NRAO

NATIONAL RADIO ASTRONOMY OBSERVATORY

RESEARCH FACILITIES *for the* SCIENTIFIC COMMUNITY

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

2012

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RESEARCH FACILITIES 2012

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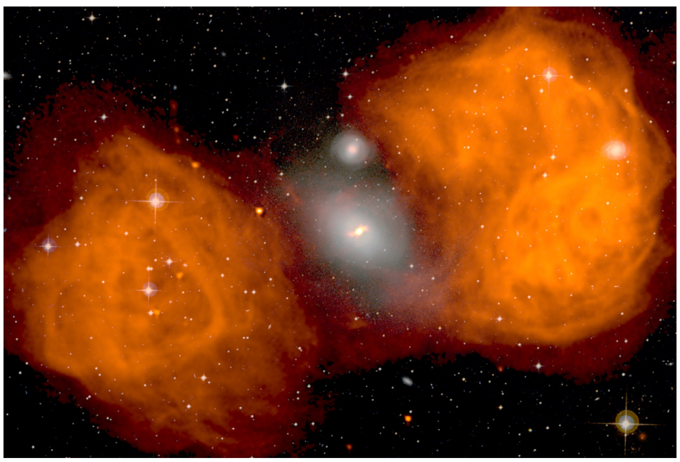


(above image)
The radio emission (orange) detected by the NRAO Very Large Array (VLA) is synchrotron radiation emitted by electrons moving at nearly the speed of light in a cosmic magnetic field. These electrons originate in enormous energy outflows from jets fueled by a supermassive black hole at the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

(cover)
The southern nucleus of the Antennae Galaxies, NGC 4038/39, as seen in an Atacama Large Millimeter/Submillimeter Array and Hubble Space Telescope composite image. The Band 7 ALMA test and science verification data (orange & yellow) trace cold, dense, optically-obscured CO gas clouds and pinpoint where new generations of stars are born. Credit: NRAO/AUI/NSF; ALMA (ESO/NAOJ/NRAO); HST (NASA, ESA, Brad Whitmore (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 National Radio Astronomy Observatory (NRAO) is delivering transformational scientific capabilities and operating a suite of four world-class telescopes that are enabling the astronomy community to address the science objectives described in the Astro2010 Decadal Survey report, *New Worlds, New Horizons in Astronomy and Astrophysics* (NWNH).

The NRAO telescope suite includes the Atacama Large Millimeter/submillimeter Array (ALMA), the Karl G. Jansky Very Large Array (VLA), the Robert C. Byrd Green Bank Telescope (GBT), and the Very Long Baseline Array (VLBA). Each is the world leader in its observing domain. Collectively, these telescopes enable scientists to observe from submillimeter to meter wavelengths with excellent resolution, sensitivity, and frequency coverage. Used individually or in combination, the NRAO telescopes provide the capabilities required to address many of the NWNH science themes, such as placing constraints on the nature of Dark Energy, imaging the first galaxies, and directly observing planet formation in proto-planetary disks.

ALMA will open new windows into the cold Universe via a major increase in sensitivity and resolution at millimeter and submillimeter wavelengths and will provide, for the first time, detailed images of stars and planets in formation, young galaxies being assembled throughout cosmic history, and much more. Early Science was initiated with ALMA in September 2011, and full science operations will begin in 2013.

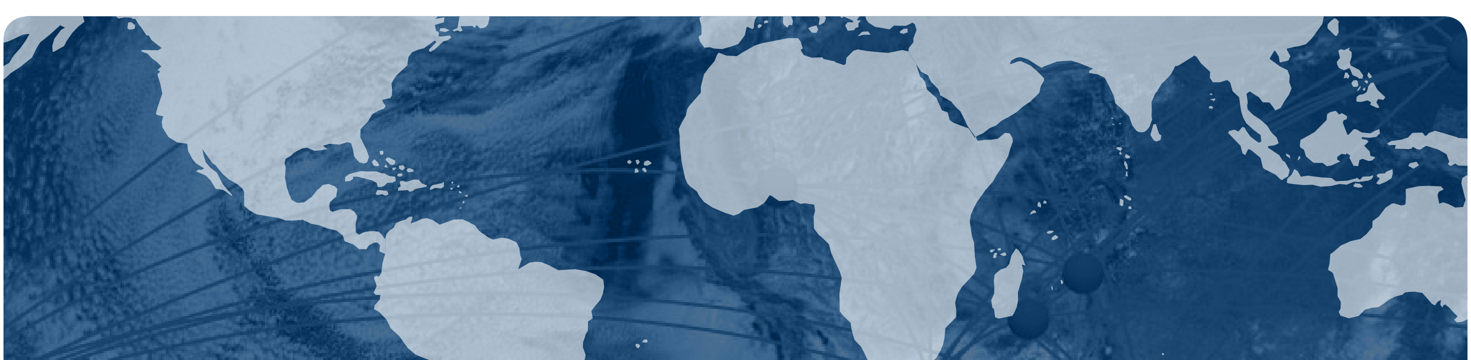
At the adjacent centimeter-wavelength range, an expanded and updated VLA will have scientific capabilities comparable to those of ALMA, but exceeding the VLA's original capabilities by one to four orders of magnitude. Delivery of the VLA's upgrades is on schedule, on budget, and is meeting all technical specifications and scientific objectives. Early Science programs were initiated on schedule in March 2010 and are already enabling a wide range of science, even as construction is being completed. A special issue of the Astrophysical Journal Letters devoted to Early Science results of the updated VLA was published in September 2011, describing cutting-edge research from the Solar System to the distant Universe. In late 2012, the mdoernized VLA will transition to full science operation as the world's most capable and versatile centimeter-wave imaging array.

The VLBA is the premier dedicated VLBI array in the world. Astrometry with the VLBA has reached the precision of a few micro-arcseconds, enabling distance and proper motion measurements of astronomical objects in the solar neighborhood, across the Milky Way, within the Local Group, and moving with the Hubble flow. VLBA scientific capabilities will continue to improve as new receivers are installed and a major bandwidth expansion project to improve sensitivity is completed. When used in conjunction with the phased VLA and the GBT, the resultant High Sensitivity Array greatly enhances the sensitivity for VLBI observations and broadens the range of novel scientific research.

To maximize the usage and science impact of the NRAO facilities, NRAO aims to broaden their access to all astronomers, through uniform and enhanced user support services. These services are provided by the North American ALMA Science Center in Charlottesville, the Array Science Center for the VLA and VLBA in Socorro, Green Bank Science Operations Center for the GBT, and are closely coordinated by Observatory Science Operations.

The NRAO is also developing forefront technology to continuously improve our facilities and to realize next generation facilities. Taking advantage of the outstanding technical expertise across NRAO, the Coordinated Development Lab oversees a science-driven research and development program that will help realize key NWNH science goals, such as the detection of gravitational waves via pulsar timing (NANOGrav), the study of the epoch of reionization (PAPER/HERA) and the development of the Frequency Agile Solar Radio-telescope (FASR).

After more than five decades of continual improvement, the NRAO comprisesthe nation's core competency in radio astronomy, an invaluable resourcefor the astronomy community in the US and around the world.

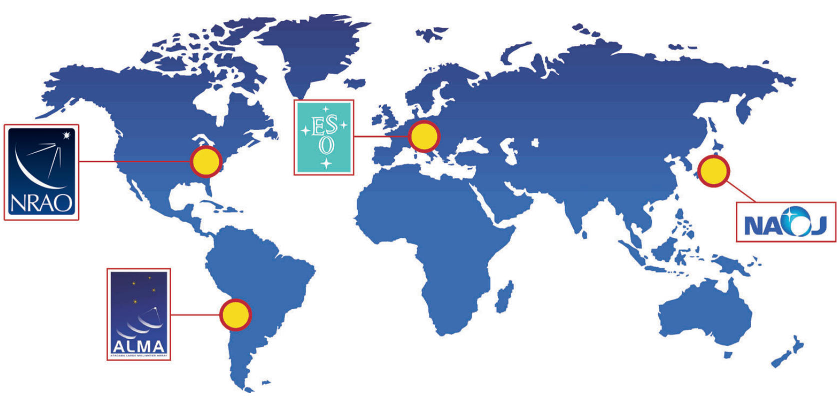


Atacama Large Millimeter/ submillimeter Array (ALMA)

Altiplano de Chajnantor, Chile

The Atacama Large Millimeter/submillimeter Array (ALMA) is under construction on the Chajnantor plain of the Chilean Andes. ALMA enables 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. ALMA can probe the first stars and galaxies, and can image interstellar gas in the process of forming new planets, thus providing a new window on cosmic origins. The ALMA site is 5000 m above sea level, where the Earth's atmosphere is largely transparent at millimeter wavelengths. Upon completion in 2013, the telescope will be composed of 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.

While ALMA is being assembled, significant observing time is being made available to the community as Early Science. ALMA began Cycle 0 Early Science observations 30 September 2011 with 16 antennas, each 12 m in diameter. Complete information on Early Science Cycle 1 capabilities will be released in early 2012. For Cycle 1, ALMA will have at least 32 x 12 m antennas, as well as 6 x 7 m antennas in the "Compact Array" and one 12 m total power antenna. Full science operations will begin in late 2013. Even during Early Science, ALMA is the most sensitive and most capable millimeter interferometer in the world.



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 Organisation 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 - Herzberg Institute of Astrophysics.

KEY SCIENCE

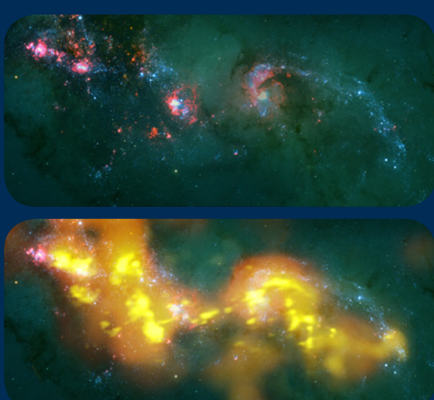
ALMA is designed to accomplish, at a minimum, three "Level 1" science goals: (1) detect CO/C+ in less than 24 hours from a normal galaxy like the Milky Way at redshift z = 3; (2) resolve protoplanetary disks around stars at a distance of 150 pc; and (3) provide precise imaging at submillimeter wavelengths 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 has wideband frequency coverage (8 GHz in dual polarization) and is capable of imaging fields larger than the primary beam using mosaics.

ALMA is a general-purpose research instrument. In addition to accomplishing the specific design goals, ALMA, upon completion, will be able 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 (Cycle 1)	Array Completion
Antennas	32 x 12 m; ≥6 x 7 m; 1 x 12 m Total Power	54 x 12 m & 12 x 7 m
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	Subset of Array Completion	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	1 km	15 km
Continuum Sensitivity (60 sec, Bands 3 – 9)	~ 0.1 – 2.5 mJy/beam	~ 0.05 – 1 mJy/beam
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 – 9)	~ 16 – 150 mJy/beam	~ 7 – 62 mJy/beam



Far left: The southern nucleus of the Antennae Galaxies, NGC 4038/39, as seen by HST (top), and in an ALMA + HST composite (bottom). The Band 7 ALMA test and science verification data (orange & yellow) trace cold, dense, optically-obscured CO gas clouds and pinpoint where new generations of stars are born. Credit: NRAO/AUI/NSF; ALMA (ESO/NAOJ/NRAO); HST (NASA, ESA, Brad Whitmore (STScI))

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

ALMA on the World Wide Web

http://science.nrao.edu/alma

http://www.almaobservatory.org

NAASC on the World Wide Web

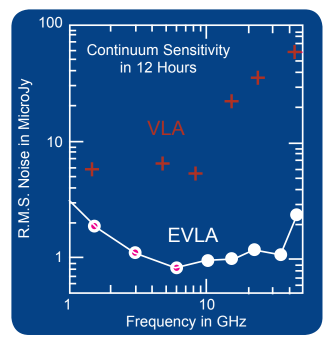
http://science.nrao.edu/alma/intro-naasc.shtml

Karl G. Jansky Very Large Array (VLA)

Socorro, New Mexico

The Karl G. Jansky 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. A suite of new receivers on all 28 antennas of the array, along with a new digital data transmission system and a new Wideband Interferometric Digital Architecture (WIDAR) correlator, combine to provide superb spectral resolution and fidelity over very wide instantaneous bandwidth, enabling astronomers to make full-beam images with very high spatial resolution and dramatically improved continuum sensitivity at frequencies from 1 to 50 GHz. The new WIDAR correlator was installed at the beginning of 2010, with first science observations in March 2010, marking the beginning of Early Science with the Jansky VLA. At that time up to 256 MHz bandwidth was offered to the general community, already a factor of 2.5 improvement over the VLA's original receiver suite. In September 2011 this increased to 2 GHz bandwidth, and in January 2013 the VLA will offer up to 8 GHz bandwidth when full science operations begin anew. This modernized VLA provides the cm-wavelength radio complement to ALMA and other next-generation instruments coming online over the next few years, with the following capabilities:

- Continuum sensitivity improvement over the foregoing 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. Calibrated visibilities and reference images for quality assurance automatically produced, with all data products archived.



The expanded VLA 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 MILESTONES

Mar 2010: Start of VLA Early Science, with up to 256 MHz bandwidth for the general user community
Sep 2011: Enhanced capabilities (up to 2 GHz bandwidth for the general user community) offered for Early Science
Mar 2012: Karl G. Jansky VLA Dedication
Jul 2012: Call for proposals for VLA full science
Sep 2012: Full acceptance of WIDAR correlator
Dec 2012: Last VLA receiver installed, EVLA project complete
Jan 2013: Start of VLA full science operations

KEY SCIENCE

The Magnetic Universe

The sensitivity, frequency agility, and spectral capability of the modernized VLA 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

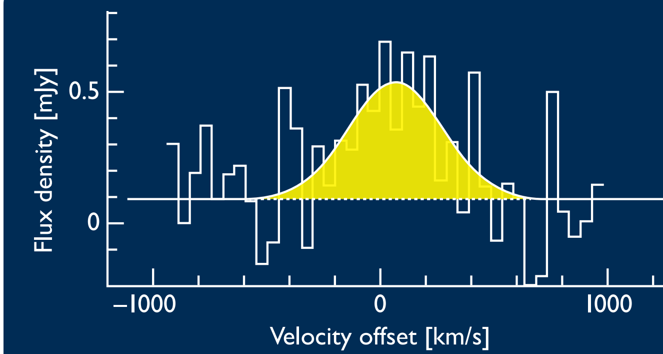
Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The updated VLA will observe through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young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

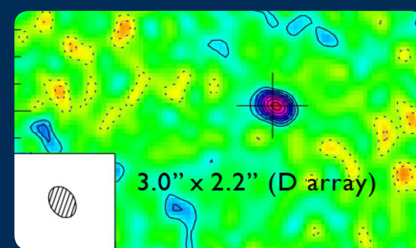
The Transient Universe

Astronomical transient sources tend to be compact objects that emit synchrotron radiation from high-energy particles, radiation best observed at radio wavelengths. The expanded VLA 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 upgraded VLA will image novae and relativistic jets anywhere in the Milky Way, and measure the sizes of many tens of gamma-ray bursts each year.

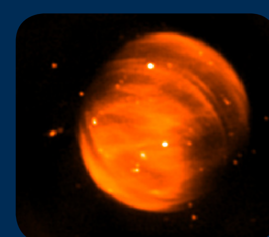
The Evolving Universe

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 enhanced VLA 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. These VLA data show the cold gas fueling the star formation and indicates more than 1010 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 VLA observation can provide data on the emission mechanisms and magnetic field strengths in these and other radio sources, inside and outside our Galaxy. A special issue of the Astrophysical Journal Letters published on September 20, 2011, showcases other examples of the modernized VLA's new capabilities and science.

Karl G. Jansky VLA on the World Wide Web

http://science.nrao.edu/evla

SPECIFICATIONS

Parameter	VLA	Karl G. Jansky VLA
Continuum sensitivity (1σ, 9 hr)	10 μJy	1 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
Coarsest frequency resolution	50 MHz	2 MHz
Finest frequency resolution	381 Hz	0.12 Hz
Frequency coverage, 1 - 50 GHz	22%	100%
Number of baselines	351	351
Maximum spatial resolution (5GHz)	0.3 arcsec	0.3 arcsec

Robert C. Byrd Green Bank Telescope (GBT)

Green Bank, West Virginia

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 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.

Image courtesy of NRAO/AUI

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.

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.

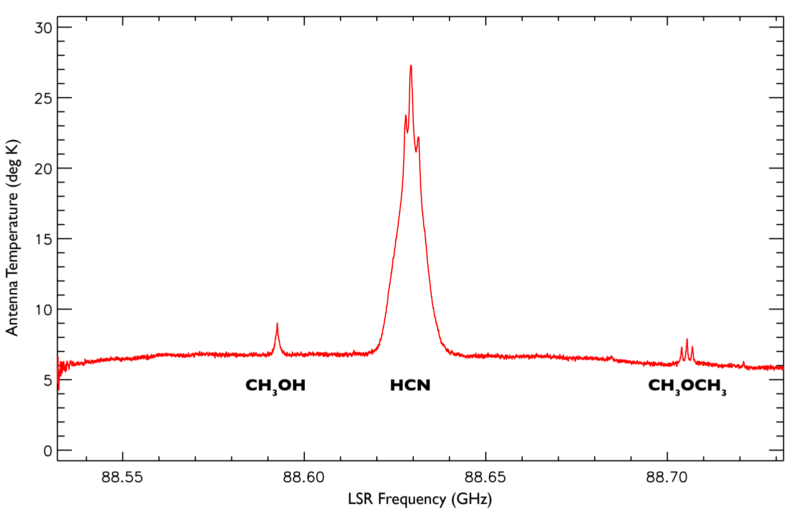


Figure 1. A spectrum of Orion-KL tuned to the HCN(1-0) triplet at 88.63 GHz observed with the new GBT 4mm receiver. Three short one minute On-Off pairs were taken in daytime under heavy cloud conditions, and no baseline subtraction was done to the data. The CH_3OH transition at 88.59 GHz and the CH_3OCH_3 triplet around 88.71 GHz are also clearly visible.

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 mapping extended HI structures.

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 has partnered with UC-Berkeley to develop a new FPGA-based spectrometer for the GBT. It will be implemented in stages, the first of which will be available in early 2012.

NEW RECEIVER FOR SPECTROSCOPY AT 4MM

A dual-beam receiver that covers 68-92 GHz in now undergoing commissioning and first science observations. The key science drivers are molecular spectroscopy and VLBI observations in this under-served band. The beamwidth at 85 GHz is expected to be about 10 arcsec and the aperture efficiency about 35%.

KEY SCIENCE

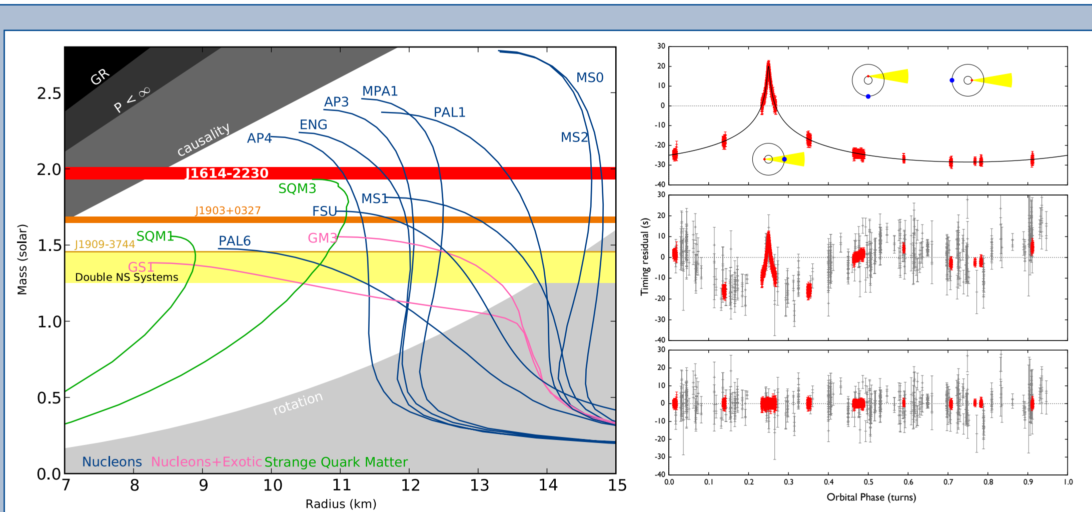


Figure-2: The recent measurement of the Shapiro delay in the radio pulsar PSR J1614-2230 yielded a mass of 1.97 +/- 0.04 M(sun), making it the most massive pulsar known to date. Its mass is high enough that, even without an accompanying measurement of the stellar radius, it has a strong impact on our understanding of nuclear matter, gamma-ray bursts, and the generation of gravitational waves from coalescing neutron stars.

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 a key instrument of the NANOGrav collaboration that seeks to use pulsar timing measurements to detect gravitational radiation directly. Through measurement of molecular transitions at high redshift, the GBT is used to limit the variation of fundamental physical constants with time.

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.

Galaxies Across Cosmic Time

The MUSTANG 3mm bolometer array has discovered hitherto unknown structures in the hot gas of galaxy clusters that reveal the evidence of mergers and cluster formation. Through measurement of H_2O masers in the accretion disks surrounding nuclear black holes, the GBT has established the mass of many black holes and shown that they are not always related to the mass of the galaxy's stellar bulge. The discovery with the GBT of H_2O masers in the HII regions of M31 provides targets for VLBI observations that will measure the proper motion and distance of this dominant galaxy in the Local Group.

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.

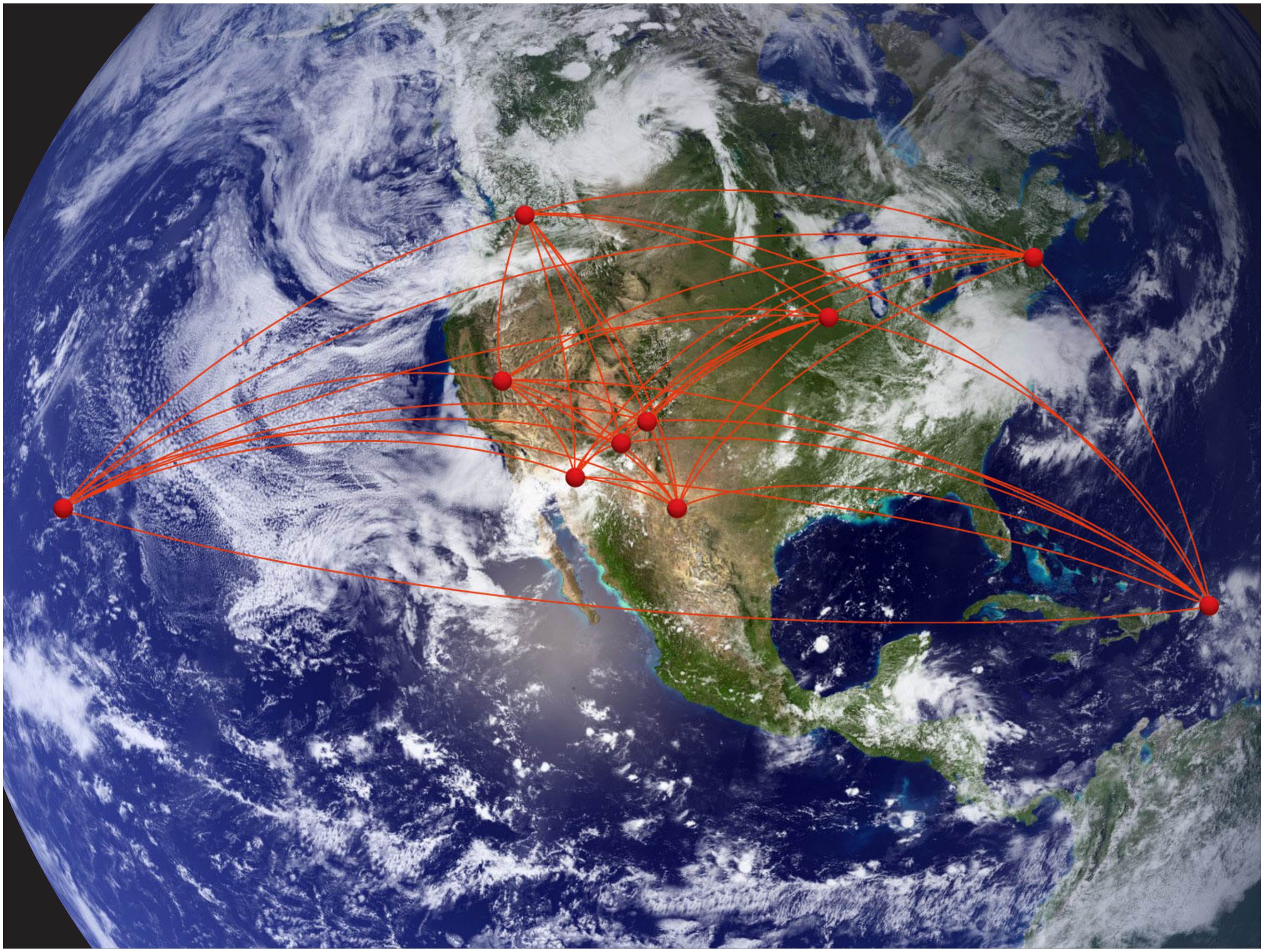
GBT on the World Wide Web

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 90 cm to 3 mm (300 MHz to 96 GHz) in ten discrete 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 Karl G. Jansky Very Large Array.

VLBA on the World Wide Web

http://science.nrao.edu/vlba

KEY SCIENCE

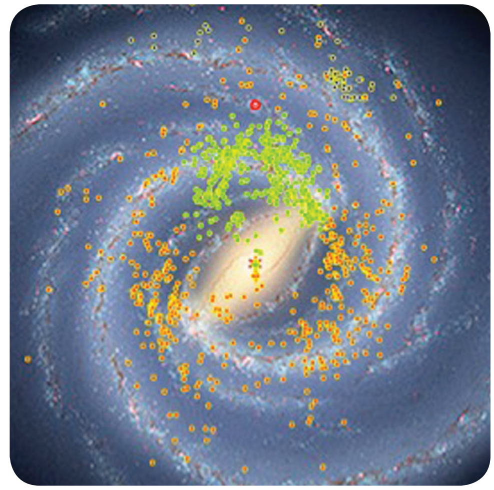
Precision astrometry is a VLBA science centerpiece. The relative astrometric accuracy of ~ 10 μas achievable with the VLBA is complementary to the accuracy the Gaia satellite is designed to achieve for most stars in its catalog. The VLBA can probe the Galactic plane well beyond the solar neighborhood because 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.

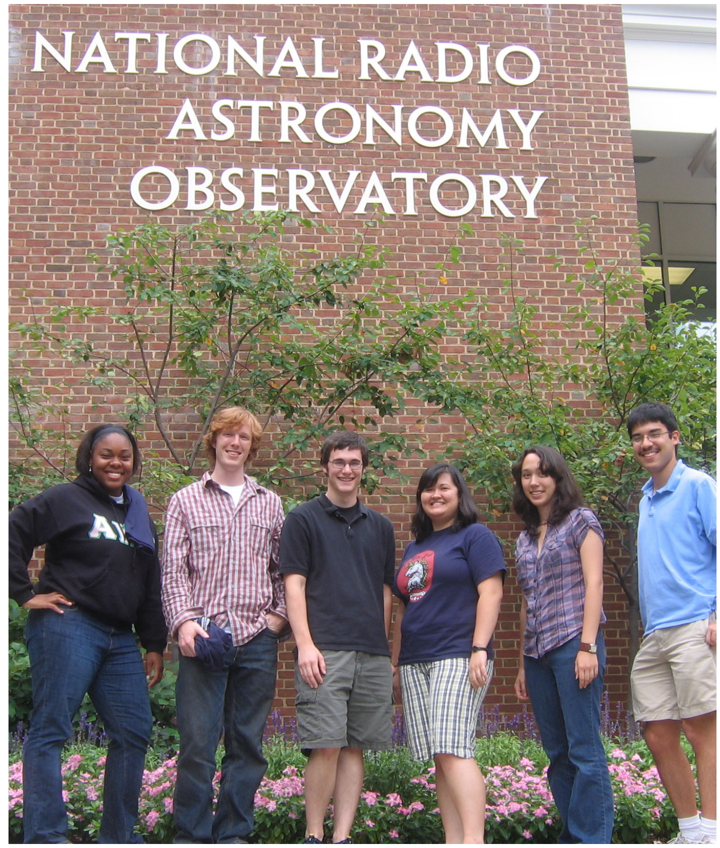
2012: Offer 500 MHz bandwidth capability to VLBA observers and complete upgrade to wideband C-band receivers.

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

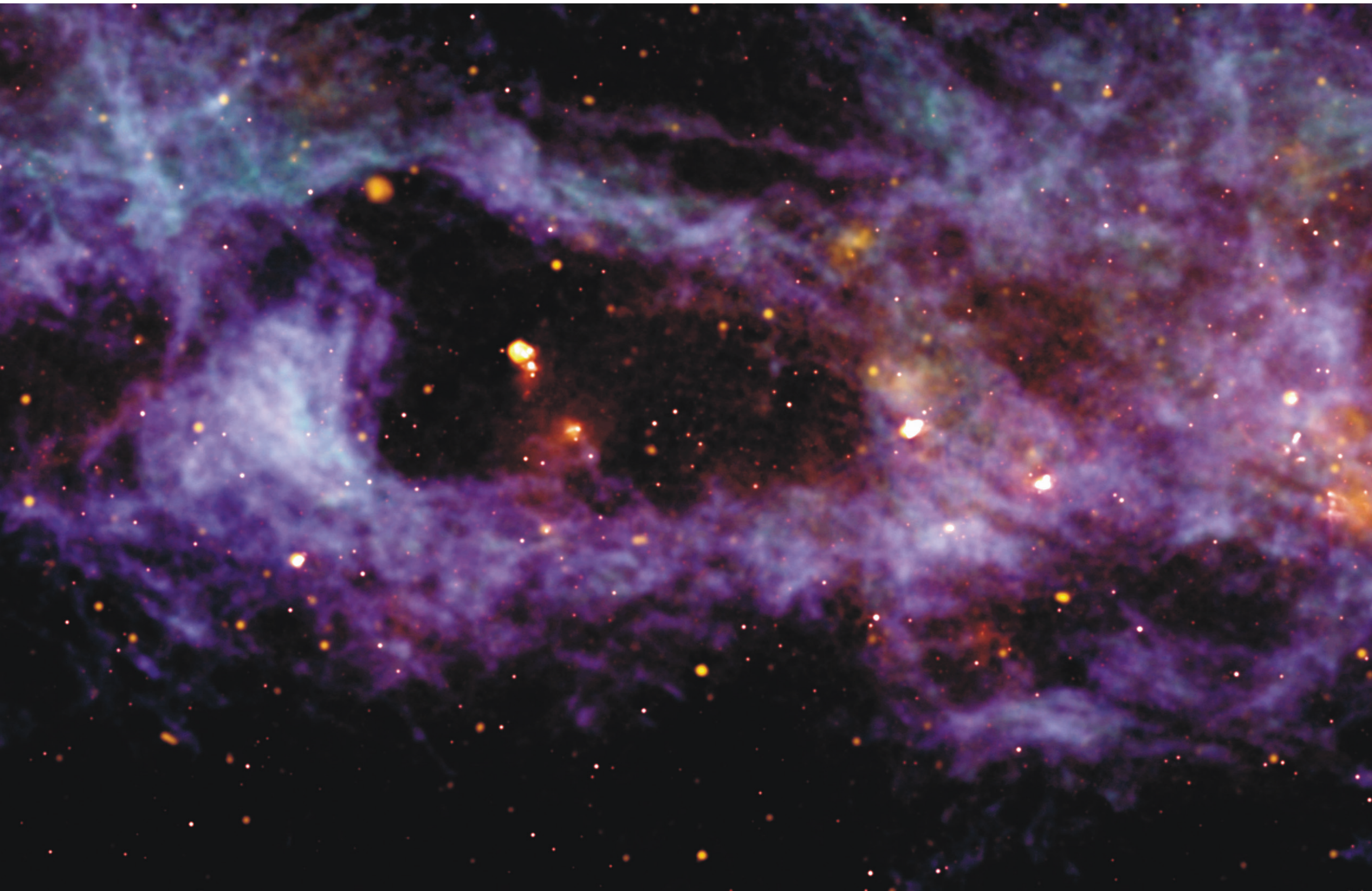
http://science.nrao.edu/opportunities

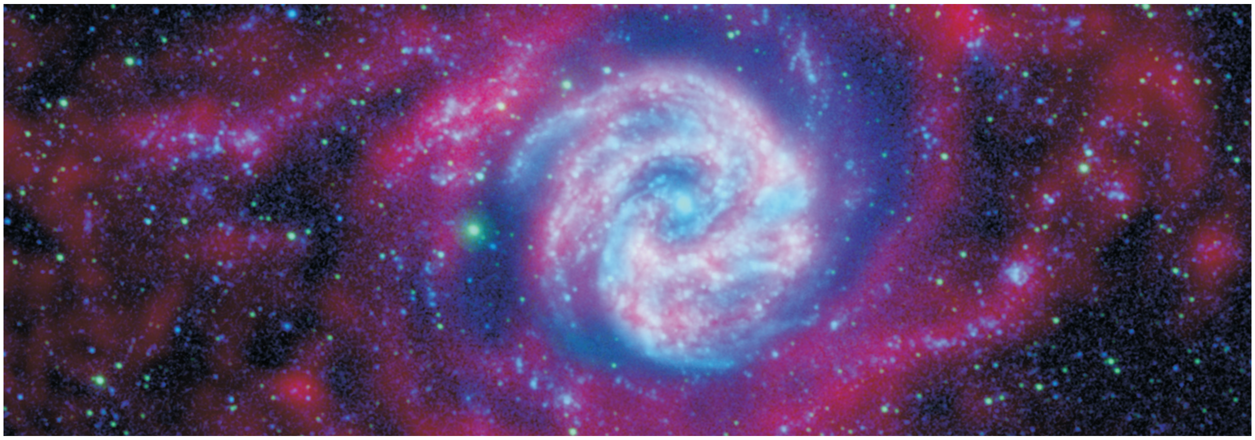
(above)

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 Karl G. Jansky 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 Karl G. Jansky 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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