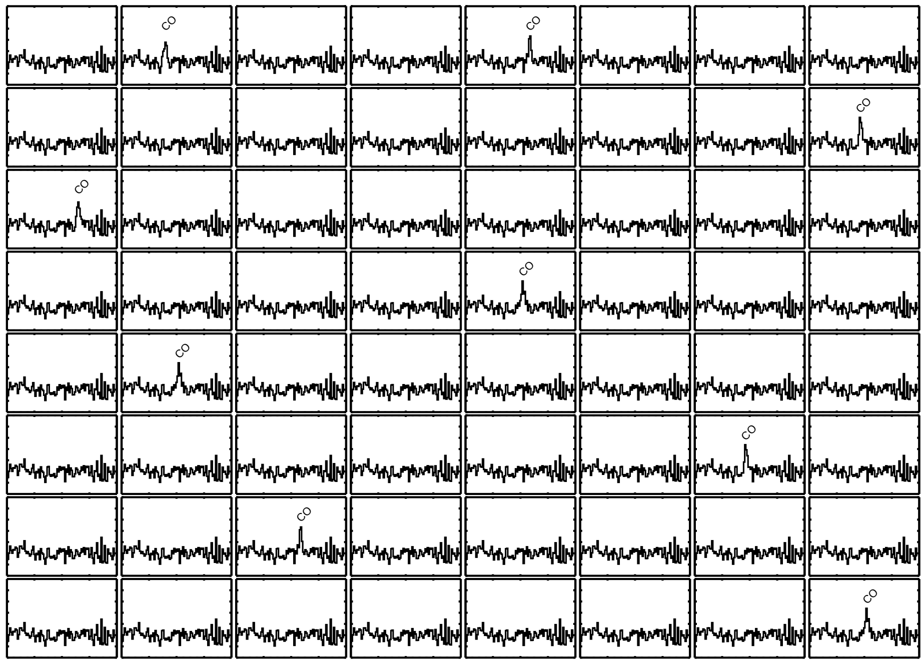

Figure 3: A simulated K-band focal-plane array observation covering 16 square arcminutes toward the 4c41.17 z $\sim$ 3.8 proto-cluster field. Each spectrum covers the frequency range, $23.6 \leq \nu \leq 24.4$ GHz, while the flux scale ranges from -100 μJy to 500 μJy. The rms per 100 km/s channel is 50 μJy

Additional Science Projects

The science possible with the 7 pixel proposed array is not limited to the primary drivers mentioned above. Examples of other science that would be enabled by an instrument like this include:

Infrared Dark Clouds

Infrared dark clouds (IRDCs) are seen in silhouette against the 8-micron Galactic plane background and are cold and dense (see Fig.4). Some have structures which are likely pre-stellar cores in the earliest phase of stellar evolution. More than ten thousand IRDCs have been detected and cataloged in the infrared (Simon et al. 2006). The Spitzer GLIMPSE observations have revealed a great number of previously unknown young stellar objects (YSOs) within IRDCs and point toward a redefinition of IRDCs as the earliest stages of star-formation. The typical angular size of an IRDC is $1'$- $5'$, well matched to the size and coverage of the proposed array.

Maps of IRDCs in molecular tracers can determine the temperature, density, and large-scale kinematics in these important clouds. H_2O and methanol masers can mark the location of protostars. There are already a number of GBT proposals to do this research and the number is likely to grow in the future. The majority of the IRDCs are in the inner Galaxy and can be observed only for a limited time each day. A K-band focal plane array will make large area surveys of IRDCs feasible with the GBT.

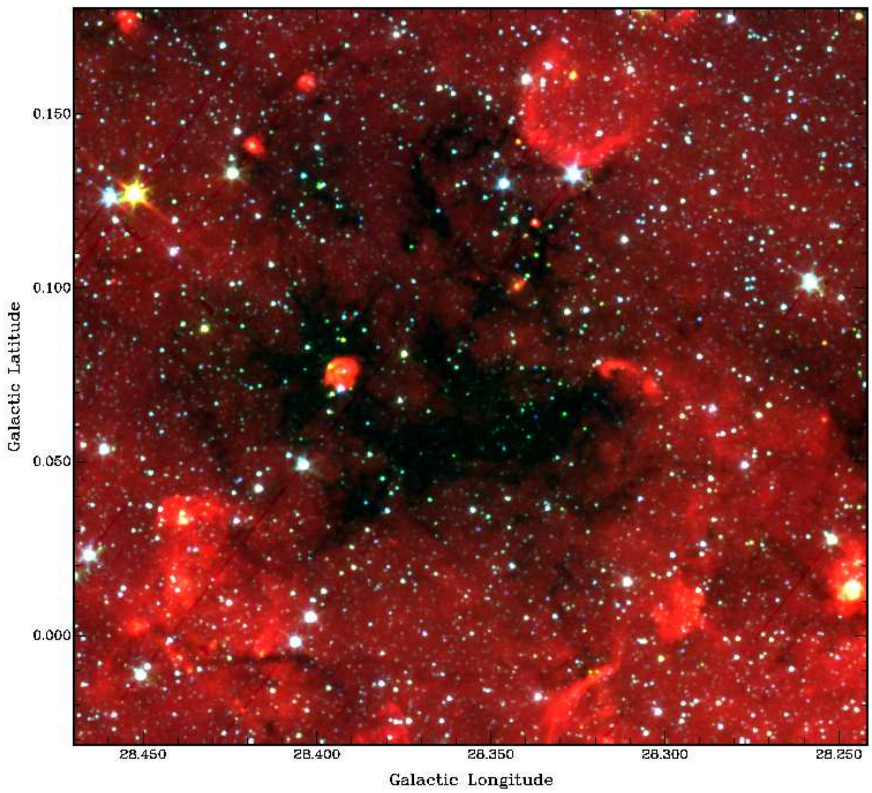

Figure 4: Spitzer GLIMPSE map of the IRDC G028.37+00.07 This image is $\sim 13' \times 13'$. The full 61 pixel K-band focal plane array would have a footprint of $\sim 12' \times 12'$.

Starless Cores

Dense molecular cores are the link between protostars and the more diffuse material in molecular clouds. Starless cores define the fundamental starting point of stellar evolution. Their study can reveal the conditions necessary for the final collapse of a molecular cloud, and may help us understand how stars form in clusters. There is no single type of observation that gives all of the important physical characteristics of a dense core, but with measurements of molecules such as NH_3 and CCS, the density and temperature in the cores can be determined as well as the proportion of thermal and turbulent motions. There are many nearby starless cores whose angular sizes are many arcminutes, ideal for study with a K-band array on the GBT.

Bright-Rimmed Clouds

Dense molecular regions at the edges of HII regions undergo photoionization and, potentially, shocks as a result of the pressure gradient created. These regions are currently the best candidates for triggered star-formation, whether by the process of radiative-driven implosion (RDI) (Bertoldi 1989;Lefloch & Lazareff 1994, 1995) or the 'collect and collapse' method proposed by Elmegreen & Lada (1977). A full census of star-formation within these clouds has only recently been completed (Morgan et al. 2007) and suggests different formation mechanisms for YSOs subject to high ionization fields as compared to isolated star-formation regions. The identification of a particular YSO as being the result of *triggered* star-formation is extremely difficult and requires detailed, complicated modeling. Maps of chemical abundance variations across these clouds can age the material and confirm or contradict theories of triggered star-formation processes. Recent observations show similarity between molecular distribution and the RDI models of Lefloch & Lazareff (1994) (Fig.5). Because the angular sizes of these regions are large, these observations are extremely time-consuming. Previous studies are limited, therefore, to a small number of objects. Studies of triggered star-formation are hampered by the small number of well studied potential regions; a K-band focal plane array for the GBT would be the ideal instrument to characterize chemical abundances across these clouds, typically $\sim 5'$ in extent, and thus place restrictions upon the timescales of dynamical interactions in regions incorporating ionized gas, PDRs and molecular material varying by as much as 5 orders of magnitude in density.

Chemistry

In addition to ammonia, the array will be ideally suited to mapping distributions of CCS, a molecule found to be anti-correlated in position with ammonia. Because of the ease with which CCS is dissociated and depleted it serves as a chemical 'clock', which, when compared to the 'old' molecule of ammonia can age regions as a function of spatial position. Ammonia often traces dense regions typically older than 10^5 years in the star-formation timescale, while CCS begins

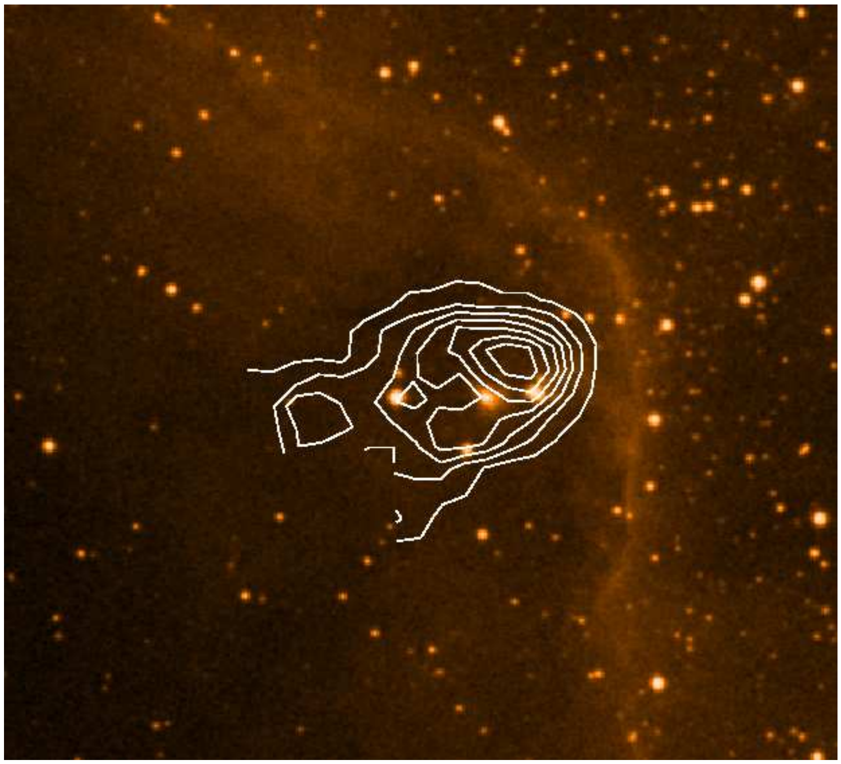

Figure 5: DSS image of the bright-rimmed cloud SFO 14 with overlaid contours of integrated ammonia (1,1) emission mapped with the GBT. Courtesy of L.Morgan

to disappear at around the same period. This fact means that the combination of the two lines serves as a very effective probe of the age and conditions within YSOs. When both molecules are detected within the same region, they provide information on the dynamics of a region; for example, by tracing differential rotation within molecular cores.

In addition to the exceptional usefulness of the CCS and ammonia molecules, the 18-26 GHz range is host to a large number of chemical emission lines which are now only just beginning to be identified and understood. The GBT has led a renaissance in studies of interstellar organic molecules; seven new ones were detected in 2006 alone. These lines are extremely sensitive to external conditions and so may be missed in single pointing observations. The proposed array will be able to map large areas of nearby molecular clouds, such as TMC-1, searching for chemical reservoirs that can serve as standards for understanding interstellar chemistry. It can be used to search for new molecular species in multiple points on a molecular cloud simultaneously. Many of the more complex and more interesting organic "pre-biotic" molecules are now known to be in extended regions whose line emission is quite weak. They thus require filled apertures like the GBT for their study, but the long integration times needed for a secure detection precludes mapping their distribution. Also, there are now detailed time-dependent chemical models of molecular clouds which make specific predictions about the abundance of particular species with position within a cloud as it evolves. Maps in multiple species are necessary to test the chemical formation models, which at this date are still quite incomplete.

Highly Redshifted Molecular Lines

Using the K-band array to map clusters of galaxies at z∼3.4-4.5 has been previously discussed, but such an array will also benefit the study of isolated point sources. By cycling through different beams of the array, a longer time is spent off-source for a given on-source integration time. For a redshift search over with an 800 MHz bandwidth, four beams can be used. This will improve the effective integration time by 50% for a given elapsed time yielding 20% better sensitivity and improved baselines (e.g. Zwaan et al. 2004).

The Galactic Center

The Galactic center is a rich environment for studies of everything from conditions around a black hole, to the dynamics of gas in a bar, to astrochemistry. The region of interest extends over several square degrees within which there are large variations in molecular abundances and chemical complexity. The gas dynamics and molecular chemistry seem to be coupled, implicating shocks. Because of the extraordinarily large area and weakness of many of the lines, the Galactic center area remains relatively unexplored. Due to the limited observability of the Galactic Center with the GBT, progress will be possible in K-band tracers only with a focal plane array.

Searching for Water Masers in Nearby Galaxies

Astronomers will be able to search for water masers associated with star-forming regions in Local Group galaxies with better sensitivity and areal coverage than previously available. Brunthaler et al. (2005,2007) have used water masers to measure the proper motions of IC 10 and M 33. These data constrain the dynamics and total mass of the Local Group.

Other Benefits of a GBT K-Band Array

Enhanced Productivity of the EVLA

We are now receiving a number of proposals to map molecular clouds in conjunction with the VLA. The GBT provides the overall context for the higher resolution data and in very many cases is critical for accounting for all of the line flux. While VLA observations are necessary to resolve fine structure in molecular clouds, these objects are so large that most molecular emission is resolved out by the interferometer (Devine, et al. 2006). There are examples where 90% of the molecular emission is simply not detected by the VLA (de Gregorio-Monsalvo et al. 2005). Indeed, even the kinetic temperature profile of small clouds cannot be derived correctly without short spacing data (Crapsi et al. 2007).

The GBT is also much more sensitive to low surface-brightness emission than an interferometer, and can detect faint extended emission. At K-band the VLA begins to resolve out structure on angular scales $2''$-$60''$ depending on the configuration, while its primary beam is $2'$. Use of the GBT with its $30''$ beam to supply short spacing data implies mapping, which is facilitated by a focal plane array.

A K-band array on the GBT will thus enhance the scientific productivity of both it and the EVLA.

The GBT: The Premier K-band Telescope

The GBT is the premier telescope for K-band observations. This is illustrated in Table 1. All of the data come from the web pages of the telescopes in question and apply to current capabilities (except for the GBT and the Sardinia 64m). In most cases, T_{sys} should be for median weather conditions, but may be low for observations at 22 GHz. Most telescopes have claimed typical winter opacities of 0.05 across the band. The median opacities for the GBT are 0.05 at 18 GHz, 0.2 at 22 GHz and about 0.1 at 26 GHz.

The signal-to-noise delivered by a telescope is inversely proportional to $T_{eff} = T_{sys}^2 e^{\tau}$. Since the opacities in K-band are less than 0.2 in median conditions, using T_{sys} in the calculations in Table 1 underestimates T_{eff} by less than 20%. Note that, with dynamic scheduling, observations with the GBT at K-band should only occur when the weather is in the top tenth percentile; in this case, the GBT's T_{sys} is 35 K. Even in median conditions, the GBT with a 7 pixel focal plane array will be faster than any other single-dish telescope in the world for point-source surveys. For extended sources, only Mopra and Sardinia are comparable and the GBT has far better resolution than either telescope (Sardinia is still under construction). With a 61 pixel focal plane array, the GBT will be almost an order of magnitude faster than any other telescope in the world. Note that all of the values in the table are for spectral-line observations assuming that each telescope has equivalent spectral resolution.

According to Condon & Balser (2007), only about 800 hours per year are suitable for observing at 22 GHz due to weather; this is less time than at any other frequency accessible to the GBT, including W-band. A K-band focal plane array maximizes the efficiency of the GBT during these conditions. Without such an array, the key projects described in this document would not be feasible.

References

Aikawa, Y., Ohashi, N., & Herbst, E., 2003, ApJ, 593, 906

Bertoldi, F. 1989, ApJ, 346, 735

Brunthaler, A., 2005, Reviews in Modern Astronomy, 18, 179

Brunthaler, A., Reid, M.J., Falcke, H., Henkel, C., & Menten, K.M. 2007, A&A, 426, 101

Carilli, C. et al. 2002, ApJ, 575, 145

Chapman, S. Blain, A., Ivison, R., & Smail, I. 2003, Nature, 422, 695

Chapman, S., Blain, A., Ivison, R., & Smail, I. 2005, ApJ, 622, 772

Condon, J.J. & Balser, D.S. 2007 DS Project Note 4.2

Crapsi, A., Caselli, P., Walmsley, M.C., & Tafalla, M. 2007, A&A, 470, 221

De Breuck, C., Downes, D., Neri, R., van Bruegel, W., Reuland, M., Omont, A., & Ivison, R. 2005, A&A, 430, L1

Devine, K. et al. 2006, IAU Symp 237, 102

Dey, A., van Breugel, W., Vacca, W.D., & Antonucci, R. 1997, ApJ, 490, 698

Elmegreen, B.G., & Lada, C.J. 1977, ApJ, 214, 725

de Gregorio-Monsalvo, I., Chandler, C.J., Gomez, J.F., Kuiper, T.B.H., Toerrelles, J.M., & Anglada, G. 2005, ApJ, 628, 789

Greve, T.R., Ivison, R.J., & Papadopoulos, P.P., 2003, ApJ, 599, 839

Greve T.R., Stern, D., Ivison, R.J., De Breuck, C., Kovacs, A., & Bertoldi, F. 2007, *arXiv:0707.4482*

Ho, P.T.P., & Townes, C.H., 1983, ARA&A, 21, 239

Johnston, S. & Gray, A., 2006, ATNF SKA Memo Series #3

Johnstone, D., Wilson, C.D., Moriarty-Schieven, G., Joncas, G., Smith, G., Gregersen, E., Fich, M., 2000, ApJ, 545, 327

Klamer, I.J., Ekers, R.D., Sadler, E.M., Weiss, A., Hunstead, R.W., & De Breuck, C. 2005, ApJ 621, L1

Larson, R.B. 2003, Reports on Progress in Physics, 66, 1651

Lefloch, B., & Lazareff, L.B. 1994, A&A, 289, 559

Lefloch, B., & Lazareff, L.B. 1995, A&A, 301, 522

Longmore, S.N., Burton, M.G., Barnes, P.J., Wong, T., Purcell, C.R., & Ott., J., 2007, MNRAS, 379, 535

Mac-Low, M.-M., Klessen, R.S. 2004, Reviews of Modern Physics, 76, 125

Morgan, L.K., Thompson, M.A., Urquhart, J.S., & White, G.J., 2007, A&A accepted

Motte, F., Andre, P., & Neri, R., 1998, A&A, 336, 150

Motte, F., Andre, P., Ward-Thompson, D., & Bontemps, S., 2001, A&A, 376, L41

Papadopoulos, P., Ivison, R.J., Carilli, C., & Lewis, G. 2001, Nature, 409, 58

Park, Y.-S. 2001, A&A, 376, 348

Reuland, M. et al. 2003 ApJ, 592, 755

Riechers D.A., et al. 2006, ApJ, 650, 604

Salpeter, E.E., 1955, ApJ, 121, 161

Scharf, C., Smail, I., Ivison, R.J., Bower, R., van Breugel, W., & Reuland, M. 2003, ApJ, 596, 105

Simon, R., Jackson, J.M., Rathborne, J.M., & Chambers, E.T. 2006, ApJ, 639, 227
Smail, I., Scharf, C.A., Ivison, R.J., Stevens, J.A., Bower, R.G., & Dunlop, J.S. 2003, ApJ, 599, 86
Stevens, J.A. et al. 2003, Nature, 425, 264
Tafalla, M., Myers, P.C., Caselli, P., Walmsley, C.M., & Comito, C. 2002, ApJ, 569, 815
Zwaan, M. et al. 2004, MNRAS, 350, 1210

Comparison of Telescopes at K-band

Telescope	T_{sys}[1] K	Gain K/Jy	HPBW[2] ″	FOV sq. arcmin	t_{int}[3]	SS_s[4]	SS_t[5]
GBT 100m with 7 pixel FPA	45	1.50	33	1.66	1.0	1.000	1.000
GBT 100m (current)	45	1.50	33	0.24	1.0	0.143	0.143
GBT 100m with 61 pixel FPA	45	1.50	33	14.5	1.0	8.714	8.714
Effelsberg 100m	74	0.84	40	0.35	8.6	0.024	0.078
Tidbinbilla 70m[6]	60	0.75	48	0.50	7.1	0.043	0.170
Sardinia 64m[7]	81	0.65	78	9.29	17	0.328	1.724
Parkes 64m[8]	140	0.17	78	1.33	753	0.001	0.082
Haystack 37m	120	0.15	72	1.13	711	0.001	0.096
Mopra 22m	45	0.07	120	3.14	460	0.004	1.889
(E)VLA 27x25m	65	1.90	0.1-3	3.14	1.3	1.453	0.0003
ATCA 6x22m	35	0.39	0.5-36	3.14	9.0	0.211	0.001

[1] median value at 24 GHz near to the main lines of ammonia
[2] The approximate half-power beamwidth at K-band
[3] The relative observing time to reach the same, single pixel, point-source sensitivity as the GBT; it is proportional to $(T_{sys}/\mathrm{Gain})^2$.
[4] The relative point-source survey sensitivity compared to the GBT. Calculated based on formula from Johnston & Gray (2006).
[5] The relative surface brightness survey sensitivity compared to the GBT. Calculated based on formula from Johnston & Gray (2006).
[6] Only three 600 MHz bands are available. There is limited astronomy time available.
[7] This telescope with 7 pixel focal plane array is due for completion in December 2008.
[8] Only the inner 45m is usable at these frequencies.