The University Radio Observatories: Centers for Scientific, Technical and Educational Innovation for Radio Astronomy

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Introduction

From the initial detection of the HI 21cm line by Ewen & Purcell in 1951 to the powerful radio, millimeter, and sub-millimeter facilities of today, university based radio observatories have made fundamental contributions to the understanding of the universe. These contributions are derived from discoveries that have opened up new scientific fields of investigation and pioneering survey campaigns that provided broad scientific insights to astrophysical phenomena. In brief, the university based radio astronomy groups are responsible for the initial discovery of molecules in interstellar space; the recognition of a violent, dynamic ISM as revealed by supershells of atomic gas driven by supernovae and the complexity of magneto-turbulent molecular clouds; the detection of rotating, gaseous disks about young stellar objects; imaging surveys of molecular line and dust continuum emission from the Milky Way and galaxies in the local universe to understand the regulatory processes of star formation; spectral surveys that reveal the chemical complexity of the ISM; temporal variations of radiation from the massive black hole environment in SgrA*; and imaging of Sunyaev-Zel'dovich effect to determine the Hubble constant. These accomplishments are often enabled by technical innovations that take place within university labs with the participation of students and postdoctoral researchers. The university based radio groups have pioneered the development of mm wave interferometry; the application of coherent and incoherent detector technologies into focal plane arrays; and digital autocorrelation spectrometers for radio astronomy. Moreover, instruments developed in university labs have been deployed onto national facilities to discover the binary millisecond pulsar (1993 Nobel Prize to Joseph Taylor and Richard Hulse), millisecond pulsars; and the detection of multiple acoustic peaks in the CMB power spectrum.

University radio astronomy groups will remain a vibrant and essential catalyst for the astronomical sciences in the coming decade. Sensitive and versatile radio astronomy platforms developed and operated by universities will provide unique capabilities that address compelling science issues described in many of the ASTRO 2010 Decadal survey science white papers. These include millimeter VLBI imaging of the event horizon of the SgrA* massive black hole, the assembly of galaxies in the early universe, gamma ray bursts from distant, cosmological events, and further exploration of the multi-scale star formation process with high spatial dynamic range imaging of the interstellar atomic, molecular, ionized gas and dust components. The efforts of the university groups complement the capabilities available at national radio astronomy facilities as well as at facilities across the electromagnetic spectrum.

University Radio Observatories

The University Radio Observatories (URO) program within the Division of Astronomical Sciences at the National Science Foundation plays a key role in radio astronomy in the United States. On a competitive basis, it provides funding for university groups whose activities are centered on the development and operations of unique radio telescope facilities. Each facility provides a research platform for the broad astronomical community. In addition, the facilities are the basis from which the university groups pursue excellence in the three elements of the URO mission: pioneering astronomical research, innovative instrument development, and graduate/postdoctoral training. The successful realization of these mission elements had led to an improved understanding of many astrophysical phenomena, increased technical capabilities for radio astronomy, and the development of the next generation of scientists and engineers that sustains and expands this critical component of observational astronomy.

Currently, the NSF URO program supports 8 university groups operating 4 radio telescope facilities. Each has advanced the field of radio astronomy both in the U.S. and on international stages.

- ***Combined Array for Research in Millimeter Wave Astronomy (CARMA)*** is a millimeter array consisting of six 10.4 meter, nine 6.1-meter, and eight 3.5 meter antennas located in eastern California for interferometric observations with wavelengths between 1.1 mm and 1cm. It is operated by a consortium of universities: California Institute of Technology, University of California Berkeley, University of Illinois, University of Maryland, and the University of Chicago.
  Notable achievements: The CARMA institutions, through their predecessor BIMA and OVRO Arrays, pioneered millimeter wavelength interferometry and opened the scientific fields of inquiry that enabled the scientific and technical case for ALMA. The arrays have surveyed the size, structure, and kinematics of disks around young stars; unveiled the rich chemistry of dense cloud cores; studied the evolution of giant molecular clouds and star formation across spiral arms in galaxies; imaged high-Z galaxies in molecular lines; imaged Sunyaev-Zel'dovich effect in a broad sample of clusters providing an alternative determination of the Hubble constant; supported 111 Ph.D thesis projects since 1990; trained 75 students and 60 postdoctoral scholars since 1990.

- ***Cal Tech Submillimeter Observatory (CSO)*** is a 10.4 meter antenna on Mauna Kea, Hawaii to carry out observations within the sub-millimeter atmospheric windows with wavelengths $300 < \lambda < 1100\ \mu m$. It is operated by the California Institute of Technology. The CSO is a partner with Cornell University and several other institutions to develop and construct the Cornell Cal Tech Atacama Telescope (CCAT).
  Notable achievements: The CSO has carried out pioneering spectral line surveys

throughout the sub-millimeter band; established the role of atomic carbon in the ISM; deployed first monolithic, large-format bolometer arrays (SHARC II, BOLOCAM) to survey the dust continuum emission from distant, dusty galaxies, GMCs along the Galactic Plane, and debris disks; developed SIS detectors for radio astronomy; demonstrated microwave kinetic inductance detectors (MKIDs), antenna coupling of continuum detectors via photolithographic phased array antennas and bandpass filters; developed grating spectrometer to determine redshifts from distant galaxies; trained 65 students and 47 postdoctoral scholars.

- ***Five College Radio Astronomy Observatory (FCRAO)*** of the University of Massachusetts is the U.S. partner with Mexico to operate the Large Millimeter Telescope (LMT), a 50 meter antenna located on Sierra Negra in central Mexico that is nearing completion. The operation wavelength band is 1.1 to 3mm. *Notable achievements:* With its predecessor 14m telescope, FCRAO has conducted the most detailed surveys of molecular line emission along the Galactic Plane, targeted giant molecular clouds and a ^{12}CO survey of 300 galaxies; pioneered the development of heterodyne focal plane arrays including the world largest and most sensitive array at 3mm, SEQUOIA; detected over 1000 submillimeter, high-z galaxies with its bolometer camera AzTEC on the JCMT and ASTE; developed an ultra-wideband heterodyne receiver and spectrometer system to measure redshifts from dusty, high-z galaxies; trained 50 Ph. D students and 32 postdoctoral scholars since 1980.

- ***The Allen Telescope Array (ATA)*** The Allen Telescope Array (ATA) is an innovative, wide-field array of 6.1 meter antennas located at Hat Creek Radio Observatory in northern California that can simultaneously observe four bands in the range $3 < \lambda < 60$ cm. Scientific goals include surveys of transient radio sky; hydrogen fueling star formation in galaxies; interstellar medium; and SETI. The ATA is a jointly developed and operated by the University of California, Berkeley and the SETI Institute. Currently in operation with 42 antennas, the ATA will ultimately be configured with 350 antennas providing 1 hectare of collecting area making it the premier survey instrument in these bands.
  Notable achievements: First working SKA pathfinder targeting large-N, small-D architecture; developed "fly's eye" search for strong transient signals and agile, expandable correlator/beamformer; initiated SETI campaign in galactic center. Since 1962, the Radio Astronomy Lab at Berkeley has trained 67 Ph.D students and 33 postdoctoral scholars.

Scientific and technical innovation has characterized the university programs. New ideas and concepts are inspired by the daily interactions between faculty, the engineering staff, postdocs, and students and the motivation to address compelling questions in astrophysics. Observational programs often drive the need for novel instrumentation, modes of data collection, and scientific analysis. The flexibility that is inherent to the universities enables creative solutions to hardware and software requirements that can be implemented onto the local telescope system in a timely manner.

The URO facilities are extremely cost effective with respect to many observatories in the U.S. and the national centers. The staffs are small in size yet effective in their charge to maintain the site infrastructure, develop new instrumentation and observing capabilities, and to support observers. The involvement of students and postdocs in the operations of the telescopes and scientific research provides an enthusiastic flexible work force that complements the efforts of staff. Finally, the host universities help defray the costs of operations and development with salaries of associated faculty and limited number of technical staff while also accepting reduced overhead rates.

The Mission of the University Radio Observatories

Astronomical Research

The URO facilities serve several critical functions for the general astronomical research community. First, each telescope facility provides a valuable and unique platform for all scientists to carry out radio observations. While all proposals to URO facilities are peer reviewed, 30-50% of the observing time is typically granted to researchers external to the operating institution. These are "open sky" systems with no requirement to collaborate with inside researchers. Documentation and support is provided for observers by the URO staff members throughout all stages of the observing process (proposal writing, data collection, and data processing to a scientific end-product).

As astronomical research increasingly requires multi-wavelength data, URO facilities have provided invaluable complementary data for many ground and space-based telescopes including the VLA, Arecibo, Hubble Space Telescope, and most recently, the Spitzer Space Telescope. Such synergy will continue with future international facilities such as the Herschel Space telescope, ALMA, JWST and the SKA. In addition, the millimeter wave URO facilities have participated in the mm-VLBI network and have supplied critical baselines to these efforts.

With the experience and knowledge of their own telescope system, the UROs are encouraged to carry out ambitious and innovative observational programs to address one or more compelling scientific questions. Such programs are larger in scope than can be typically considered at the national centers. Frequently, a large observational program is the major component of a doctoral dissertation that allows the candidate to sample more targets or obtain larger areal coverage to facilitate more general scientific conclusions that contain higher impact. While these require a significant investment of resources (telescope time, postdocs and students, engineering), the scientific return from such large-scope projects exceeds that provided by smaller, more targeted programs as reflected in the number of publications and citations. The key projects are most frequently led by observatory faculty and staff including postdocs but have also have substantial involvement of community researchers. Often, key projects form the basis for one or more Ph.D theses. Data collected by such key projects are made available to the community within a reasonable time to further extend the scientific return.

Instrument Development

The development and deployment of innovative instrumentation, software, and data analysis are the lifeblood of a modern astronomical observatory. The capability and productivity of a telescope is a function of collecting area, instrument sensitivities, stable and efficient control systems, and robust software that processes raw data into a final science product. Its performance can be enhanced through developments of detectors with increased sensitivity or multiplexing capabilities, and spectrometers with increased bandwidth and resolution. Such multiplexing is realized spatially with focal plane arrays or spectrally by broad band processing to observe multiple line frequencies or continuum bands simultaneously. Similarly, control systems comprised of hardware and software components can augment the data collection by minimizing inefficiencies and enabling new observing capabilities.

The UROs have been able to compete with larger national and international telescopes owing to their development of such innovative instrumentation and software implementations. The key to this success has been their location within a university environment. The scientific and technical observatory staffs and students are exposed to and engaged in the development of key technologies. Indeed, there is often a close and collaborative relationship of the staff with the local engineering and computing science groups on campus as well as the national research labs. This proximity leverages broader university, NSF, and NASA investments to bring emerging technologies to astronomical instrumentation. Examples include the use of Monolithic Microwave Integrated Circuits (MMICs) in radio astronomy receivers by FCRAO, pop-up and spider web bolometers by CSO, and fast digital sampling and field-programmable gate arrays (FPGA) in the CARMA and ATA correlators. Moreover, the UROs have further enhanced their systems with pioneering developments of data collection and analysis methods, These include the mosaicking of interferometer primary fields for larger, high resolution maps, the formation of multiple beams on the sky from the telescope array signals, and On-the-Fly mapping with large format focal plane arrays.

Technical innovation is also a product of the URO's mission to focus on targeted science goals rather than providing a broader range of capabilities. The UROs can focus on instruments and methods to provide the best system performance for particular science objectives.

Student/Postdoc training

The education of students and postdocs with a university class radio telescope is, in itself, a novel and effective learning environment. The groups bring together the people who built, maintain, and innovate the hardware, faculty with vast experience and knowledge, and student and postdocs with a wide range of experience. Learning occurs at all levels: expert to novice, peer-to-peer, and joint exploration of new ideas and capabilities. The integration of the students and postdocs into the operations of a radio telescope facility provides hands-on experience with many functions of an observatory. The data that emerges from the radio telescope is not the product of a proverbial "black box"; students and postdocs participate in the creation and commissioning of new capabilities and the maintenance and trouble-shooting of the operating facility. The details of system are exposed, and often a component of a new development or capability becomes a component of a Ph.D thesis.

The reach of the training experience extends throughout the community. The URO's have an "operate-your-self" approach whereby everyone with a TAC approved project, the desire, and the time commitment becomes involved in the operation. Student Ph.D thesis are strongly supported and recognized as a training commitment for the facility. Currently, and over the years, the URO's support a significant number of Ph.D projects from the community.

This experience is invaluable for their immediate scientific research, and it instills a technical grounding for the students and postdocs to make qualified and informed decisions in the future as they sit on national or international committees or in their roles as staff members or directors of radio facilities. The participants are given a direct view of the requirements and processes necessary to operate a modern astronomical observatory. If their experience extends to several URO facilities, they can compare the difference implementations for common functions. In every sense, student and postdoc participation in the operations of a URO facility offers the optimal training for future leadership in radio astronomy and the development of astronomical infrastructure.

Finally, URO sites and other university groups are the primary training ground for future instrument developers in the radio, millimeter, and submillimeter bands. As noted above, new instrumentation is essential to maintain the vitality and productivity of existing telescope systems. The students and postdocs engaged in instrument development activities as part of their dissertation can continue the rich legacy of US based investigators that has expanded radio astronomy capabilities over the last 40 years. As we embark on the ALMA era, these are the individuals who will drive the next generation of innovative instruments on ALMA and other telescope facilities.

The Future of University Radio Observatories

In their report submitted to the Division of Astronomical Sciences at the NSF, "From the Ground Up: Balancing the NSF Astronomy Program", the Senior Review Committee noted the achievements of the UROs,

> *The SR was impressed by the scientific and technical accomplishments of the URO program. ..... The UROs have been heavily subscribed observationally and are very productive scientifically. They play vital roles in training students and providing testbeds for new instrumentation and techniques. They are supported very competitively and funding is not renewed when they are no longer able to contribute at the highest level.*

Their recommendation for the radio-millimeter-submillimeter base program at NSF:

> *The Radio-Millimeter-Submillimeter Base program should comprise the Atacama Large Millimeter Array, the Green Bank Telescope and the Expanded Very Large Array operations together with support for University Radio Observatories and technology research and development through the Advanced Technologies and Instrumentation program.*

By all measures of science and technical achievement, the URO program has been a success. It has maintained the presence of radio astronomy within a university environment and fostered both scientific and technical innovation while training the next generation of research scientists. These scientific and technical accomplishments in the millimeter and submillimeter bands have, in part, motivated the development and construction of the Atacama Large Millimeter Array (ALMA). The ATA provides a powerful and scientifically productive prototype for the Square Kilometer Array (SKA) – the next, ambitious international project under consideration.

Yet even with these more powerful facilities in operation, both current and future UROs will continue to have a significant impact on the field. The expense and complexity of operating facilities like ALMA and SKA will limit their ability to experiment with novel instruments, data collection methods or carry out scientific programs with higher risk but potentially, large payoffs. The UROs can fill that void as valuable testbeds for new ideas that may ultimately be implemented at the larger facilities to improve performance. The UROs will continue their rich legacy of survey programs that will complement the more restricted target lists and areal coverage of ALMA. The deployment of novel instrumentation onto the URO platforms can make these telescopes both competitive and complementary to ALMA and SKA for focused scientific questions. Finally, the most important role of the UROs in the coming decade is the development of human resources within the United States that can contribute to the scientific and technical missions of radio astronomy. The students and postdocs who emerge from the URO programs are the long term users, instrument developers, and leaders of ALMA and SKA that can best optimize the scientific productivity of these instruments to justify the large federal investments in radio astronomy.