2

What Now?

"Failure is simply the opportunity to begin again, this time more intelligently."

Henry Ford

Demise of the 25 Meter Project

US National Science Foundation, 1800 G Street NW, Washington, DC, April 6, 1982: A vote of the Advisory Committee for Astronomical Sciences (ACAST) on a motion to endorse the construction of the 25 m diameter millimeter wavelength telescope proposed by NRAO was defeated, with three in favor, seven opposed, and one abstention.[1] The proposal was essentially dead and shortly thereafter NRAO withdrew it. In reality, the project had all but died months before. It had become a victim of inflation, political necessity, and a growing unease in the US millimeter astronomy community about what it really wanted next in the way of a new telescope.[2]

Support for ground-based radio astronomy research in the United States – including operational support for the NRAO and funding for new telescopes – comes, with few exceptions, through NSF. Since being proposed to NSF in 1977, the 25 Meter proposal had experienced a number of existential crises but had nevertheless remained on NSF's radar screen for potential future projects. By late 1981, the 25 Meter had simply spent too much time waiting in the wings while the state of millimeter astronomy and the priorities of the US astronomy community (and NRAO) had continued to evolve. The ACAST vote, while only formally advisory to NSF, was proof of the fact that the consensus of the US astronomy community for the project had eroded beyond the point of viability. The decision of the incoming Reagan administration to put a hold on all new

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project starts in the Federal budget for the fiscal year 1982, made in the face of an alarming inflation rate of nearly 15 percent, was the final blow.

The loss of the 25 Meter was regrettable. From the start, the proposed telescope had been intended to retain and extend the leadership of the United States in millimeter wavelength astronomy, a field of research the country had pioneered in the late 1960s. By the late 1970s, that leadership was being challenged by the start of construction in Europe of the IRAM 30 Meter Telescope and the 45 Meter Telescope in Japan.

But while Europe did take over leadership in some areas of millimeter wave astronomy, the advance of neither the science nor its supporting technologies slowed in the United States during the 1980s. The field, which became established around 1970, was barely a decade old, and there was much in the way of low-hanging scientific fruit that needed only imagination and opportunity to fall into the hands of observers. In the absence of a large, new US antenna, American millimeter wave astronomers continued to develop innovative research programs that were structured around available domestic millimeter wavelength telescopes. At the same time, engineering research in the United States was leading the way to progressively more sensitive and robust millimeter and submillimeter wave receivers. Even more important, during the late 1970s and early 1980s, groups at the Hat Creek Radio Observatory (HCRO) of the University of California, Berkeley, and at the California Institute of Technology (Caltech) Owens Valley Radio Observatory (OVRO) had begun construction on the first generation of millimeter wave radio interferometers.

Although by present standards those instruments' early sensitivities and imaging capabilities would be modest, they were paving an important groundbreaking path. Interferometers have an intrinsic advantage relative to single-antenna radio telescopes. The imaging detail possible with an interferometer can be enhanced by simply adding antennas separated by progressively greater distances and extending the computational capacity of the signal correlator. This scalability offered millimeter astronomers an alluring pathway for planning instruments vastly more sensitive than the existing millimeter wave radio telescopes, and with the potential to make images of the sky even more detailed than those of the still-to-be launched, Hubble Space Telescope. The outcomes of these projects are described in the sections to come.

With the collapse of NRAO's 25 Meter project in April 1982, one strategic factor stood out clearly: US leadership in millimeter wave radio astronomy demanded a large, new world-class instrument for US radio astronomers. Under the aegis of NSF's Division of Astronomical Sciences, an effort to refocus scientific and political support for such an instrument began almost immediately. The as yet incomplete California interferometers would be crucial guide posts in this process, and their lineal descendant, the Millimeter Array (MMA), only dimly grasped at this time, would evolve and take the shape over 30 years to become part of the largest ground-based radio telescope yet: the Atacama Large Millimeter/submillimeter Array (ALMA).

Community Action

The US millimeter astronomy community was keenly disappointed at the loss of the 25 Meter. They focused the blame on NRAO even though forces beyond NRAO's control – inflation-driven escalating costs and federal budget constraints – were more responsible. The community's first constructive response was to hold a meeting at Bell Labs Crawford Hill to discuss the future. Representatives from NRAO were not invited. The organizers of the meeting were Bob Wilson (Bell Labs), Phil Solomon (SUNY Stony Brook), and Lew Snyder (U. Illinois, Urbana). Fifteen accepted the invitation to attend.[3] The letter of invitation[4] asked what new instrument would be best in the circumstances, an "mm VLA" or a cheap 25 m class telescope? By "mm VLA" the organizers meant an array like the Very Large Array operated by NRAO but capable of millimeter wavelength observations.

Discussion quickly led to a consensus that an "mm VLA" would be the instrument for the future. The group composed a letter[5] outlining the case for a millimeter array to Pat Bautz and her superior Francis Johnson, Director of NSF's AST and NSF Assistant Director for the Directorate of Astronomy, Atmospheres, Earth, and Oceans, respectively. Addressing the letter to Bautz's superior was done to ensure a response. The science goals of the array were star and planetary formation; structure, evolution, and dynamics of galaxies; and cosmology. The letter was sent on 29 October 1982, and Bautz replied to it on 23 November 1982.[6] The group's lack of confidence in Bautz, shown by addressing the letter to Johnson as well, was unwarranted. Before receiving the letter, she had already appointed a committee to advise on the future needs of millimeter and submillimeter wavelength astronomy. It was to hold its first meeting on 3 December 1982. The committee came to include four who were present at the Bell Labs meeting, in particular, Alan Barrett of MIT, who was to chair the NSF committee.

The Barrett Committee was technically a subcommittee of the ACAST, the very committee that had refused to endorse the 25 Meter Telescope. There was clearly an awareness at NSF of the need to address the future of US millimeter astronomy in the wake of the 25 Meter's demise. The Barrett Committee was charged with examining the following questions: What are the emerging emphases in millimeter/submillimeter science? Are the millimeter/submillimeter facilities in the United States and abroad adequate to address the science? Are these facilities accessible to US scientists? What new facilities and instrumentation are required, and what are the relative priorities for implementation? A report was requested in time for the April 1983 meeting of the ACAST.

The principal speakers at the Barrett Committee's first meeting were: Jack Welch who discussed the existing millimeter interferometers at the Hat Creek and Owens Valley observatories; Ron Ekers, who presented a new look at millimeter wavelength possibilities; Frazer Owen, who presented a concept for an "mm VLA"; Mark Gordon, who showed a different concept of a 25 Meter Telescope; Tom Phillips, who presented a concept for a submillimeter telescope for Maunakea: Charles Lada, who showed plans for a joint U. Arizona/Max Planck Institut für Radioastronomie (MPIfR) telescope; and Dennis Downes, who reviewed the IRAM facilities. A concept for a giant fixed reflector operating at millimeter wavelengths, similar in design to the Arecibo Telescope, was proposed by Frank Drake.

The Barrett Committee met on two more occasions. A meeting at Bell Labs in February 1983 discussed the scientific justification for a large millimeter array in a series of presentations. This meeting was widely attended by the community and helped form the basis of a broad consensus on what should be done. The third and final meeting of the Committee was held in Chicago, in April 1983, to write their report.

The Barrett Report

The Barrett Committee met their deadline, finishing a report[7] in time for submission to the ACAST at their April 1983 meeting. With respect to the questions posed in the charge to the committee, they found the following:

- The fact that millimeter/submillimeter radiation penetrates the densest interstellar clouds of matter, in contrast to other wavelengths, opens up entirely new opportunities for the study of star formation, galactic structure, and the evolution of galaxies.
- To make advances in these areas requires an instrument with 1 arcsecond resolution or better at the frequency of the CO (1-0) transition, a total collecting area of 1,000–2,000 m^2, and useable spectral coverage to 1 mm wavelength. No existing instrument met these requirements.
- Foreign instruments under construction have not concluded their guest observing policies but, in any event, would not be able to serve the entire US community.

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- The next steps should be: a design study of a facility that meets the above requirements, defining the array, site, and costs; the construction and provision for operation of a 10 m diameter class submillimeter telescope on a dry site; and the provision of support for research and development at millimeter/submillimeter wavelengths: support for scientists, upgrading existing facilities, and the development of new technology.

The report then discussed potential research that could be addressed by the recommended new facilities. As we will see, ALMA's achievements have far exceeded the highest hopes and wildest dreams of the Barrett Committee. ACAST endorsed the report, transmitting it to the NSF and encouraging the AST to support its recommendations. NSF welcomed and embraced the recommendations to the extent that all were fulfilled. Superficially, this seems remarkable. In fact, AST had taken pains during the course of the Committee's deliberations to encourage a robust future for US millimeter astronomy and for a national millimeter array. Vernon Pankonin, who was the liaison between the NSF and the Committee, deserves credit for his encouragement of the Foundation and coordination with the community in addressing a matter of great urgency to US millimeter astronomy. It was a watershed moment for US millimeter/submillimeter astronomy that led to the MMA being proposed as a new national millimeter wavelength facility, one that eventually became part of the international partnership called ALMA. It also was an outstanding example of how a unified scientific community and a supportive funding agency could work together.

The report received comment in the scientific press.[8] An article in *Nature* by Peter David noted that the recommendation of a millimeter array was timely, coming just as President Reagan's budget request to Congress was released, which included a 24 percent increase for NSF astronomy for the fiscal year 1984. Mitch Waldrop opined in a *Science* article that a millimeter array might not be built until 1990 given that it was behind the Very Long Baseline Array (VLBA) and other projects at NSF. It did, in fact, take considerable time for the recommendation of a national millimeter array to be realized; ALMA was not inaugurated until 2013.

Impact of the Barrett Report

AST took the advice in the Barrett Report seriously. Although not stated in the report, there was an assumption, supported by NSF, that a national millimeter array would be developed by NRAO. But NSF did not leave it at that. The millimeter community received generous support for their research and development of new instrumentation, in particular, for the construction and operation of millimeter interferometers as well as the establishment of a submillimeter observatory. When the Barrett Report was issued, there were two millimeter interferometers[9] under development in the United States, largely funded by the NSF, one at HCRO and another at OVRO, both with three antennas at that time. Both observatories enjoyed NSF support that allowed pioneering developments in millimeter astronomy, while being managed by universities.

University of California, Berkeley, and HCRO – The HCRO was founded in 1958 to study interstellar atomic hydrogen. This work was done with an 85 ft telescope, built in 1962. Work to enable millimeter wavelength observations at HCRO began in the early 1970s with an interferometer of two antennas. The pioneering work of Jack Welch produced the first scientific results obtained with a millimeter interferometer and those will be discussed in Chapter 3.

HCRO Interferometer and BIMA – Work had begun at HCRO with a two-element interferometer consisting of a 3 m and a 6.1 m antenna operating at 22 GHz, and observing at 3 mm began in 1978. A third antenna, of a newer design and diameter 6.1 m, became operational in 1985. In 1988, an agreement was concluded between U.C. Berkeley, U. Illinois, and U. Maryland to form the Berkeley–Illinois–Maryland Association (BIMA). This provided an infusion of funds for the construction of nine new antennas. Funding also came from an insurance settlement following the loss of the HCRO 85 foot antenna in a storm. After the original two antennas were scrapped, BIMA was an array of ten 6.1 m antennas. An extension of baselines enabled sub-arcsecond resolution observations. New receivers incorporating superconductor-insulator-superconductor (SIS) receivers supported observations at 1 mm wavelength. Jack Welch has described BIMA's instrumentation,[10] and Dick Plambeck has given an account of BIMA's scientific results.[11] Hundreds of publications reported the results of BIMA observations, from the mapping of molecular species in the circumstellar envelope of the evolved star IRC+10216 to the study of solar flares, the first detection of interstellar acetic acid by Lew Snyder, and the CO Survey Of Normal Galaxies (SONG), to highlight only a few. Significant technical advances came out of HCRO besides the development of millimeter wavelength interferometry. For example, the wideband Gunn oscillators developed by John Carlstrom as a graduate student are found at radio observatories worldwide. The BIMA array is shown in Figure 2.1.

In 2004, BIMA was decommissioned and the nine newest antennas were moved to a site above OVRO to join with the six antennas of the OVRO millimeter array to form the Combined Array for Research in Millimeter-wave Astronomy (CARMA).

Figure 2.1 BIMA in its compact configuration. Jack Welch in the foreground. Credit: Plambeck (2006); ©ASP, reproduced by permission.

California Institute of Technology, and OVRO – The first radio telescope, a 32 ft diameter dish, was installed at the OVRO in 1958 under the leadership of John Bolton and Gordon Stanley. It was quickly followed by two 90 ft diameter antennas. Ten years later, a 130 ft diameter telescope was built. These telescopes were used to study a wide variety of phenomena at centimeter wavelengths. The start of millimeter wavelength astronomy at OVRO began with the development and construction of innovative 10.4 m diameter telescopes for a millimeter array. OVRO is known for its technical contributions to radio astronomy.

OVRO Millimeter Array – Beginning in the late 1970s, Caltech astronomers began a program to build a millimeter wavelength array at OVRO. It was centered on 10.4 m diameter antennas built using an innovative design and construction technique[12] developed by Robert Leighton starting in 1974. By 1978, the OVRO array had three 10.4 m diameter antennas although they were not operational until later. Leighton's reflectors were an assembly of hexagonal aluminum–honeycomb sandwich tiles mounted to a carefully designed backup (support) structure. The surface of an assembly was precision cut by a rotating blade that traveled in the radial direction on a precision arm. The assembly rotated underneath the arm on the precision air bearing that had been used to grind

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Figure 2.2 The OVRO Millimeter Array. Courtesy of Anneila Sargent, reproduced by permission.

the mirror for the 200 Inch Telescope on Mt. Palomar. After the cutting operation, aluminum sheeting was secured to the surface of each shaped honeycomb tile. The assembly could be taken apart, shipped, and reassembled with high accuracy. The accuracy of the antenna surface allowed for efficient observing to wavelengths as short as 1 mm in the right conditions. Over time, three more of these antennas were added, the last in 1996. During and after the development of the array, until the formation of the CARMA, an extensive program of research was conducted with the OVRO array that was heavily focused on CO in external galaxies,[13] in particular, merging galaxies like Arp 220, Galactic star formation, and emission surrounding young stars[14] such as HL Tauri, which could indicate the presence of a protoplanetary disk. The six antennas comprising the OVRO Millimeter Array are shown in Figure 2.2. Figure 2.3 records the group that took an impromptu hike in the Inyo Mountains to view potential sites for future millimeter arrays. The hike occurred during a conference, 14–16 October 1994, celebrating the scientific results coming out of the OVRO Millimeter Array. A site nearby would later host CARMA.

Combined Array for Research in Millimeter-wave Astronomy – The speed with which an interferometer can image the sky depends on the number of elements among other factors. Combining the OVRO Millimeter Array of six antennas with BIMA's nine antennas would make for a much more powerful array. That fact, plus growing concern over the cost of supporting two independent university-based millimeter arrays, led the NSF to urge the two groups to find a way to merge their efforts. The result was CARMA,[15] a 15-element array, shown in Figure 2.4. The site

Figure 2.3 The “search party” at a place near the Bristle Cone Pines. Left to right: John Carlstrom, Steve Scott, Harry Hardebeck, Anneila Sargent, Paul Vanden Bout, Pat Thaddeus, Nick Scoville, and Phil Solomon. Courtesy of Dave Woody, reproduced by permission.

Figure 2.4 CARMA: six OVRO 10.4 m antennas on the left and nine BIMA 10 m antennas to the right. Courtesy of Anneila Sargent, reproduced by permission.

was above the Owens Valley on Cedar Flat at 2,200 m elevation in the Inyo National Forest. Cedar Flat allowed for up to 2 km separation of antennas, corresponding to 0.13 arcsecond resolution at 1 mm wavelength. CARMA was inaugurated on 5 May 2006. Starting in 2008, CARMA saw the addition of eight 3.5 m diameter

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antennas from the University of Chicago – John Carlstrom's Sunyaev-Zel'dovich Array. The project manager for CARMA construction was Tony Beasley, who was able to persuade the US Forest Service to grant permission for the construction in an environmentally sensitive area only 15 km from the Methuselah Bristle Cone Pines Grove. CARMA provided a powerful tool for US millimeter astronomers as a counterpart to the IRAM interferometer on the Plateau de Bure. Thirty percent of the CARMA observing time was reserved for observers in the community at large. The large number of users, the power of the array, and excellent observing conditions resulted in an impressive scientific record, with topics covering the Solar System, Galaxy, and distant Universe. CARMA operated from 2005 until 2015, when the NSF stopped supporting all university-based millimeter radio observatories. Today Cedar Flat displays not a hint of CARMA. Six of the 6.1 m BIMA telescopes were sold to the University of Arizona to be used as ground stations in Arizona and Colorado. The rest of the telescopes were moved back to the Owens Valley for storage. Cedar Flat has been totally restored, down to the wild flowers that were catalogued before construction.

Submillimeter Array – A project of the Smithsonian Astrophysical Observatory (SAO) was contemporaneous with the development of the above NSF-supported projects. The Submillimeter Array (SMA) was the vision of SAO director Irwin Shapiro for the participation of the Harvard Center for Astrophysics (CfA) in millimeter/submillimeter astronomy. (The CfA is an umbrella organization that encompasses SAO and the Harvard College Observatory.) Shapiro initiated the SMA in 1983. Construction took place on a site in the "saddle" of Maunakea, which also hosts the CSO and the James Clerk Maxwell Telescope (JCMT). The area is known as "Millimeter Valley" for its facilities. A state-of-the-art receiver laboratory was established at Harvard in 1987. The SMA began operation in 2003, with funding from the Smithsonian Institution. The SMA now has eight 6 m diameter antennas; the two additional antennas were the result of a partnership with the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) of Taiwan. The SMA can make observations at frequencies from 180 to 418 GHz and achieve sub-arcsecond resolution. It continues to operate, a successful Northern Hemisphere counterpart to ALMA. The SMA, CSO, and James Clerk Maxwell Telescope (JCMT) are shown in Figure 2.5, a panorama of "Millimeter Valley" (perhaps more properly "Submillimeter Valley") on Maunakea.

Millimeter Arrays in Japan and Europe

The impetus given millimeter interferometry in the United States by the Barrett Report was matched by two developments abroad, whereby both Japan and Europe built arrays of significant size.

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Figure 2.5 Millimeter Valley on Maunakea: far left – the Caltech Submillimeter Observatory (CSO); center – the SMA operations center is the shorter structure to the right of the taller JCMT; and right – the SMA. Courtesy of Jonathon Weintroub, reproduced by permission.

Figure 2.6 The Nobeyama Millimeter Array at the Nobeyama Radio Observatory. Courtesy of Masato Ishiguro, reproduced by permission.

Nobeyama Millimeter Array – In 1982, the National Astronomical Observatory of Japan (NAOJ) completed construction of the Nobeyama Millimeter Array (NMA), which with five 10 m diameter antennas was intended to be the largest millimeter array at that time (Figure 2.6). First observations with the NMA at the Nobeyama Radio Observatory (NRO) were made in 1984. The NMA stopped operation in 2007 when Japan entered the ALMA project. Over the 23 years of its operation the NMA produced over 100 studies of Galactic and extragalactic sources.

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Figure 2.7 The IRAM NOEMA Interferometer on the Plateau de Bure, France. Credit: ©IRAM, reproduced by permission.

IRAM Plateau de Bure Interferometer – IRAM installed a millimeter interferometer on a high plateau near Grenoble France in 1982. The interferometer has been extraordinarily productive. The demonstration that infrared-luminous galaxies are merging galaxies is only one of the significant results in many areas that could be cited. The interferometer received a significant upgrade in recent years, the Northern Extended Millimetre Array (NOEMA), shown in Figure 2.7, now consisting of twelve 15 m diameter antennas.

The Barrett Report's advice to NSF and the Foundation's subsequent support of the development of millimeter interferometry in the United States laid the groundwork for the Report's main recommendation, namely, that a large millimeter array was needed to study star formation, galactic structure, and the evolution of galaxies. The concept development of that facility and the proposal to build it, submitted in 1990, is the story of Chapter 3.

Notes

1 Voting for: Bernie Burke (MIT), Dave Hogg (NRAO), and Don Osterbrock (U. California, Santa Cruz); against: Jacques Beckers (NOAO), Riccardo Giacconi (STScI), Fred Gillett (NOAO), Roberta Humpheries (U. Minn.), Dick McCray (U. Colorado), Peter Pesch (SUNY Stony Brook), and Joe Taylor (Princeton U.); abstaining: Eric Becklin (U. Hawaii). From Gordon (2005).

2 No one worked harder to realize the 25 Meter Telescope than Mark Gordon, long-time manager of the very successful 36 Foot, then 12 Meter, Telescope. An account of the

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project can be found in his book *Recollections of "Tucson Operations": The Millimeter Wave Observatory of the National Radio Astronomy Observatory* (Gordon, 2005).

3 Nick Scoville (U. Mass.), Paul Vanden Bout (U. Texas, Austin), Jack Welch (U.C., Berkeley), Bobby Ulich (Multi-Mirror Telescope Obs.), Frank Lovas (National Bureau of Standards), Marc Kutner (Rensselaer Polytechnic Institute), Pat Palmer (U. Chicago), Paul Goldsmith (U. Mass.), Jill Knapp (Princeton U.), Ed Churchwell (U. Wisconsin), Alan Barrett (MIT), Pat Thaddeus (Goddard Institute of Space Studies), Tom Phillips (Caltech), Tony Stark (Bell Labs.), and John Bally (Bell Labs.).

4 Wilson to Vanden Bout and others, NAA-NRAO, MMA, MMA Planning, Box 1. https://science.nrao.edu/about/publications/alma

5 Notes taken throughout the meeting by Solomon, his hand-written draft of the letter to Bautz and Johnson, and a copy of the 29 October 1982 letter can be found at NAA-NRAO, MMA, MMA Planning, Box 1. https://science.nrao.edu/about/publications/alma

6 Bautz to Wilson and Co-Signatories, 23 November 1982, NAA-NRAO, MMA, MMA Planning, Box 1. The members Bautz appointed were Alan Barrett, Chair (MIT); Dennis Downes (IRAM), Charles Lada (U. Arizona); Pat Palmer (U. Chicago); Lew Snyder (U. Illinois, Urbana); and Jack Welch (U.C. Berkeley). Ex-officio: Vernon Pankonin (NSF Staff Liaison) and H. Crismond (NSF), secretary to the committee.

7 *Report of the Subcommittee on Millimeter and Submillimeter Wavelength Astronomy, NSF Astronomy Advisory Committee*, April 1983, NAA-NRAO, MMA, MMA Planning, Box 1. https://library.nrao.edu/public/memos/alma/main/memo009.pdf

8 See David (1983) and Waldrop (1983) for the complete articles.

9 A third interferometer intended for observation of H_2O sources was constructed at MIT by Bernie Burke. Its operation was never realized.

10 Welch (1996)

11 Plambeck (2006)

12 Woody, Vail, and Schall (1994) describe the design, construction, and performance of the Leighton 10 m antennas.

13 See, for example, Scoville, et al. (1986).

14 See, for example, Sargent and Beckwith (1987).

15 Woody, Beasley, and Bolatto (2004) describe CARMA.

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