

**National  
Radio  
Astronomy  
Observatory**

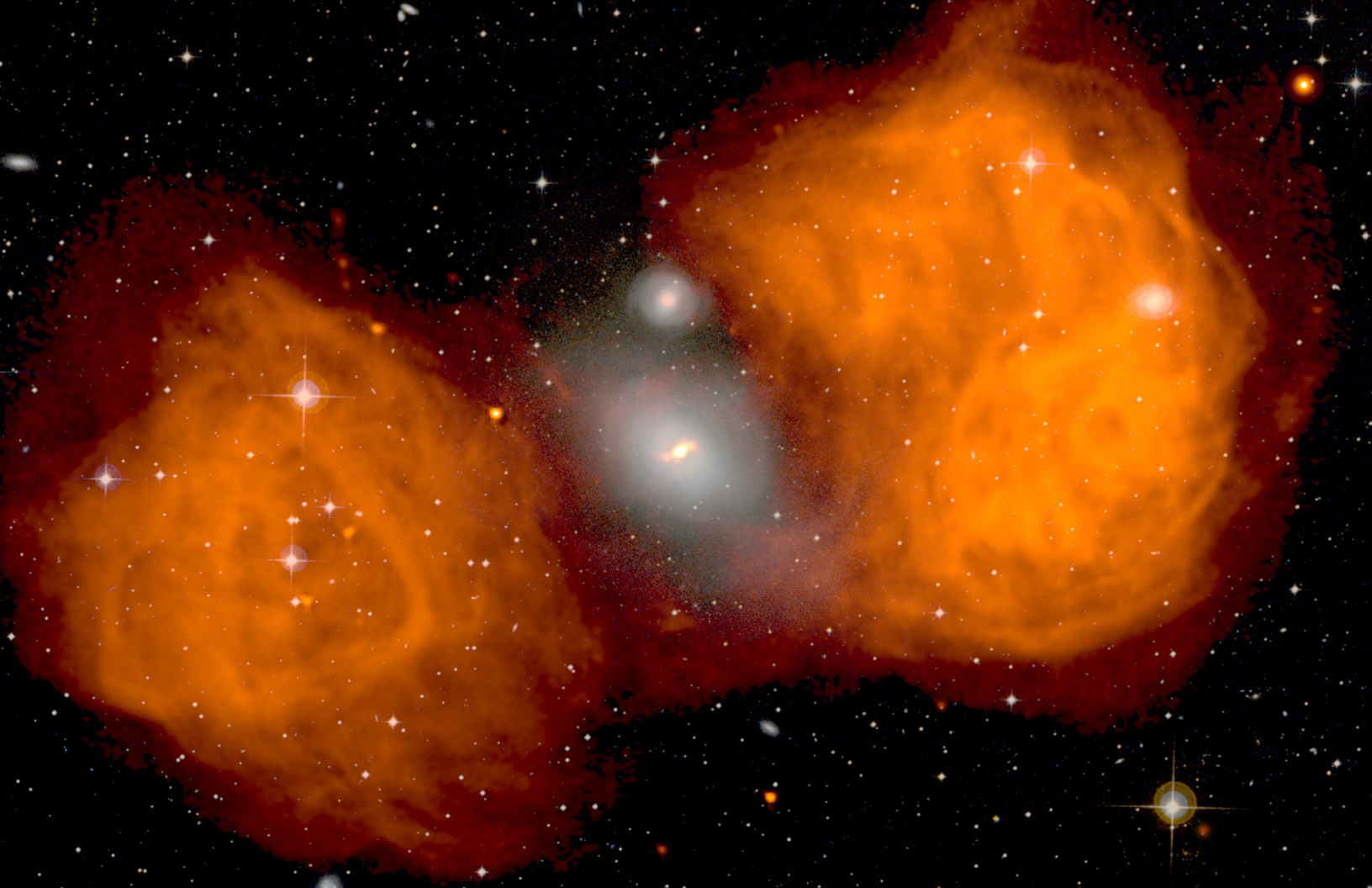
# RESEARCH FACILITIES for the Scientific Community



2010

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





The National Radio Astronomy  
Observatory enables forefront  
research into the Universe at  
radio wavelengths.

(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)

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

(back 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).

# CONTENTS

## Research Facilities 2010

Atacama Large Millimeter/submillimeter Array . . . . .	2
Expanded Very Large Array . . . . .	4
Green Bank Telescope . . . . .	6
Very Long Baseline Array . . . . .	8
Square Kilometre Array Program . . . . .	10
Student & Visitor Programs . . . . .	11



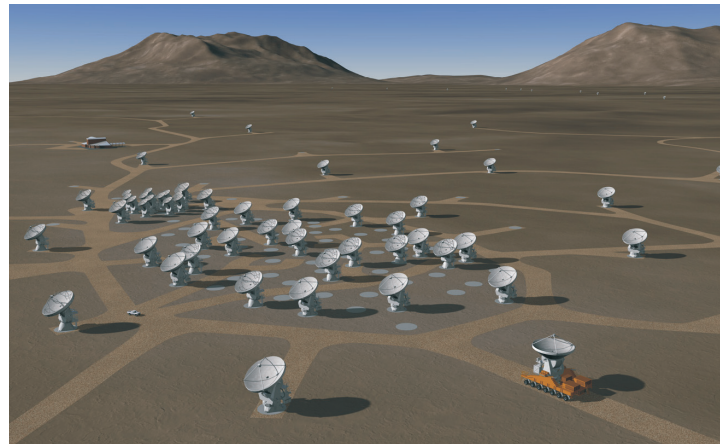
## The Atacama Large Millimeter/submillimeter Array (ALMA)

Altiplano de Chajnantor, Chile

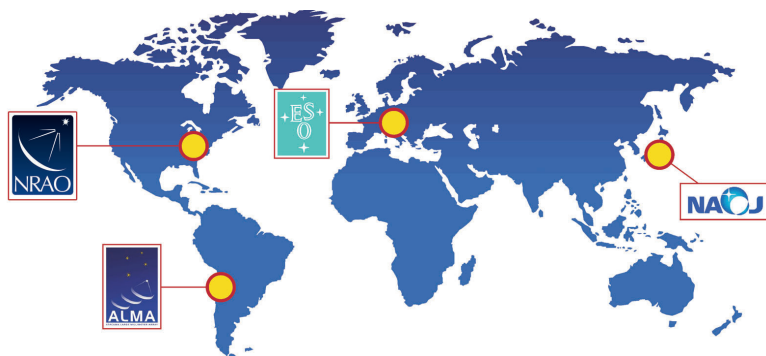
ALMA, the Atacama Large Millimeter/submillimeter Array, will be a single research instrument composed of at least 66 high-precision antennas, located on the Chajnantor plain of the Chilean Andes in the District of San Pedro de Atacama, 5000 m above sea level. ALMA will enable transformational research into the physics of the cold Universe, regions that are optically dark but shine brightly in the millimeter portion of the electromagnetic spectrum. ALMA will probe the first stars and galaxies, and directly image the planet formation process, thus providing astronomers a new window on cosmic origins. ALMA will operate at wavelengths of 0.3 to 9.6 millimeters, where the Earth's atmosphere above a high, dry site is largely transparent, and will provide astronomers unprecedented sensitivity and resolution. Resolutions as fine as 0.005'' will be achieved at the highest frequencies, a factor of ten better than the Hubble Space Telescope.

A call for ALMA Early Science proposals (using less than the full-up array and a subset of receiving bands) is expected in late 2010, with a proposal deadline two months later:

ALMA will be a complete astronomical imaging and spectroscopic instrument for the millimeter/submillimeter, providing scientists with capabilities and wavelength coverage that complement those of other research facilities of its era, such as the Expanded Very Large Array (EVLA), the European Extremely Large Telescope (E-ELT), the Giant Segmented Mirror Telescope (GSMT), and the James Webb Space Telescope (JWST).



Artist's conception of ALMA in a compact configuration © ESO.



The Atacama Large Millimeter/submillimeter Array (ALMA), an international astronomy facility, is 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 U.S. 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).

Access to ALMA observing time by the North American astronomical community is through the North American ALMA Science Center (NAASC), based at the NRAO headquarters in Charlottesville, Virginia. The NAASC is operated by NRAO in partnership with the National Research Council of Canada.

### ALMA on the World Wide Web

<http://science.nrao.edu/alma>   <http://www.almaobservatory.org>



## SPECIFICATIONS

		12 m Array	Atacama Compact Array (ACA)
Array	Number of Antennas	up to 64	12 (7 m) + 4 (12 m)
	Total Collecting Area	up to 7240 m <sup>2</sup>	460 + 450 m <sup>2</sup>
	Angular Resolution	0.02'' ( $\lambda$ / 1 mm)(10 km/baseline)	5.7'' ( $\lambda$ / 1 mm)
	Baseline Lengths	15 - 15 300 m	
Antennas	Diameter	12 m	7 m, 12 m
	Surface Precision	<25 $\mu$ m	<20 $\mu$ m, <25 $\mu$ m
	Offset Pointing	<0.6''	<0.6''
Correlator	Baselines	up to 2016	120
	Bandwidth	16 GHz per baseline	16 GHz per baseline
	Spectral Channels	4096	4096



*Far left: A simulation (Wolf & D'Angelo 2005) of ALMA observations at 950 GHz of a protoplanetary disk and an embedded protoplanet of 1 Jupiter Mass around a 0.5 solar mass star. The assumed distance is 100 parsecs.*

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

## 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	ALMA Inauguration
Antennas	$\geq 16$ (12 m)	$\geq 50$ (12 m + 7 m)
Bands	$\geq 3$ Bands (Bands 3, 6, 7, 9 likely)	Bands 3, 6, 7, 9 (+ 4, 8 & 10 on some)
Maximum Bandwidth	16 GHz (2 pol $\times$ 8 GHz)	16 GHz (2 pol $\times$ 8 GHz)
Correlator Configurations	$\geq 5$	71 configs (0.01-40 km/s)
Maximum Angular Resolution	0.02'' ( $\lambda$ / 1 mm)(10 km/max baseline)	0.02'' ( $\lambda$ / 1 mm)(10 km/max baseline)
Maximum Baseline	At least 250 m (may reach 1 km)	15.3 km
Continuum Sensitivity (60 sec, Bands 3 - 9)	$\sim 0.2 - 4.2$ mJy	$\sim 0.05 - 1$ mJy
Spectral Line Sensitivity (60 sec, 1 km/sec, Bands 3 - 9)	$\sim 30 - 250$ mJy	$\sim 7 - 62$ mJy

## ALMA TIMELINE

Call for ALMA Early Science Proposals  
Early Science Proposal Submission Deadline  
Begin Early Science

Late 2010  
Early 2011  
Mid 2011

ALMA Inauguration  
66 ALMA Antennas Operational

Mid 2012  
2013

## 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. A new correlator 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 will be turned off in early 2010 and be replaced by the new Wideband Interferometric Digital Architecture (WIDAR) correlator. At the same time, the direction of the array configuration cycle will reverse to facilitate WIDAR commissioning. The correlator and array configuration transitions will signal the beginning of EVLA Early Science in March 2010. Early Science will feature 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.

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 Tecnología in Mexico.



© NRAO/AUI & Kristl Armendariz

### EVLA on the World Wide Web

<http://science.nrao.edu/evla>

#### EVLA MILESTONES

Begin Early Science  
Last antenna retrofitted to EVLA design  
Complete commissioning of full WIDAR correlator  
Last EVLA receiver installed

Mar 2010  
Aug 2010  
Jan 2011  
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

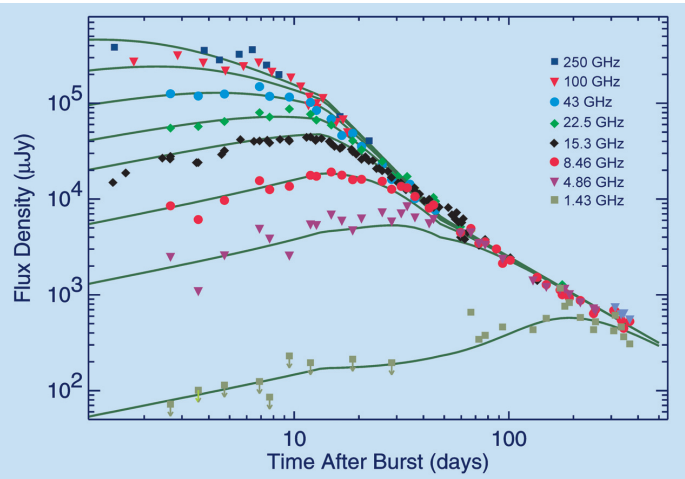
Phenomena such as star formation and accretion onto massive black holes occur behind dense screens of dust and gas that render optical and infrared observations impossible. The EVLA will observe through these screens to probe the atmospheres of giant planets, measure thermal jet motions in young stellar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



Radio light curves from the afterglow of the bright gamma-ray burst of March 29, 2003 at frequencies from 250 GHz (top) to 1.4 GHz (bottom). As the shock from the gamma-ray burst expands and slows, the emission is shifted to radio wavelengths from X-ray and optical. This means that radio afterglow measurements are well-suited to determining the total energy released by the nascent black hole. Image courtesy of D. Frail

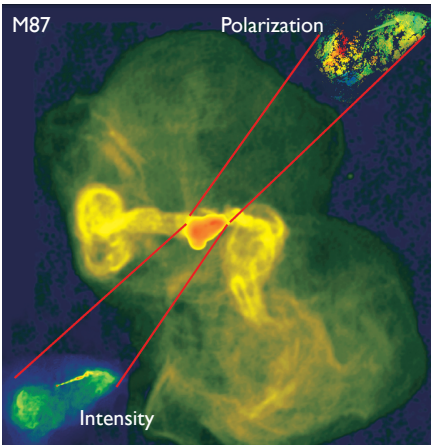


Image of M87, the giant radio galaxy at the center of the Virgo cluster. Its radio structure has been studied on scales ranging from 30 kpc (the largest extent of the source) to 0.08 pc. The insets illustrate the different probes offered by imaging total intensity and polarization of radio sources. Image courtesy of F. Owen.

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

Continuum sensitivity in 12 hrs.  $1\sigma$

Maximum bandwidth

Number of frequency channels at maximum bandwidth

Maximum number of frequency channels

Frequency coverage, 1 - 50 GHz

Number of baselines

Spatial Resolution (5GHz)

VLA

10  $\mu$ Jy

0.1 GHz

16

512

22%

351

0.3 arcsec

EVLA

0.8  $\mu$ Jy

8 GHz

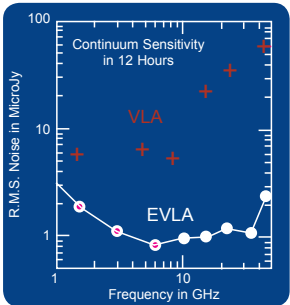
16,384

4,194,304

100%

351

0.3 arc





## Robert C. Byrd Green Bank Telescope (GBT)

Green Bank, West Virginia

The Green Bank Telescope (GBT) is the world's premiere single-dish radio telescope operating at centimeter-millimeter wavelengths. The GBT is in robust, routine, and effective operation from 300 MHz through 50 GHz, with a 64-pixel bolometer array at 81-98 GHz. Located in the National Radio Quiet Zone, the GBT benefits from an extraordinarily low radio-frequency interference environment that provides excellent sensitivity for continuum and spectral line research across the radio spectrum. NRAO personnel in Green Bank also contribute to ALMA and EVLA development, and conduct a broad range of education and public outreach programs.



Image courtesy of NRAO/AUI

### GREEN BANK TELESCOPE CAMERA DEVELOPMENT PROGRAM

The NRAO is designing and building new camera systems that will provide the next quantum leap in GBT science capabilities. These will include conventional feed horn arrays, phased array receivers, and bolometer arrays. The first of these camera systems is now operational, another is nearing completion, and work has begun on a third. 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)

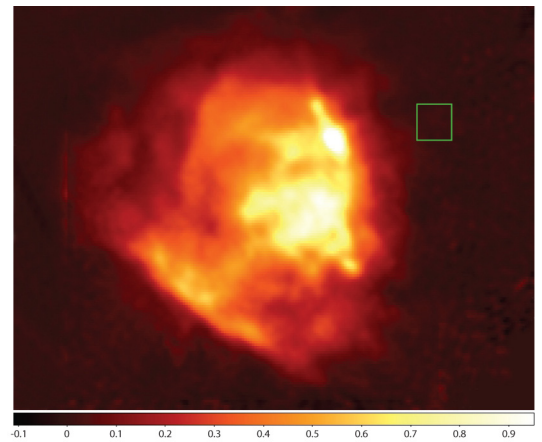
The GBT has a 64-pixel bolometer array that uses transition edge sensor technology, MUSTANG. This bolometer array at the GBT yields a 0.4 mJy rms over a 3' x 3' field in one hour of integration time. The noise scales inversely with the square root of the integration time over periods of at least several hours. The GBT – MUSTANG combination yields a typical angular resolution of 9" FWHM and a 40" x 40" instantaneous field-of-view.

#### **K-Band Focal Plane Array**

A 7-pixel 18-26 GHz array of traditional heterodyne receivers will be completed and commissioned for the GBT, with a planned release of the instrument for general use in late 2010. This instrument will be the first to have a full data reduction pipeline.

#### **Phased Array Development**

The NRAO is working with Brigham Young University, the University of Massachusetts, and other groups on the development of phased array technology with the goal of building sensitive, many-pixel arrays for the GBT. Research and development is ongoing.



A 90 GHz MUSTANG image of the Orion star-forming region. The intensity scale is Jy per beam; the small square (top right) illustrates the instantaneous field-of-view.

### **GBT on the World Wide Web**

<http://science.nrao.edu/gbt>

## GUPPI (Green Bank Ultimate Pulsar Processing Instrument)

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  $\mu$ sec. GUPPI is currently available for observations using the incoherent filter bank; coherent de-dispersion modes will be available in early 2010. GUPPI is a collaboration between the NRAO, UC-Berkeley, Univ. of Cincinnati, and Xilinx, Inc.

## GREEN BANK TELESCOPE IMPROVEMENTS

### Improved aperture efficiency

The latest holography maps of the GBT indicate that the surface error on small scales has been reduced to 210  $\mu$ m rms over the whole dish. Although the effective surface accuracy varies due to thermal deformation on larger scales, it reaches values as low as 240  $\mu$ m rms during stable thermal conditions. As a result, the latest nighttime aperture efficiency measurements at 43 GHz are above 60%. The efficiency at 90 GHz is expected to be above 30%, and will be measured using MUSTANG in winter 2009–2010.

### Dynamic Scheduling System

A new Dynamic Scheduling System (DSS) has been released that significantly increases the flexibility of the GBT scheduling process. The system's goal is to improve the efficiency of GBT observations by matching the observing schedule to current weather conditions while allowing each observer to retain interactive control of the telescope.

## PULSAR SEARCH COLLABORATORY

Funded by the National Science Foundation, the Pulsar Search Collaboratory (PSC) partners the NRAO with West Virginia University to provide high school students with opportunities to learn 21st Century skills while conducting world-class research in pulsar astronomy. PSC students join an international team of scientists to analyze more than 100 Terabytes of GBT data in a search for new pulsars.

## SINGLE DISH SUMMER SCHOOL

The NRAO and the National Astronomy and Ionosphere Center organize a Single Dish Radio Astronomy Summer School every two years, alternating between the Arecibo Observatory site in Puerto Rico and the NRAO site in Green Bank, WV. This unique school offers a week-long intensive series of lectures by experts and provides graduate students, post-doctoral fellows, and experts in other fields of astronomy with knowledge and practical experience in the techniques and applications of single-dish radio astronomy. A significant part of each participant's time at the school is devoted to a hands-on radio-astronomy project including data analysis and interpretation. The next Single Dish Summer School will take place in 2011 in Green Bank.



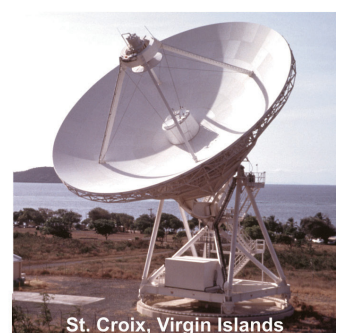
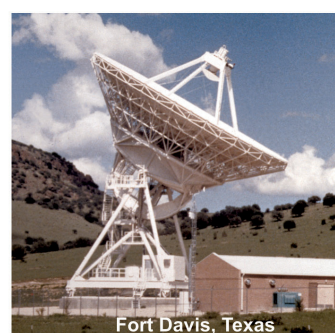
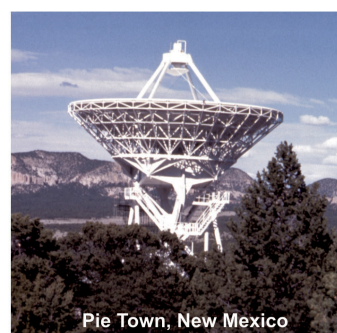
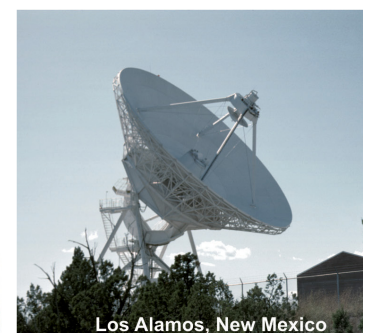
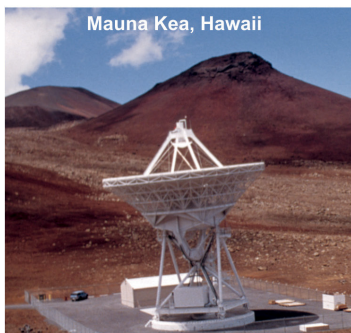
Top: Lucas Bolyard, a West Virginia high-school student and PSC participant, has discovered a strange type of neutron star called a rotating radio transient. Lucas was honored as a special guest at the White House Star Party on October 7. Above: West Virginia Governor Joe Manchin III (center) with the students and teachers of the 2008 West Virginia Governor's School for Math and Science.



## The 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 on transcontinental baselines 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 discrete bands plus two narrow sub-gigahertz bands, including the primary spectral lines that produce high-brightness maser emission. The array can be scheduled dynamically, and its continuum sensitivity can be improved significantly by adding the Green Bank Telescope and, eventually the phased Expanded Very Large Array.

### VLBA on the World Wide Web

<http://science.nrao.edu/vlba>



## VLBA KEY SCIENCE

Precision astrometry is a VLBA science centerpiece. The relative astrometric accuracy of  $\sim 10 \mu\text{as}$  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 will begin a long-term program to determine the 3D structure of the Milky Way by measuring parallaxes with  $10 \mu\text{as}$  accuracy or better to  $\sim 400$  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.

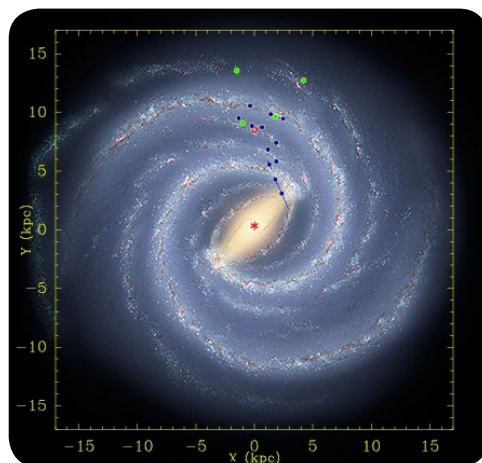
The VLBA is also expected to anchor High Sensitivity Array observations of the center of M31 in an effort to detect the galaxy's nucleus with significant signal-to-noise and enable a first-epoch position measurement. The ultimate goal is the proper motion of M31 relative to the Milky Way, which should 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 last year. In 2010, 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  $\text{H}_2\text{O}$  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.

## VLBA SENSITIVITY ENHANCEMENT PROGRAM

Since its 1993 dedication, the VLBA sensitivity has been limited by the original sustainable recording rate of 128 Mbits/sec, which allowed 16 MHz bandwidth in dual polarization. Technology has progressed, however, and a substantial increase in data rate, hence an increase in bandwidth and continuum sensitivity, is now affordable. Thus, the NRAO has embarked on a program to increase the VLBA bandwidth to 500 MHz (dual polarization) by 2011, an increase of a factor of 16 over the original bandwidth of 32 MHz. This enhancement and other sensitivity improvements are being undertaken with our international partners to provide new scientific capabilities for the VLBA user community.



*This artist's conception of the Milky Way shows the four-arm spiral structure confirmed by recent VLBA distance measurements to star-forming regions, indicated by green and blue dots. Red dots mark the locations of the Galactic Center and our Solar System.*

*Credit: IPAC-R. Hurt/CfA-M. Reid/NRAO/AUI/NSF*

## VLBA MILESTONES

**2007-2010:** Development of a new digital backend for the VLBA, in collaboration with the UC-Berkeley CASPER and South African KAT groups, and with MIT Haystack Observatory, to digitize the entire span of the two 500 MHz intermediate frequency channels presently available on VLBA.

**2008:** Completed 22 GHz amplifier replacement, resulting in 30% sensitivity improvement, in partnership with the Max Planck Institut für Radioastronomie.

**2010:** Complete implementation of VLBA digital backends. Complete conversion of VLBA to higher-bandwidth software correlator. Initial deployment of new recording system at antenna stations. Initiate conversion of VLBA to subscriber facility, with emphasis on Key Science Projects.

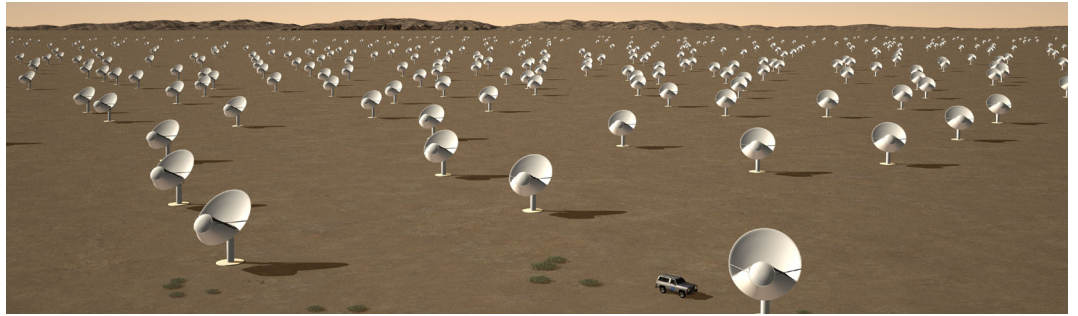
**2009-2011:** Expand data recording media pool and software correlator processor cluster. Complete full correlator commissioning.

**2011:** Complete implementation of 500 MHz bandwidth capability.

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## The NRAO Square Kilometre Array (SKA) Program

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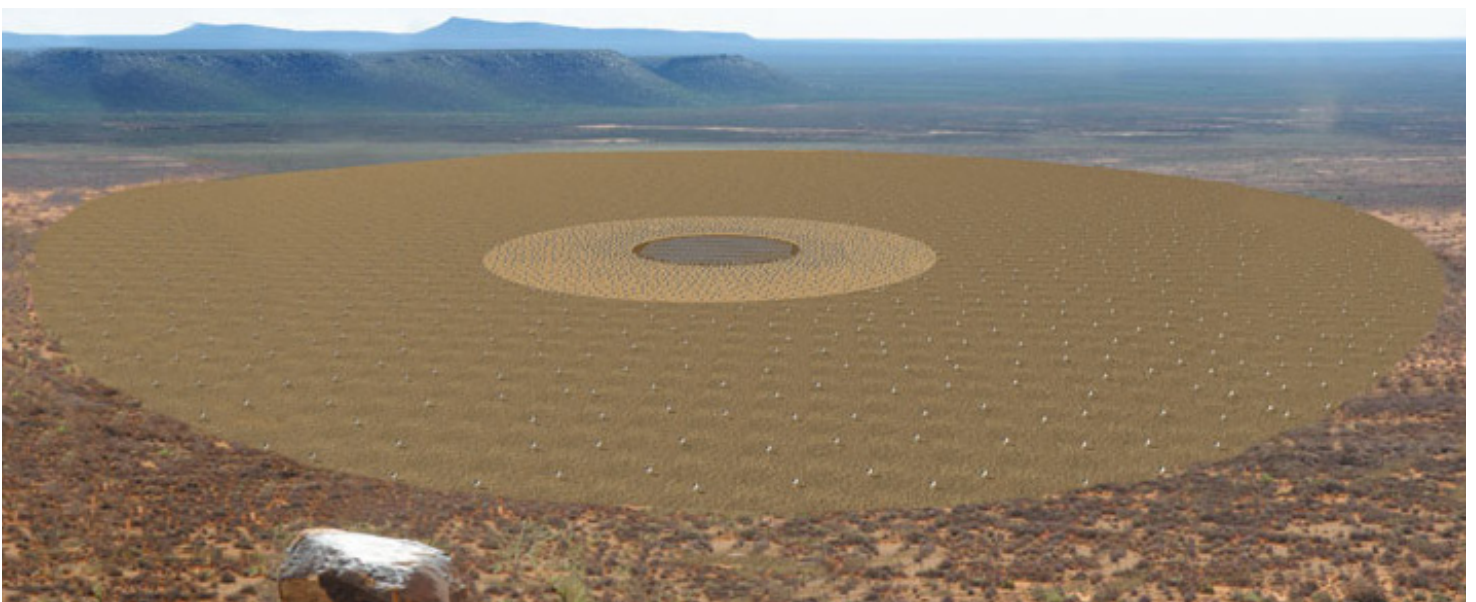


The NRAO is working with the international astronomical community to develop the scientific and technical concepts for the next generation of centimeter- and meter-wavelength telescopes after the Expanded Very Large Array (EVLA). These concepts comprise the Square Kilometre Array (SKA) Program, which ultimately may be realized by building several large international telescopes. Within the Observatory, an NRAO SKA Program Office has been formed as part of our participation in SKA. Its primary goals are to coordinate and plan NRAO participation in the various SKA activities, and to ensure a coherent Observatory approach by focusing NRAO development activities on the long-term goal of realizing the SKA.

In the Astro2010 decade survey, the NRAO participated with the US SKA Consortium in a program submission for construction of the mid-frequency portion of the SKA, which will cover a frequency range of roughly 0.5 GHz to 3-10 GHz. This may be primarily a survey instrument, exploring the evolution of galaxies, Dark Energy, transient sources, and the realm of strong gravity. Detailed testing of prototype low-cost dish antennas is expected to be carried out in the next few years in combination with the Expanded Very Large Array (EVLA).

NRAO is presently engaged in partnerships with several institutions, including the Radio Astronomy Laboratory of UC Berkeley, for deployment of PAPER (Precision Array to Probe the Epoch of Reionization), a possible precursor array to the lowest frequency component of the SKA. After initial testing at Green Bank, the first few PAPER antennas now have been deployed at the candidate SKA site in South Africa.

Finally, NRAO is planning for construction of the high-frequency component of the SKA in the decade beginning in 2020. Covering a frequency range from 3 GHz or higher to  $\sim 25$ -50 GHz, this will be primarily a pointed instrument, following on from the discoveries of ALMA and EVLA to explore the formation of planets, stars, planets, and galaxies. NRAO led the Astro2010 submission for the North America Array, a possible realization of SKA-high based on the infrastructure of EVLA.



*SKA prototype/concept images courtesy Xilo Studios*

### **NRAO SKA Program on the World Wide Web**

<http://science.nrao.edu/ska>

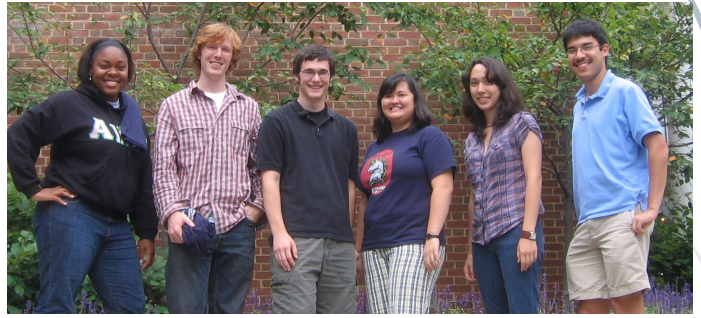
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## Student & Visitor Programs

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### 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 U.S. 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 Ph.D. 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>



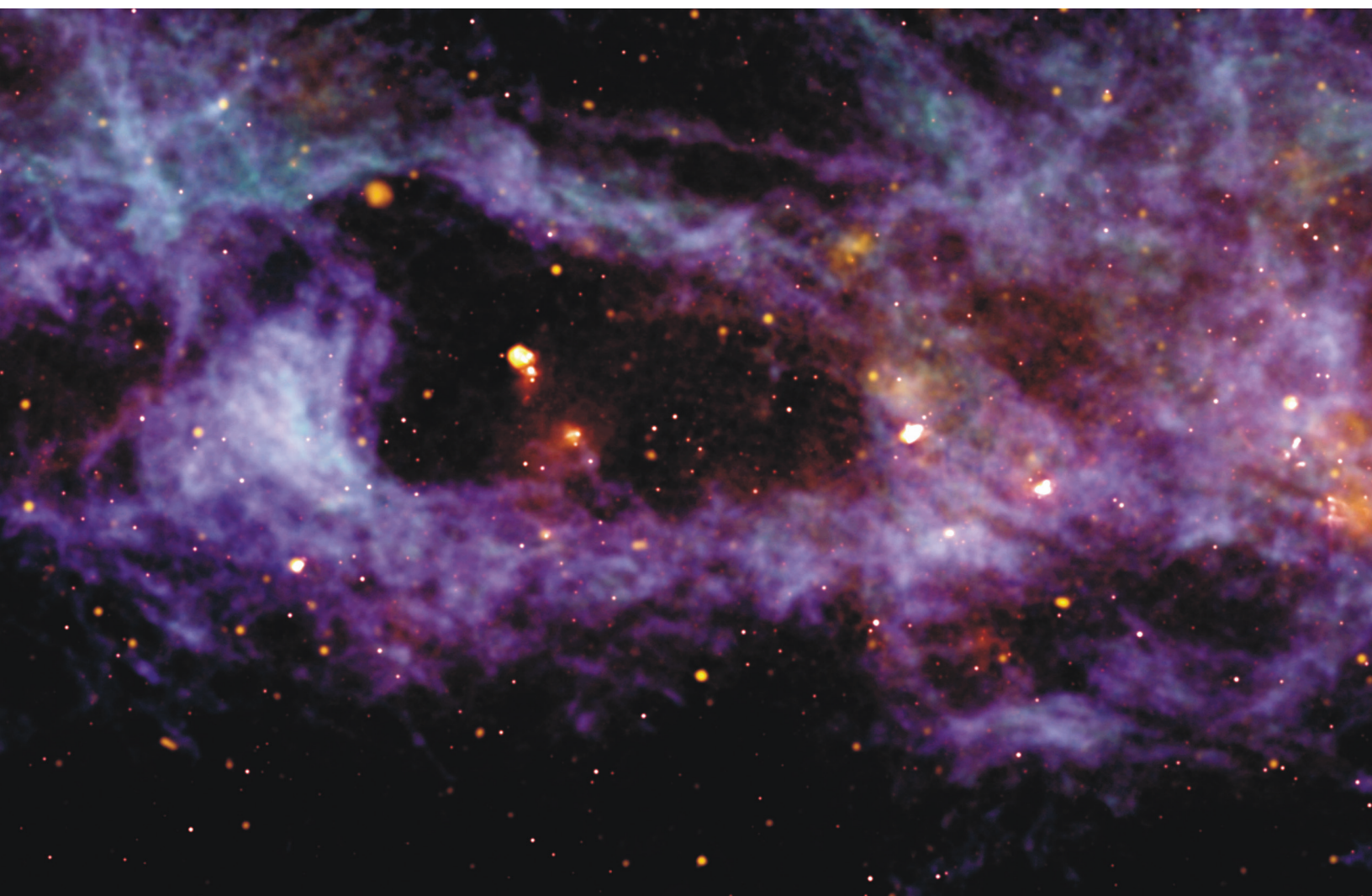


(above)

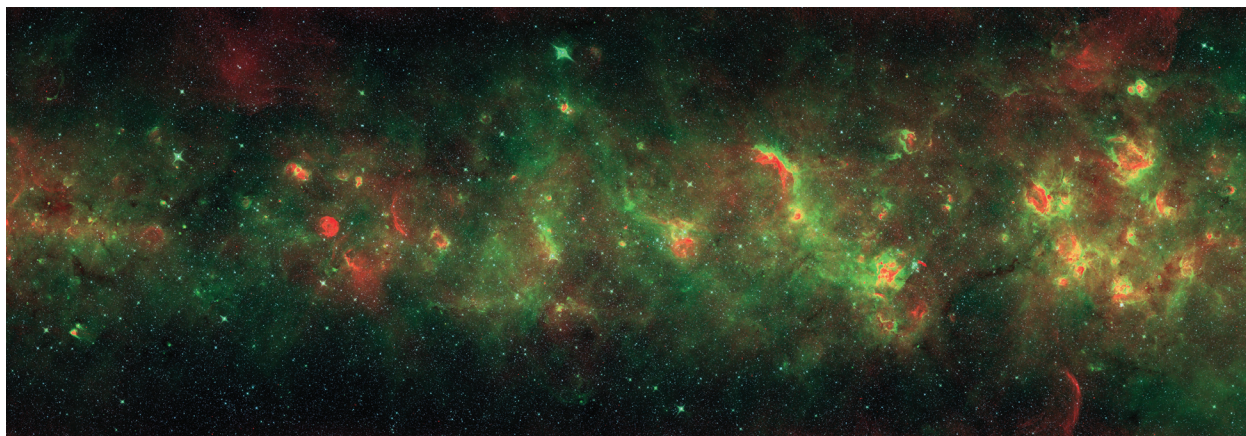
This image of the spiral galaxy M 51, the Whirlpool Galaxy, and its companion NGC 5195 combines observations of neutral hydrogen emission acquired at the NRAO Very Large Array with optical images (R, B) from the Second Palomar Observatory Sky Survey - STScI Digital Sky Survey. The optical data show the 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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