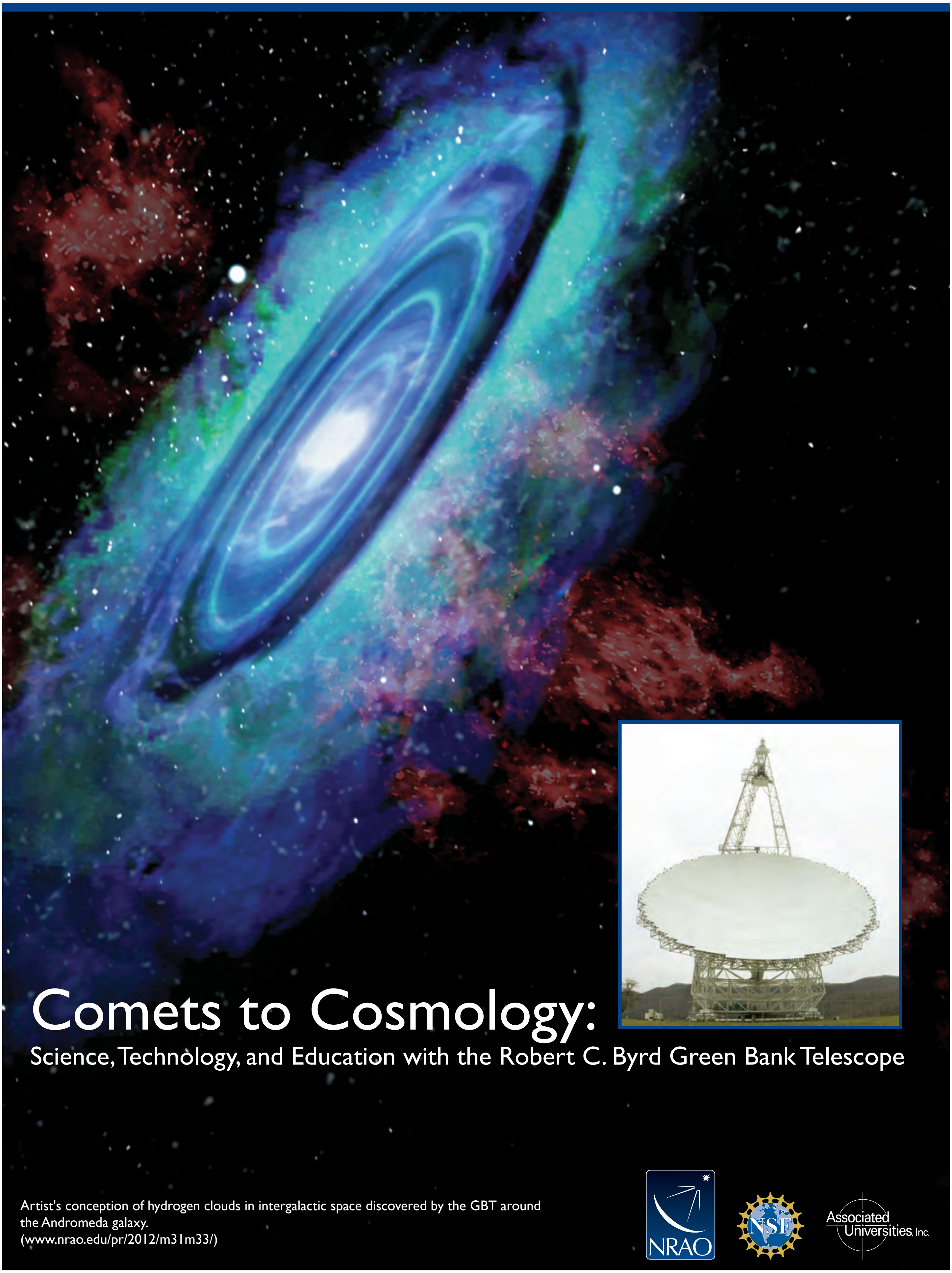


Comets to Cosmology:

Science, Technology, and Education with the Robert C. Byrd Green Bank Telescope

Artist's conception of hydrogen clouds in intergalactic space discovered by the GBT around the Andromeda galaxy.
(www.nrao.edu/pr/2012/m31m33/)

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Comets to Cosmology: Science, Technology, and Education with the Green Bank Telescope

THE GBT

The Robert C. Byrd Green Bank Telescope (GBT) is the world's premiere single-dish radio telescope at meter to millimeter wavelengths. Its 100-meter diameter collecting area, unblocked aperture, excellent surface, and unique site offer the scientific community unrivaled capabilities across the telescope's full 0.1 -116 GHz (3.0m – 2.6mm) operating range. It is a facility of the National Science Foundation, and part of the National Radio Astronomy Observatory. There is no telescope with comparable performance anywhere in the world.

WHAT IS THE GBT?

A powerful, versatile, flexible telescope optimized for research over three decades of the electromagnetic spectrum with capabilities that are unequalled worldwide.

The GBT has the best protection of any US observatory from many forms of man-made radio frequency interference as it is located in the National Radio Quiet Zone and the West Virginia Radio Astronomy Zone. The Observatory's location in a lightly-populated valley in the Monongahela National Forest, surrounded by extensive ranges of mountains in all directions, provides further protection from interfering signals.

Fig. 1: The Robert C. Byrd Green Bank Telescope, or GBT, located in Green Bank, West Virginia. (science.nrao.edu/facilities/gbt)

The GBT is used by hundreds of scientists each year for a large and varied series of programs. It has a collecting area and sensitivity comparable to the Atacama Large Millimeter/submillimeter Array (ALMA) and the Karl G. Jansky Very Large Array (VLA) and thus excellent response to point sources such as pulsars. But as a filled aperture it also has the highest possible sensitivity to extended, low surface-brightness emission of the kind associated with comets, molecular clouds, and distortions of the cosmic microwave background. The GBT also joins the Very Long Baseline Array (VLBA) for interferometric observations to provide a critical threshold of sensitivity for the highest angular resolution studies. The single focal plane is ideal for rapid, wide-field imaging using multi-pixel cameras. It thus serves as the wide-field imaging complement to ALMA and the VLA.

The GBT is flexible and easy to use, and can respond to new ideas from the scientific community rapidly. It is straightforward for a small group to build and install a new instrument, providing them access to a world-class research facility. State-of-the-art instruments now under development in collaboration with university groups will continue to keep the GBT equipped with the latest technology. Graduate students use the GBT to gain hands-on experience with a major telescope, an increasingly rare opportunity and critical for their training.

Time on the GBT is allocated through community-based peer review. The telescope is oversubscribed, on average by a factor of four, with a much higher oversubscription at high frequencies and for some parts of the sky. It is scheduled dynamically to match project needs to the available weather, and is used for astronomy about 6500 hours per year. Green Bank has several thousand hours of clear skies with a precipitable water vapor content <10mm throughout the year, allowing extensive operations at short wavelengths. Since 2010 about 2000 hours have been available for weather-dependent high-frequency observations, a number which should increase as telescope control is improved.

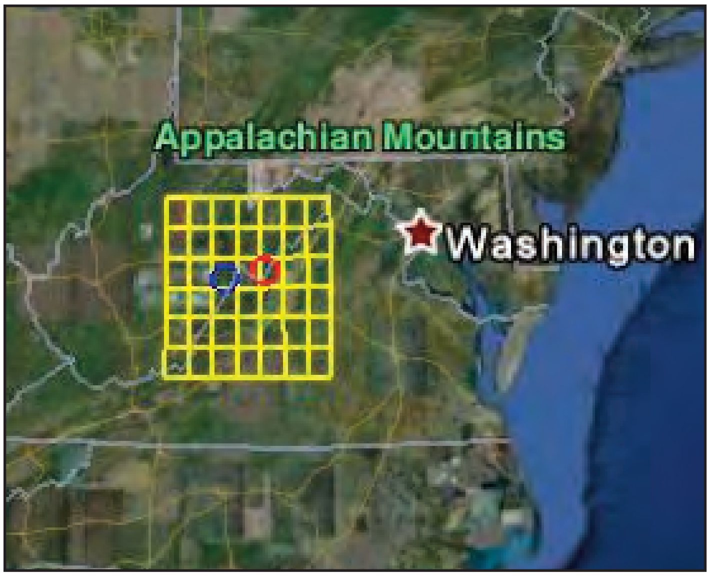


Fig. 2: The Green Bank Observatory is surrounded by a 13,000 square-mile National Radio Quite Zone (yellow checkerboard) designed to protect radio astronomy. (www.gb.nrao.edu/nrqz/nrqz.shtml)

The Observatory is also a major resource for education and public outreach, and as such is an outstanding advocate for basic research and the work of the National Science Foundation. The Observatory produces nationally acclaimed programs in education, and the training of science and engineering students and teachers. These activities center on the Green Bank Science Center, with its auditorium, classrooms, and large exhibit hall, which is visited by 50,000 people every year. Thousands of K-12 teachers and students partake of residential educational programs using older radio telescopes no longer involved in research.

The Observatory's laboratories, utilities and support facilities make it an attractive location for independent research experi-ents, and it serves as the field station for several university-based research teams.

LOCATION, LOCATION, LOCATION

- The GBT sits in a valley in the Monongahela National Forest, an area with low population density minimizing local sources of interference. It is surrounded by extensive mountain ranges providing substantial protection against distant sources of interference.
- It lies within two radio quiet zones that provide legal protection for radio astronomy against new transmitters, unique in North America.
- Its latitude gives horizon-to-horizon access to all declinations above -46°, 85% of the celestial sphere.
- Inland, and at an elevation of 850 meters, it sees extensive periods of cold dry weather throughout the year, ideal for mm-wave astronomy.
- On the East Coast of the US, it is ideally situated for Very Long Baseline Interferometry (VLBI) with telescopes in Europe and the western US.

Over the next 10-20 years the GBT will make discoveries in areas as diverse as the detection of gravitational radiation; the formation of stars, galaxies and galaxy clusters; the origin of life; the composition of the planets and their satellites; and the scientific principles that govern the Universe.

GBT OVERVIEW

- 100m diameter fully steerable reflector
- Accesses 85% of the entire celestial sphere
- Unblocked aperture for high dynamic range
- Located within two radio quiet zones
- Dynamic schedule matches science to weather
- Used 6500 hours each year for astronomy
- State of the art receivers from 0.3-100 GHz
- Largest radio telescope at mm-wavelengths
- Unique active surface optimizes performance
- Ability to change rapidly between 9 receivers
- Suite of detectors for continuum, spectral line, pulsar and VLBI studies

Community-Driven Science

The GBT is a versatile facility that responds entirely to demand from the scientific community, and thus is used for research ranging from comets to cosmology. Many programs fall into the primary science themes identified by the American science community through the two recent decadal survey reports – New Worlds New Horizons (NWNH) and Visions and Voyages – but some are breaking new ground in ways unforeseen even a few years ago. Below are some current and future research areas for which the GBT is in high demand and for which it provides unrivaled capabilities, illustrated with the titles of a few of the proposals that have been accepted for scheduling during 2012.

Gravitational Wave Astronomy and Compact Objects

One of the most significant discoveries in Astronomy and Astrophysics will be the direct detection of gravitational waves, first predicted by Einstein but never observed directly. An important and competitive method for detecting the expected stochastic background of nano-Hertz gravitational waves is through high precision timing of millisecond pulsars. This requires regularly spaced measurements of the arrival time of pulses over 5 - 10 years from at least 20 pulsars spread across the sky, measurements made with ~100 nanosecond timing accuracy at two frequencies. The pulsars act as the far ends of the arms of a Galactic-scale gravitational wave detector.

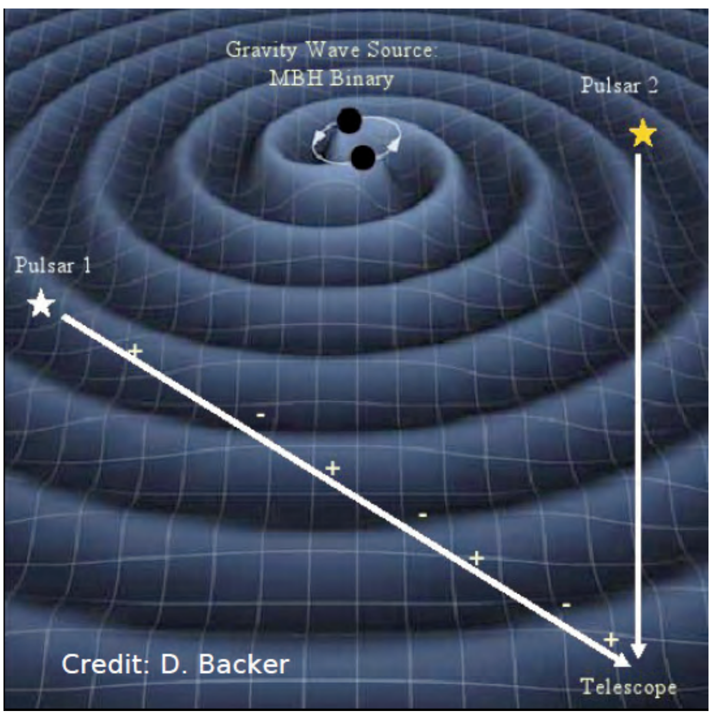


Fig. 3: Artist's conception of the generation of gravitational waves by merging supermassive black holes, and their detection through measurement of pulsars. (www.nanograv.org)

WHO USES THE GBT?

More than 900 different scientists and their students have used the GBT during the last five years. In 2012 alone the GBT received proposals from more than 600 researchers, typically organized in teams of 4 to 5. The majority of the proposals have at least one student as a co-investigator. The GBT user community is diverse and includes many physicists, planetary scientists and chemists, as well as astronomers and astrophysicists. The telescope is oversubscribed by a factor of more than four.

As the world's premier telescope for pulsar observations outside the limited declination range of the Arecibo radio telescope, the GBT is the central instrument for the North American effort, known as the North American NanoHertz Observatory for Gravitational Waves (NANOGrav). In the 2010 Decadal Survey, NANOGrav was ranked highly as a compelling project. NRAO played a key role in establishing NANOGrav in order to be able to commit GBT observing time over the long term. The Observatory built a new instrument for timing pulses and is developing an essential wide-band timing system. While direct detection of gravitational waves will be extremely exciting, NRAO is committed to supporting the larger goals of the NANOGrav community as well – to go beyond mere detection and use gravitational waves to probe the physics of the gravitational wave sources, and observe the Universe at its earliest moments.

GBT studies of pulsars continue to produce exciting discoveries in stellar evolution, general relativity, and the physics of compact objects.
http://www.nrao.edu/pr/2010/bigns/
http://www.nrao.edu/pr/2009/mspulsarbirth/
http://www.nrao.edu/pr/2008/doublepulsar/
http://www.nrao.edu/pr/2006/mspulsar/

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- Deep Searches for Radio Emission from Magnetars (2.3 GHz)
- Timing and General Relativity in the Double Pulsar System (0.8 & 1.4 GHz)
- Searching for Millisecond Pulsars in Extremely Low Mass White Dwarf Binaries (0.35 GHz)
- Deep Searches for Young Pulsars in Two Globular Clusters (1.4 GHz)
- Confirmation of Intermittent Pulsars from the Sculptor Dwarf Spheroidal Galaxy (0.35 GHz)
- Continuing the GBT All-Sky 350 MHz Pulsar survey (0.35 GHz)
- Expansion of the NANOGrav Pulsar Timing Array Project (0.8 & 1.4 GHz)

Ultra-High Precision Astrometry

When the GBT is added to NRAO's Very Long Baseline Array (VLBA) the increase in sensitivity creates a unique instrument for precision astrometry. The NWNH report pointed out that direct geometric measurements of distances to the Galactic Center, to major regions of star formation in the Milky Way, to nearby galaxies, and, most importantly, to galaxies at cosmological distances are possible using precision radio astrometry.

In the next five years, scientists will directly map for the first time the spiral structure and dynamics of the Milky Way to unprecedented precision, via VLBA+GBT measurements of the distance and proper motion of 6.7 GHz methanol masers in massive, highly obscured, star-forming regions throughout the Galaxy. Closer to the solar neighborhood, a key project will measure the parallax and proper motion of all pre-main sequence stars with detectable radio emission in the Gould's Belt to provide accurate distances and velocities. The VLBA+GBT will also continue searches for exoplanets around M-dwarf stars and pre-main sequence stars.

The GBT has just begun VLBI operations at 3mm, and its enormous sensitivity will transform astrometry at short wavelengths. It will provide such an increase in sensitivity for mm-wave astrometry that the results can hardly be predicted, but it will allow a parallactic measurement of the distance to the Galactic Center, fixing the fundamental distance scale of the Milky Way. When ALMA is equipped for long-baseline interferometry at 3mm, the GBT+ALMA combination will create another breakthrough in sensitivity for high angular resolution astronomy.

Beyond the Galaxy, the VLBA+GBT is measuring the relative motions of the Local Group galaxies, determining the past and future configurations of the Milky Way and its neighbors. VLBA and GBT observations of H_2O mega-masers have produced angular diameter distance determinations to galaxies in the Hubble Flow, without resorting to the extragalactic distance ladder. They will continue to improve the accuracy of the Hubble constant, and thus knowledge of the expansion rate of the Local Universe.
http://www.nrao.edu/pr/2009/megamaser/

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- The Megamaser Cosmology Project. V (22 GHz)
- Proper Motion of Galaxies in and Beyond the Local Group (22 GHz)
- Determining the Nature of the 20-40 GHz Radio Emission from active M Dwarfs (8.4, 24 GHz)
- RadioAstron-GBT Space VLBI Survey of AGN at the Largest Angular Resolution (1.4, 5.0, 22.0 GHz)
- A Resolution of the Pleiades Distance Controversy (8 GHz)
- Towards Precision Supermassive Black Hole Masses Using Megamaser Disks (22 GHz)

Origins

Deciphering the origin of the first stars, galaxies, black-holes, planetary systems and life itself requires understanding the mechanisms of their formation out of primordial gas. The spectral lines from ionized, atomic and molecular gas in the regions of formation at high redshift fall within the frequency coverage of the GBT. The inverse-K correction due to the shape of the far-IR radiation distribution and lines means that the GBT can detect the gas and dust in the first galaxies beyond z~10, when the Universe was only 4% of its present age.

Cosmology

The GBT is the instrument that was used to develop the technique of 21cm intensity mapping: measuring the collective hydrogen signal from very distant galaxies too faint to be detected individually. (www.nrao.edu/pr/2010/highzhi/)
The GBT is now undertaking a large program of intensity mapping to trace fluctuations in neutral hydrogen near a redshift of one, thereby tracing the dark matter and measuring the amplitude of baryon acoustic oscillations, the expansion of the Universe, and dark energy. Another GBT experiment has searched for small temporal changes in the frequency of highly redshifted absorption lines, and placed a direct limit on cosmic acceleration.

Origin of Galaxy Clusters

The GBT is imaging the gas in galaxy clusters through high resolution measurements of the shadows it casts against the microwave radiation from the Big Bang, the Sunyaev-Zel'dovich Effect (SZE). The GBT provides an unequaled combination of surface brightness sensitivity and high angular resolution for SZE studies. The GBT

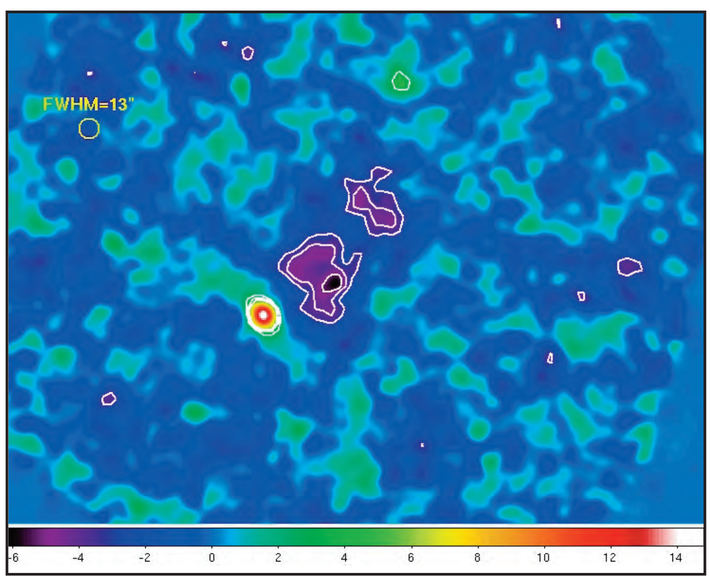


Fig. 4: A high-angular resolution map of the Sunyaev-Zel'dovich effect in a cluster of galaxies measured with the GBT. Two areas of SZE decrement (contours) mark regions of hot shocked gas within a cluster. A bright active galactic nucleus lies at the center.

measurements, when combined with X-ray data, can determine the cluster gas pressure and identify shocks as well as evidence of past merger activity and ongoing subcluster mergers. The GBT is the most sensitive instrument in existence for such high-resolution SZE measurements and is providing extensive information on the merging history and processes of galaxy clusters, not easily accessible by other means.

The GBT is also used to study the molecular gas in cluster cooling flows and the generation and maintenance of cosmic ray electrons in clusters on Mpc scales.

Massive Black Holes

Through GBT detection of H_2O masers in accretion disks around nuclear black holes, and their subsequent measurement using the GBT as part of the High Sensitivity Array, the mass of nuclear black holes can be determined with errors of only a few percent, independent of stellar-dynamical measurements. This research is allowing investigators to study the connection between the formation and evolution of galaxies and their nuclear black holes.

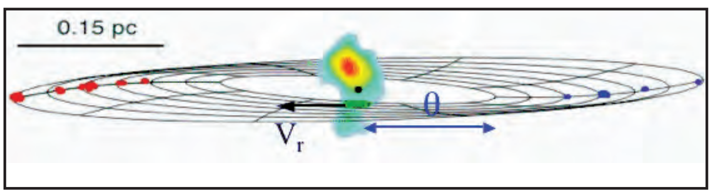


Fig. 5: Model of an accretion disk with H2O masers surrounding a black hole in the nucleus of a galaxy.

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- Baryon Acoustic Oscillations with 21cm Intensity Mapping (0.7-0.9 GHz)
- Secular Drift of Absorption Line Systems and the Cosmic Acceleration (0.3-1.2 GHz)
- MUSTANG Imaging of the CLASH Cluster Samples (90 GHz)
- Cool Gas Physics in the Brightest Cluster Galaxies (80 GHz)
- Distinguishing Cosmic-Ray Acceleration Models in Massive Clusters (1.4, 2.3, 5.0 GHz)
- Towards Precision Supermassive Black Hole Masses Using Megamaser Disks (22 GHz)

Origin and Evolution of Galaxies

Observations in the Infrared and sub-mm wavelengths have discovered a population of luminous sources that are likely proto-galaxies being assembled in an enormous burst of star formation. The GBT is being used as a highly efficient instrument to measure molecular lines and determine the redshift, gas mass and kinematics of these objects. This provides statistical data on large samples and identifies interesting objects for higher resolution studies with the VLA and ALMA. The GBT is also used for measurement of redshifted HI and OH in studies of the atomic and diffuse molecular components of distant galaxies.

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- Molecular Gas Excitation in Lensed, Herschel-selected Submillimeter Galaxies (27-36 GHz)
- The Molecular Content of Optically 'Invisible' z~2.6 HLIRGs (27-36 GHz)
- The Death of Ultraluminous Dusty Starbursts: AGN Feedback Caught in the Act (27-36 GHz)
- Where is the Missing Material in High-Redshift Active Galaxies? (0.6 GHz)
- Obtaining the Cosmic Gas Mass Density from 21cm in MGII Absorbers (0.8 GHz)

Structure and Evolution of Galaxies in the Local Universe

The flow of baryons in and around galaxies and the processes by which galaxies evolve are revealed in surveys of the raw materials of star formation as traced by HI, CO, and HCN. GBT imaging of the neutral gas around nearby galaxies and the Milky Way provides otherwise unattainable surface brightness sensitivity to faint hydrogen. GBT studies of the Magellanic Stream have already revealed crucial information about the recent evolution of the Galactic Neighborhood. The study of high velocity clouds in our Galaxy and nearby galaxies is revolutionizing our understanding of the lifecycle of galaxies, and how gas flows relate to, and possibly drive, star formation. Studies of galaxy groups, including the Local Group, are revealing evidence of past interactions and accretion in the form of streams of very faint hydrogen clouds. The GBT is reaching HI detection levels ten times below that of other instruments.

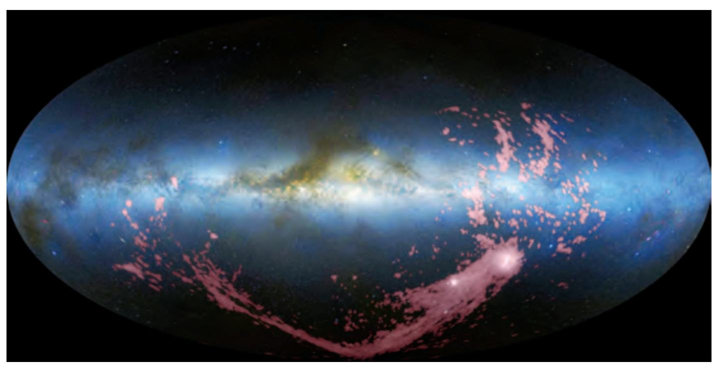


Fig. 6: The Magellanic Stream (shown in pink) is traced for more than 200 kpc across the sky in observations of neutral Hydrogen using the GBT. (http://www.nrao.edu/pr/2010/magstream/)

The GBT is extending molecular observations to nearby galaxies, providing critical information on the large-scale evolution of galactic systems and the correlation between gas, stellar mass and star formation. The GBT is also making surveys of selected samples of thousands of galaxies for their HI content, kinematics, and mass.

http://www.nrao.edu/pr/2008/m81clouds/
http://www.nrao.edu/pr/2008/smithscloud/

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- A Census of Molecular Gas in z=0.3 Luminous Infrared Galaxies (80 GHz)
- Dense Gas Heating and Diagnostics within Starburst Galaxies (80 GHz)
- Dense Gas Observations of Individual Molecular Clouds In Andromeda (70-85 GHz)
- Molecular Outflows in Early Type Galaxies (1.7 GHz)
- HI Gas Mass and Gas-to-Dust Ratios in Major-Merger Pairs (1.4 GHz)
- An HI 21cm Survey of Active Galaxies Detected in Very Hard X-rays (1.4 GHz)
- Finding Local Group Dwarf Galaxies with the GBT (1.4 GHz)
- Mapping the Low Column Density HI around M31 (1.4 GHz)
- The Flow of Gas in the Milky Way Halo (1.4 GHz)

Origin of Stars and Planets

There are many mysteries about star formation. It occurs on the scale of a solar system, but can be triggered by events at the scale of a galaxy, through density waves, tidal encounters, AGN activity, feedback from earlier star formation, and cloud collisions. Advances in our understanding of star formation require observations on all angular scales. The wide-area, highly sensitive mapping capabilities of the GBT are an essential complement to the detailed high-resolution data provided by ALMA, the VLA, and other interferometers. The GBT is ideally suited for measuring physical conditions in infrared-dark clouds, the likely progenitors of stellar clusters. Although thousands populate our Galaxy, their physical conditions and evolution are poorly understood. The GBT's 18-26 GHz camera is being used to image and measure the temperature, density, turbulence, and kinematics of a large sample of dark clouds, providing new quantitative insights into star formation and the initial conditions (e.g., interactions, shocks, self-gravity) that control dark cloud evolution. The GBT is also discovering hundreds of previously-unknown regions where massive stars are being formed in the Milky Way. These trace the large-scale pattern of star birth and chemical evolution in our galaxy.

http://www.nrao.edu/pr/2012/clumpcores/
http://www.nrao.edu/pr/2013/mwcensus/

Fig. 7: An infrared-dark cloud measured in NH_3 emission (contours) with the GBT.

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- A Next Generation Survey of Starless Cores in the Taurus Molecular Cloud (22 GHz)
- Characterizing a New Population of Protostars in Orion Identified by Herschel (22, 85 GHz)
- A Census of Diverse Environments in Infrared Dark Clouds (22 GHz)
- Mapping the Dust emission from OMC 2/3 (90 GHz)
- Do the Properties of Star Forming Dense Gas Vary Across the Galactic Disk? (22 GHz)
- Constraining Stellar and Galactic Chemical Evolution with 3-Helium Abundances (8 GHz)

Solar System

The GBT plays a major role in the study of the solar system. It is a fundamental instrument for bi-static radar studies of solar system objects including asteroids, the Moon, Mercury, Venus and Europa. With radar, it is possible to map surface details of planets and the Moon with accuracies better, in some cases, than with an orbiter. Radar polarimetry can reveal properties of subsurface rocks and geological features of the Moon hidden from visual inspection. The discovery of Mercury's molten core resulted from bi-static radar measurements of its spin state using the GBT. This technique is now being applied to study the subsurface ocean of Jupiter's satellite Europa.

http://www.nrao.edu/pr/2007/mercury/
http://www.nrao.edu/pr/2008/phoenix/

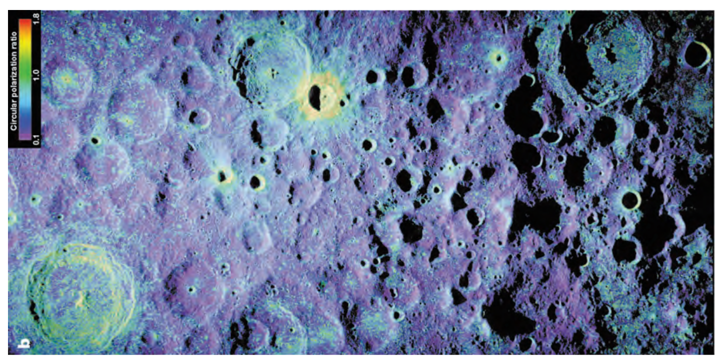


Fig. 8: Radar polarimetry of the Lunar surface from Arecibo-GBT observations reveals details of subsurface structure on scales ~40 meters.

Comets contain primitive material from the Solar System's formation. Their study is critical to our understanding of problems ranging from Solar System formation to the origin of life on Earth. Observing comets requires an instrument that can make rapid measurements with high angular resolution over a wide field of view and have high sensitivity to low surface-brightness lines. Researchers now depend on the occasional spectacular comet (e.g., Comet Hale-Bopp, C/1995 O1) to produce sufficient signal for the detection of numerous molecular species. The 90 GHz camera

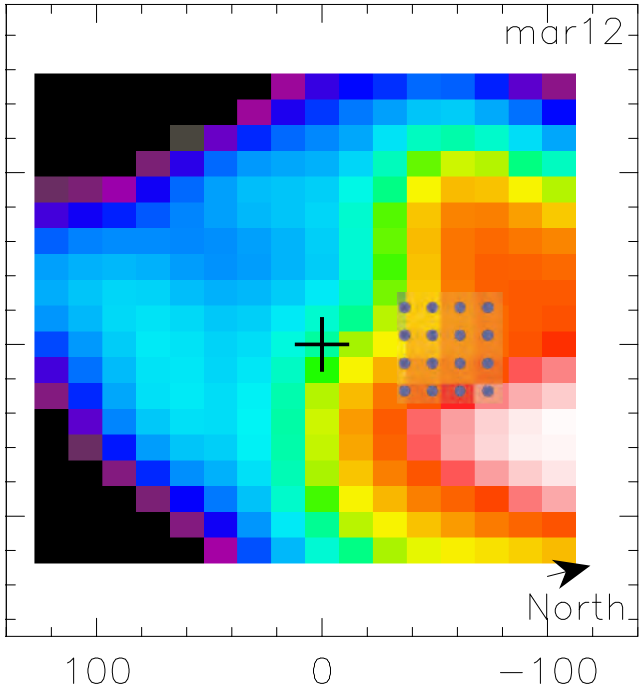


Fig. 9: Footprint of the 3mm GBT camera (dots) now under development on an image of HCO+ in comet Hale-Bopp.

that is under development for the GBT will provide such capability for several comets every year, each detectable for about 3 – 4 weeks. It will transform cometary studies.

The GBT is helping to determine the trajectories of near-Earth asteroids through bi-static radar measurements with transmitters at Arecibo and Goldstone. We know of nearly 10,000 asteroids whose orbits either cross or come near to the Earth. They have sizes of up to tens of kilometers, and have trajectories that are affected by unknown quantities, such as their shape and rotation. With the GBT detecting radar reflected from the asteroids it is possible to measure their spin, shape, and orientation as they pass near the Earth, giving us an understanding of their structure, origin, and eventual fate.

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- A Radar Mapping Search for Recent Volcanism on Venus (2.3 GHz)
- Interior Structure of Europa and Ganymede (8.6 GHz)
- 12.6 cm Radar Mapping of the Near Side of the Moon (2.3 GHz)
- Venus Spin Dynamics (8.6 GHz)
- Bi-static Radar Imaging of Near-Earth Asteroids (2.3 GHz)

Life

How did life arise on Earth? This question is as old as humanity, and the answer will require research across many fields, from biology and chemistry to physics and astronomy. The chemistry of life on Earth most likely originated in the proto-solar nebula, and analogous chemical processes may be observable in interstellar clouds around the Galaxy. The complexity of interstellar chemistry and the existence of plausible delivery mechanisms such as comets and meteorites suggest that some part of pre-biotic chemistry on the early Earth and similar planets occured in interstellar and proto-solar gas clouds. Large-scale variations in chemistry within the parent molecular cloud foster planetary diversity and may lead, in turn, to different chemistries on the surface layers of planets.

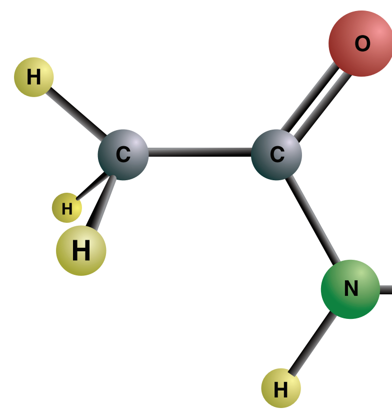


Fig. 10: The molecular structure of acetamide, one of the many organic interstellar molecules recently discovered using the GBT.

The GBT is a leader in this research, and has detected many new organic molecules in space through its ability to measure weak, spatially extended spectral lines over a wide range of frequencies. It will become an increasingly important facility now that its capabilities have been extended into the lower part of the 3mm band, outside the current ALMA frequency coverage and in a region of the spectrum where no large telescope operates. It is the most capable instrument for initial identification and characterization of molecular sources and species in these wavebands.
http://www.nrao.edu/pr/2009/cosmiccradle/
http://www.nrao.edu/pr/2008/molmine/
http://www.nrao.edu/pr/2007/biganion

Representative GBT Proposals Scheduled in 2012 (title and frequency)

- Confirmation of Interstellar CH_2D+, Corner Stone of Hydrocarbon Chemistry (80 GHz)
- Confirmation of Interstellar Benzonitrile (C_6H_5CN) Towards TMC-1 (15 GHz)
- GBT 68-92 GHz Spectral Line Survey of Orion-KL (68-92 GHz)

The GBT was designed to allow ready upgrades and changes to all aspects of its hardware and software. A specialty (or principal-investigator driven) instrument can be installed on the telescope with relative ease, making it feasible for an individual or group of researchers to outfit the telescope to meet their particular science goals. The GBT also has a vigorous development program in collaboration with college and university groups to take advantage of the latest technology and provide our user community with a constantly improving facility. Development projects will continue through the coming decade and have already led to important discoveries in a number of areas.

Imaging the Radio Universe (Camera Development)

The GBT camera development is a collaboration between the NRAO and more than 20 university, college, and industry groups to design, develop, and build a suite of radio cameras that will increase the GBT's capabilities dramatically. Three types of instrumentation are planned: conventional feed horn arrays, phased array receivers, and bolometer arrays. The science achievable with these new instruments on the GBT is extraordinary and varied: rapid, sensitive maps of outflows from comets and of molecular clouds in nearby galaxies; studies of pre-biotic molecules and chemical processes throughout the Galaxy; studies of hot gas in galaxy clusters to complement X-ray images and reveal how cosmic structures form and evolve; and discovery of the most distant galaxies from the emission of cold dust and redshifted molecular lines. In addition, the cameras will improve capabilities for pulsar searches and very deep observations of HI that trace past galaxy interactions. The power and flexibility of these instruments will make it possible to perform experiments that cannot now be done on any telescope.

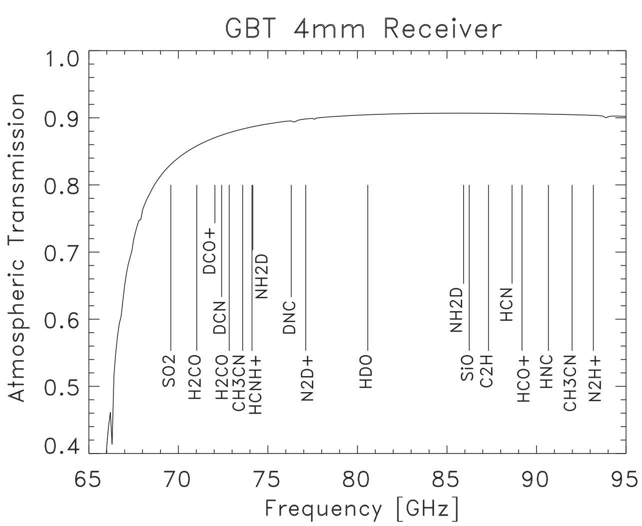


Fig. 11: The new GBT 4mm receiver covers many important molecular species in a band not observable with other large telescopes. The curve shows the atmospheric transmission for typical winter observing conditions in Green Bank.

Focused Science Instruments

In addition to cameras, is it important to develop receiver systems that are optimized to a given science case and that can rapidly be put into operation on the GBT. There are three such instruments now being built – a 4mm receiver for molecular line and VLBI studies, the early version of which entered service in 2012; a wide-bandwidth receiver optimized for the NANOGrav Gravitational Wave detection pulsar experiment at 15cm; and a broadband receiver covering 12-18 GHz for the detection and study of pulsars in the Galactic Center.

Cyberdiscovery – Software Development and High Performance Computing

Discovering the unusual or unexpected in scientific data is often the path to the most fundamental breakthroughs. Yet as scientific data become more complex, our ability to find the unexpected is rapidly diminishing. New scientific instruments will regularly create data sets of 50-100 TB or more in a single observing project, data sets which are far too large to be examined using existing methods. Yet close scrutiny of the data is required to discover unexpected signals or unusual events. A paradigm shift must occur in the approach used to view and analyze these massive amounts of data. GBT staff members are teaming up with universities, industry and other national laboratories to research, design, and test the algorithms and tools needed for modern data analysis.

Maximizing the Science – Improved Telescope Performance and Infrastructure

NRAO staff are working with the scientific community to ensure that the GBT performance and infrastructure is sufficient to meet future scientific demands. The new digital servo system will improve the movement of the GBT, increasing the telescope pointing accuracy and observing efficiencies at high frequencies. Continued upgrades to the surface modeling and better understanding of the weather effects on telescope performance will increase the number of good weather hours available for high-frequency observing from the 1,800 scheduled high frequency (>18 GHz) hours in 2010 to 3,000 hours or more in coming years.

The signal processing and data transmission of the GBT is also being improved to provide higher sensitivity, increased bandwidth, and improved flexibility for all GBT science. The Configurable Instrument Collection for Agile Data Acquisition program (CICADA) is an NRAO collaboration with the **University of California at Berkeley, Xilinx Inc.**, and many university groups around the world. The CICADA program is developing digital signal processing and data transmission systems using reconfigurable, off-the-shelf hardware platforms and software tools that allow rapid design, verification, and deployment of astronomical signal processing systems. The program is based on hardware and tools developed by U.C. Berkeley's CASPER group. The CICADA collaborators are working with the CASPER hardware and software to research, define, and implement astronomical signal processing systems that have numerous applications. This work will allow development of detectors that can encompass the entire band of a radio camera at high frequency resolution, improving the throughput of the GBT by an order of magnitude. A new data transmission system will also improve instrumental stability and reduce instrumental effects for the most sensitive observations.

Training the Next Generation of Scientists and Engineers

An active Research Experience for Undergraduates program has been in place at Green Bank for more than 50 years. In 10-12 week internships undergraduate students in STEM majors experience life and work at a major research facility. Participants have gone on to successful careers in science, engineering and academics. A co-operative education program brings several undergraduates to Green Bank throughout the year to work with astronomers, electronics and software engineers. The Observatory has resident pre-doctoral and post-doctoral fellowships and internships. Every two years the Green Bank Observatory co-hosts a summer school in single-dish radio astronomy with Arecibo Observatory that teaches 60 students the hands-on techniques of radio astronomy. Area high school students can spend a week at the Observatory assisting staff in a mentorship program in electronics, accounting, astronomy, or engineering. The flexibility and breadth of science on the GBT, and the availability of local professional researchers, provides students at all levels with a meaningful and significant experience.

University Collaborations

All new instrumentation for the GBT is being built in collaboration with research groups at universities. This not only leverages efforts of GBT staff and supports University faculty, but also provides a valuable training ground for students to become future instrument builders. Collaborations were arranged between the NRAO, the **University of Pennsylvania**, and six other institutions to develop the 3mm bolometer array MUSTANG. The **University of Maryland** built the Zpectrometer, an analog signal processor to measure signals from distant galaxies. Work with the University of California-Berkeley's CASPER group has led to two FPGA-based instruments, GUPPI (for detecting and timing pulsars) and VEGAS (used for high resolution spectral line studies). **Cornell University** has built and installed a signal processing system designed to process radar signals transmitted from the **Arecibo Observatory** or **NASA's Goldstone Radar** facility, and then reflected from bodies within the solar system. Students from the **California Institute of Technology,** working with NRAO staff, developed an optimized continuum receiver. Radio cameras are also being built for the GBT – the **University of Massachusetts, Bringham Young University,** and NRAO staff are collaborating on phased array feed systems to work at 1.4 and 100 GHz, and a group at **Stanford University** is leading a collaboration to build a traditional feed array for 3mm wavelength spectroscopy.

Fig. 12: The Green Bank Ultimate Pulsar Processing Instrument (GUPPI) is a pulsar detector built with off-the-shelf hardware and custom software.

Although our primary mission is operation of the GBT, the Green Bank Observatory is a center for Science, Technology, Engineering and Mathematics (STEM) education and public outreach. The Observatory is actively engaged with the community, the region, the State and the Nation. http://www.gb.nrao.edu/epo/edhome.shtml

STEM Education and Public Outreach

The Green Bank Observatory has a rare combination of assets: 1) a laboratory where frontier research is an ongoing activity; 2) a professional staff of scientists and engineers who are also involved in education; 3) facilities such as the Green Bank Science Center, radio telescopes, housing and food services, all available for education and outreach. The Observatory staff use these assets to develop and present programs that would not be possible at other institutions. It is a showcase for NSF-funded basic research.

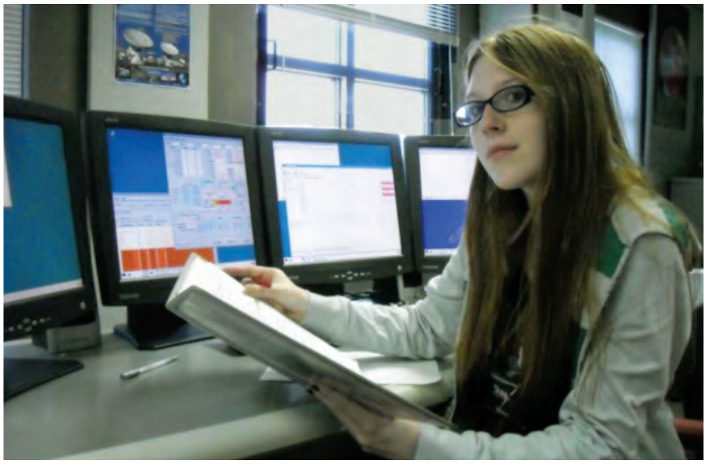
The Green Bank Observatory hosts numerous programs for teachers. Residential teacher institutes provide a research experience for K-12 teachers and pre-service teachers through projects on the 40-Foot Radio Telescope under supervision of the Green Bank staff. Begun in 1987 and supported initially by the NSF and NASA, this program has trained over 1000 teachers in the fundamentals of scientific research. Each year, a Chautauqua Short Course Program for undergraduate college faculty is held to update their content knowledge. In the several dozen years of the program, over 650 undergraduate faculty have participated.

Over the past 13 years, the NSF-sponsored Research Experience for Teachers has matched 27 teachers from grades 7-12 with Green Bank astronomers to perform astronomical research over an 8-week summer period. All these activities involve site scientists and engineers as lecturers, advisors, and mentors.

The Pulsar Search Collaboratory (PSC) is a unique program in partnership with **West Virginia University** that enables middle and high school students to participate in active pulsar research using data from the Green Bank Telescope. In a summer residential program, high school teachers and their students work with astronomers to learn how to analyze data produced by the telescope, and then form PSC teams back at their schools. Funded by the NSF, the Collaboratory has so far engaged 103 teachers and 709 students from 18 states in pulsar research. Student teams have thus far discovered 6 new pulsars and one transient object, increasing the interest in science and technology at their schools, and gaining national recognition.
http://www.nrao.edu/pr/2007/pulsarcollab/
http://www.nrao.edu/pr/2011/studentpulsar/

A new NSF-funded program is giving middle-school-aged youth the chance to take remote control of the NRAO 20-meter-diameter telescope, bringing the excitement of hands-on research to young people via 4-H, the nation's largest youth development organization. Skynet Junior Scholars will provide some 1,400 4-H youth with access to robotically-operated, research-grade telescopes. They will use the telescopes to survey galaxies, track asteroids, monitor variable stars, and learn first-hand how scientific research is done. In addition to the NRAO 20-meter radio telescope, the network includes optical telescopes in Wisconsin, North Carolina, Chile and Australia. http://www.nrao.edu/pr/2012/skynet/

Fig. 13: Shay Bloxton (below) and Lucas Bolyard (above, left) are among the high school students who have discovered new pulsars using the GBT.



http://www.nrao.edu/pr/2009/pulsarstudent/
http://www.nrao.edu/pr/2010/shaypulsar/
http://www.whitehouse.gov/blog/Always-Reach-for-the-Stars-Astronomy-Night-at-the-White-House

For the past 8 years, the Green Bank Observatory has been host to the WV Governor's School for Math and Science, a 2-week residential astronomy camp operated in collaboration with the National Youth Science Foundation, aimed at increasing interest in STEM careers. Over 400 rising 9th graders have participated in the program, which is funded by the State of West Virginia. The Observatory also hosts National Youth Science Camp tours and directed studies.

The 40-Foot telescope is a working radio telescope outfitted specifically for use by students and teachers. It is the centerpiece of a hands-on research experience offered by the Green Bank staff. Each year a total of 2500-3000 scouts, students and teachers visit Green Bank in groups ranging in size from 10-40 for visits that often last several days. The groups are housed in the site bunkhouse and have meals in the cafeteria. They receive training, full access and use of the 40-Foot telescope, in-depth tours of the electronics labs, and interactions with the Observatory staff.

Fig. 14: The 40 Foot Radio Telescope with some student users.
http://www.gb.nrao.edu/epo/fieldtrip.shtml

Fig. 15: The NRAO Green Bank Science Center.
http://www.nrao.edu/index.php/learn/gbsc

The Science Center is a multi-purpose building that draws 50,000 visitors each year, a remarkable number for so remote a location. Visitors experience the many interactive displays in a 4,000 square-foot exhibit hall, partake in presentations about radio astronomy from the Science Center staff, and enjoy a guided bus tour around the site.

The Science Center is also used for monthly star parties, an annual 4-day gathering of amateur astronomers called Star Quest, the annual meeting of the Society of Amateur Radio Astronomers, community days, and other events. It serves as the focus for school field trips throughout the year.

Use of Site Infrastructure

The Green Bank Observatory is a large protected site with laboratories, utilities and support facilities, making it an attractive location for staging research projects not directly connected with the NRAO mission. In addition, because of the National Radio Quiet Zone and the West Virginia Radio Astronomy Zone, it is uniquely protected from many forms of man-made radio frequency interference. For these reasons, it is used as the Northern site for the PAPER telescope, an instrument to study the epoch of reionization. PAPER is run by a partnership of university groups which also operates a sixty-four element array in the Karoo desert of South Africa.
http://astro.berkeley.edu/~dbacker/eor/

Fig. 16: The 140 Foot Radio Telescope.

The 45-Foot telescope, built originally as part of the VLA prototype interferometer then transformed into a ground station for the Japanese HALCA satellite, is now functioning as a Solar Radio burst Spectrometer, providing dynamic spectra of solar radio bursts during daylight hours at Green Bank.

The 140-Foot telescope was recently operated under contract to MIT Lincoln Laboratory for ionospheric studies and is now in use as a spacecraft data downlink station.

The University of Texas (Brownsville) is leading the installation of a Low-Frequency All-Sky Monitoring Array at the Observatory to study the transient universe.

The West Virginia University Department of Physics fluxgate magnetometer was installed at the Green Bank site in 2009. The project is a collaboration between the WVU, NRAO, and the **University of California at Los Angeles (UCLA)**. The instrument is operated by the WVU plasma physics group for research and education purposes and also contributes to measurements of UCLA's Magnetometers along the Eastern Atlantic Seaboard for Undergraduate Research and Education (MEASURE) array.

Meetings and Workshops

The housing and cafeteria facilities make the Green Bank Observatory an excellent location for small, intense scientific workshops. The first was a joint US-USSR symposium held in 1961, at a time when scientific contact between the two nations was rare. Since then there have been more than three dozen workshops covering millisecond pulsars, gaseous halos of galaxies,

Fig. 17: Participants at a scientific workshop celebrating the 35th anniversary of the discovery of the Tully-Fisher relationship, April 2012. https://science.nrao.edu/science/event/tf35

chemistry in the universe, cometary radio astronomy, the search for extra-terrestrial intelligence, and data management issues in astronomy, to name just a few. On average 2-3 workshops are held on site each year, with anywhere from 40-100 participants.

The Green Bank Observatory and the Community

The Green Bank Observatory has tight links to the local community, the region and the State. In addition to the mentorship experiences offered to local secondary school students, there is significant outreach into the community. Staff members often teach STEM classes in the local schools, mentor science and math students, serve as science fair mentors and judges, and are on county and state educational committees and boards. Observatory facilities are used for community meetings and by organizations such as the Boy Scouts and National Forest Service, and are a vital part of the county emergency services plan.

Fig. 18: NRAO software engineers teaching an elective in robotics to Green Bank Middle School students.

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FIGURE CREDITS

All figures are NRAO/AUI/NSF except:

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Fig. 5: The Megamaser Cosmology Project (https://safe.nrao.edu/wiki/bin/view/Main/MegamaserCosmologyProject)

Fig. 6: The 200° Long Magellanic Stream System, Nidever, D. L., et al., 2010, ApJ, 723,1618

Fig. 7: Courtesy of J.M. Jackson and S.C. Finn, Boston University.

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