Revealing the Molecular Universe: One Antenna Is Never Enough
ASP Conference Series, Vol. 356, 2006
D. C. Backer and J. L. Turner and J. M. Moran

The Future of the UC Berkeley Radio Astronomy Laboratory

Leo Blitz

Astronomy Department and Radio Astronomy Laboratory, University of California, Berkeley, CA

Abstract. The future of Berkeley's Radio Astronomy Laboratory is examined in the light of a number of current radio, millimeter and submillimeter projects around the world. There are several models that are viable in the changing world of university-based radio astronomy. However, it seems unlikely that observatories built and operated by a single university will be viable in the future.

1. THE PAST

Berkeley's Radio Astronomy Lab, the RAL, was founded as an organized research unit of the University of California at Berkeley by Harold Weaver in 1958. Its stated mission, to foster research in radio astronomy, has been accomplished through a combination of instrument design and construction, astronomical observations, and graduate student training. The RAL is funded in part by the University of California, in part from NSF funding and now, in part through private funding channeled through the SETI Institute.

The first major project was the construction of a 33-foot telescope at Hat Creek Radio Observatory (HCRO) followed by an 85-foot centimeter-wave telescope that was funded by the Office of Naval Research and commissioned in 1962. A photograph of the 85-foot made by the famed nature photographer Ansel Adams, commissioned by Weaver, is shown in Figure 1. The 85-foot telescope operated continuously until 1993, when it was blown down in a 100+ mph wind storm, a once in a century event. One of the major projects undertaken with the telescope was the Weaver-Williams survey of atomic hydrogen in the Galactic plane (Weaver & Williams 1973, 1974); it was the standard in the field for nearly 25 years. At the same time, Carl Heiles and Harm Habing did the first complete off-plane HI survey to complement the Weaver-Williams survey (Heiles & Habing 1974). Heiles describes these surveys elsewhere in this volume. Weaver and his colleagures at the RAL also discovered the first interstellar maser with the 85-foot (Weaver et al. 1965), which he dubbed "mysterium." Fortunately, that name didn't stick. See accounts by Weaver and by Heiles in this volume.

Jack Welch succeeded Harold as Director of the RAL in 1972, having been part of the RAL since the early 1960s. He pushed toward higher frequency operations, moving Sam Silver's 10-ft millimeter-wave dish to Hat Creek. In 1968, together with Al Cheung, Dave Rank, Charlie Townes and Doug Thornton, Jack discovered the first polyatomic molecule, NH_3 (Cheung et al. 1968), and shortly afterwards discovered interstellar water, also in the form of a maser (Cheung et

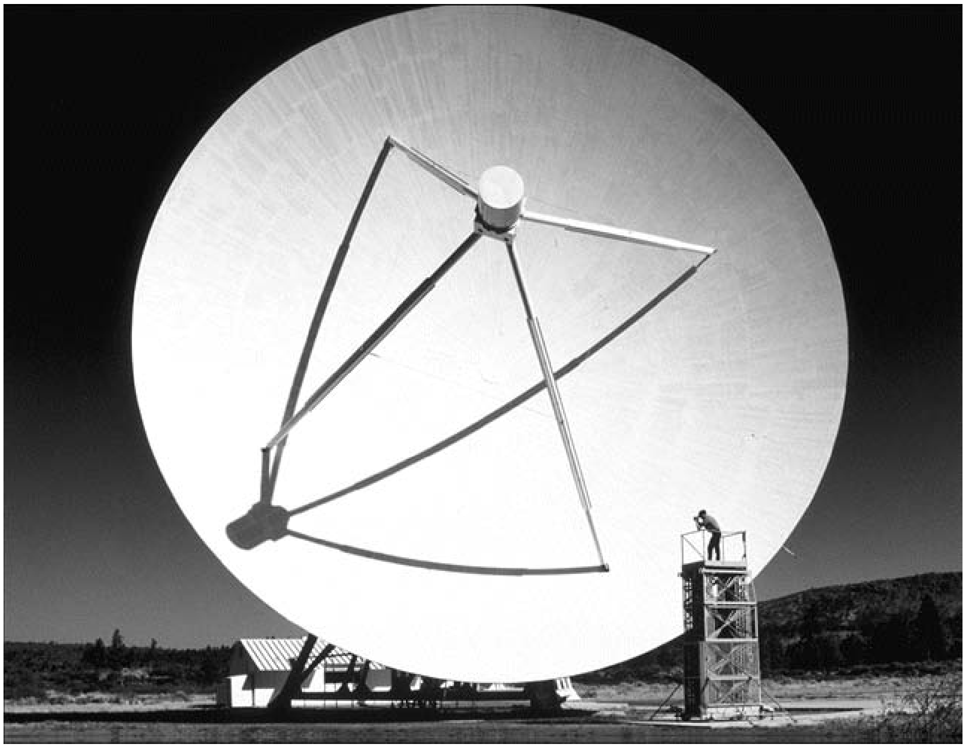

Figure 1. Image of the 85-ft telescope taken by nature photographer Ansel Adams.

al. 1969); see Townes account in this volume. These were groundbreaking discoveries for several reasons. First, polyatomic molecules were completely unexpected because it was thought that they would take too long to build up through binary collisions in the ISM. Second, George Field, the chair of the Astronomy Department and an outstanding theorist, told Charlie Townes that a simple calculation showed that interstellar molecules simply couldn't exist in detectable numbers. Nevertheless, the observations at Hat Creek proved not only that molecules existed in large numbers, but also that polyatomic molecules could be quite abundant. Third, it captured the imagination of the public. Imagine, water in interstellar space! An ordinary compound with which we were all familiar was found in great quantities in space! Water is the stuff of life; without it, life as we know it can't exist. But there it was, just floating around out there and on top of it all, it radiated through maser emission. Lasers, which seemed at the time so exotic and difficult to manufacture, occurred naturally in the interstellar medium manifested by their lower frequency counterparts: masers.

Soon thereafter, through a long series of major technical developments, Jack moved the RAL in the direction of millimeter-wave astronomy and built the first millimeter-wave interferometer, which ultimately became the 10-antenna BIMA Array (Fig. 2; see also Plambeck account in this volume). Jack's vision ushered in an era that is culminating with the construction of the Atacama Large Millimeter Array (ALMA) in the Atacama desert in northern Chile.

Figure 2. The 10-antenna BIMA array in a compact configuration. Can you find them all?

When I became RAL director in 1996, inheriting an outstanding scientific and technical staff, I was eager to move the RAL in a new direction. After briefly flirting with the idea of building an array of feeds to do Cosmic Microwave Background and Sunyaev-Zeldovich Array work at λ 3mm, it seemed that the most interesting and productive path was to develop a cheap, low frequency array, an idea hatched by Jack and Sandy Weinreb, as described by Tarter in this volume. This idea ultimately morphed into the Allen Telescope Array, the ATA (Fig. 3). To further the work being done at the millimeter wavelengths, with ALMA looming on the horizon (then known at the Millimeter Array (MMA)), I thought it important to join the BIMA array with the Owens Valley Radio Observatory (OVRO) millimeter array to form what is now known as California Array for Millimeter Astronomy (CARMA), which is currently in the process of being commissioned. See contribution by Bock in this proceedings.

What links all of these instruments together is that they are all observatory facilities: general purpose telescopes that could be used for a wide variety of astronomical observations by a sizable cohort of scientists. Use of the instruments will continue for at least 10 years; long enough so that we can look to a rosy future for radio astronomy at Berkeley for the foreseeable future, barring major disruptions in funding.

But unless we continue to make new developments, there is the possibility that the RAL will become arthritic and be threatened with the loss of the first rate scientific and technical staff that has been its mainstay. Furthermore, unless we continue to do new science with new instruments, we will slowly lose our attractiveness to students. We are, after all, an educational organization. In other words, an organization like the RAL needs always to be looking forward, with an innovative plan for the future. Otherwise, when the future becomes the present, we might be caught flat-footed as the rest of the astronomical community roars ahead.

But where does the future lie? In new observatories either in the radio, or at sub-millimeter or far infrared wavelengths? Or do we need to look at a new model for the RAL in the medium term future 5-10 years from now when CARMA and the ATA are making routine observations.

Figure 3. The first antennas of the Allen Telescope Array in Hat Creek, CA.

2. THE PRESENT

Let's look at a number of the major projects going on in radio astronomy today, and try to characterize them.

CARMA and the ATA—These two projects are part of the present and near term future of the RAL. Both projects are consortia between universities and/or research institutes. CARMA is a four-university project on a scale that would have been difficult for one university to do entirely on its own. Neither BIMA nor OVRO had the manpower or financial resources (even with NSF support) to complete such a large undertaking in a reasonable amount of time. As it is, the array will be coming on line only 4 – 6 years before ALMA, which will have a much greater collecting area at a much better site. The ATA needed the combined power of both the SETI Institute and the RAL; the former for its fundraising prowess and strategic vision, and the latter for its infrastructure, technical expertise in interferometery and science goals.

ALMA—Although ALMA started out as a national project, and the CARMA Array is approaching half of the collecting area of ALMA's earlier incarnation, the MMA, the scale of ALMA has vastly exceeded what could be done by any single country at the time that serious funding was being sought. ALMA is thus an international governmental consortium, and even so, it is doubtful that the full 64-antenna array originally proposed can be built and operated within realistic budgetary constraints.

Figure 4. The CARMA Array at Cedar Flat in the California Inyo Mountains.

SKA—Although the Square Kilometer Array (SKA) is really a project of the future, considerable planning is going on now. The SKA, if it is to have anything close to the one square kilometer of collecting area and the wide frequency coverage that astronomers desire, needs to be a broad international governmental consortium in order to get built. The science case (Carilli & Rawlings 2004) alone consumed the time of many individuals from around the world for more than two years. From the beginning, design concepts from around the globe were debated, and sites anywhere that can promise low cost and low radio interference are being considered. At a cost somewhere in the vicinity of 1 billion current US dollars, planners have recognized that the project would need international planning and coordination from the outset.

SZA—The Sunyaev-Zeldovich Array has been conceived and executed as a university physics experiment. Because of its small scale, it could be built and operated by a small, dedicated team led by John Carlstrom. While it will provide groundbreaking observations of a very important effect for cosmology, its usefulness as a general purpose observatory is rather limited. As a result, the plan is to incorporate it into the CARMA Array to provide even better imaging than is possible with the 15-antenna BIMA and OVRO arrays.

SMA—The Submillimeter Array began as a single institution project of the Smithsonian Astrophysical Observatory (SAO), and attracted additional funding from the Taiwanese government through the Academica Sinica Institute for Astronomy and Astrophysics (ASIAA). As originally conceived, it was to have been built by a single academic laboratory group, the Center for Astrophysics. As opposed to most other American radio astronomy projects, it has been funded by the Smithsonian Institution rather than the NSF. See description by Moran in these proceedings. In today's funding climate, it is unlikely that NSF funding in the amount needed to build the SMA would be forthcoming. Thus, its ability to attract international funding, has significantly improved its scientific usefulness, turning it into an instrument built by a consortium of two nationally funded research centers.

SPT—The South Pole Telescope (SPT) is a single dish off-axis millimeter and submillimeter wave telescope with a thousand element bolometric array receiver funded by the Office of Polar Programs at the NSF. Designed as a physics experiment to do large surveys of the Sunyaev-Zeldovich effect, and to look at temperature and polarization fluctuations in the microwave background. It is a multi-university consortium that includes Chicago, Berkeley, Case Western Reserve, Illinois and the Harvard-Smithsonian Center for Astrophysics. As with the SMA, it is unclear whether such a telescope could have been funded by the Astronomy Division of the NSF, and a consortium became necessary to make the complex technological developments needed for the instrument. Interestingly, this telescope has capabilities that could eventually make it desirable as a general purpose observatory; it will be the fastest, most sensitive millimeter and submillimeter telescope in the world. If this happens, it will be the transition case between a physics experiment and a submillimeter observatory.

EoR—Some Epoch of Reionization (EoR) experiments, which aim to detect highly redshifted λ 21cm line emission, are by and large in the mold of physics experiments, but others have been designed as observatories that will continue to operate after the EoR signal has been detected. PAPER (Precision Array to Probe the Epoch of Reionization), Don Backer's project to detect evidence of this first epoch of star formation in the history of the Universe, is firmly in the mold of a physics experiment. The larger scale projects, such as the Mileura Widefield Array–Low Frequency Demonstrator (MWA-LFD) in Australia and Low-Frequency Array (LOFAR) in the Netherlands. require resources greater than those that are likely to be mustered by a university laboratory such as the RAL. MWA-LFD is an international consortium, and LOFAR is a major initiative being built by government laboratories and is even expanding into Germany. Given the scale and frequency coverage of the arrays under construction, there seems to be little role left for a medium-size effort that can be undertaken by a university laboratory.

3. SOME POSSIBLE MODELS

As is the case for the RAL, most of the telescopes listed above are general purpose observatory facilities. The SZA and the SPT and some EoR experiments are exceptions. The SZA will need to join CARMA to maintain its usefulness beyond its intial two or so years of operation. The SPT may yet turn into a general purpose observatory. However, these are not the only projects that are being done in radio astronomy, and thus are not the only potential future modes of operation for the RAL. Here are some others:

The Physics Experiment Model—Characterized as telescopes or facilities that are meant to have a relatively narrow purpose such as measurement of some fundamental parameters of the physical universe. The SZA is just one example of such projects that are underway, or planned for the future. The various Cosmic Microwave Background experiments are other examples. Although some, such as WMAP (Wilkinson Microwave Anisotropy Probe) have required the resources of NASA, others have been successfully built by university groups even smaller than the RAL. These include MAXIMA, CBI, DASI amongst others.

The Observatory Model—If one looks at the projects listed in the previous section, the observatory model, the current model for the RAL, seems to be dominated by consortia. Indeed, with the construction of ALMA, astronomers will have covered the entire radio frequency range accessible from the ground (up to Terahertz frequencies). Larger instruments with greater sensitivity and resolution will be beyond the means of a university laboratory.

There is one aspect of the observatory model that can, however, be done on a university scale: large, all-sky surveys. Such surveys can be carried out either with arrays of small telescopes like the ATA, or with larger single-dish telescopes equipped with multibeam receivers such at Parkes (which has undertaken the successful HIPASS and PMB pulsar search) and Arecibo (where the ALFA surveys are currently underway). In the latter two cases, the implementation of focal plane array receivers has been crucial to their success. Telescopes such as ALMA have such a small field-of-view, that smaller arrays such as CARMA can be faster in surveying the large areas covered by millimeter-wave sources with reasonably sized focal plane arrays. Survey speed is proportional to the product NMD, where N is the number of apertures, M is the number of beams formed on each aperture, and D is the aperture diameter.

The advantages of all-sky surveys have been illustrated by the spectacular success of the Sloan Digital Sky Survey (done with a modestly sized telescope). The transient sky is virtually untouched by radio telescopes, and would greatly benefit from repeated all-sky surveys. Surveys with sufficient sensitivity would likely lead to discovery of entirely new phenomena.

The Facility Instrument Model—This model envisages building backends for radio telescopes in exchange for some exclusive use of the instrument. Examples include wide-bandwidth correlators, focal plane arrays, new generation high frequency receivers for facility instruments, high throughput digital backends, multi-element bolometers, etc. This model has been successfully adopted by Reinhard Genzel's group in the near infrared; by Andy Harris who is designing and building the Zpectrometer, a wide bandwidth backend for installation on the GBT; and by a few pulsar groups who have brought frontier signal processing to national observatories.

This is a mode that is always open to university based groups such as the RAL, but requires partnerships with the managers of the facilities, and there is generally limited PI-time available.

University Consortia—This seems to be the only way to build the next generation of radio telescopes, because they will be sufficiently large and complex that they will be beyond the scale of any individual university group's resources. This mode is being successfully implemented by CARMA, the ATA, the SMA, and the largest of the low frequency arrays. It will require a high degree of cooperation between individual institutions. University optical observatories have been moving in this direction for some time to maintain viable research programs in the Keck Telescope era and beyond.

4. The Future

Several things appear to be clear from our current vantage point. First, the era of the general purpose radio observatory designed, built and operated by a single university appears to be over. It is hard to imagine how a single university could design and build a front line radio observtory with the level of resources available to it alone. It will still be possible to build such observatories, but only in the consortium mode.

Second, because the most talked about instruments both in the radio and the optical, the SKA and the TMT (Twenty or Thirty Meter Telescope) are so large, it will be difficult to get students significantly involved in the instrumentation design and development phases, and not just commissioning and use. These telescopes will be built and operated with the help of either the NRAO (in the case of the SKA), or other non-university organizations (such as NOAO, NASA, or some other group) in the case of the TMT. Where, then, will the next generation of instrumentalists be trained? Will we become a society of theorists and observers who are so far removed from the instruments, that the development of yet newer instruments is starved because of a lack of people to build them?

To address this second point, it seems to me that a greater degree of cooperation between NRAO and the universities will be required than has been practiced in the past. This cooperation must, in addition, continue down to the staff level if it is to be effective. Without it, the radio astronomy community, which has remained close to its engineering roots, will find itself shriveling up for lack of new talent.

In light of these realities, it will probably be necessary for the RAL to reinvent itself yet another time. The first incarnation was the establishment of the laboratory building telescopes at centimeter wavelengths, the second, was the push to high frequencies and interferometry, and the third the development of two facilitites at high and low frequency with the ability to do large surveys. Which of these directions the RAL will take will be up to the next RAL Director, and it will be a challenge to him or to her to keep the RAL functioning at the same high level it has for nearly 50 years.

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