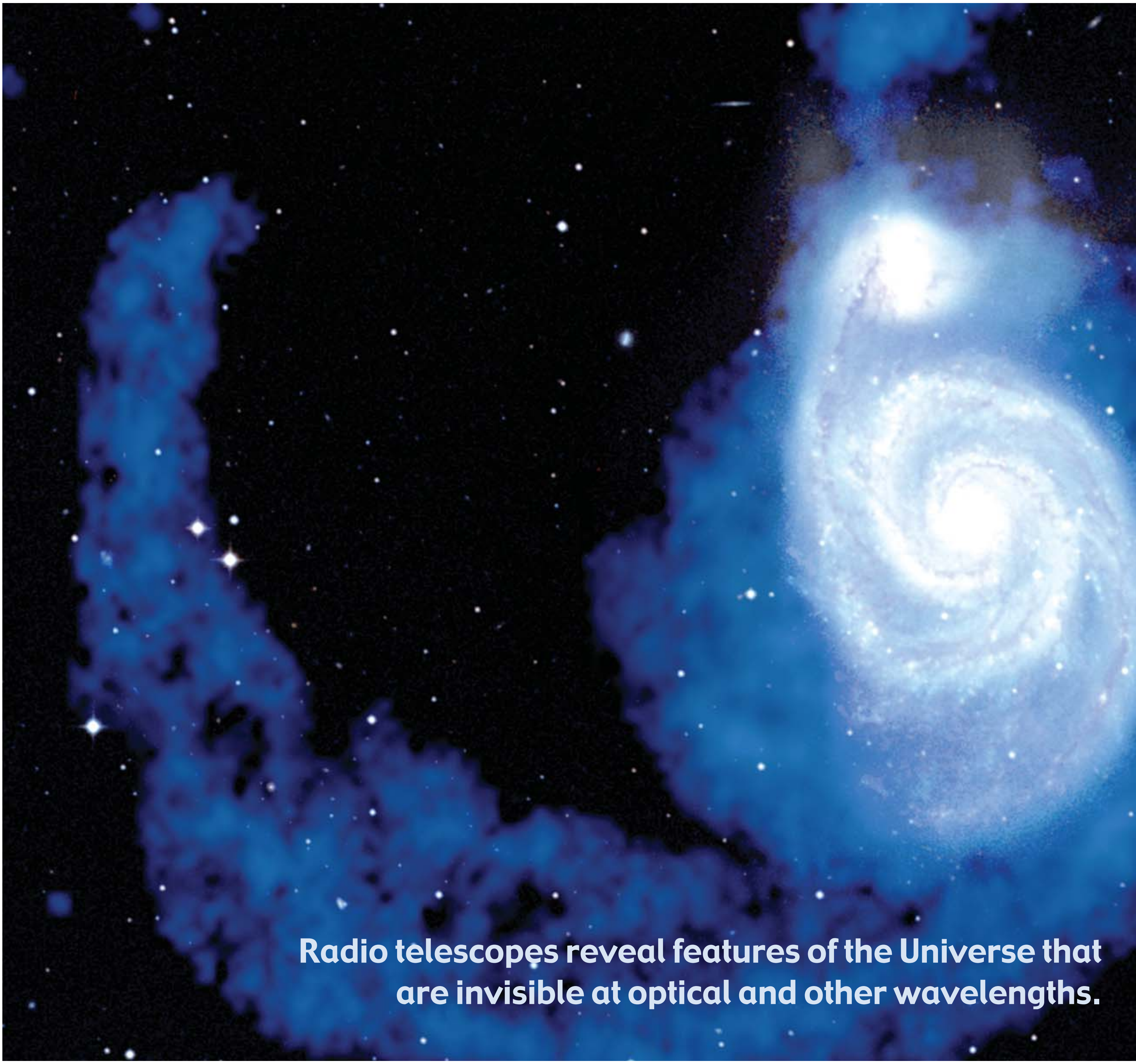
NRAO

National Radio Astronomy Observatory

The National Radio Astronomy Observatory (NRAO) enables cutting-edge research in the study of the Universe using radio astronomy techniques, attracts and trains future scientists and engineers, and stimulates public interest in science.

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 supermassive black holes at the centers of galaxies.
Credit: NRAO/AUI, J. M. Uson

(cover image)
NRAO VLA located in New Mexico.



This composite image of the Whirlpool Galaxy, Messier 51, shows that the radio emission from the galaxy's cold hydrogen gas (blue) extends well beyond the optical light emitted by its stars.
Credit: NRAO/AUI, J.M. Uson

RADIO ASTRONOMY

1905
Einstein's theory of relativity published

1932
Jansky detects radio radiation from space

1937
Reber systematically studies the radio sky

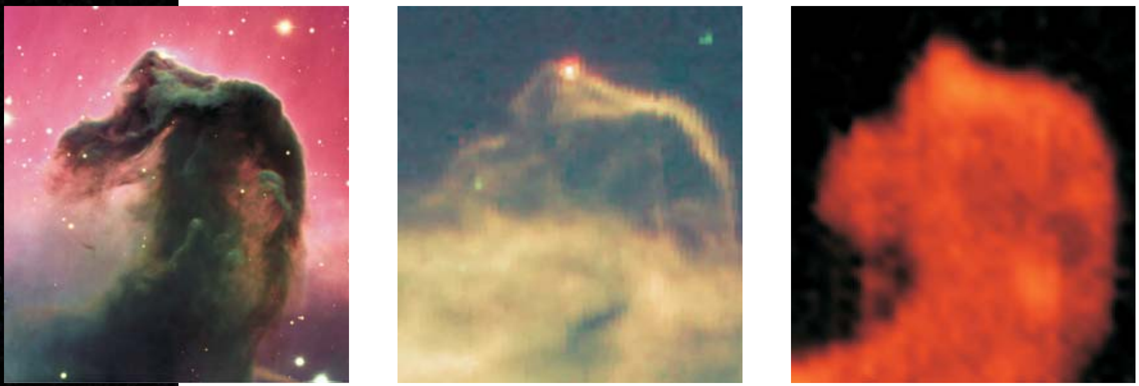
1951
Radio emission detected from neutral hydrogen

1956
National Science Foundation establishes the NRAO

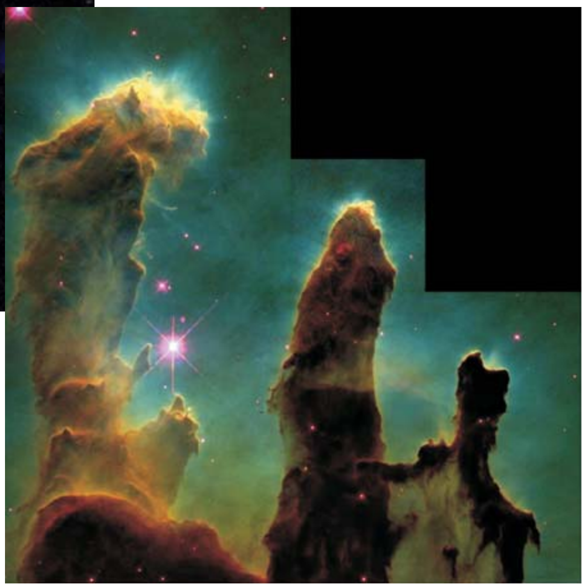
1963
Quasars discovered

The Invisible Universe

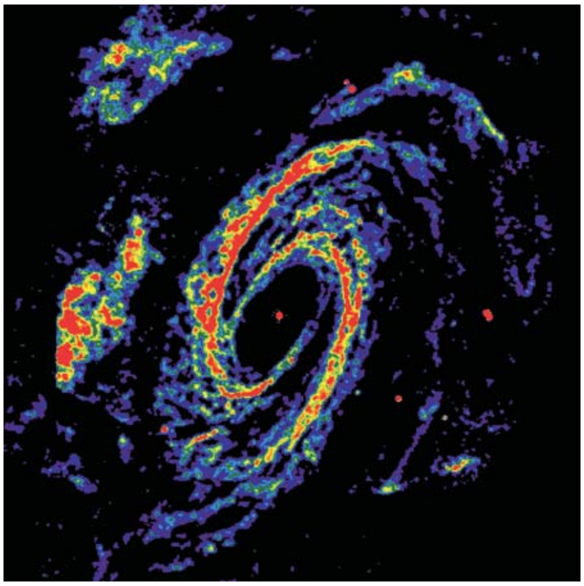
Radio waves penetrate dust, allowing scientists to study regions that are completely obscured at optical wavelengths such as the center of the Milky Way. Radio waves also allow astronomers to trace the location, density, and motion of hydrogen gas, which constitutes three-fourths of the ordinary matter in the Universe. Unlike optical telescopes, radio telescopes can operate around the clock, in daylight or at night.



The Horsehead Nebula as recorded by optical (left), infrared (center), and radio (right) telescopes. Radio telescopes, such as ALMA, will soon routinely yield images with resolutions comparable to this optical image.
Credits: (Left) ESO, (Center) ESA/ISO, (Right) CSO



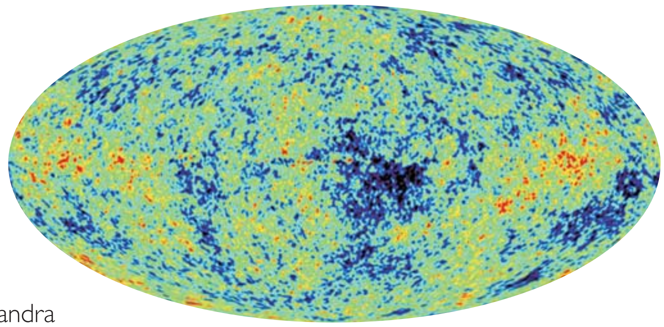
Newborn stars emerge from dense, compact pockets of interstellar gas in this Hubble Space Telescope image of the Eagle Nebula. Rising from a molecular hydrogen wall, columns of cold gas and dust send out finger-like features. Inside, the interstellar gas is dense enough to collapse, forming young stars.
Credit: J. Hester, P. Scowen (AZ State Univ), NASA



Radio emission from the galaxy Messier 81 traces the spiral pattern of the galaxy's cold hydrogen gas and star formation. Red and blue indicate higher and lower gas densities respectively.
Credit: NRAO/AUI

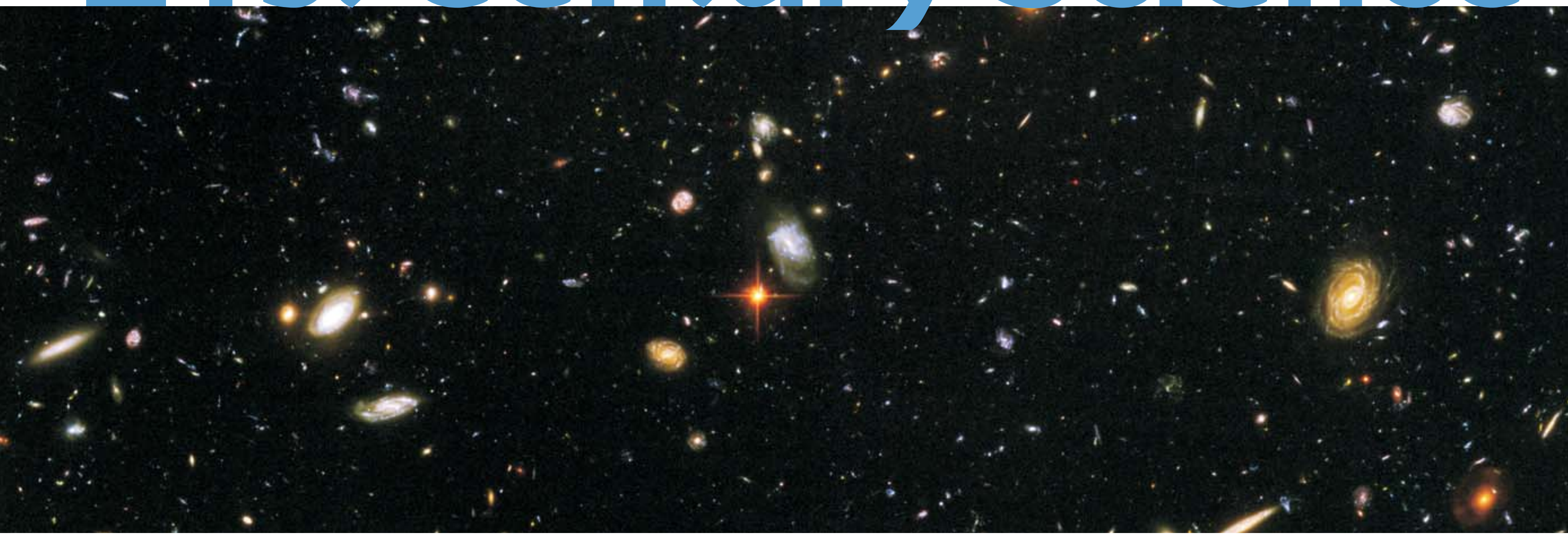
Observations at radio wavelengths allow scientists to address fundamental questions about our Universe.

Using radio astronomy techniques, astronomers can observe the Cosmic Microwave Background Radiation, which is the remnant signal of the birth of our Universe in the Big Bang. They can probe the "Dark Ages" before the onset of the first stars or galaxies, and study the earliest generation of galaxies. Radio astronomers analyze the dust-shrouded environments where stars and planets are born and explore the black holes that live at the hearts of most galaxies. Observations made with NRAO telescopes are often combined with observations at other wavelengths using telescopes such as the Spitzer Space Observatory, Chandra X-Ray Observatory, Hubble Space Telescope, Very Large Telescope, W. M. Keck Observatory, Gemini Observatory, and Subaru. NRAO observations enable scientists to make major contributions to scientific progress.



This all-sky map of the Cosmic Microwave Background Radiation was observed by the Wilkinson Microwave Anisotropy Probe satellite. Colors indicate "warmer" (red) and "cooler" (blue) spots. These microwave data trace the first structures that formed very early in the Universe, and gave rise to today's galaxies and clusters of galaxies.
Credit: WMAP Team

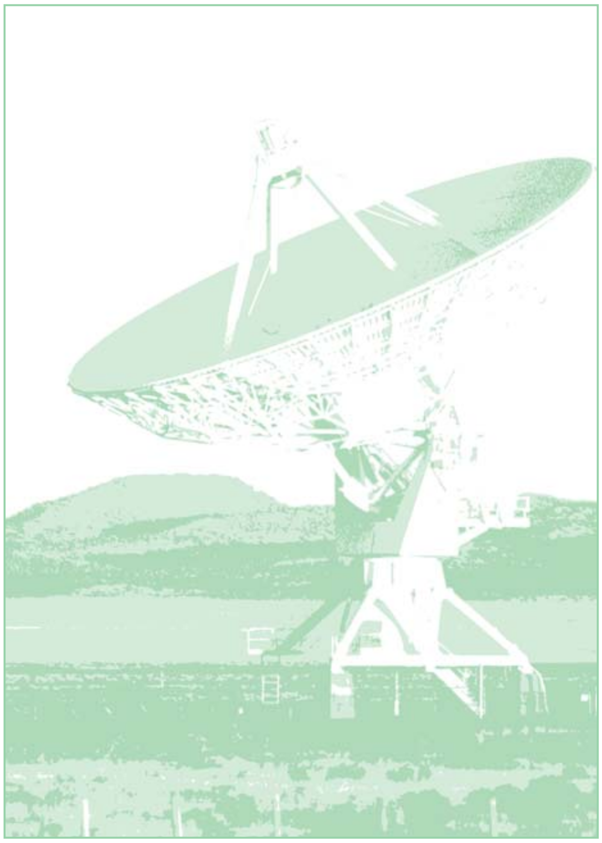
21st Century Science



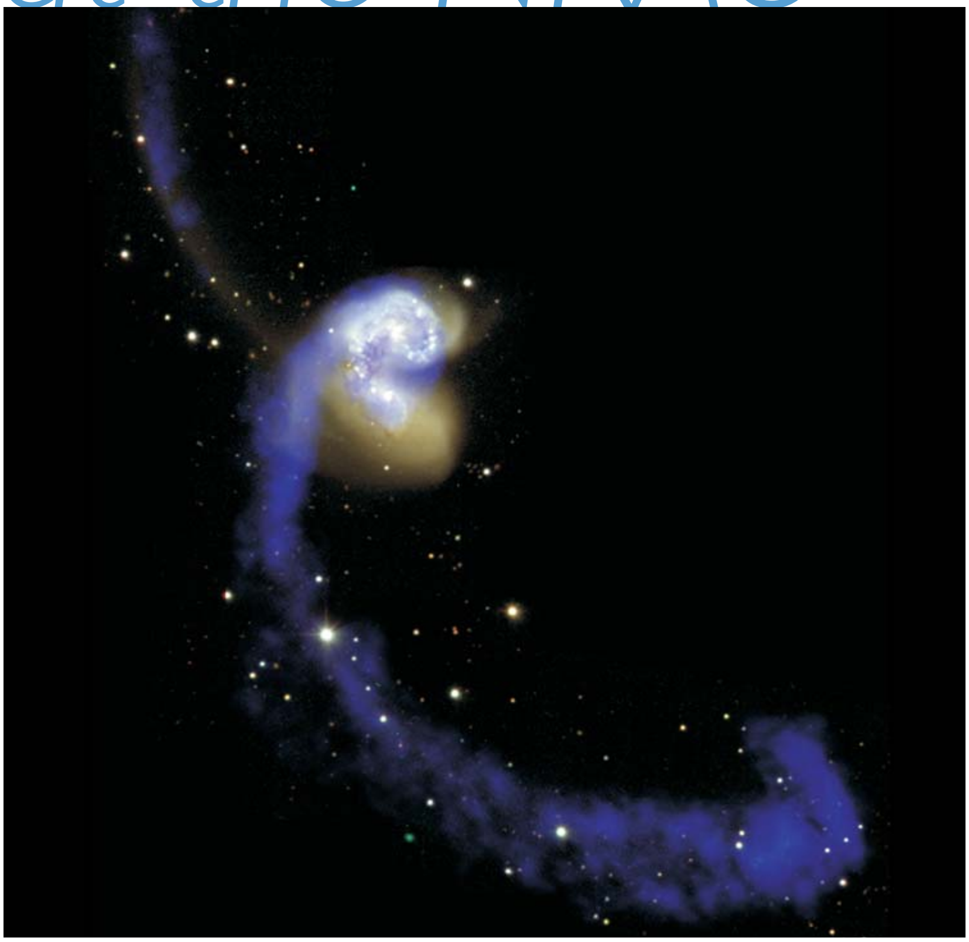
This Hubble Space Telescope million-second exposure shows galaxies at many distances and stages of evolution.
Credit: R. Williams (STScI), Hubble Deep Field Team, and NASA

How and when did galaxies form and evolve in the early Universe?

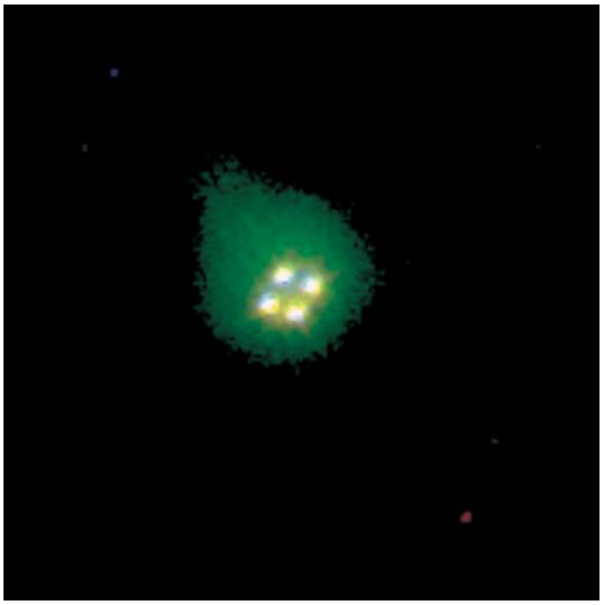
Radio telescopes can reveal the gas, dust, stars, dark matter content, and star-formation in the first galaxies. Two NRAO telescopes - Atacama Large Millimeter Array (ALMA) and Expanded Very Large Array (EVLA) - will observe galaxies in their formative stages, as they were approximately 10 billion years ago, and will establish the star-forming history in near and distant galaxies without the uncertainties caused by dust extinction.



at the NRAO



These two colliding galaxies are collectively known as "The Antennae." This radio-optical composite image illustrates the enormous tidal tails (blue) of neutral hydrogen seen by radio telescopes. This material is being pulled out of the two galaxies as they gravitationally interact.
Credit: NRAO/AUI; J. Hibbard



Radio emission from hydrogen cyanide molecules is a reliable signature of intense star formation. Here such emission (green) is seen superposed on a Hubble Space Telescope image of a distant quasar where star formation is underway. This quasar is being gravitationally lensed into four distinct images by a massive but unseen galaxy along our line of sight.
Credit: NRAO/AUI, STScI

21st Century Science

Multi-wavelength observations are the norm in modern astronomy. This image of NGC 5128 combines radio (pink, green), X-ray (blue), and optical (yellow, orange) data. Jets of high-energy particles from the SMBH at the galaxy's center bisect a band of dust and cold gas, and large arcs of hot gas occupy the galaxy's outskirts.
Credit: (Radio) NRAO/VLA; (X-ray) NASA/CXC; (Optical) STScI/UKIRT

NGC 3603, located about 20,000 light-years from Earth, is an interesting example of a star-forming region in the Milky Way Galaxy that is giving birth to numerous stars much more massive than our Sun.
Credit: ESO

How do supermassive black holes form and evolve?

A black hole is a concentration of matter so dense that not even light can escape its gravitational pull. Astronomers believe that a "supermassive" black hole (SMBH), with a mass of about 4 million Suns, lies at the Milky Way's center, and that SMBHs are common in other galaxies. Together, the EVLA, VLBA, and ALMA provide astronomers the tools to explore SMBHs and the centers of galaxies, yielding a better understanding of their formation and evolution.

How do stars and planets form, and where did the chemistry of life originate?

High-resolution studies of the earliest dust-enshrouded phases of star formation are the exclusive domain of radio astronomy. ALMA and the EVLA are poised to make breakthroughs in our understanding of star and planet formation, imaging the dust and gas in such environments, and probing their chemistry and the key role of magnetic fields. Another NRAO radio telescope, the Green Bank Telescope (GBT), provides the sensitivity needed to detect the weak emission of complex organic molecules, the necessary precursors to life, in dark clouds.

1965
Afterglow of Big Bang discovered

1967
Pulsars discovered

1970
Carbon monoxide discovered in space

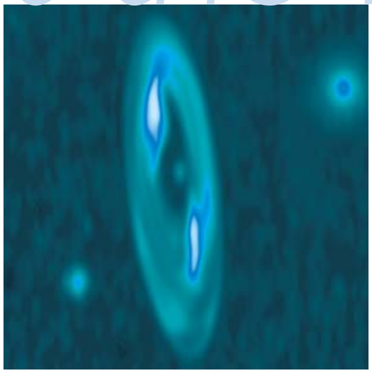
1972
Superluminal motion discovered

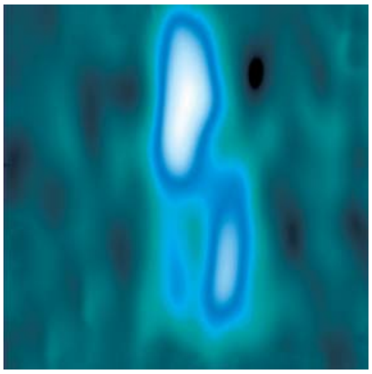
1974
Black hole discovered at our Galaxy's center

1980
VLA dedicated

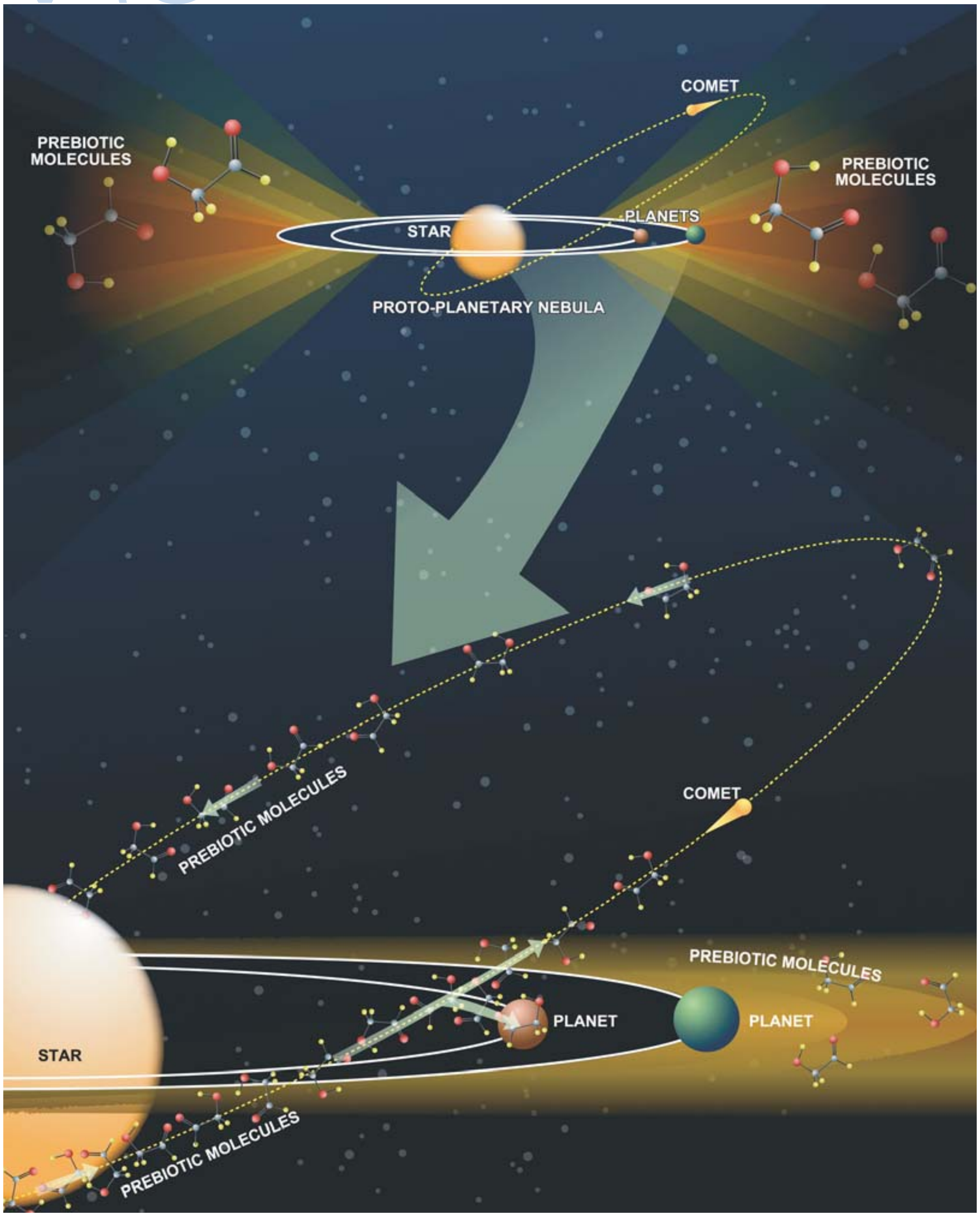
RADIO ASTRONOMY

at the NRAO



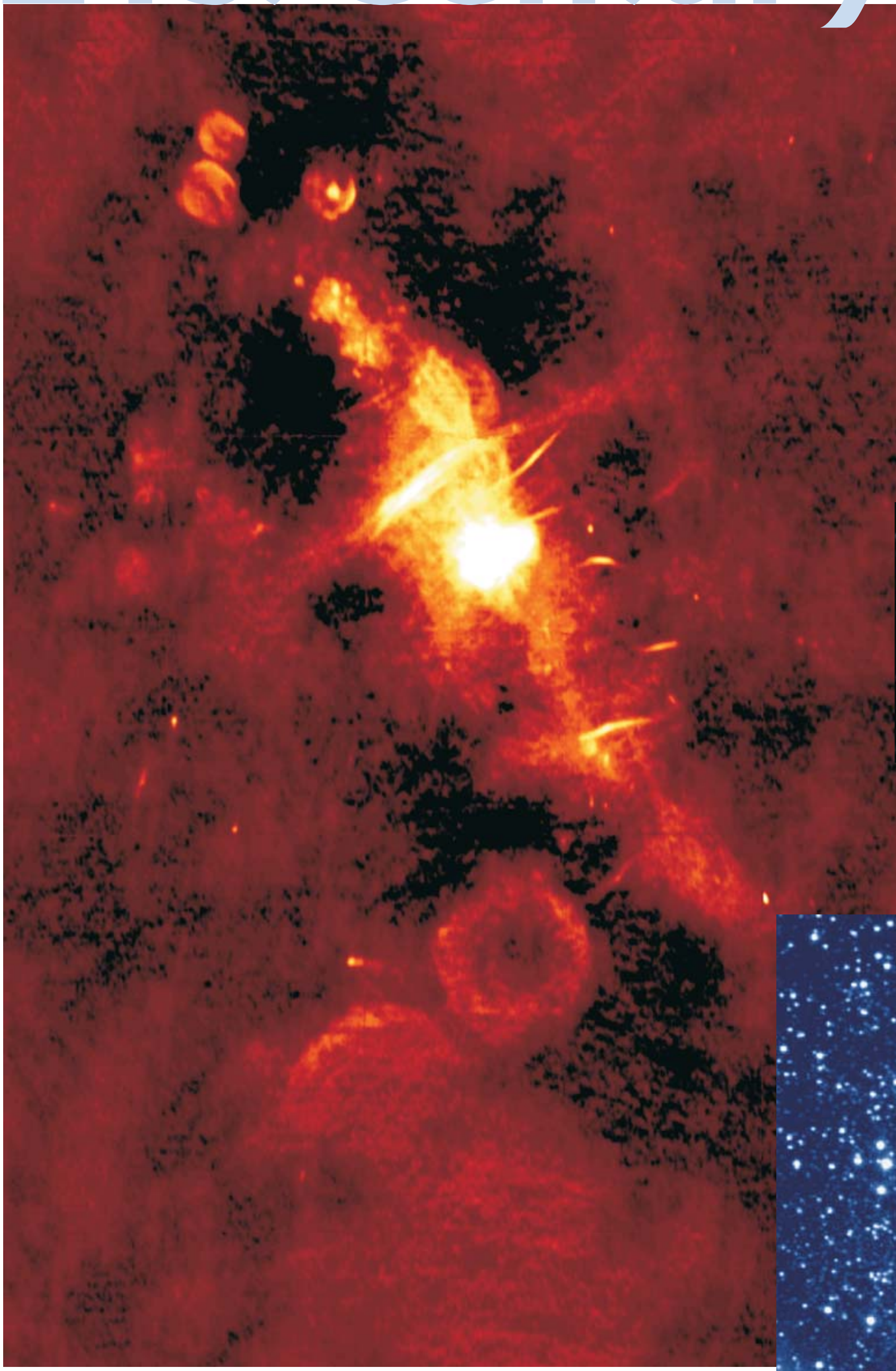


The top image is a simulation of the rich detail that ALMA will probe when it observes the disks of material surrounding many stars. The bottom low-resolution image represents the best that existing radio telescope arrays can achieve.
Credit: NRAO/AUI; A. Wootten

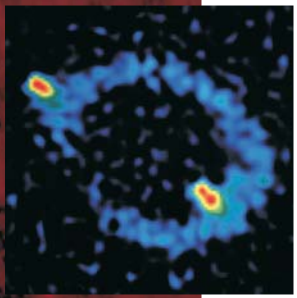


The formation of a planetary system is a hot process that would likely destroy any molecular precursors of life. However, a repository of such "prebiotic" molecules might exist in a planetary system's cooler outer regions. This is also where comets form. Astronomers believe that a collision with a comet or an encounter with a comet's tail might "seed" a young planet with prebiotic material.
Credit: NRAO/AUI; B. Saxton

21st Century Science



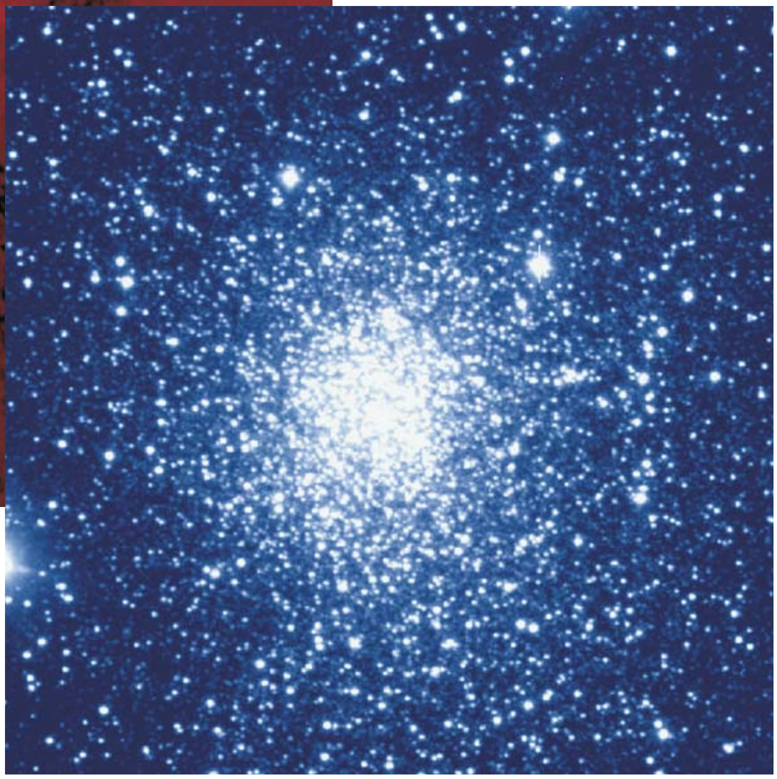
Forever hidden behind a thick veil of dust and gas, the center of our Milky Way Galaxy cannot be seen in visible light. This view of the Milky Way's center was made by astronomers using the NRAO Very Large Array.
Center: NRAO/AUI, N.E. Kassim (NRL)



Gravitational Lensing: An Einstein Ring forms when the gravity of a massive galaxy or black hole along the line of sight to the Earth symmetrically bends or "lenses" the radiation from a more distant galaxy or quasar into a ring.
Credit: NRAO/AUI

Imaging the Black Hole at the Milky Way's Center

NRAO telescopes, using the techniques of very long baseline interferometry, offer the best prospect for actually imaging the supermassive black hole at the center of our Galaxy. Astronomers hope to detect the gravitational "shadow" which this black hole casts by bending light.



Terzan 5 is one of the richest of the 150 globular clusters in our Galaxy and contains more than 30 radio-wave emitting neutron stars known as pulsars.
Credit: ESO, S. Ortolani

at the NRAO

What new contributions can radio astronomy make to frontier physics?

Understanding Dark Matter and Dark Energy

Dark matter and dark energy are among the most intriguing problems in modern physics. Together they comprise 96% of the mass and energy in the Universe, but nobody knows what either is. Dark matter is invoked to explain why galaxies hold together. Dark energy is necessary to account for the fact that the Universe is not just expanding, but accelerating at an ever-faster pace. New observations by the GBT and the VLBA of water masers in other galaxies are yielding additional precise distances to galaxies, which will allow a more precise measurement of the expansion rate of the Universe, and probe the characteristics of dark energy.

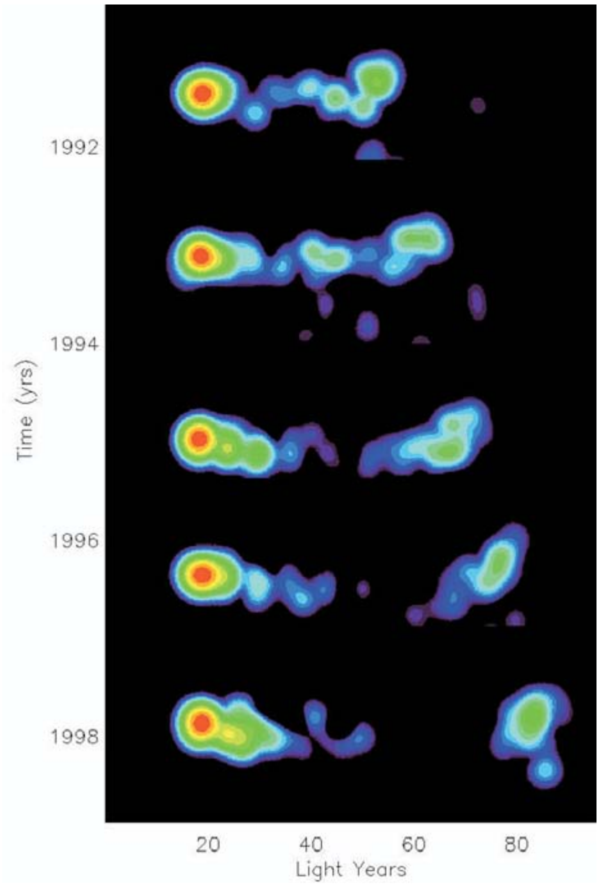
Probing Extremes of Speed and Energy

One of very long baseline interferometry's great successes was its discovery of the extremely fast and apparently faster-than-light (superluminal) motions in the nuclei of some galaxies. The most extreme of these sources are the blazars, each of which likely harbors a central supermassive black hole and relativistic jets that emanate in opposite directions from near its poles. These sources are unique probes of the most extreme speeds and energies known in the Universe. VLBA radio images of these sources will reveal the physical conditions (magnetic fields, pressures, etc.) in the particle acceleration regions. Combined with X-ray and gamma-ray observations, these images will constrain the models for these most powerful particle accelerators in the Universe.

Testing Einstein's General Theory of Relativity

GBT observations of pulsars are providing stringent tests of Einstein's General Theory of Relativity. In addition, the high masses and short rotation periods of pulsars recently discovered by the GBT in globular clusters are providing constraints on the exotic physics of high-density matter. The VLA and the VLBA also provide some of the highest precision tests of Einstein's theory. VLBA observations of how radio waves are bent by Jupiter's gravity, for example, are the most precise measurements of this relativistic effect.

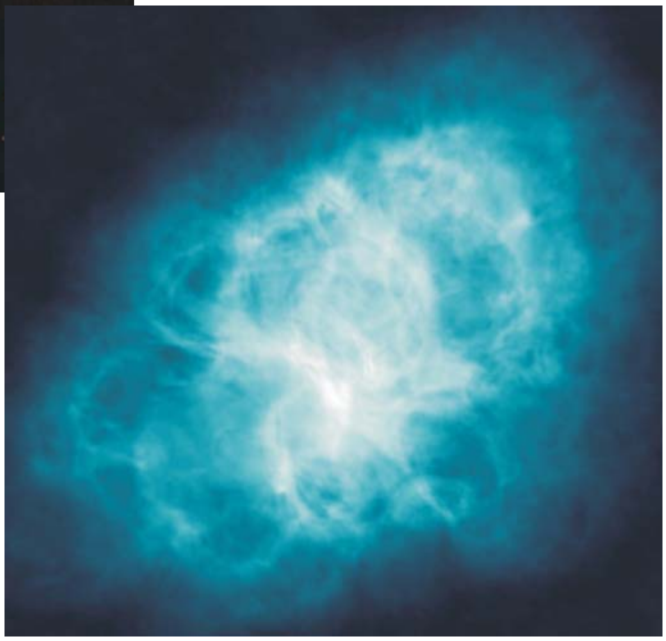
Galaxies typically occur in groups or clusters. The Coma Cluster of galaxies is especially large and rich, containing more than a thousand individual galaxies.
Credit: R. Lupton, Sloan Digital Sky Survey Consortium



These five VLBA observations of the quasar 3C279 span 7 years and seem to show faster-than-light or "superluminal" motion. The rightmost radio emission, e.g., seems to move 25 light years from 1991 to 1998. This emission only appears to exceed the speed of light, however, because of "time dilation," an effect predicted by Einstein.
Credit: NRAO/AUI

Research

Two galaxies emit jets of material from around the supermassive black holes at their centers. These jets are seen in the radio data (purple), which is overlaid on a color optical image. The shorter jet from the galaxy at lower right is colliding with a cloud of hydrogen gas (dark blue). The pressure from the jet triggers the collapse of gas within this cloud, which then forms stars. Black holes are bringing new, young stars into the Universe.
Credit: NRAO/AUI, S. Croft



The Crab Nebula is the remnant of a star that exploded in 1054 AD. The nebula is now 10 light-years across and is still expanding at about 600 miles per second. All that remains of the original star is a small and rapidly spinning neutron star, or pulsar (not visible here).
Credit: NRAO/AUI, M. Bietenholz

The NRAO operates a complementary suite of powerful telescopes (GBT, VLA, VLBA), and is building two new major research facilities that will significantly enhance astronomers' research capabilities. ALMA is a partnership with Europe and Japan that will enable transformational science at millimeter and sub-millimeter wavelengths. EVLA is a partnership with Canada and Mexico and is a major step towards the international Square Kilometre Array (SKA), a next generation, centimeter-wavelength telescope.

The NRAO collaborates with the university astronomy community to develop new instrumentation and technology, and helps train the next generation of scientists through its student, co-op, postdoctoral, and Fellowship programs. A new data management system will soon improve every astronomer's access to NRAO data products for research and education.

RADIO ASTRONOMY

1983 First experimental evidence for gravitational waves

1987 First Einstein Ring observed

1993 VLBA dedicated

1994 Microquasars discovered

1997 Radio emission detected from a gamma-ray burst

2000 GBT dedicated; sugar molecules discovered in space

for Today & Tomorrow

The intriguing distribution of hydrogen gas in spiral galaxies in the nearby Virgo cluster of galaxies is shown superposed on the X-ray emission from hot gas that lies at the cluster's center. While shown in their proper positions in the cluster, each galaxy's size has been increased by 10 times.
Credit: NRAO/AUI, A. Chung

The Atacama Large Millimeter Array (ALMA)
Altiplano de Chajnantor, Chile

An international project of astonishing scope and scientific promise, ALMA will provide an unprecedented combination of sensitivity, resolution, and imaging capability at the shortest radio wavelengths for which the Earth's atmosphere is transparent. An international consortium representing North America, Europe, and Japan is building ALMA, and the NRAO/AUI is the North American Executive for the construction and operation of this extraordinary research facility.

Located in the Atacama Desert of northern Chile, the telescope array will reside at an elevation of 16,500 feet above sea level, well above most of the atmospheric water vapor that could interfere with observations. ALMA will feature a giant array of up to sixty-four 12-meter diameter antennas, plus an additional "compact array" of twelve 7-meter and four 12-meter diameter antennas. The advanced electronics, antennas, and software required for ALMA are now under construction. ALMA will begin astronomical research in 2010 and will be completely operational by 2013. The millimeter and sub-millimeter wavelength region is one of astronomy's last frontiers. ALMA will open this frontier to scientific exploration and will undoubtedly yield breakthrough discoveries. ALMA will give scientists a window on celestial origins, capture new information about the very first stars and galaxies in our Universe, and directly image the formation of planets.

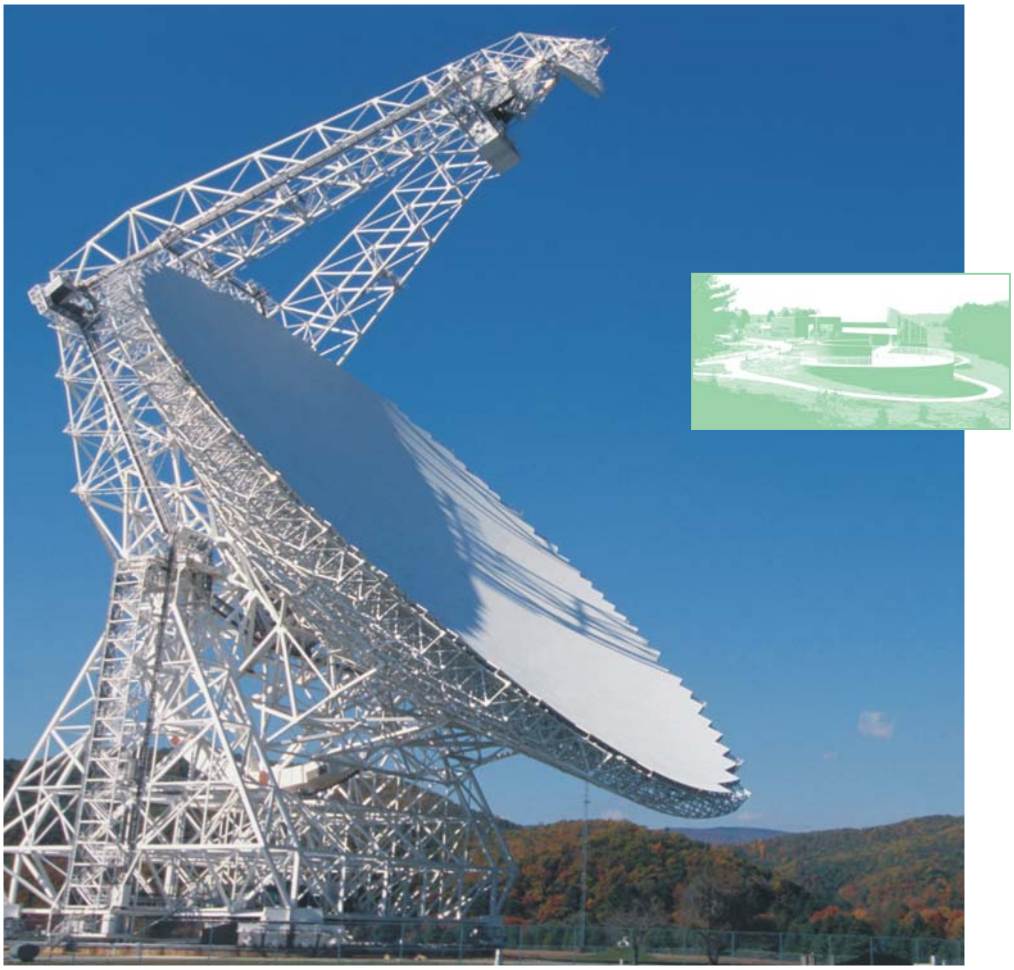
Credit: ESO

Research *for Today & Tomorrow*

Located on the Plains of San Agustin in New Mexico, these 27 antennas are the NRAO Very Large Array.
Credit: NRAO/AUI

Expanded Very Large Array (EVLA)
Socorro, New Mexico

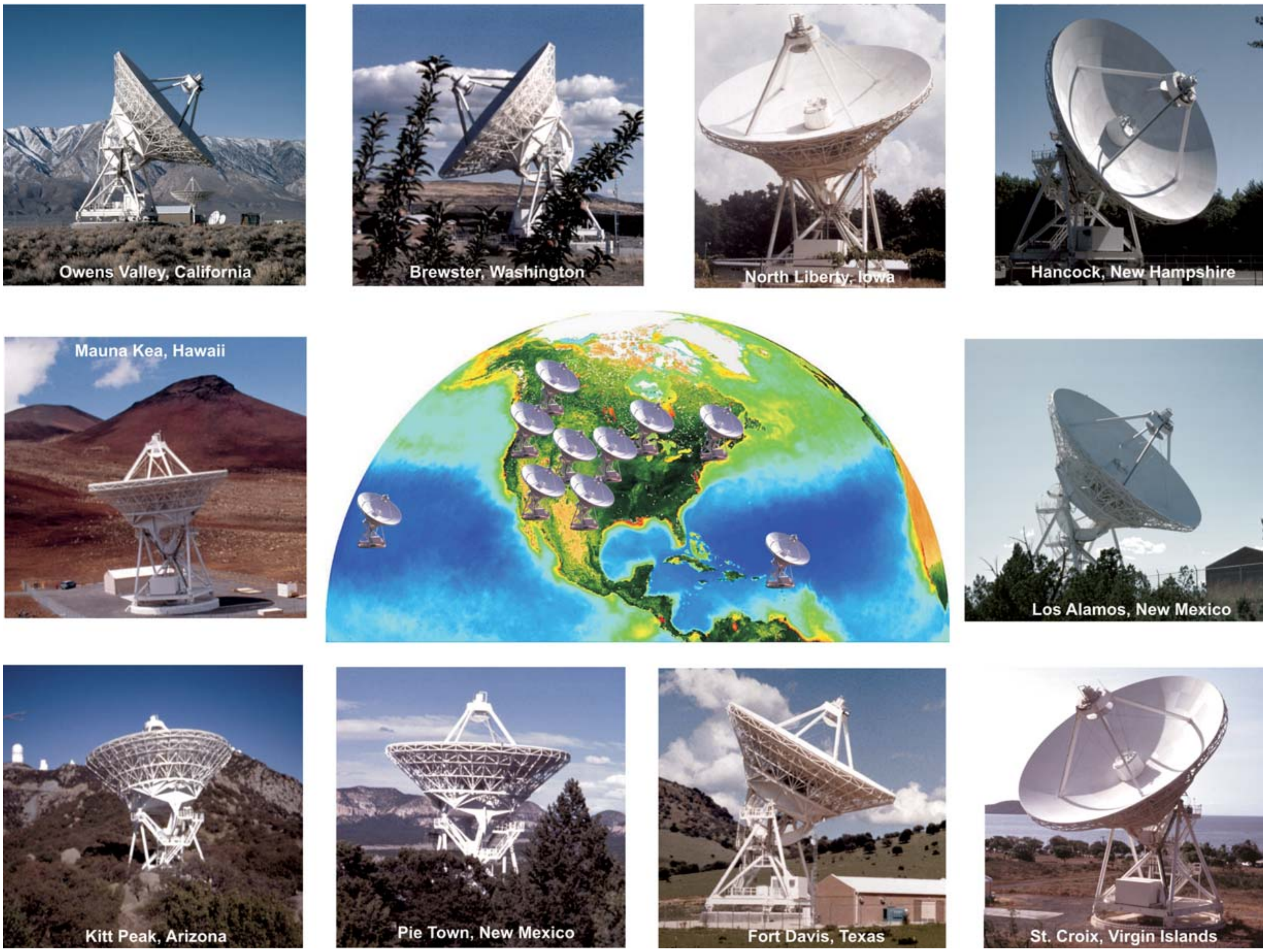
Dedicated in 1980, the VLA has been an extraordinarily productive scientific instrument. Astronomers from around the world use it to study objects from our Solar System to the edges of the known Universe, billions of light years from Earth. The telescope array consists of twenty-seven, 230-ton, 25-meter dish antennas. Together they comprise a single radio telescope system. The VLA has made key observations of black holes and protoplanetary disks around young stellar objects, discovered magnetic filaments and traced complex gas motions at the Milky Way's center, probed the Universe's cosmological parameters, and provided invaluable data on the physical mechanisms that produce radio emission. The VLA is now being transformed into the EVLA as older equipment is replaced with state-of-the-art electronics and software, improving the array's sensitivity by more than ten times. Reinvigorated by new technologies, the EVLA will continue to push the frontiers of science and knowledge for decades to come.



Credit: NRAO/AUI

Robert C. Byrd Green Bank Telescope (GBT)
Green Bank, West Virginia

Dedicated in 2000, the Robert C. Byrd Green Bank Telescope is the most technically advanced single-dish radio telescope. Its 110-meter by 100-meter dish boasts more than two acres of area for collecting faint radio waves from the Universe. Weighing 17 million pounds, the GBT is the largest moving structure on land. And since it is located within the National Radio Quiet Zone, the GBT's sensitive receiving system is well protected from radio frequency interference. The GBT has established itself as a leader in the discovery and study of pulsars, dense neutron stars that serve as "laboratories" where astronomers can study the physics of extreme states of matter and enormous magnetic fields. The GBT can also detect the "fingerprints" of atoms and complex molecules far into the distant Universe, yielding new information about such diverse problems as star formation, the structure and motions of gas in galaxies, and Nature's fundamental constants.



Credit: NRAO/AUI

Very Long Baseline Array (VLBA)
Western Hemisphere

Since its dedication in 1993, the Very Long Baseline Array has produced a wide range of scientific results and images of extraordinary detail, with fifty times the resolution of images from the Hubble Space Telescope. The VLBA consists of ten, 240-ton, 25-meter diameter dish antennas spread across the Western Hemisphere, from Hawaii to St. Croix, Virgin Islands. These ten antennas work together to produce the VLBA's sharp radio "vision." The VLBA has made landmark measurements of the distances to objects within our own Galaxy, and has refined the astronomical yard-stick used to measure the entire Universe. Research performed with the VLBA has revealed important facts about magnetic fields, stellar winds, the motions of stars and galaxies, and the jets of material emitted by black holes. The VLBA also provided the first identification of a supermassive black hole with an orbiting accretion disk.

Credit: NRAO/AUI

Detection of the radio waves emitted by astronomical objects demands technology and signal processing that push the state-of-the-art. The scientists and engineers at the NRAO Central Development Laboratory (CDL) perform much of the innovative research and development that yields the requisite instrumentation and processing advances. Technical innovations developed or enhanced for radio astronomy have also contributed to improvements in: communication antennas, transistors, cryogenic coolers, medical and scientific imaging, time and frequency standards, atomic clocks and GPS navigation, 911 emergency call location, and precision spacecraft navigation. NRAO technology increases our understanding of our Universe and contributes to American competitiveness.

NRAO *Technology*

Amplifiers and Receivers

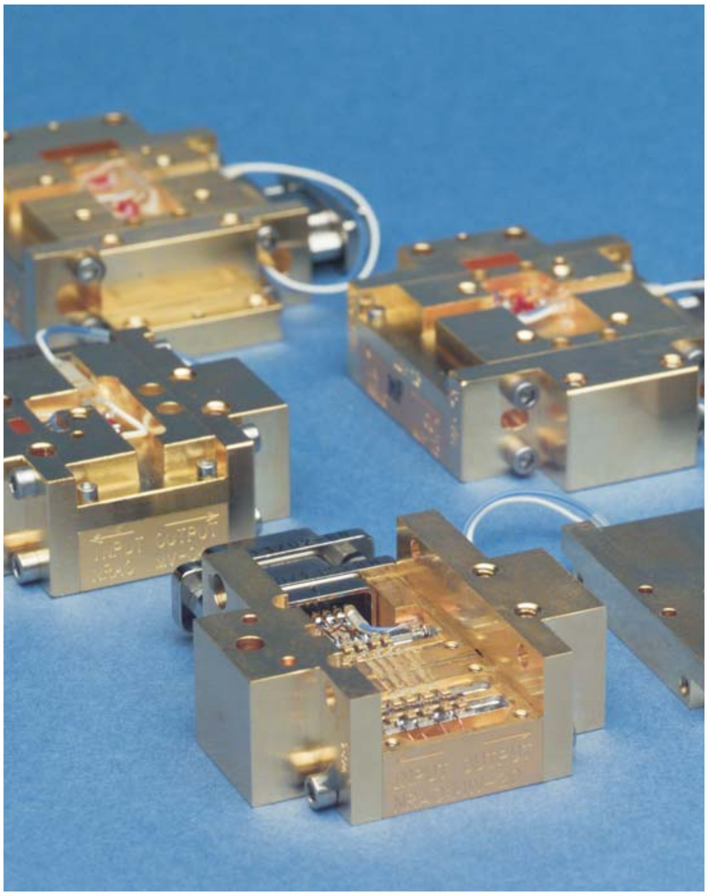
The receivers that detect radio waves almost universally use electronics known as HFET (heterostructure field-effect transistor) amplifiers. The CDL has pioneered the development of these critical components and is largely responsible for their high performance and wide acceptance. CDL amplifiers, for example, were crucial to the success of the Wilkinson Microwave Anisotropy Probe (WMAP) satellite, which accurately measured the remnant signal from the Big Bang.

Digital Correlators

Digital auto- and cross-correlators are the heart of digital data processing for all radio telescopes, and the CDL is a world leader in their development and construction. CDL personnel are currently building the ALMA correlator, the world's fastest supercomputer, capable of more than 17,000,000,000,000,000 calculations per second using a custom processor chip.

Mixers

Superconductor-Insulator-Superconductor (SIS) tunneling junctions that convert radio waves to intermediate frequencies are the foundations of many sensitive radio astronomy receivers. In collaboration with the Microelectronics Laboratory at the University of Virginia, the CDL has developed a reliable junction fabrication process that can be used in many different superconducting electronic circuits. CDL research and development has led to SIS mixer designs that are broadband, require no mechanical tuners, and achieve record-low noise temperatures.



These WMAP amplifiers were designed and built at the NRAO CDL.
Credit: NRAO/AUI

RADIO ASTRONOMY

2004
Carbon monoxide molecules detected in most distant quasar

2005
More than 30 millisecond pulsars discovered in one globular cluster

2005
Proper motion of Triangulum Galaxy, M33, measured

2006
Fastest pulsar discovered

2012
EVLA fully operational

2013
ALMA fully operational

These complex receiver electronics were built by the NRAO CDL to detect radiation collected by the GBT at frequencies of 40 to 52 GigaHertz.
Credit: NRAO/AUI

The prototype ALMA antennas deployed by Alcatel, VertexRSI, and Mitsubishi (left to right) at the ALMA Test Facility in New Mexico. Each of these antennas has been designed to meet ALMA's exacting technical specifications, and will have 10 – 100 times more sensitivity and angular resolution than current millimeter wavelength telescopes.
Credit: NRAO/AUI

The NRAO seeks to bring the excitement of modern astronomy to persons of every age. The Green Bank Science Center in West Virginia, and the Very Large Array Visitor Center in New Mexico offer numerous opportunities to explore astronomy through hands-on exhibits, tours, informative videos, and shops. Special activities and programs are available for school and youth groups of all ages.

Credit: NRAO/AUI

Want to *Learn More?*

The Green Bank Science Center is located adjacent to the Robert C. Byrd Green Bank Telescope, 300 miles west of Washington D.C. in Pocahontas County, West Virginia. The VLA Visitor Center is located at the Very Large Array, south of Albuquerque, New Mexico, and 50 miles west of Socorro, New Mexico, on Highway 60. For detailed maps, operations hours, program opportunities and times, and other information please visit the NRAO on-line at www.nrao.edu/epo, or contact us by phone or email.

The NRAO offers special summer programs for qualified teachers, undergraduate and graduate students, and opportunities to do research with NRAO scientific staff. Additional information about these professional development programs can be found on-line at www.nrao.edu/students.

Credit: NRAO/AUI

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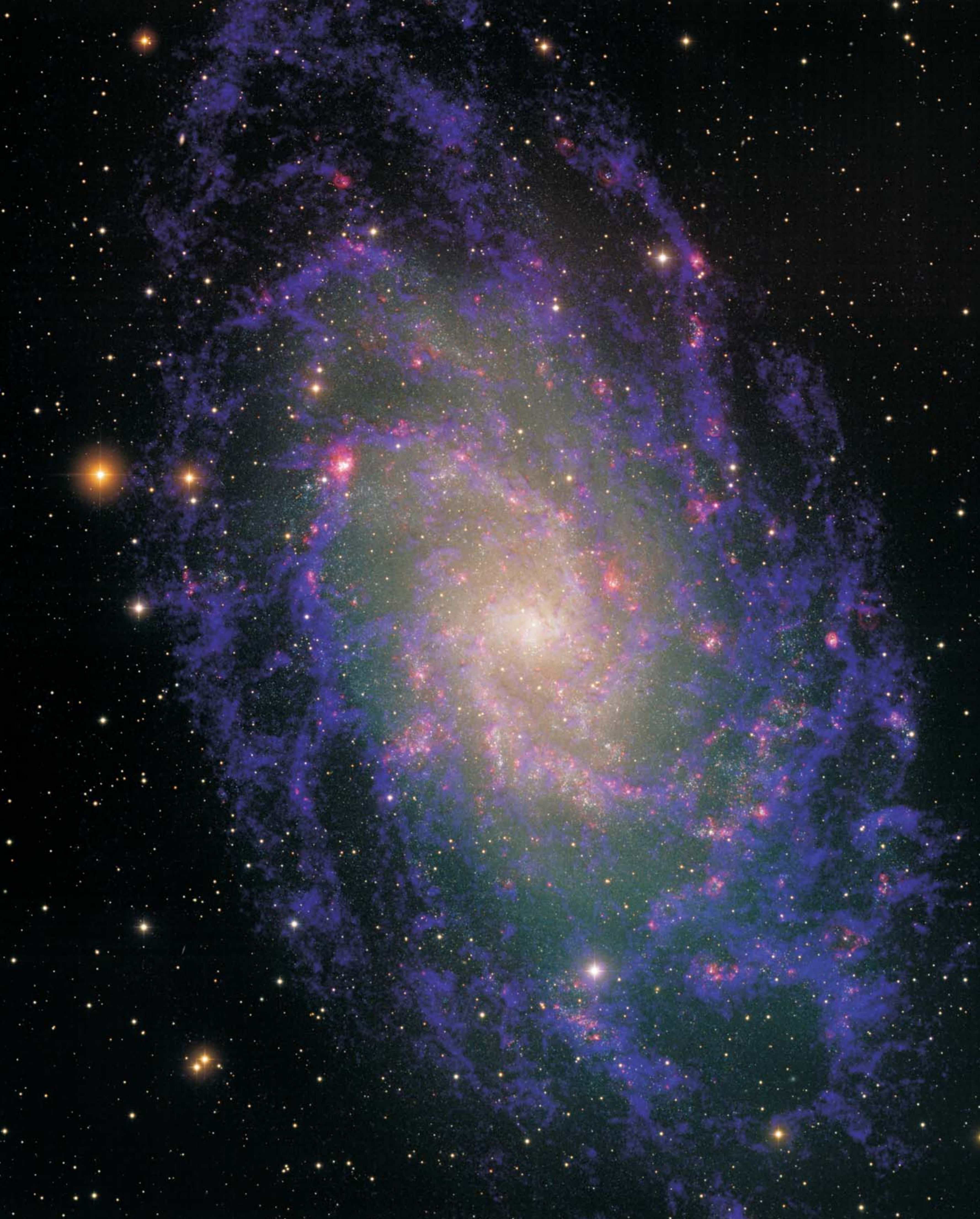
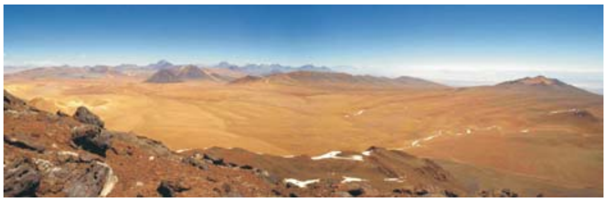
(opposite page)
A composite radio-optical image of the nearby spiral galaxy Messiar 33. The optical image shows the galaxy's stars and hot hydrogen gas (red). The radio data (purple) reveal the cool hydrogen gas, invisible to an optical telescope. Note that the hydrogen gas extends well beyond the region that contains the galaxy's stars.
Credit: NRAO/AUI, NOAO/AURA, T. Rector (U. Alaska)

Back cover image credits: (Top) NRAO/AUI, (Center) NRAO/AUI, J. Uson, (Bottom) R. Williams (STScI), Hubble Deep Field Team, NASA





National Radio Astronomy Observatory

www.nrao.edu

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

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