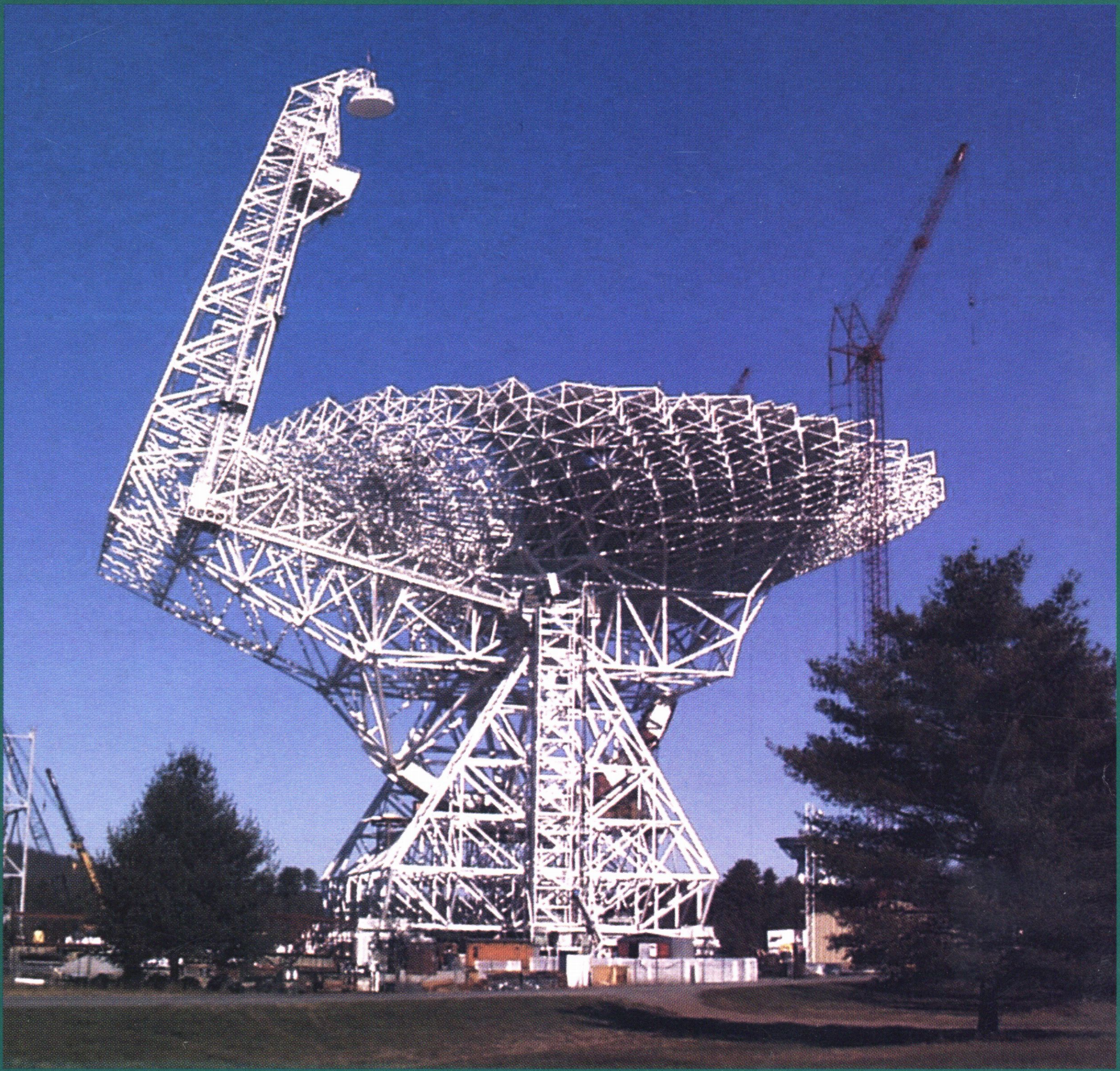
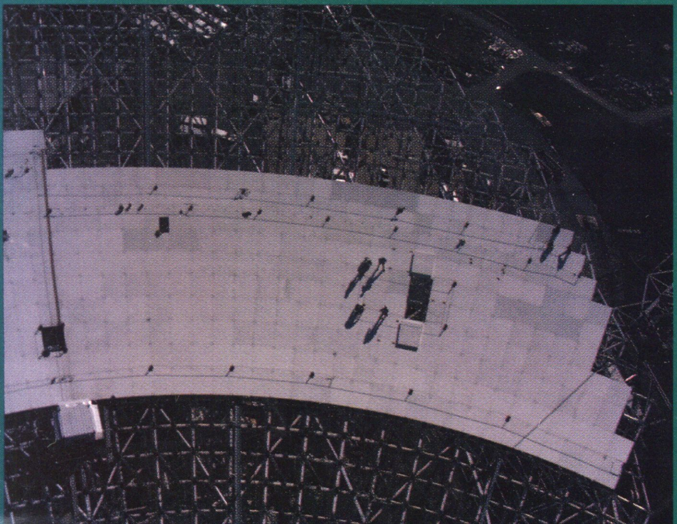
US/GR BK/

THE GREEN BANK TELESCOPE



PROTO-GALAXIES TO PULSARS



The Green Bank Telescope (GBT) is a new-generation radio telescope with unprecedented scientific capabilities. Located in the National Radio Quiet Zone, the GBT has a diameter of 100 m and will operate at wavelengths as short as 3 mm. The GBT's advanced design features - unblocked aperture, active surface, laser metrology system, flexible instrument selection, and wide frequency coverage - will allow study of astrophysical phenomena ranging from proto-galaxies to pulsars.

Science with the GBT

From Meters to Millimeters

The GBT is designed for precision, sensitivity, and versatility. It can operate over a wavelength range of 3 meters (100 MHz) to 3 millimeters (100 GHz). The unblocked aperture improves sensitivity through lower blockage and system noise, reduces standing waves that can limit many spectroscopy projects, and improves image fidelity through lower sidelobe response. The active surface and metrology system will help the antenna achieve its best possible efficiency at a given frequency and to maintain that efficiency over a wide range of tracking angles. Up to ten receivers can be mounted at a time, and the receiver selection system allows any of those receivers to be positioned and activated within minutes. The new GBT Spectrometer has an order of magnitude more resolution and bandwidth than previous instruments and will facilitate detailed atomic and molecular line studies. These design and performance features will make the GBT a unique scientific facility for addressing a wide range of astrophysical problems.

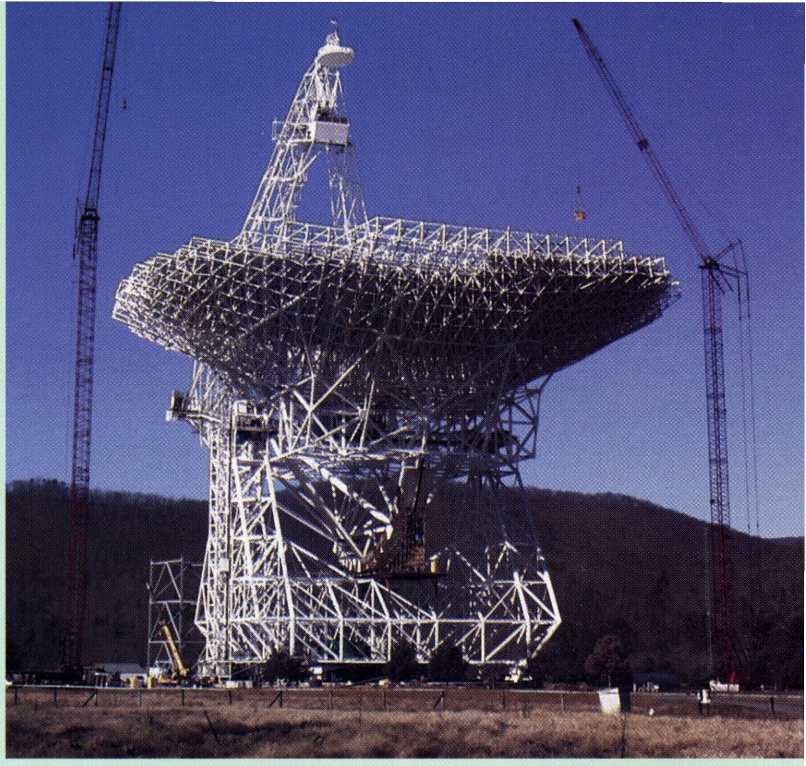
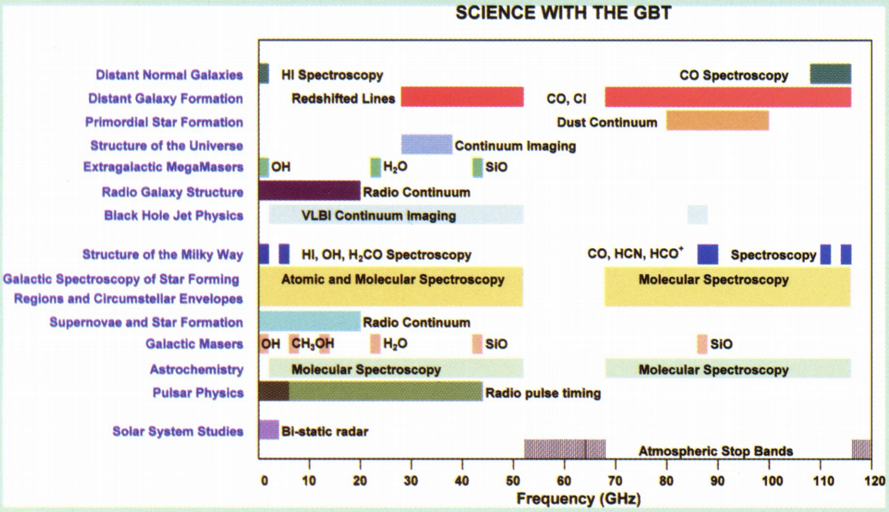


Photo of the GBT in November 1999. About 60% of surface panels were installed at this time. (Cover photo insert shows panel installation).

The range of astrophysical topics that the GBT will address over its operational frequency range.

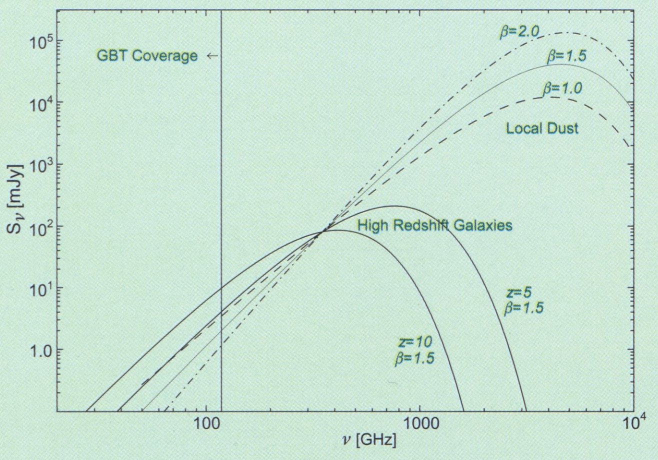


The Early Universe

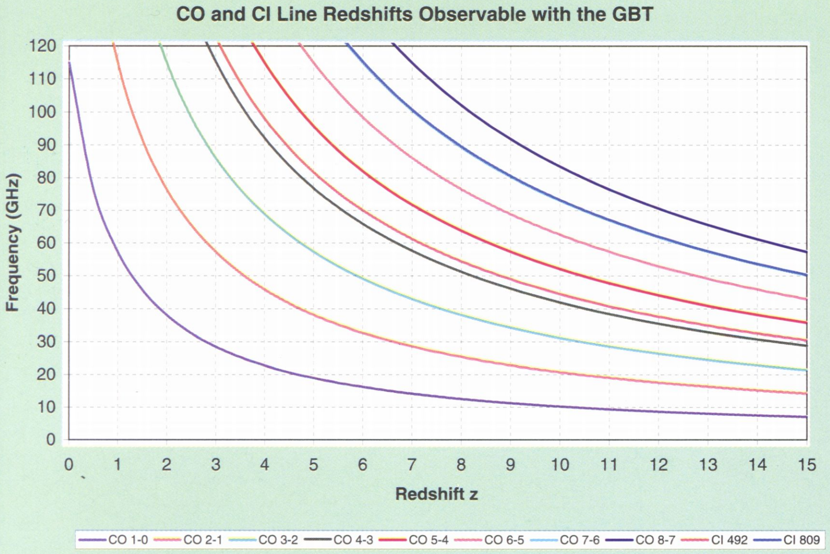
The GBT's sensitivity at millimeter wavelengths will make it a powerful tool for observing highly redshifted dust and spectral lines from the earliest epochs of galaxy formation. At present, only a few galaxies with redshifts as high as z~2-4 have been detected in their dust continuum and CO line emission, and only because they are amplified by intervening gravitational lenses. With the sensitivity of the GBT, it is likely that many unlensed systems can be detected. The GBT's frequency coverage is ideal for studying the most abundant molecular species in high-redshift galaxies. For example, a galaxy with a redshift of 4 will have its CO $J=1\rightarrow0$, $2\rightarrow1$, $3\rightarrow2$, and $4\rightarrow3$ emission redshifted to 23, 46, 69, and 92 GHz, respectively. The strongest CO line emission for z~2-4 is expected to occur in the 3 mm band, where the GBT will have unprecedented sensitivity. For both spectral line and continuum observations of high redshift objects, noise levels that require tens of hours to achieve with existing instruments can be reached in a few minutes with the GBT. With this sensitivity advance, the GBT may be the first instrument capable of studying the earliest stages of galaxy formation in the redshift ranges z~5-15.

Atmospheric transmission in the 3 mm band is excellent in Green Bank for as much as 30% of the year. Calculations show that a new-generation 3 mm bolometer camera placed on the GBT would have extraordinary sensitivity to continuum emission from redshifted dust. There are plans to obtain such a camera for the GBT.

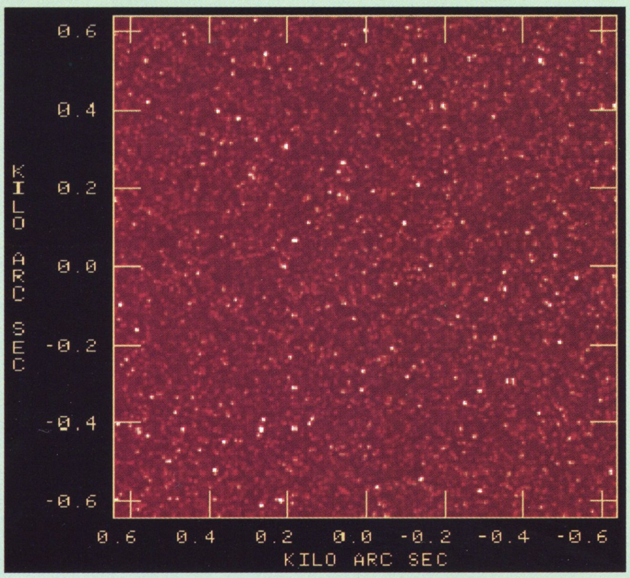
The high sensitivity, good absolute calibration, and low sidelobes of the GBT will also make it ideal for cosmological studies. The GBT will have excellent performance at 1 cm (30 GHz), a preferred window for studies of the cosmic background radiation.



Dust emission spectrum in the rest frame and at the high redshift values of $z=5$ and $z=10$. β is the assumed value for the dust spectral index. The spectral region between 80 and 100 GHz can be measured with high sensitivity by the GBT and will provide a critical discriminator of the spectral energy distribution of high redshift objects.



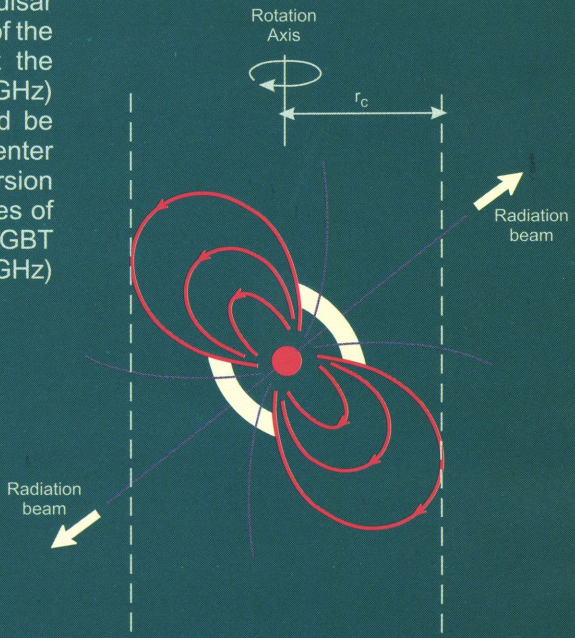
The redshifts of extragalactic CO and CI spectral lines in GBT observing windows. For redshifts between the ranges of 4 and 15, which may cover the first epochs of stellar processing in the early universe, many of the most likely lines of CO fall in the frequency ranges covered by the GBT.



A "Deep Field" simulation showing the galaxies (as light colored spots) that may be detectable with the GBT in the 3 mm continuum in a 22' x 22' field.

Pulsars

The GBT has a number of features that will provide a major advance in pulsar observing: large collecting area, sensitive receivers, observing coverage of 85% of the celestial sphere, a low-interference site, and low sidelobes that help reject the interference that does exist. Sensitive searches for radio pulses (100 MHz to ~43 GHz) from magnetars, Geminga and other "radio quiet" (x-ray loud) pulsars, should be fruitful. The GBT will also be unique in its sensitivity to pulsars in the Galactic Center region and in southern globular clusters. Both interstellar scattering and the dispersion caused by free electrons in the interstellar medium broaden the distinctive pulses of pulsars at low frequencies, making them difficult to detect. The sensitivity of the GBT will allow single pulse observations to be extended to higher frequencies (e.g., $\geq$5 GHz) where the effects of pulse broadening are not as pronounced.



Conceptual Diagram of a Pulsar (adapted from *Pulsar Astronomy,* A.G. Lyne and F. Graham-Smith, 1990, Cambridge Univ. Press).

Very Long Baseline Interferometry

Many of the most interesting astrophysical problems requiring ultra-high angular resolution, such as probes of active galactic nuclei, also require extremely high sensitivity. For certain projects, the addition of the GBT will improve the VLBA's imaging sensitivity by up to an order of magnitude. The GBT and VLA will form a very high sensitivity, east-west baseline for inclusion in the VLBA and the European VLBI Network. In particular, the GBT adds sensitivity to the longest baselines of the VLBA and EVN. The added sensitivity the GBT provides makes possible many important projects that were impossible before, including radar studies of small solar system objects, water masers in distant galaxies, and early detection and imaging of gamma ray burst sources.

Radio and Millimeter-wave Imaging

The GBT will offer new capabilities for high-fidelity imaging on large angular scales. At its Gregorian focus, the GBT has a large field of view that will allow it to accommodate future focal plane array receivers and detectors, including large-format bolometer cameras. The GBT Spectrometer and the Monitor and Control System can support fast-sampling, on-the-fly observing from single or multiple receiver inputs and wide bandwidth spectroscopic imaging. With these facilities, the GBT will map the structure of our Galaxy and nearby external galaxies with high dynamic range, at high frequencies, and over large angular areas. Surveys of large areas for radio population studies and frequent patrols of large areas to identify source variability will also be possible.

HI and Atomic Spectroscopy

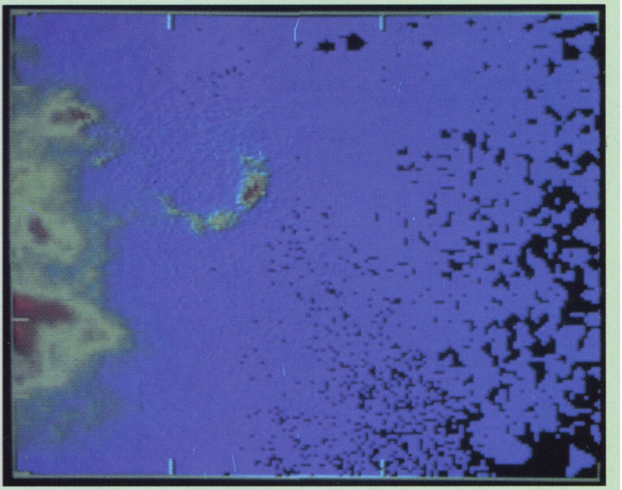


Image of an arc of Galactic neutral hydrogen that has been accelerated to forbidden velocities, most probably by a supernova or group of supernovae. The data are from the NRAO 140 Foot and 300 Foot Telescopes. The arc contains about 10^4 solar masses of hydrogen, and probably 10^{50} ergs in kinetic energy. It has no known counterpart at other wavelengths (Lockman).

With the GBT, measurement of highly accurate and absolutely calibrated Galactic 21 cm HI can be done quickly and routinely. This will be of benefit to those who need to correct for Galactic interstellar absorption in observations of extragalactic objects in the UV and soft X-ray, for studies of the soft X-ray background, and for comparisons of 21cm HI spectra with spectra of other species.

The low sidelobes of the antenna will make possible study of faint HI in the Galactic halo and studies of the energetics of the ISM, which depend on very accurate measurement of the wings of Galactic HI profiles. 21 cm HI profiles from the GBT should have unsurpassed dynamic range and accuracy of calibration. The GBT's good instrumental polarization characteristics will allow Galactic magnetic fields to be mapped using observations of HI Zeeman splitting.

The unblocked aperture of the GBT will be ideal for studies of wide, weak lines such as the hyperfine transitions of $^3He^+$, an important light element for constraining stellar evolution models and Big Bang nucleosynthesis. Radio recombination lines of hydrogen, helium, and carbon along with the continuum emission will probe the physical properties of ionized gas in HII regions and planetary nebulae. Electron temperatures, non-thermal velocities, the excitation of the ionizing stars, and $^4He^+/H^+$ abundances can be determined. With the wide-band spectrometer, the GBT can observe many radio recombination lines simultaneously while also providing good measurements of the continuum. At lower frequencies the radio recombination line emission arises from the extended low-density ionized gas in the Galaxy, an important component of the interstellar medium. Observations of C radio recombination lines in conjunction with other data will probe the physical properties of photon dominated regions that lie in star formation complexes between the zones of hot fully ionized gas and cold molecular gas. In these regions important chemical, photo-dissociative, and recombinant processes take place.

Star Formation

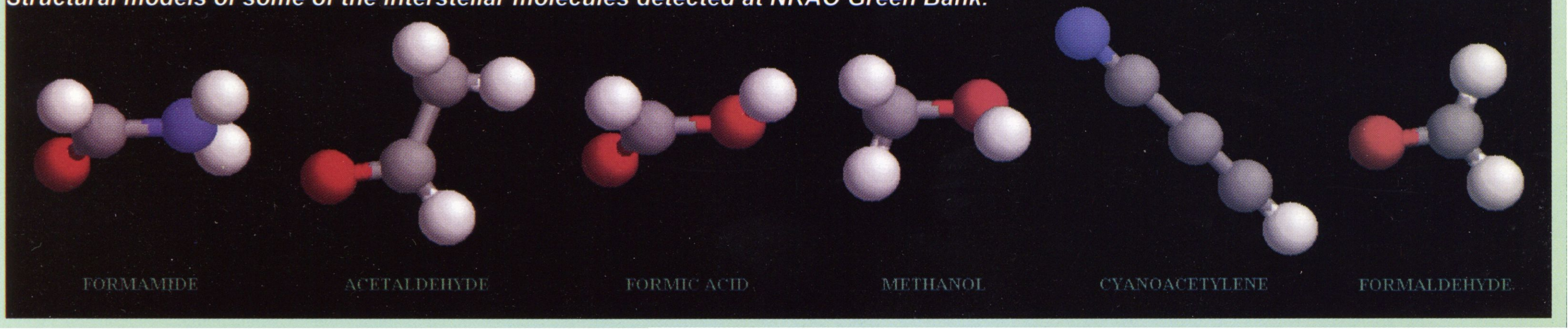
Broad frequency coverage, high sensitivity, and high angular resolution make the GBT an ideal tool for studies of the dense cold dust disks surrounding protostars and young stellar objects. Several molecular species have Zeeman effects as strong as that of the H atom, but for reasons of chemistry probe gas at densities associated with star formation. With the GBT, the classical question of the role of magnetic fields in star formation could be addressed for the first time. NH_3 at 23 GHz is one of the best molecules to study the density and temperature structure of prestellar cores and young protostars, and the GBT will offer significant new capabilities in this area. At higher frequencies the GBT will be truly unique. In the 40-50 GHz band, molecules such as SiO can be used to study jets and shocks in the outflows from young stars, while CS will reveal the density structure of even the coldest prestellar cores. Continuum observations in this band and at higher frequencies will allow a much deeper census of young stars embedded in dense cores than is possible now.

In the 3 mm band the GBT will offer extraordinary sensitivity both for line and continuum observations. A variety of molecular tracers can be used in this band to study and characterize the earliest phases of young low-mass star formation. Because this band contains many ground state transitions of simple, abundant molecules, the GBT can detect fainter and colder gas than can be achieved in the submillimeter. In the 3 mm band the GBT has about the same angular resolution as current large submillimeter telescopes. By using optically thin, low excitation molecules one can map the velocity field in the outer layers of cool accretion disks. By combining optically thick and thin molecular tracers one can see infall and accretion in protostellar objects that are so young that they have not yet formed a stellar core.

Astrochemistry and Astrophysical Molecular Spectroscopy

The frequency coverage and agility of the GBT and the capabilities of the spectrometer for wide bandwidth spectral line imaging will make the GBT a powerful new instrument for studies of the chemistry in interstellar and circumstellar clouds. At its lower operating frequencies, the GBT can provide unique data on heavy molecules, including those of biological significance. In its high frequency range, the GBT can observe the many species in the rich,3 mm spectral window. The spectroscopic capabilities of the GBT should be ideal for detecting new interstellar molecular species.

Structural models of some of the interstellar molecules detected at NRAO Green Bank.



Solar System Studies

The large collecting area and high sensitivity of the GBT will make it a prime instrument for the study of solar system objects. Used as the receiving system in bistatic radar experiments with the powerful Arecibo and JPL/Goldstone transmitters, the GBT will be able to image planetary surfaces, near-Earth asteroids and comets. Such radar images have resolutions orders of magnitude finer than other ground-based imaging techniques, and are thus uniquely able to characterize an asteroid's shape and surface texture. Used in conjunction with the VLA or other large telescopes, the GBT will contribute sensitive baselines in very high-resolution interferometry experiments to map objects close to the Earth and more distant planetary surfaces.

The GBT will also be an excellent tool for spectral observations of comets and planetary atmospheres. The facility will allow sensitive mapping in both space and velocity of millimeter wavelength spectral lines of molecules outgassed by comets. In addition to typical molecular species such as HCN, OH, and CO, heavier molecules that are rarer and hence more difficult to detect will be an important target of study for the GBT. Monitoring of centimeter wavelength lines from species such as water and ammonia in comets and planetary atmospheres will greatly contribute to the understanding of conditions and chemistry occurring on these bodies.

The GBT and the Family of NRAO Instruments

The GBT will work in concert with the other major NRAO instruments – the VLA, VLBA, the 12 Meter, and in the future, ALMA – to provide a powerful and comprehensive capability for studies at radio and millimeter wavelengths. The GBT has point-source sensitivity comparable to that of both the VLA and ALMA, and is also sensitive to emission structures on large angular scales. Whereas the interferometers will be unique in their ability to image small structures, the GBT will be most adept at imaging larger fields to set the astrophysical context, while not missing detections of interesting compact objects. The GBT's ability to use incoherent detectors such as bolometers and to take advantage of the rapid technological advances in bolometer cameras will be particularly important for continuum imaging on large scales. The GBT also forms a critical bridge in frequency coverage between the VLA at centimeter wavelengths and ALMA at millimeter wavelengths. Observing techniques and strategies of the GBT will build upon the pioneering work of the NRAO 12 Meter. As discussed above, the enormous collecting area of the GBT will be of great advantage to many VLBA projects requiring the highest sensitivities.

GBT Commissioning and Observing Plans

Much of the year 2000 will be devoted to commissioning the GBT, but it is anticipated that some visitor observations will begin during the year. The first observations will be at the lower frequencies, and will allow, for example, HI and OH spectroscopy and pulsar projects. Toward the end of 2000, frequencies approaching 50 GHz may be available, which will open up a range of projects that are not possible with current facilities. Observations in the 100 GHz range should be possible by the end of 2001. The first call for observing proposals is anticipated for the spring of 2000. The observing community will be notified of the dates and parameters of the first call for proposals by e-mail, newsletters, and Web announcements on the NRAO Green Bank homepage at (***http://www.gb.nrao.edu***).

GBT Operating Specifications

Diameter	100 x 110 m
Surface area	7853 m^2
Surface accuracy (rms)	
Open loop surface	<360mm
Closed loop with metrology	<220mm
Pointing accuracy (rms)	
Conventional	3 arcsec
Closed loop with metrology	1 arcsec
Slew rate	40 deg/min Az
Beam size (FWHM)	720 arcsec / n (GHz)
Flux sensitivity	1.85 K/Jy (@20 GHz)

GBT Receivers

Receivers	Operating Range/Spec.	Status
Prime Focus 1	290 – 920 MHz	Completed
Prime Focus 2	910 – 1230 MHz	Under Construction
L Band	1.15 - 1.73 GHz	Completed
S Band	1.73 - 2.60 GHz	Completed
C Band	3.95 - 5.85 GHz	Completed
X Band	8.2 – 10.0 GHz	Completed
Ku Band	12.4 – 15.4 GHz	Completed
K Band	18 – 26.5 GHz	Completed
Ka Band	26 – 40 GHz	Planned
Q Band	40 – 50 GHz	Under construction
W Band	68 - 90 GHz / 90 – 115 GHz	Proposal stage
Bolometer Camera	3 mm band	Planned

GBT Spectrometers, Continuum, and Pulsar Backends

Backend	Specifications	Status
GBT Spectrometer	Maximum channels per IF: 262,144 Bandwidth modes for multi-inputs: 8 x 800 MHz or 32 x 50 MHz Maximum spectral resolution: 48 Hz @ 12.5 MHz bandwidth Pulsar mode: 4096 samples x 256 lags each msec	Completed
Spectral Processor	2 x 1024 channels x 40 MHz 1, 2, 4, or 8 IF modes	Transferred from 140 Foot
Digital Continuum Backend	V/F Converter into 28 bit counters, 16 inputs, 10 switching phases, 100 nanosec phase time resolution	Completed
VLBI	VLBA and S2 Recorders	Completed

GBT Sensitivity in 60 seconds Total Integration Time*

Spectral Line Sensitivity	Bandwidth	RMS Noise
1420 MHz (HI)	1 km/sec	0.06 K / 32 mJy
22 GHz (H_2O)	1 km/sec	0.03 K / 18 mJy
43 GHz (SiO, etc.)	1 km/sec	0.03 K / 15 mJy
89 GHz (HCN, etc.)	1 km/sec	0.04 K / 40 mJy
Continuum Sensitivity		
14 GHz	3 GHz	55 μJy
90 GHz	7 GHz (future heterodyne Rx)	270 μJy
90 GHz	20 GHz (future bolometer)	120 μJy

* *with Closed Loop Surface and Laser Metrology.*

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