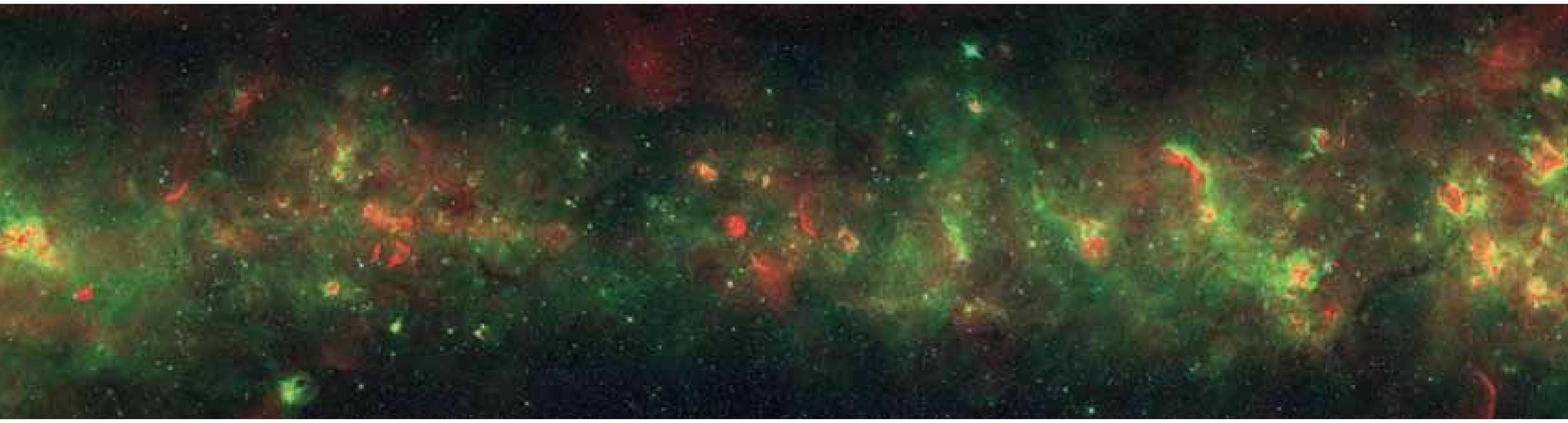
National
Radio
Astronomy
Observatory

RESEARCH FACILITIES
for the Scientific Community



2011

Atacama Large Millimeter/submillimeter Array
Expanded Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

NRAO

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RESEARCH FACILITIES 2011

(above image)
The radio emission (orange) detected by the NRAO Very Large Array (VLA) is synchrotron radiation emitted by electrons moving at nearly the speed of light in a cosmic magnetic field. These electrons originate in enormous energy outflows from jets fueled by a supermassive black hole at the center of the galaxy NGC 1316 (center, blue-white). Credit: NRAO/AUI, J. M. Uson

(cover)
This panorama of the Scutum-Aquila Milky Way illustrates the dynamic interplay between the birth and death of massive stars. This image combines 20 cm radio data from the Very Large Array (red) with mid-infrared data from the Spitzer Space Telescope (green and blue-white). Regions where radio and infrared emission are prominent appear yellow. Credit: D. Helfand (Columbia), R. Becker (UC-Davis), R. White (STScI).

(back cover)
The outlying regions of the Southern Pinwheel Galaxy (M83) are highlighted in this composite image from NASA's Galaxy Evolution Explorer and the NRAO Very Large Array. The Galaxy Evolution Explorer far- and near-ultraviolet data (blue and green, respectively) highlight the galaxy's farthest-flung clusters of young stars, which are up to 140,000 light-years from its center. The Very Large Array 21 cm observations (red) highlight the hydrogen gas that comprises the extended spiral arms. Credit: NASA/JPL-Caltech/NRAO VLA/MPIA

The NRAO in the Coming Decade

The research facilities of the National Radio Astronomy Observatory play critical roles across all of modern astrophysics. Radio astronomy probes the earliest, most intense, and optically obscured phases of planet, star, galaxy, and black hole formation, and reveals the cool dense gas from which stars form. Radio telescopes allow astronomers to make precision cosmological measurements, test fundamental physics, analyze complex magnetic fields and their effects, probe high-energy phenomena, and understand the physics and chemistry of extreme environments.

In the coming decade, the National Radio Astronomy Observatory will operate a suite of telescopes that will enable broad astrophysical discovery. The Atacama Large Millimeter/submillimeter Array (ALMA) will begin Early Science in late 2011 and be fully operational in 2013, opening a new window into the physics of the cold Universe and providing enormous improvements in resolution, sensitivity, and frequency coverage.

The Expanded Very Large Array (EVLA) leverages existing NRAO infrastructure to create an entirely new research instrument and improve our ability to explore the Universe at centimeter wavelengths by an order of magnitude. The EVLA initiated Early Science operations in March 2010 and will remain the most powerful radio telescope in the world in this portion of the electromagnetic spectrum through at least the next decade.

The Robert C. Byrd Green Bank Telescope has matured into an extremely productive research tool, with ever-increasing sensitivity, efficiency, and imaging capabilities that will soon enable deep, wide-field studies of the Galaxy and beyond. The NRAO and its international partners are also delivering significantly improved sensitivity at the Very Long Baseline Array, enabling a wide range of innovative science that benefits from the array's unique precision astrometry and high-resolution imaging capabilities.

The NRAO is also working with the astronomy community to develop the scientific and technical concepts for the next generation of research facilities including the Frequency Agile Solar Radiotelescope (FASR), the North American Nanohertz Gravitational Observatory (NANOGrav), the Precision Array to Probe the Epoch of Reionization (PAPER), and the Square Kilometre Array (SKA).




Atacama Large Millimeter/ submillimeter Array (ALMA)

Altiplano de Chajnantor, Chile

The Atacama Large Millimeter/submillimeter Array (ALMA) will enable transformational research into the physics of the cold Universe, regions where the sky is dark in the visible part of the spectrum but shines brightly at millimeter wavelengths. Operating at wavelengths from 0.3 to 9.6 mm, ALMA will probe the first stars and galaxies, and directly image interstellar gas in the process of forming new planets, thus providing a new window on cosmic origins. ALMA is being built on the Chajnantor plain of the Chilean Andes in the district of San Pedro de Atacama, 5000 m above sea level, where the Earth's atmosphere is largely transparent at millimeter wavelengths. Upon completion, the telescope will be composed of at least 66 high-precision antennas, providing unprecedented sensitivity and imaging the sky at resolutions as fine as 0.005 arcsec, a factor of ten better than the Hubble Space Telescope.

ALMA construction will be completed in late 2013. While the array is still being assembled, significant observing time will be made available to the community as Early Science, beginning in late 2011. A call for ALMA Early Science proposals will be issued during the first quarter of 2011, with the proposal deadline about three months later. Even during Early Science, ALMA will provide significantly better capabilities than other present-day millimeter interferometers. Initially the telescope will include at least 16 antennas producing resolutions as fine as 0.4 arcsec, and the capabilities will improve as the telescope approaches full operations.

ALMA is an international astronomy facility, a partnership of Europe, Japan, and North America in cooperation with the Republic of Chile. ALMA is funded in Europe by the European Organization for Astronomical Research in the Southern Hemisphere (ESO) and in Japan by the National Institutes of Natural Sciences (NINS) in cooperation with the Academia Sinica in Taiwan, and in North America by the US National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC) and the National Science Council of Taiwan (NSC). ALMA construction and operations are led on behalf of Europe by ESO, on behalf of Japan by the National Astronomical Observatory of Japan (NAOJ) and on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI).

The North American ALMA Science Center (NAASC)

The North American ALMA Science Center, based at the NRAO headquarters in Charlottesville, Virginia, supports the science use of ALMA by the North American astronomical community, and the research and development for future ALMA upgrades. The NAASC provides a number of key services to users. These include organizing and hosting conferences and training workshops, supporting users during the preparation and submission of ALMA proposals and observations, and helping users reduce and analyze their ALMA data both remotely and through visits to the NAASC site in Charlottesville. The NAASC also prepares and maintains ALMA user documentation and web sites, and operates the ALMA helpdesk. More information on the NAASC is available at http://science.nrao.edu/alma/intro-naasc.shtml. The NAASC is operated by NRAO in partnership with the National Research Council of Canada.

KEY SCIENCE

ALMA is designed to accomplish, at a minimum, three "Level 1" science goals: (1) detect CO/C+ in less than 24 hours from a normal galaxy like the Milky Way at redshift z = 3; (2) resolve protoplanetary disks around stars at a distance of 150 pc; and (3) provide precise imaging at submillimeter wavelengths with 0.1 arcsec resolution, in which the sky brightness is accurately represented for all points above 0.1% of the peak flux in the map. ALMA will thus be capable of high fidelity imaging both in the continuum and in spectral lines. It will have wideband frequency coverage (8 GHz in dual polarization) and will be capable of imaging fields larger than the primary beam using mosaics.

ALMA will be a general-purpose research instrument. In addition to accomplishing the specific design goals, ALMA will be able, e.g., to image dust continuum emission from galaxies at z = 10, showing how galaxies assemble during their earliest stage of formation. ALMA will enable blind surveys of molecular gas in the early Universe, thus revealing the star-formation history of the Universe. ALMA will image molecular gas in the nuclei of nearby active galaxies with spatial resolutions of 10-100 pc, revealing the structure of the putative obscuring torus in active galactic nuclei. ALMA will also enable detailed studies of the full life cycle of stars and will be able to detect heavy, prebiotic molecules in newly forming solar systems. ALMA will probe the gas dynamics in young stellar systems as the disk, jet, and central star itself form. And in the spectacular supernova explosions that mark the end of the stellar life cycle, ALMA will show heavy elements and chemicals as they re-seed the interstellar medium with new material that will form the next generation of stars.

RECEIVER BANDS

Band #	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Frequency Range (GHz)	84 - 116	125 - 163	163 - 211	211 - 275	275 - 373	385 - 500	602 - 720	787 - 950
Wavelength Range (mm)	3.57 - 2.59	2.40 - 1.84	1.84 - 1.42	1.42 - 1.09	1.09 - 0.80	0.78 - 0.60	0.50 - 0.42	0.38 - 0.32

	Early Science	Array Completion
Antennas	≥ 16 (12 m)	At least 54 x 12m & 12 x 7m
Bands	Bands 3, 6, 7, 9	Bands 3, 4, 6, 7, 8, 9 & 10
Maximum Bandwidth	16 GHz (2 pol x 8 GHz)	16 GHz (2 pol x 8 GHz)
Correlator Configurations	5 – 21	71 configs (0.01-40 km/s)
Maximum Angular Resolution	0.02" (λ /1 mm)(10 km/max baseline)	0.02" (λ /1 mm)(10 km/max baseline)
Maximum Baseline	250 m (may achieve 500m)	15 km
Continuum Sensitivity (60 sec, Bands 3 – 9)	~ 0.2 – 4.2 mJy/beam	~ 0.05 – 1 mJy/beam
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 – 9)	~ 30 – 250 mJy/beam	~ 7 – 62 mJy/beam

Far left: A simulation of an 8-hour ALMA observation at 345 GHz, showing how ALMA will image the gap swept up by the proto-planet, the disk surrounding the star, and the proto-planet itself. Image courtesy S. Wolf, from Wolf & D'Angelo (2005)

Left: An ALMA antenna rides atop a transporter to the 5000m elevation Array Operations Site in northern Chile.

ALMA TIMELINE

Call for ALMA Early Science Proposals	Early 2011
Early Science Proposal Submission Deadline	Mid 2011
Begin Early Science	Late 2011
66 ALMA Antennas Operational	2013

ALMA on the World Wide Web

http://science.nrao.edu/alma

http://www.almaobservatory.org

NAASC on the World Wide Web

http://science.nrao.edu/alma/intro-naasc.shtml

Expanded Very Large Array (EVLA)

Socorro, New Mexico

The Expanded Very Large Array is a radio telescope of unprecedented sensitivity, frequency coverage, and imaging capability that is being created by modernizing the Very Large Array. Its new Wideband Interferometric Digital Architecture (WIDAR) correlator, when deployed in full, will provide superb spectral resolution and fidelity over very wide instantaneous frequency bands, enabling astronomers to make full-beam images with very high spatial resolution and dramatically improved continuum sensitivity. The VLA correlator was turned off in January 2010 and replaced by the new WIDAR correlator. At the same time, the direction of the array configuration cycle was reversed to facilitate WIDAR commissioning. These two events marked the beginning of EVLA Early Science in March 2010. Early Science features two programs offering enhanced scientific opportunities to the community: an Open Shared Risk Observing program for the general user community, and a Resident Shared Risk Observing program. Over time, an increasing range of WIDAR capabilities will be made available to the scientific community through these two programs.

When complete in 2012, the EVLA will complement next-generation instruments such as ALMA and the James Webb Space Telescope, and provide:

- Continuum sensitivity improvement over the VLA by factors of 5 to 20.
- Operation at any frequency between 1.0 and 50 GHz, with up to 8 GHz bandwidth per polarization, 64 independently tunable sub-band pairs, each providing full polarization capabilities.
- A minimum of 16,384 and a maximum of 4,194,304 spectral channels, adjustable frequency resolution between 2 MHz and 0.2 Hz, and extensive capabilities to allocate correlator resources.
- Spatial dynamic range > 10^6, frequency dynamic range > 10^5, with noise-limited, full-field imaging in all Stokes parameters.
- Dynamic scheduling based on weather, array configuration, and science requirements. Reference images automatically produced, with all data products archived.

The EVLA Project is funded by the U.S. National Science Foundation, with additional contributions from the National Research Council in Canada, and the Consejo Nacional de Ciencia y Tecnologia in Mexico.

EVLA on the World Wide Web

http://science.nrao.edu/evla

EVLA MILESTONES

Begin Early Science	Mar 2010
Last antenna retrofitted to EVLA design	May 2010
Enhanced capabilities offered for Early Science	Sep 2011
Complete commissioning of full WIDAR correlator	Jan 2012
Last EVLA receiver installed	Dec 2012

KEY SCIENCE

The Magnetic Universe

The sensitivity, frequency agility, and spectral capability of the EVLA will allow astronomers to trace the magnetic fields in X-ray emitting galaxy clusters, image the polarized emission in thousands of spiral galaxies, and map the 3D structure of magnetic fields on the Sun.

The Obscured Universe

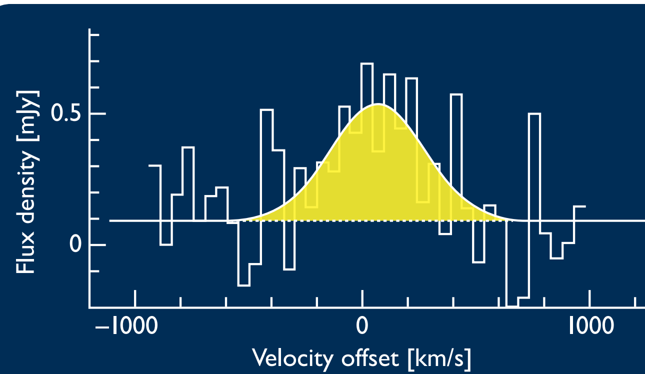
Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The EVLA will observe through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young stellar objects, and image the densest regions in nearby starburst galaxies.

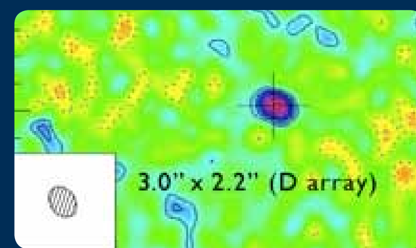
The Transient Universe

Astronomical transient sources tend to be compact objects that emit synchrotron radiation from high-energy particles, radiation best observed at radio wavelengths. The EVLA will be ideal for studies of variable sources because of its high sensitivity, ability to observe day and night under most weather conditions, and the rapid response enabled by dynamic scheduling. The EVLA will image novae and relativistic jets anywhere in the Milky Way, and measure the sizes of many tens of gamma-ray bursts each year.

The Evolving Universe

Radio telescopes can trace the evolution of neutral hydrogen and molecular gas, and provide extinction-free measurements of synchrotron, thermal free-free, and dust emission. The EVLA will distinguish dust from free-free emission in disks and jets within local star-forming regions, and will measure the star-formation rate, irrespective of dust extinction, in high-z galaxies.

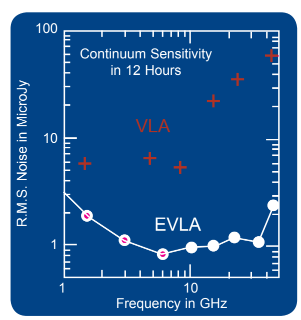




The CO(2-1) emission from the most distant hyper-starburst galaxy (AzTEC-3), at z = 5.3, about 1 billion years after the Big Bang. This EVLA data shows the cold gas fueling the star formation and indicates more than 10^{10} solar masses of dense gas in this still-forming elliptical galaxy (Riechers et al, 2010).

The supernova remnant (SNR) G93.3 at 5 GHz. Predictions indicate there should be many more Galactic SNRs than are known. SN remnants are typically hidden by the Galactic Plane and detectable only at radio wavelengths. A single EVLA observation can provide data on the emission mechanisms and magnetic field strengths in these and other radio sources, inside and outside our Galaxy.

CHARACTERISTICS



- New digital electronics and modern digital wide-band correlator
- Full frequency coverage from 1 to 50 GHz
- Fiber-optic transmission system and new on-line control system
- 28 antennas
- Resolution: 45 arcsec (D-configuration) to 1.3 arcsec (A-configuration) at 1.5 GHz
- Imaging Field of View: 30 arcminutes at 1.5 GHz. Larger fields available through mosaicing.

SPECIFICATIONS

Parameter	VLA	EVLA
Continuum sensitivity in 12 hrs. 1σ	10 µJy	0.8 µJy
Maximum bandwidth	0.1 GHz	8 GHz
Number of frequency channels at maximum bandwidth	16	16,384
Maximum number of frequency channels	512	4,194,304
Frequency coverage, 1 - 50 GHz	22%	100%
Number of baselines	351	351
Spatial Resolution (5GHz)	0.3 arcsec	0.3 arcsec

Robert C. Byrd Green Bank Telescope (GBT)

Green Bank, West Virginia


Image courtesy of NRAO/AUI

The Green Bank Telescope (GBT) is the premier single-dish radio telescope operating at centimeter and millimeter wavelengths. Its receivers extend from 300 MHz - 50 GHz, with a 64-pixel bolometer array at 81-98 GHz in routine operation, and a 68-92 GHz heterodyne receiver under construction for 4mm band spectroscopy. The GBT has a suite of detectors optimized for spectroscopy, pulsar observations, continuum, and very long baseline interferometry (VLBI). Located in the National Radio Quiet Zone, the GBT benefits from a low radio-frequency interference environment. The GBT surface has an accuracy of 250 µm, yielding an aperture efficiency of 35% at 90 GHz. Observations are scheduled dynamically to match scientific requirements to the weather conditions.

GREEN BANK TELESCOPE CAMERA DEVELOPMENT PROGRAM

The NRAO is designing, building, and commissioning new camera systems that will provide the next quantum leap in GBT science capabilities, including conventional feed horn arrays, phased array receivers, and bolometer arrays. The camera development program is a collaboration between the NRAO and more than twenty university, college, and industry research groups.

Multiplexed SQUID TES Array at Ninety Gigahertz: MUSTANG Bolometer Array

The MUSTANG 64-pixel bolometer array covering 81-98 GHz (3 mm) is in routine use at the GBT, and a more efficient 100 pixel array is under development. MUSTANG on the GBT has an angular resolution of 9 arcsec over a 40 x 40 arcsec fully-sampled field-of-view.

Early science from the K Band Focal Plane Array. NH_3 (1,1) integrated intensity contours are shown on a Spitzer Space Telescope image of the dark cloud surrounding the extremely young Serpens South cluster. The field is 28 x 20 arcmin. GBT observations probe the cloud's physical properties at a resolution of 0.06 pc (Friesen et al 2010).

K-Band Focal Plane Array

The 7-pixel, dual-polarization array of heterodyne receivers for 18-26.5 GHz is now available for regular use. Though optimized for mapping in the NH_3 lines it can be used for other species. Receiver temperatures are ~ 25 K across the band, giving total zenith system temperatures as low as 39 K in good weather at an aperture efficiency of 69%. A new software pipeline allows near real-time data reduction.

W-Band Focal Plane Array

Preliminary design work is underway on a large format heterodyne focal-plane array for use in the upper end of the 3mm band.

Phased Array Receiver Development

The NRAO is working with Brigham Young Univ., the Univ. of Massachusetts, and other groups on the development of phased array technology with the goal of building sensitive, multi-pixel arrays for the GBT. A prototype 7-beam system at 1.4 GHz is being built primarily for engineering tests, but it may also be competitive as a pulsar search instrument and for extended HI structure mapping.

NEW DIGITAL SIGNAL PROCESSORS

The Green Bank Ultimate Pulsar Processing Instrument (GUPPI) is a field-programmable gate array (FPGA) based pulsar processing instrument that provides 200-800 MHz bandwidths with 2048-4096 spectral channels, full Stokes parameters, and integration times as short as 40.96 μsec. The GUPPI coherent de-dispersion modes are now available. GUPPI is a collaboration between the NRAO, UC-Berkeley, Univ. of Cincinnati, and Xlinx, Inc. The NRAO is also partnered with UC-Berkeley to develop a new FPGA-based spectrometer for the GBT that will be released in 2012.

NEW RECEIVER FOR SPECTROSCOPY AT 4MM

A 4mm dual-beam receiver is being built to cover 68-92 GHz. Its key science driver is molecular spectroscopy, and VLBI observations will also be supported. Commissioning with the possibility of shared-risk science observations is expected in late 2011.

KEY SCIENCE

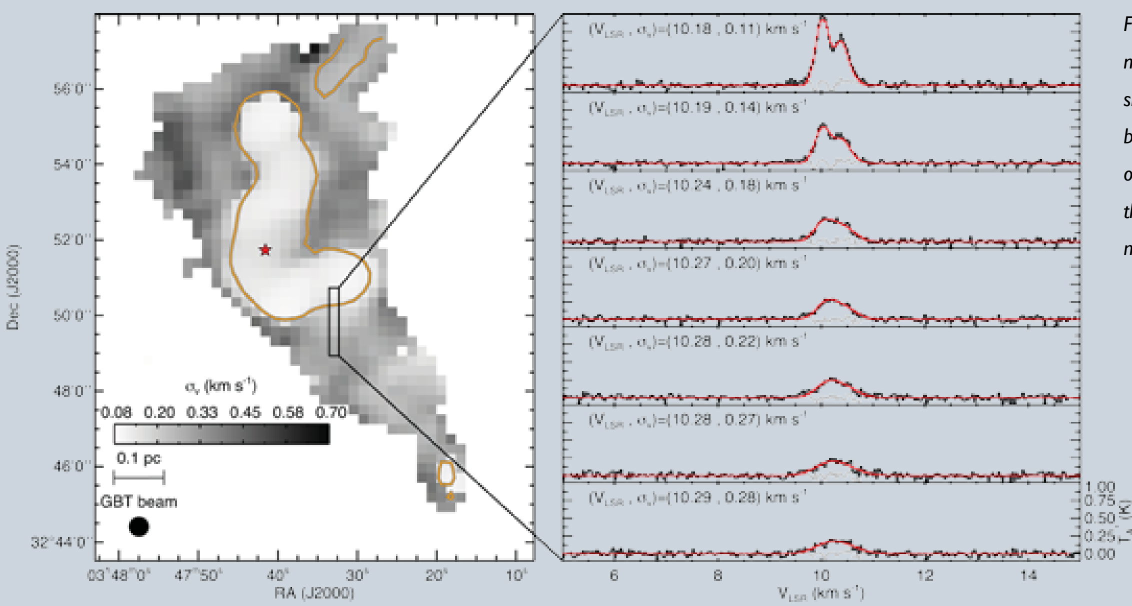


Figure-2: This GBT velocity dispersion map of NH_3 lines in a dark cloud shows, for the first time, the transition between the supersonic turbulent outer layers and the smooth flow of the inner parts as it collapses into new stars (Pineda et al 2010).

Fundamental Physics

With its sensitivity, wide sky coverage, and state-of-the-art instrumentation, the GBT is a premier instrument for studying pulsars and other compact objects that probe fundamental physics. The GBT is also vital to the on-going efforts to directly detect gravitational radiation by timing an array of pulsars around the sky.

Star Formation

With good angular resolution and sensitivity to extended sources, the GBT has made the first definitive detection of the transition from turbulent to coherent flow in the dense core of a star-forming dark cloud. By mapping NH_3 transitions, Pineda et al (2010) discovered a sharp boundary between supersonic and subsonic turbulent motions that naturally defines a dense core and suggests a shock or other instability for its origin.

The Structure and Evolution of Galaxy Clusters

The MUSTANG 3mm bolometer array has revealed hitherto unknown structures in the hot gas of galaxy clusters. MUSTANG observations of the Sunyaev-Zel'dovich (S-Z) effect reveal the presence of shock-heated gas that is otherwise difficult to detect. Several clusters show this distinctive sign of mergers, the remnants of the processes that have formed them.

Origin of Life

Determining the origin of life on Earth requires research across biology, chemistry, physics, and astronomy. The GBT will play a major and unique role in this work by measuring interstellar chemical processes and their variation across the Milky Way, determining the characteristics and extent of pre-biotic chemistry in star-forming regions, and by rapid imaging of the molecular content of comets in our Solar System.

GBT on the World Wide Web

http://science.nrao.edu/gbt

Very Long Baseline Array (VLBA)

St. Croix, VI • Hancock, NH • North Liberty, IA
Fort Davis, TX • Los Alamos, NM •
Pie Town, NM • Kitt Peak, AZ • Brewster, WA
Owens Valley, CA • Mauna Kea, HI

The Very Long Baseline Array (VLBA) is an interferometer of 10 identical antennas with baseline lengths up to 8000 km (Mauna Kea, Hawaii to St. Croix, Virgin Islands). The VLBA is controlled remotely from the Science Operations Center in Socorro, New Mexico. Each VLBA station consists of a 25 m antenna and an adjacent control building. The received signals are amplified, digitized, and recorded on fast, high capacity recorders. The recorded data are sent from the individual VLBA stations to the correlator in Socorro.

The VLBA observes at wavelengths of 28 cm to 3 mm (1.2 GHz to 96 GHz) in eight discreet bands, plus two narrow sub-gigahertz bands. New receivers are being developed for the VLBA that are capable of tuning between 4 and 8 GHz, and are expected to be available in mid-2012. The array can be scheduled dynamically, and its continuum sensitivity can be improved significantly by adding the Green Bank Telescope and, soon, the phased Expanded Very Large Array.

VLBA on the World Wide Web

http://science.nrao.edu/vlba

KEY SCIENCE

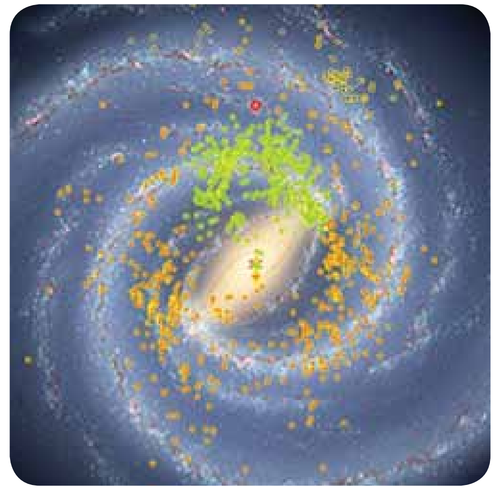
Precision astrometry is a VLBA science centerpiece. The relative astrometric accuracy of ~ 10 μas achievable with the VLBA, for example, is better than the Gaia satellite is designed to achieve for most stars in its catalog. Unlike Gaia, the VLBA can probe the Galactic plane well beyond the solar neighborhood because the radio emission is affected little by extinction.

In 2010, the VLBA began a long-term program to determine the 3D structure of the Milky Way by measuring parallaxes with 10 μas accuracy or better to ~ 400 high-mass star-formation regions. This program is expected to eventually measure the fundamental galactic rotation parameters with 1% accuracy, helping to quantify the distribution of luminous and dark matter in the Galaxy.

The VLBA is also expected to anchor High Sensitivity Array observations of the center of M31 in an effort to detect the galaxy's nucleus with significant signal-to-noise and enable a first-epoch position measurement. The ultimate goal is the proper motion of M31 relative to the Milky Way, which should help distinguish between scenarios proposed for the formation of the Local Group and provide a measurement of the mass of M31 and its dark-matter halo.

The NASA Fermi Gamma-ray Space Telescope released its first gamma-ray source catalog in 2009. In 2011, the VLBA will participate in several cooperative observational programs with Fermi. These programs will focus on active galactic nuclei, or blazars, several thousand of which should be detected by Fermi over the next few years.

A long-term VLBA program to study Active Galactic Nuclei containing central H_2O megamasers will continue. This program has two primary scientific goals: (1) acquire geometric distance measurements that enable an accurate determination of the Hubble Constant and related dark-energy parameters; and (2) directly measure the masses of central black holes with accuracies of at least 10%, much better than any other technique used for sources outside the Milky Way.



The Bar and Spiral Structure Legacy Survey program (Mark Reid et al.) will measure accurate distances and proper motions for about 400 high-mass star-forming regions in the Milky Way between 2010 and 2015. This survey will yield accurate distances to most of the high-mass star-forming regions in our Galaxy that are visible from the northern hemisphere, as well as very accurate measurements of fundamental parameters such as the distance to the Galactic center, and the Milky Way rotation velocity and rotation curve. Credit: IPAC-R. Hurt/CfA-Mark Reid/NRAO/AUI/NSF.

SENSITIVITY ENHANCEMENT PROGRAM

At its 1993 dedication, the VLBA sensitivity was limited by the available bandwidth, 16 MHz in dual polarization. Technology progressed, however, and substantial increases in bandwidth and continuum sensitivity became affordable. Thus, since the array's dedication, the NRAO has quadrupled the available VLBA bandwidth, and the Observatory will quadruple it again in 2011. This enhancement and other sensitivity improvements are being undertaken with our international partners to provide new scientific capabilities for the VLBA user community.

VLBA MILESTONES

2007: The NRAO, in collaboration with the UC-Berkeley CASPER and South African KAT groups, and with MIT Haystack Observatory, initiated development of a new VLBA digital backend to digitize the entire span of the two available 500 MHz intermediate frequency channels.

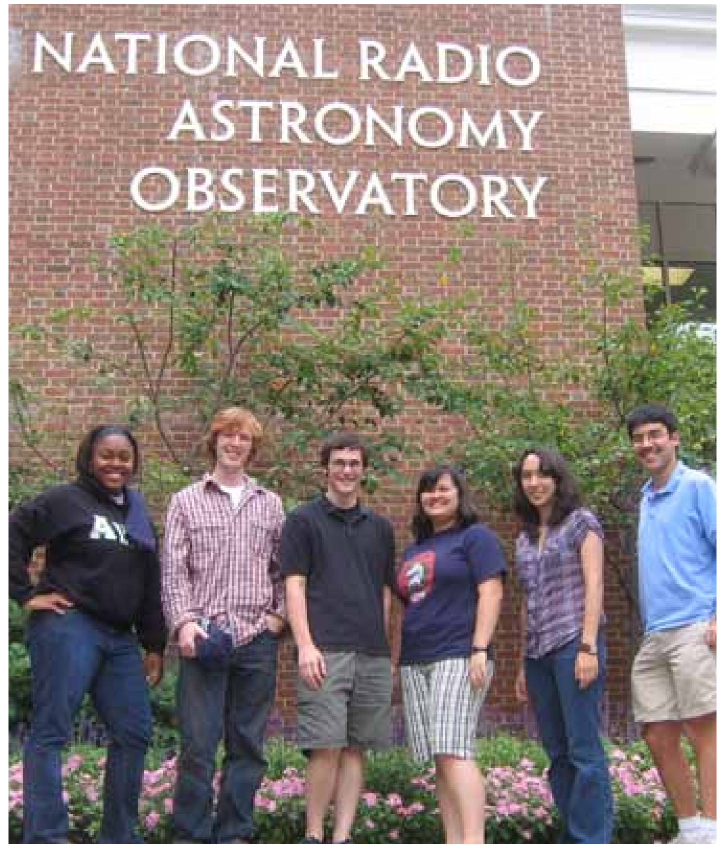
2008: In partnership with the Max Planck Institut fur Radioastronomie, completed the 22 GHz amplifier replacement, resulting in 30% sensitivity improvement.

2010: Completed conversion of the VLBA to higher-bandwidth software correlator. Initial deployment of new recording system at antenna stations. Initiated conversion of VLBA to subscriber facility, with an emphasis on Key Science Projects.

2009-2011: Expand data recording media pool and software correlator processor cluster. Complete full correlator commissioning.

2011: Complete implementation of 500 MHz bandwidth capability and new VLBA digital backends.

Student & Visitor Programs



Summer Student Programs

Summer students conduct research at the NRAO under the supervision of a scientific staff member in Socorro, Green Bank, or Charlottesville. The project may involve any aspect of astronomy and often results in scientific journal publications. Students receive relocation support, a monthly stipend, and partial support may be available to present summer research results at an American Astronomical Society meeting. Students also participate in an extensive lecture series.

Undergraduate students who are U.S. citizens or permanent residents are eligible for the NRAO Research Experiences for Undergraduates (REU) program. Students who do not meet REU guidelines may be eligible to apply for the NRAO Undergraduate Summer Student Research Assistantship program. First and second year graduate students are eligible to apply for the NRAO Graduate Summer Student Research Assistantship program. **Applications are due at the end of January each year.**

Co-op Program

The NRAO has developed relationships with many US universities with strong engineering and computer science departments. Each semester the NRAO sponsors one or more paid undergraduate students. These co-op students, normally juniors and seniors, spend three alternating semesters working with an NRAO mentor. Typical co-op assignments include engineering tasks related to the design, prototyping, testing, or production of radio astronomical instrumentation or programming tasks related to radio telescope monitor and control.

Graduate Student Internships

The Graduate Student Internship program is for students in the early years of a graduate program who are interested in radio astronomy or related research. Students who are U.S. citizens or permanent residents, are enrolled in an accredited U.S. graduate program, or who are otherwise eligible to work in the U.S., will receive a stipend. Some travel and housing assistance may also be available. Appointments may be made for periods from a few weeks to six months. An NRAO staff member supervises each student.

Pre-Doctoral Research Program

The NRAO pre-doctoral research program supports upper-level graduate students who have completed their academic institution's requirements for becoming doctoral candidates. Astronomy, engineering, and computer science students are encouraged to participate. Under the joint supervision of an

NRAO staff member and his/her academic advisor, the student pursues research full-time toward completion of a doctoral dissertation. An NRAO scientist or a student's academic advisor nominates them for the program. Students may be supported for six months to two years or longer while they work at an NRAO site. Applications are accepted throughout the year, though candidates are strongly encouraged to seek the support of an NRAO scientist before applying.

Student Observing Support Program

To help train new generations of scientists, the NRAO supports research by graduate and undergraduate students at U.S. universities and colleges. Regular observing time proposals submitted for the GBT, VLBA, and the High Sensitivity Array (HSA) are currently eligible for funding under this program, though regular VLA proposals are not. Large Proposals for the VLBA, GBT, HSA, VLA, and any combination of these telescopes, are also eligible.

Visitor Program

The Visitor Program is open to PhD scientists and engineers in radio astronomy and related fields who wish to visit an NRAO site to collaborate with Observatory staff. The NRAO is particularly interested to support visits by junior faculty at colleges and universities, and to encourage collaborations that can lead to "first light" science with new instruments. Visit terms are negotiable, and their length may range from a few weeks to several months.

NRAO Student & Visitor Programs on the World Wide Web

http://science.nrao.edu/opportunities

(above)

This image of the spiral galaxy M 51, the Whirlpool Galaxy, and its companion NGC 5195 combines observations of neutral hydrogen emission acquired at the NRAO Very Large Array with optical images (R, B) from the Second Palomar Observatory Sky Survey - STScI Digital Sky Survey. The optical data show the emission of stars and dust in these galaxies, foreground stars in our Galaxy, and some background galaxies. The radio wavelength spectral-line observations of neutral atomic hydrogen (depicted by bluish hues) illustrate the distribution and kinematics of this gas. The long tidal tail of neutral hydrogen was shaken loose by the dance of these two galaxies. Investigators: A. H. Rots (NRAO), J. M. van der Hulst (Groningen), P.E. Seiden (IBM), R.C. Kennicutt (Minnesota), P. C. Crane (NRAO), A. Bosma (Marseille), L. Athanassoula (Groningen), and D.M. Elmegreen (IBM and Vassar). Image composition: J. M. Uson (NRAO).

(right)

Radiation emitted by atomic hydrogen reveals a gas shell surrounding an interstellar bubble, sculpted by the wind and radiation from hot, massive stars and the shock waves generated by supernovae. Known as galactic shell GS 62.1+0.2-18, this bubble is at a distance of 30,000 light years and measures about 1,100 by 520 light years. This image shows only a small part of a survey that uses the NRAO Very Large Array and the Green Bank Telescope to trace the cool gas in our Galaxy. The gas has been colored purple, blue, and green; the bright yellow-orange dots are clusters of young, massive stars surrounded by hot gas located closer to us than the bubble; heated dust, imaged in the infrared by the Midcourse Space Experiment (MSX) satellite, is shown as red. Investigators: J. M. Stil and A. R. Taylor (Calgary), J. M. Dickey (Tasmania), D. W. Kavars (Minnesota), P. G. Martin (CITA, Toronto), T. A. Rothwell (Toronto), A. I. Boothroyd (CITA), Felix J. Lockman (NRAO), and N. M. McClure-Griffiths (Australia Telescope). Image composition: J. English (Manitoba), J.M. Stil and A.R. Taylor (Calgary).

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