GBT MEMO 109

Long Millimeter-wave Science with the GBT

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CHARACTERISTICS OF THE SPECTRA OF MOLECULAR CLOUDS

The spectrum of molecular clouds is richest where the density exceeds about 10^4 particles cm^{-3}. At this density typical collisional rates begin to exceed radiative rates for typical electric dipole transitions. The regions of molecular clouds where densities exceed this value tend to be $\sim$ 0.1 pc in size. These regions are also the locale of star formation in the clouds; here we designate them 'cloud cores'. For frequencies above 15 GHz and cloud distances within 500 pc, the Green Bank Telescope (GBT) beam will resolve dozens of known cloud cores. At 49 GHz, many cores (in Ophiuchus, Taurus, and Orion, for example) will show emission over regions whose diameter will be more than one hundred beam diameters (θ=15"). There will also be many molecules whose emission will be visible over such regions. In this memo I consider possible receiver designs which could maximize the throughput of the telescope.

Many fairly abundant molecules are sufficiently excited for several transitions lying in the cm range to be fairly strong. Integration times can be very short–even seconds. Furthermore, for large telescopes, moving from point to point for mapping can be a major inefficiency factor.

Matching mapping observations of strong transitions with models will provide maps showing how temperature, density or molecular abundance varies within a cloud core. Intercomparison of these maps among the many nearby cloud cores will help to delineate the role of star formation in modifying the physical properties of the core, and vice versa. Such studies are of sufficient interest that there will be a strong demand on the GBT to carry them out. Because of the anticipated strong demand, NRAO will want to design the instrument to execute these studies efficiently.

Existing demand has motivated the world's observatories to design systems capable of multiplexing observations in different ways. At the NRAO 12m and the FCRAO 14m telescopes, multi-beam systems have been built to maximize throughput; similar systems are under study or construction at all other major facilities. As most of the lines are strong, observers will want to be able to map several key transitions simultaneously, and perhaps will be willing to

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sacrifice one polarization channel in order to, for example, feed a second receiver operating at a different frequency. It is not necessary to sacrifice one polarization channel, but this has been done under current practice. Both the IRAM 30m and the NRO 45m, for example, use this observing mode nearly all of the time. Using a flexible IF system, the NRO 45m, the IRAM 30m and the OVRO and BIMA interferometers have allowed observers to place segments of the spectrometer at various places within the receiver IF in order to cover many spectral lines simultaneously. This capability is also an as-yet-unimplemented though highly desirable feature of the NRAO Hybrid Spectrometer at the 12m.

I think that the GBT must be designed with an optics system capable of observing different transitions of key molecules simultaneously. It appears to me that Roger Norrod's 'Plan B' Feed turret is more compatible with this goal than the older design. But perhaps it would be useful to try to compile a list of the most important molecules, and where their most important transitions lie, in order to set a baseline for future discussions. I will also review existing and planned receiver systems to try to suggest how GBT receivers might be optimally matched to scientific needs. Finally, I will discuss the spectrometer requirements necessary to meet these needs.

Key Transitions and Frequencies

The most important aspect of the GBT, from a molecular spectroscopist's point of view, is that it reaches much higher frequencies than the 43m can, and that there is a very good chance that it will perform better at 50 GHz than the 43m performs at 24 GHz. In fact, comparing the specification I have seen with the actual performance of the 45m and the 30m suggests that astronomers will find it competitive up to 90 GHz. Believing this to be a reasonable goal, I have thought about what molecular probes could be most interesting on a telescope operating at about 90 GHz and below. As operation above 52 GHz is not anticipated during the first few years, the focus will be on frequencies below this.

The three most interesting molecular probes (in addition to ammonia, whose lines nearly all lie at one frequency, hence do not strongly affect the optics design), will probably be CS, HC_3N and H_2CO.

The only two lines of CS which will be available are the J=1-0 line, and perhaps the J=2-1 line. Because of the abundance of CS, and the excellent expected performance of the GBT at its 49 GHz fundamental transition, I expect this line will be the most important line molecular spectroscopists will want to observe with the telescope–it will be to the GBT as CO is to the 12m. Like CO, however, it will probably not be a particularly good molecule for extracting information on physical conditions. The problem is, that the 49 GHz line is a resonance line of an abundant molecule, so the envelope of a cloud will scatter radiation emerging from the interior, and in so doing it will hide information about physical conditions in the interior. But because the line is strong, it will be useful for probing cloud dynamics, for detection in single objects from stars to galaxies, and for information on sulfur chemistry. CS, and even the isotopic $C^{34}S$ line, has been detected in external galaxies (Mauersberger et al. 1989 A&A 226, L5).

Formaldehyde has been a staple molecule for cm telescopes for many years. Unfortunately, only two lines have been available for study–the lines at 6cm and at 2cm. These lines are maximally affected by the well known excitation anomaly which causes the lines to be viewed in absorption against the 3 degree background over much of a cloud's extent. Fortunately, the GBT will make available several very interesting new transitions. I believe that formaldehyde will be the molecule of choice for probing physical conditions in clouds with the GBT. In addition to the 6 and 2 cm lines, the 3(1,2)-3(1,3) line at 28.975 GHz, the 4(1,3)-4(1,4) line at 48.3 GHz, the 5(1,4)-5(1,5) line at 72.4 GHz, and the fundamental 1(0,1)-0(0,0) line at 72.8 GHz will be available to the observer on the GBT. These lines are very useful densitometers–Mangum noted in his dissertaion (1990) that these K-doublet transitions have a 'spatial density filter' built into their excitation; for densities below 10^5 the formaldehyde lines are in absorption for J of 4 or below, while for densities above this value all are in emission. At J of 5 or above, all lines will be in emission where the excitation is sufficiently robust. Thus an observation of, for example, the J=4 line can tell us that the excitation in the region observed is sufficient for its excitation, and if the line is in absorption we know that the density does not exceed 10^5. Mangum also showed that formaldehyde is less susceptible to abundance peculiarities than some other molecules, notably ammonia, which render interpretation of the observations difficult. Formaldehyde observations at higher frequencies will provide the GBT with an excellent densitometer, free from the complex cloud-envelope effects which plague interpretation of lower-lying formaldehyde lines. Formaldehyde has been detected in several external galaxies (see Baan et al. 1990 Ap. J. 353, 132); the additional higher frequency lines should be detectable in several galaxies with the GBT, providing valuable density information.

Cyanoacetylene (HC_3N) will provide another excellent densitometer, particularly in carbon-molecule-rich regions such as the Taurus clouds. Vanden Bout et al. (Ap. J. 271, 161) noted the utility of these lines in a study of several clouds–numerous transitions are excited and easily observed at typical cloud temperatures and densities; and the lines appear to be relatively optically thin, minimizing problems associated with the transfer of radiation from the core through the cloud envelope. Plots showing the variation of antenna temperature with upper level J (Figs 5 and 6 of the above reference) show that the peak emission temperature is reached for lines in the 40-75 GHz region. Using the many lines available to the GBT, good modeling can be achieved. Accessible lines include the J=1-0 line at 9 GHz, J=2-1 at 18 GHz, J=3-2 (27 GHz), J=4-3 (36 GHz), J=5-4 (45 GHz), J=8-7 (72 GHz), J=9-8 (82 GHz) and the J=10-9 line at 91 GHz. Currently, only the two lower lines can be reached at the 43m; these lines are not particularly useful for density determinations. Several lines have been detected in external galaxies–in NGC253 Mauersberger et al. (1990 A&A 236, 63) measured two distinct density components.

Cyclopropenylidene, C_3H_2, has been used to probe density in clouds, and several lines lie within the range of the GBT. Most important for early operations will be the pair of lines at 51.8 GHz (the $1_{1,1}$-$0_{0,0}$ resonance line) and 46.7 GHz (the excited $2_{1,1}$-$2_{0,2}$ line). Comparison of these two lines, optimally observed simultaneously, could provide a map of density within a molecular cloud.

Methyl acetylene (CH_3C_2H) and methyl cyanide (CH_3CN) also will be useful temperature-density probes. Each has transitions ranging from J=1-0 near 18 GHz to J=5-4 near 87 GHz available. Because these molecules are symmetric tops (like ammonia), at each transition there is a cluster of lines arising from different K ladders which can be detected. Calibration is facilitated, as lines of very different excitation lie close together in the spectrum. The separate rotational ladders of these molecules are connected only through collisions, resulting in a nearly thermal distribution of populations. Hence, the symmetric top molecules are outstanding probes of temperature in molecular clouds. Recently, Mauersberger et al. (MPIfR preprint No. 435) report detection of both molecules in external galaxies.

One last molecule which I feel will be very interesting with the GBT is SO, tracing oxygen-rich regions in clouds. Transitions at 13, 30, 36 and 86 GHz will securely probe the distribution and excitation of this molecule, already known to show patterns of peculiar abundance enhancements. Many sulfur dioxide transitions will be reached. Again, the important transitions lie above the range the 43m has investigated. Of course, for specific purposes CH_3OH and other molecules will prove useful.

Lastly, emission has been observed from galaxy-scale objects in which the CO J=1-0 line has been shifted to 35 GHz (z=2.3). Not enough is known about the luminosity function of very luminous galaxies to predict how many might be observed with the GBT. Verter (1991) has used the observed luminosity function of normal galaxies to predict that the GBT will be able to observe 4×10^6 galaxies with detectable CO at z=0.1 to 0.4. This tallies to about 100 galaxies per square degree, each bright enough to be detected in ten minutes or so. CO redshifted into the Q-band window (z>1.3) will be detectable from many galaxies with the GBT.

Clearly, there are several aspects to multiplexing the GBT for most efficient observations of molecular lines. A multi-beam receiver provides instant images of extended moleculat clouds. A wideband receiver provides the possibility of simultaneously observing several spectral lines lying nearby in frequency. Lastly, through the use of band-separating optics, such as a Martin Puplett interferometer, several bands might be observed simultaneously. There are many possible combinations of these possibilities, but for convenience I will discuss each separately.

Possible Frequency Siting of a Multi-Beam Receiver

A seven-beam receiver has been used at Green Bank on the 93m and 43m telescopes for continuum work. Spectral line multi-beam receivers in use in the world include the NRAO 8-beam receiver at 218-245 GHz on the 12m, and the FCRAO 15-beam QUARRY receiver at 85-115 GHz on the 14m. The frequency considerations in the previous paragraph suggest that a GBT receiver would cover the most useful spectral lines if it covered the 43-51 GHz spectral region. The telescope would provide excellent resolution and good performance within this range, and the atmosphere should be very good in this range at Green Bank. HEMT receivers have achieved noise temperatures below 30 K in this range, and bandwidths this large should be achievable. In existing arrays, adjacent beams on the sky are measured in orthogonal polarizations to minimize crosstalk. The Fall 1991 GBT receiver plan envisions two independent dual polarization beams, a minimal array. For many of the lines mentioned in the previous paragraph, and for many dozens if not hundreds of objects, emission will extend over at least an area of four by four GBT beams at 45 GHz. A 3x5 or 4x4 array seems a reasonable minimum for the next step toward an imaging array.

Note that, even with a two-beam array, rotation of the array to track parallactic angle is very desirable. Consider, for example, detection of CS or other lines in a spiral galaxy. Emission will be extended, for many nearby galaxies. An observer will want to place the two beams, separated by perhaps four beamwidths (1'), at different places on the major axis of the galaxy as projected upon the sky. Frequently, the rotation curve of the galaxy will put the signal in different velocity channels for one beam, than for the other, and for each beam, the remaining beam will provide an effective 'OFF' spectrum. Observers will want both beams on the galaxy.

The elements of a focal plane array receiver should be as simple as possible. To date, array receivers have operated relatively narrow band. A broadband IF system would allow coverage of the entire bandwidth of the HEMT. It should be possible to construct such an array for the GBT, so let's consider its advantages.

A wideband IF, say 8 GHz at 46 GHz, would provide excellent continuum sensitivity. Note that at 7mm, emission from interstellar dust will be observed in a large number of objects, and will be a primary science goal for the telescope, in view of its tremendous sensitivity. For T_{sys}=50K, 1 mJy (0.5 mK) will be reached in one second with such a system! Note that a protoplanetary system similar to the paradigm 'minimum mass solar nebula', with 0.01 $M_{\odot}$of matter at 200K, produces 1 mJy of flux; the GBT could detect such a system in seconds. The array could produce images of cool material in whole complexes within reasonable periods of observing time. Once located by the GBT, each of these systems could be imaged with the VLA operating at Q-band, or with the MMA at this or higher frequencies.

In addition, wideband frequency coverage is desirable so that any of the spectral lines within the IF window could be selected via an LO and observed with a spectrometer section. An 8 GHz IF amplifier at 20K could provide a rugged, cheap and reliable second stage. The single LO would cover the operating range, so that a single oscillator and phase lock system could power the array. For frequency switching, the single oscillator could be modulated. A second local oscillator system would be used to select lines within the receiver coverage. Each of these lines should be Doppler tracked individually over such a wide frequency range. A typical selection, for instance, might include the CS J=1-0 line at 48.991 GHz, the HC_3N J=5-4 line at 45.49 GHz, the $4_{1,3}$-$4_{1,4}$ H_2CO line at 48.28 GHz and/or the $1_{1,1}$-$0_{0,0}$ (51.8 GHz) and $2_{1,1}$-$2_{0,2}$ (46.7 GHz) lines of C_3H_2. Of course, even with the two beam system currently envisaged for the GBT, observers would like the opportunity to observe these lines simultaneously–this is standard practice at the millimeter interferometers, or at Nobeyama.

Multi-band Observations

A major drawback for an array receiver is its cost. Throughput of the GBT may be increased more economically through clever use of optics, allowing observations of several band simultaneously. First, we discuss which band pairs would be optimal, from the point of view of an interstellar medium spectroscopist, then we consider methods currently employed at other observatories.

I think that it is pretty clear that an attack designed to extract physical conditions from a cloud core will want to use several high frequency receivers simultaneously on the GBT. Clearly, one would like to operate in the 70-90 GHz band at least; if deployed the size of the mapping increments would be set by this receiver. Most likely, any tradeoffs in system performance will be made to the advantage of this highest frequency receiver. In practice, for measuring densities, the data will be regridded spatially to the resolution of a lower frequency dataset. Clearly there are two parts of the 'Q band' which are of great interest–one is essentially that covered by the HEMT on the 43m, from about 27 GHz up to just above 36 GHz. The more important band covers transitions of all the molecules I have mentioned between 43 GHz and 52 GHz or so.

I think that an optimal design would provide the observer with four frequency bands simultaneously. One possibility, employed at Nobeyama and IRAM, polarization splits the incoming beam. For the GBT I might allow one polarization into the K and upper Q band recievers, the other polarization into lower Q and 3mm receivers. Each polarization then passes through a dichroic polarization rotator such as is available on the 30m, and has been planned for the 12m for some time. This will introduce some losses when two receivers are used simultaneously, but these are minimized when the frequencies are in ratios of 2 or three, as they nearly are for the most interesting cases. One can minimize losses for either receiver, a common practice will be to minimize losses for the higher frequency receiver. I think that an optics design such as this would place the GBT in a category clearly above other instruments from the point of view of the molecular spectroscopist, and should be a high priority in focal plane optical designs. Furthermore, it allows the GBT to use high frequency weather to its, and the astronomer's, optimal advantage.

It should be possible to split the incoming signal into different frequency bands without suffering loss of a polarization. In the NRAO plan for the Orbiting Submillimeter Telescope, a Martin Puplett interferometer was proposed to split bands at, for instance, 550 and 570 GHz recovering both polarizations with a minimal signal loss. As construction of this device requires a number of grids and mirrors, they will be more suited to higher frequencies.

Spectrometer Requirements

The existing spectral processor provides 2048 channels across 80 MHz with the possibility for 8 IF inputs. This will provide capability for observing two lines in two polarizations in two spatially separate beams. Clearly, observations which are multiplexed in any of the ways discussed above will quickly exhaust the capacity of this device.

The scientific requirements in the draft GBT electronics instrumentation plan call for 16 IF inputs, each with 2000 frequency channels covering bandwidths as broad as 320 MHz.

The total of 32,000 channels was dictated by search requirements for HI absorption toward distant objects. This number of channels seems comfortable for any of the observing modes envisioned here.

The maximum bandwidth for the spectrometer, 320 MHz, was selected to reflect the width of a 1000 km s^{-1} wide CO line at $z>1.3$, with a factor of two margin for baseline. A spectral survey of a galactic cloud also requires large bandwidth, with good resolution. The 32,000 channels available over 320 MHz provides 40 kHz resolution when divided between two polarizations and two beams, just adequate at the higher frequencies at which spectral surveys are most productive.

At least 4 IF inputs will be used for each band (two polarizations, two beams) under the multi-band observing mode considered above. Simultaneous observing of three or four bands will quickly exhaust the capacity of the correlator. An array comparable in size to those available today would exhaust the capacity of the correlator. Even with a single receiver, deploying IF sections to four spectral lines in each of two polarizations in two beams exhausts the available number of IF ports. Of the trio of spectrometer requirements, that is number of channels, bandwidth and number of IF inputs, it seems to me that the latter is most severely taxed under any of the multiplexing schemes discussed here, and I would prefer at least 32 IF inputs.