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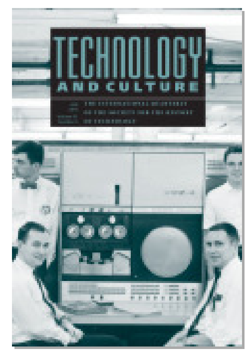

Technology and Culture, Volume 42, Number 2, April 2001, pp. 265-291 (Article)

Published by The Johns Hopkins University Press
DOI: 10.1353/tech.2001.0076

What Makes a Failure?

Designing a New National Telescope, 1975–1984

W. PATRICK McCRAY

For an expert community, choosing the design of a new technology is not as simple as running a cost-benefit analysis on the available options. During the decision-making process, members of the communities involved learn what is feasible, educate each other, and articulate their priorities as they move toward a solution.[1] Historians, sociologists, anthropologists, and policy makers have begun to produce a body of literature that investigates the process and motives at work when a scientific or technological community wrestles with an important project's early stages. During the 1970s and 1980s, American astronomers, engineers, and science administrators formed such a decision-making community as they debated the design and use of larger telescopes, including a new national telescope. They balanced science goals against technological possibilities and they weighed the intellectual well-being of the entire astronomy community against the desires of individuals and institutions. In the end, they made perhaps the toughest choice of all: not to build. Did that decision signal

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This article is dedicated to the memory of W. David Kingery (1926–2000).

0040-165X/01/4202-0003$8.00

1. See, for example, *History and Technology* 9 (1992), a special issue of the journal devoted to the subject of choosing big technologies; Marcel Lafollette and Jeffrey Stine, eds., *Technology and Choice: Readings from "Technology and Culture"* (Chicago, 1991); and Pierre Lemmonier, *Technological Choices: Transformation in Material Cultures since the Neolithic* (New York, 1993), for an anthropological perspective.

failure? A closer look suggests otherwise, that the ultimate success or failure of a big technological project must be judged on more than whether or not it is ever actually built.

Ever since astronomers began to use telescopes they have wished for bigger instruments. A bigger telescope collects more light, enabling an astronomer to observe fainter, more distant, and older celestial objects. A larger telescope also collects light more efficiently, and, in the context of modern astronomy, that means that more astronomers can have access to the instrument and do their research more quickly. Throughout the twentieth century, scientists and engineers proposed novel designs for telescopes with increased light-collecting power. Choosing a design and implementing it, however, demands the proper combination of community interest, technological capability, institutional support, and financial resources. In the late 1970s and early 1980s a confluence of factors—scientific, technical, and social—led astronomers and engineers to develop detailed plans for very large telescopes, much larger than any built before. Popular astronomy magazines regularly described them as "monster telescopes" or "new giant eyes."[2] The funding climate of American astronomy, the perceived need for a new national telescope, the recognized technological limitations of previous large telescopes, and the research agendas of American astronomers all fueled a fundamental transformation in the way that new large telescopes were designed and built.

By about 1975, the community of people who relied on large telescopes for their work was in crisis.[3] The traditional model for such instruments, based on the famous 200-inch Hale telescope on California's Palomar Mountain, could no longer accommodate the financial constraints on and research expectations of U.S. astronomers.[4] At the same time, the nation's

2. See, for example, Leif Robinson, "Monster Mirrors and Telescopes," *Sky and Telescope*, June 1980, 469–77; "Update: Telescopes of the Future," *Sky and Telescope*, July 1986, 23–25; "Monster Telescopes for the 1990s," *Sky and Telescope*, May 1987, 495.

3. Historians of technology have coined various terms to describe the sort of situation that arose in the 1970s as engineers and astronomers considered how to increase the collecting areas of large telescopes. Familiar examples include Thomas Hughes's "reverse salients," Edward Constant's "presumptive anomalies," and Richard Hirsh's "technological stasis": see Hughes, *Networks of Power: Electrification in Western Society 1880–1930* (Baltimore, 1983); Constant, *The Origins of the Turbojet Revolution* (Baltimore, 1980); Hirsh, *Technology and Transformation in the American Utility Industry* (Cambridge, 1989).

4. Astronomers typically refer to telescopes by the size of their light-collecting area or the primary mirror, expressed in metric units except in the case of the Hale telescope, which is often called "the 200- inch" (equal to about five meters). I have adopted the convention of astronomers and refer to the size of the telescopes in meters (except for the Hale telescope, which is conventionally referred to in English units). For the purposes of this article I will limit my definition of "telescope" to traditional ground-based reflecting telescopes, such as have been used by astronomers for centuries, and of "astronomy" to traditional ground-based astronomy with observations made in the visible or near ultraviolet or infrared parts of the spectrum.

large telescopes were increasingly oversubscribed; simply observing faint objects for longer times was not feasible logistically. This was true especially at the national centers, where requests for observing time typically outnumbered nights available by more than three to one.[5] Astronomers and engineers reevaluated their telescope design concepts because of the limitations of traditional technology and their understanding of what new designs offered in terms of performance and scientific capabilities.

Over the next decade, astronomers competed fiercely to have their designs adopted and funded. One monster telescope under consideration in the 1980s was the National New Technology Telescope (NNTT), first proposed by astronomers and engineers at Kitt Peak National Observatory, headquartered in Tucson, Arizona. The NNTT was to be an innovative new telescope that would be available to all astronomers. It would have a collecting area of 15 meters, five times larger than the Hale telescope, the biggest telescope in the United States at that time, and more than twenty-five times that of the planned Hubble Space Telescope. Between 1980 and 1984 the astronomy community considered two different design concepts for this telescope. In 1984 a national panel of astronomers selected a design after months of heated debate. Several national astronomy organizations endorsed the panel's choice, the National Science Foundation (NSF) spent millions of dollars on technology development for the project, and advocates worked passionately to generate community support. Yet in 1987 science managers responsible for the NNTT canceled the project, and American astronomers decided to focus their efforts on a completely different design concept.

One of the most contentious technological issues in these debates had to do with the heart of a telescope: its primary mirror. A telescope's primary mirror collects light from distant sources and focuses it onto a detector, such as a spectrograph. The size of the mirror determines the amount of light a telescope can collect and the sharpness of the image produced. In addition to critically affecting a telescope's performance, the primary mirror is the most difficult and expensive part of a telescope to fabricate. Typically made of glass, the mirror blank is eventually covered with a metal coating a few micrometers thick. In the biggest telescopes, thousands of pounds of glass, exquisitely polished and costing millions of dollars, serve to precisely support a few ounces of reflective silver or aluminum.

As early as January 1980, when more than two hundred astronomers and engineers gathered in Tucson, Arizona, for a conference titled "Optical and Infrared Telescopes for the 1990s," the range of competing ideas about the best way to fabricate a primary mirror for a large telescope became obvious. Papers at the six-day meeting summarized current thinking about

5. See, for example, National Academy of Sciences, *Astronomy and Astrophysics for the 1980s*, vol. 2, *Reports of the Panels* (Washington, D.C., 1983), 397–400.

the design of large telescopes and the science to be done with them.[6] Participants addressed such broad issues as the role of ground-based telescopes in the coming era of the Hubble Space Telescope, institutional collaboration, and funding for new telescope projects. At one of these sessions, William Howard of the NSF summed up the funding community's viewpoint: "The instrument ought to be designed in such a way that it is nationally available to the extent that national funds are used, and that it should be sufficiently general purpose to assure broad participation and support by as many different subgroups of optical and infrared astronomy as exist." In that same session a telescope engineer commented, "it's interesting to me to see the coherence that is starting to develop now as compared to the early 1970s, particularly in the scientific community. . . . And given what I now see plus some money, we engineers will give you guys the moon."[7] These comments were prescient, but it would be several more years before astronomers, engineers, and funding agencies came to an agreement on how to design, fund, and build a national telescope for the American astronomical community.

This complicated story of competing and then changing priorities calls to mind at least two areas of current interest to historians of technology. On one hand, building a new, expensive, and innovative telescope requires what John Law calls heterogeneous engineering.[8] Engineers must develop new technology and testing methods; astronomers have to provide a scientific justification for the facility; interest and support must be generated in the scientific community and among politicians; and project advocates must gain and retain a commitment from the institutions that manage and fund astronomy. On the other hand, the NNTT appears to fit in the genre of failure studies, an area of strong and growing interest. Technological failure or success is partly a social construction. For whom is a project or a technology a failure? As Graeme Gooday has noted, technological failures have their own form of interpretive flexibility.[9] In 1987, after seven years of

6. Adelaide Hewitt, ed., *Optical and Infrared Telescopes for the 1990s: Proceedings, Kitt Peak National Observatory Conference, Tucson, Ariz., 7–12, January 1980*, 2 vols. (Tucson, 1980). Volume 2 contains transcripts of several discussion sessions held at the meeting.

7. Hewitt, 1191, 1182.

8. John Law, "Technology and Heterogeneous Engineering: The Case of Portuguese Expansion," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Trevor Pinch, and Thomas P. Hughes (Cambridge, Mass., 1987), 111–34.

9. Graeme Gooday, "Re-Writing the 'Book of Blots': Critical Reflections on Histories of Technological Failure," *History and Technology* 14 (1998): 265–91. Several notable studies address the question of technological success or failure: see, for example, Gregory Kunkle, "Technology in the Seamless Web: 'Success' and 'Failure' in the History of the Electron Microscope," *Technology and Culture* 36 (1995): 80–103, and Bruno Latour, *Aramis, or the Love of Technology* (Cambridge, Mass., 1996). John Staudenmaier, *Tech-*

development and planning, astronomers and science administrators canceled the NNTT project. Many of the astronomers I interviewed saw the NNTT as a failure, a technological dead end or misguided program, if they remembered it at all. Despite the fact that the NNTT was never built, was it indeed a technological failure? Or did it influence the way astronomers and engineers conceived of large telescopes? I will argue that despite its outcome, the NNTT project was more than just a curious detour in the development of new large telescopes.

Postwar Astronomy in the United States

After the Second World War, astronomy in the United States changed in several important ways. American astronomers, aided by wartime technology and generous federal funding, began to observe in new wavelength regions, such as the radio and ultraviolet spectrums. Indeed, according to Jesse Greenstein, who became director of the California Institute of Technology's astronomy program in 1948, optical astronomy in the 1970s was living on the "borrowed glory" of new exploration into radio, X-ray, and infrared spectral regions. As astronomers mined these new wavelengths, they argued that bigger, better, and more efficient telescopes were the tools needed to obtain new knowledge about the universe.[10]

During the 1970s, astronomers gradually shifted their research focus away from planetary astronomy, stars, and stellar phenomena and toward topics associated with galactic structure and cosmology.[11] The increasing tendency of astronomers to focus on extragalactic objects had important ramifications for the development of new ground-based, optical telescopes. American astronomers insisted that if they were going to pursue research efficiently on ever fainter and more distant objects, larger telescopes that could collect more light at a reasonable cost were needed desperately. It is within the context of astronomers' demand for large, affordable telescopes that the competing designs for the new national telescope must be considered.[12]

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nology's Storytellers (Cambridge, Mass., 1985), 145–46, notes the relative paucity of failure studies prior to 1985.

10. Jesse Greenstein, "Resume of Conference and Introduction to Panel Discussion," in *Optical Telescopes of the Future*, ed. F. Pancini, W. Richter, and R. Nelson (Geneva, 1978).

11. Thomas Gieryn, "Patterns in the Selection of Problems for Scientific Research: American Astronomers, 1950–75" (Ph.D. diss., Columbia University, 1980). On changes in areas of research interest as evidenced by publication patterns, see Helmut Abt, "Growth Rates in Various Fields of Astronomy," *Publications of the Astronomical Society of the Pacific* 100 (1988): 1567–71.

12. No comprehensive account of the changes in American astronomy after the Second World War exists. John Lankford, *American Astronomy: Community, Careers, and*

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The most significant change on the institutional landscape of astronomy after the Second World War was the establishment of national observatory facilities making telescopes available to the entire American astronomical community. Prior to this, only a few telescopes were federally funded and operated. Most flourished or floundered on the private support they could enlist. Privately run observatories are unique to America, and before the war they limited the availability of the largest and best optical telescopes to a fraction of the astronomical community. In 1957, seven American universities came together to form the Association of Universities for Research in Astronomy (AURA).[13] This association managed the Kitt Peak National Observatory (KPNO) after its creation in 1958.[14] With the formation of AURA and KPNO, an increasingly common pattern emerged in American astronomy: research consortia formed by universities and other institutions, sometimes on an international basis, to build and operate increasingly expensive telescope facilities. By 1971 the NSF was spending about 10 percent of its overall research budget on astronomy, and two-thirds of this money went to support the national observatories.[15]

Notable developments in instrumentation occurred as well. Astronomers and engineers improved on wartime technology and developed new detectors, such as image tubes and photomultipliers.[16] The postwar era also witnessed the commissioning of a 200-inch telescope on Palomar Mountain, in Southern California, in 1949.[17] This telescope, named after George

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Power, 1859–1940 (Chicago, 1997) takes the story up to 1940. Various entries in John Lankford, ed., *History of Astronomy: An Encyclopedia* (New York, 1997) treat the history of American astronomy in the postwar era. On American planetary astronomy after 1945, see Ron Doel, *Solar System Astronomy in America: Communities, Patronage, and Interdisciplinary Science 1920–1960* (Cambridge, 1996), and Joseph Tatarewicz, *Space Technology and Planetary Astronomy* (Bloomington, Ind., 1990).

13. The seven were the University of California, the University of Chicago, Harvard University, Indiana University, the University of Michigan, Ohio State University, and the University of Wisconsin. They planned to cooperatively develop and manage new national astronomy facilities in the United States under contract to the NSF. See Frank Edmondson, *AURA and its National Observatories* (Cambridge, 1997).

14. Kitt Peak began operation in 1960 with the dedication of a 0.9-meter telescope. A 2.1-meter telescope followed in 1964 and was followed in turn, ten years later, by the largest national telescope in the United States, a 4-meter instrument.

15. Compare this to about 15 percent of the NSF's budget given to chemistry and 20 percent granted to physics. On government support for United States astronomy before the 1970s, see National Academy of Sciences, *Astronomy and Astrophysics for the 1970s*, ed. J. Greenstein, vol. 2, *Reports of the Panels* (Washington, D.C., 1973), 350–408.

16. David DeVorkin, "Electronics in Astronomy: Early Applications of the Photoelectric Cell and Photomultiplier for Studies of Point-Source Celestial Phenomena," *Proceedings of the Institute of Electrical and Electronics Engineers* 73, no. 7 (1985): 1205–20; see also Robert Smith and Joseph Tatarewicz, "Replacing a Technology: The Large Space Telescope and CCDs," *Proceedings of the Institute of Electrical and Electronics Engineers* 73, no. 7 (1985): 1221–34.

17. Ron Florence, *The Perfect Machine: Building the Palomar Telescope* (New York,

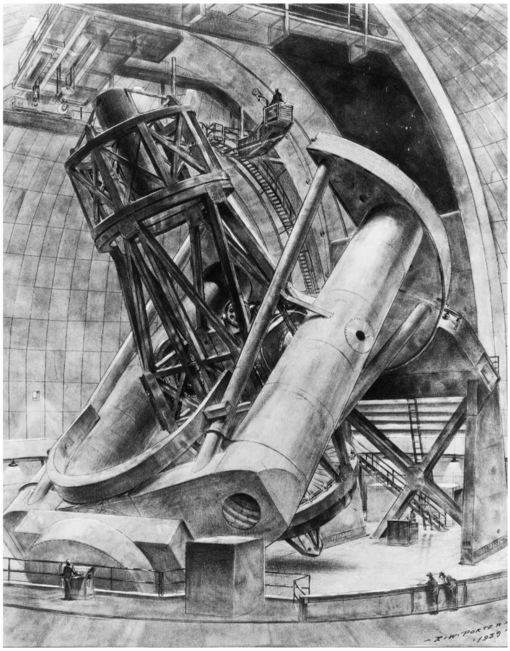

FIG. 1 The Hale Telescope looking northwest; 1939 drawing by Russell Porter. (Courtesy of the Archives, California Institute of Technology, Pasadena.)

Ellery Hale, remained the largest in the United States for over forty years. Extremely innovative for its time, the Hale telescope represented the basic "technological paradigm" for large telescope design and construction well into the 1970s.[18]

The Hale telescope powerfully influenced the way engineers and astronomers conceived of telescopes over the next three decades. Its basic design (fig. 1), with its tremendous dome structure, primary mirror made of a single massive piece of glass, and use of an immense horseshoe-shaped bearing with an equatorial mount, was widely copied in other telescopes over the next twenty-five years.[19] In many ways, the Hale telescope served

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1994). It is worth noting that the biggest hurdle engineers faced in building the telescope was making the primary mirror.

18. The Hale telescope remains an important one and is equipped with innovative instrumentation, such as the Palomar Adaptive Optics system developed by California Institute of Technology staff. I use the term "technological paradigm" in the general, metaphorical sense in which it is defined by Giovanni Dosi, in "Technological Paradigms and Technological Trajectories," *Research Policy* 11 (1982): 147–62: "a 'pattern' of solution of *selected* technological problems based on *selected* principles derived from natural sciences and on *selected* material technologies" (emphasis in original).

19. This point is explicitly made by David Crawford, "AURA's Two 150-Inch Tele-

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to define what a large telescope *should* look like.[20] Larry Barr, a longtime telescope engineer at Kitt Peak, said "telescopes built in the 1960s and 70s were all offshoots of Palomar. [Because of this] we had a good idea of why you couldn't build bigger telescopes using conventional techniques."[21]

Over time a certain mystique enveloped the Hale telescope.[22] Its status was enhanced by the fact that the privately owned telescope was not accessible to all American astronomers. The data it produced was central to many important scientific programs, such as Allan Sandage's determination of the Hubble constant and Maarten Schmidt's quasar observations. As one astronomer from the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts, remarked, "I think there was a real feeling of mystery . . . that the 200-inch telescope was something . . . produced by wizards and elves and set down on this earth."[23]

There are complex reasons why astronomers and engineers did not

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scopes," in *Large Optical Telescopes*, ed. R. West (Geneva, 1971), 23–36. Crawford, in discussing the progress on building the two national 4-meter telescopes, notes: "We wanted to design and build a large telescope to work on limited problems of research, for the amount of money we felt could be obtained, and to do so as rapidly as possible. . . . Therefore, we adopted many of the design features of the 200-inch and 120-inch telescopes" (23).

20. It has also been argued that some of the features of the Hale telescope inhibited the construction of telescopes that deviated from its basic design concepts. Richard Learner examined its impact in "The Legacy of the 200-inch," *Sky and Telescope*, April 1986, 349–53. His claims did not meet with universal acceptance. Leo Goldberg, director of KPNO from 1971 until 1977, challenged Learner's conclusions; see "Comments on Learner's Article 'The Legacy of the 200-Inch'," Leo Goldberg papers, Harvard University Archives, HUG FP 83.10, Box 13, "Learner article." I thank Dr. DeVorkin for pointing these out to me.

21. Larry Barr, interview by author, Tucson, Ariz., 17 November 1998. A note on sources: In this paper, I draw on a number of interviews with some two dozen engineers, astronomers, and administrators who were involved in the events I describe or who otherwise provided essential background information. With a few exceptions, I conducted the interviews myself; transcripts and tapes are in my working files. The National Optical Astronomy Observatories, which operates Kitt Peak, does not maintain an archive, nor does Steward Observatory. The technical reports and grant proposals to the NSF I cite are available at the NOAO library. Much of the remaining documentation was found in the personal papers of astronomers and administrators. I am grateful to Roger Angel, Larry Barr, Robert Gehrz, Peter Strittmatter, and Wayne van Citters for allowing me to examine and copy relevant documents. These copies are in my working files and will be turned over to a suitable scholarly repository at the conclusion of this research project.

22. The Hale telescope was the world's largest telescope until 1976, when a 6-meter instrument was commissioned by the Soviets. That telescope, which had one of the first altitude-azimuth mountings, was plagued by shortcomings associated with its massive monolithic primary mirror.

23. Nathaniel Carleton, interview by David DeVorkin, 10 May 1989, transcript, Smithsonian Institution Archives, RU 9542, sess. 2, p. 3. This interview, part of the Smithsonian Videohistory Program, is one of a series on the history of the multiple-mirror telescope.

build a larger telescope for over forty years. These include difficulties in making larger primary mirrors in the traditional fashion, improvements in light detector efficiencies that effectively increased light-collecting power at less expense, and the financial constraints associated with making large telescopes. Moreover, telescope design based on the "Palomar paradigm" was quite successful for many years.

Hints of a potential technological revolution can be found well before the 1948 dedication of the Hale telescope, most notably in the pioneering work of George Willis Ritchey.[24] But the implementation of Ritchey's novel ideas required more than that they be technically feasible; the proper balance of community interest, research needs, institutional interest, and financial resources was also necessary. Following his dismissal from the Mount Wilson Observatory in 1919, Ritchey spent several years in France experimenting with new telescope designs. In an article published in 1928 by the *Journal of the Royal Astronomical Society of Canada*, Ritchey wrote: "[We] shall look back and see how inefficient, how *primitive* it was to work with thick, solid mirrors, obsolete mirror curves, equatorial telescope-mountings of antiquated types requiring enormous domes and buildings, and similar anomalies in a progressive age."[25] Many of Ritchey's ideas were not accepted as part of large telescope design until years after his death. But his concepts of what future telescopes would look like were farsighted.[26]

The techniques Ritchey had at his disposal in the 1920s for fabricating larger primary mirrors—a combination of gluing and fitting the separate glass pieces—were not up to the challenge of fashioning optics to the necessary tolerances. As a result, the astronomy community largely ignored Ritchey's concepts during his lifetime. Ritchey proposed his ideas at a time when mainstream approaches for designing large telescopes were still quite useful. In short, there was no clear example of a "functional failure" that prevented building telescopes that were, in their day, quite large.[27] The Hale

24. Donald Osterbrock, *Pauper and Prince: Ritchey, Hale, and Big American Telescopes* (Tucson, Ariz., 1993), and Deborah Mills, "George Willis Ritchey and the Development of Celestial Photography," *American Scientist* 54, no. 1 (1966): 64–93.

25. George W. Ritchey, "Astronomical Photography with High Magnification," *Journal of the Royal Astronomical Society of Canada* 22, no. 9 (1928), 376, emphasis in original.

26. While in France, Ritchey began to experiment with making cellular mirrors, using thin glass ribs, each a few inches thick, to separate the top and bottom faceplates, forming a lightweight cellular structure. For pictures of these experimental mirrors and a description of their manufacture, see George W. Ritchey, *The Development of Astro-Photography and the Great Telescopes of the Future* (Paris, 1929). While Ritchey's ideas for reducing the weight of the telescope's mirror blank were not adopted by the astronomy community, the Hale telescope did incorporate weight-saving features in the mirror blank—specifically, a ribbed back, much like a waffle, used in conjunction with an active mounting system to support the disk.

27. Edward Constant defines functional failure as occurring when a "conventional system fails to adequately perform its traditional function"; see Constant (n. 3 above), 12–13.

telescope was proof of what could be accomplished within the existing technological paradigm.

Astronomers and engineers, however, came to believe that scaling up the design of the Hale telescope was physically and financially impossible. For example, a primary mirror larger than 5 meters made of a single solid piece of thick glass was too massive to support precisely against gravitational forces. By the early 1970s, astronomers estimated the cost of a new telescope as proportional to the diameter of its primary mirror raised to the power of about 2.5.[28] Using these calculations, building a telescope on the Hale model with a primary mirror of fifteen meters, for example, would cost over a billion dollars. This was well beyond the financial capability of any funding source, private or federal. Even when astronomers disregarded the technological limitations, they did not always agree about the need for telescopes bigger than the Hale telescope, or on the best way to go about building one.[29]

Prior to 1980, rapidly increasing availability and efficiency of electronic detectors offered a means of collecting more light efficiently. Because of these improvements, astronomers and telescope designers devoted much of their energy and resources in the 1960s and early 1970s to improving the instrumentation of the telescope and not on increasing its size. But, as Jesse Greenstein pointed out in 1978, the only long-term solution to the quest for greater light-gathering power was simply "more photons."[30]

The Next Generation Telescope Program

By 1974 AURA was operating two 4-meter national telescopes, both comparable to the Hale telescope, which was then twenty-five years old.[31] But discontent with the Hale paradigm had been simmering for some time. Moreover, the astronomy community recognized that the efficiency gains

28. Aden Meinel, "An Overview of the Technological Possibilities of Future Telescopes," in Pancini, Richter, and Nelson (n. 10 above), 13–26.

29. See, for example, Ira Bowen, "Problems in Future Telescope Design," *Publications of the Astronomical Society of the Pacific* 73, no. 431 (1961): 114–24, and "Telescopes," *Astronomical Journal* 69, no. 10 (1964): 816–25. A conference on large telescope construction met in Pasadena, California, in April 1965, and the conference proceedings present the thinking about possibilities and limitations in building big telescopes that prevailed until the early 1970s; see David Crawford, ed., *The Construction of Large Telescopes* (New York, 1966).

30. Alec Boksenberg, "Review of Trends in Detector Development," and Jesse Greenstein, "Resume of Conference and Introduction to Panel Discussion," both in Pancini, Richter, and Nelson.

31. These were located at Kitt Peak, near Tucson, Arizona, and Cerro Tololo Inter-American Observatory, near La Serena, Chile. In the 1970s, four other telescopes operated by other organizations, 3.6 to 3.8 meters in size and based on the Palomar paradigm, were commissioned.

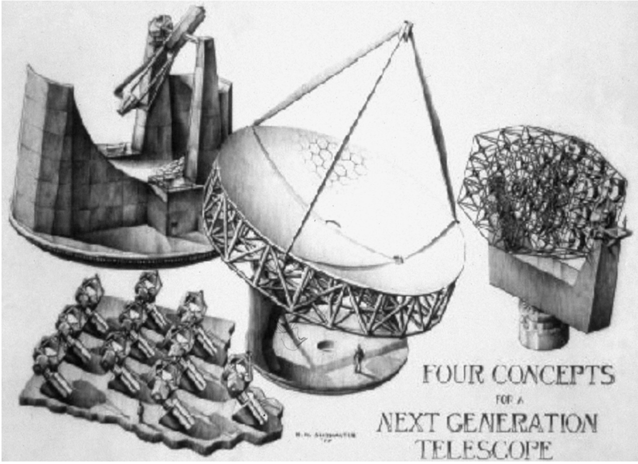

FIG. 2 Design concepts for the Next Generation Telescope; the PALANTIR concept is in the upper left. (Copyright Association of Universities for Research in Astronomy Inc. [AURA], all rights reserved; reproduced with permission.)

from improved electronic detectors were not going to continue indefinitely. In the summer of 1975, KPNO director Leo Goldberg initiated the Next Generation Telescope Program. Its goal was a new national telescope with a 25-meter collecting area. Kitt Peak staff saw their program as a reaction against the tradition of making telescopes in the style of the Palomar instrument.[32] The size of the proposed national telescope meant, according to the conventional wisdom of telescope designers, that a primary mirror made from a single, massive piece of glass was not possible.

Between 1975 and 1979, Kitt Peak engineers and scientists prepared several different concepts for the Next Generation Telescope in a series of reports (fig. 2). An early design was called PALANTIR, an acronym derived, with some liberties, from "Plan for a Large Aperture Novel Thousand Inch Telescope."[33] PALANTIR's appearance, shown in the upper left of figure 2, was unlike other optical telescopes, having more in common with large-dish radio telescopes, such as the one at the Arecibo Observatory in Puerto Rico.[34] Instead of a single massive glass mirror, PALANTIR's primary mir-

32. Larry Barr, interview by author, Tucson, Ariz., 13 January 1999.

33. Its true source was J. R. R. Tolkien's trilogy *The Lord of the Rings*. Tolkien's *palantíri*—in one of his invented languages, "that which looks far off"—were stones that allowed those who could control them to see across both time and space.

34. For the telescope's design, see National Optical Astronomy Observatories, "The PALANTIR: A Concept for a 25 Meter Telescope," proposal submitted to the NSF, January 1977. A copy of this proposal along with the other internal reports cited here can be found at the library of the National Optical Astronomy Observatories (NOAO) in Tucson.

ror was made up of hundreds of polished metal segments that created a vast reflecting surface.[35] The primary mirror would be supported on a massive "shoe-like" structure some eighty meters in diameter—hence its unofficial name, the "Rotating Shoe." An advantage of PALANTIR that Kitt Peak staff touted was that the primary mirror segments remained immobile with respect to gravity and would not be subjected to distorting effects as the telescope moved. Despite its gargantuan size, KPNO engineers felt that PALANTIR did not require technological developments beyond those currently available: "[I]t is the considered opinion of the Kitt Peak group that a telescope of this aperture is within the limits of current technology and could be built within the next decade. . . . The conceptual design . . . represents the most technologically conservative approach."[36]

In 1977 Kitt Peak staff submitted a proposal for PALANTIR to the NSF that in the end was not funded. Reviewers of the proposal cited the telescope's small field of view and estimated cost ($104 million) as problems. Critics also noted that PALANTIR's tremendous size would require a flat mountaintop site some 100 meters in diameter. In spite of the problems with the design, the possibility of a 25-meter telescope attracted enough attention that the NSF added two hundred thousand dollars to the Kitt Peak budget to fund further study.

Also in 1977, Geoffrey Burbidge, an English physicist turned astronomer, succeeded Leo Goldberg as Kitt Peak's director. Burbidge became an active supporter of the 25-meter telescope project and worked to ensure that funds were available to the project. Over the next year, from February 1977 to June 1978, staff working on the Next Generation Telescope program prepared a series of reports, with the help of outside consultants, describing several different concepts for a 25-meter telescope.[37]

35. The telescope's overall collecting area, according to the design report, was about seventy-five meters by twenty-five meters. Light striking the metal primary mirror would be picked up by a secondary mirror assembly that scanned the primary. The 25-meter aperture, a design goal of the telescope, was the portion of the primary mirror that the secondary mirror was viewing at any particular time. Additional optics would relay the light to detectors or spectrographs.

36. National Optical Astronomy Observatories, "The PALANTIR: A Concept," vol. 2, sec. 1, 5–6.

37. NGT Report No. 1, "Astronomical Potential and Scientific Uses for a Large Aperture Optical Telescope"; NGT Report No. 2, "A Concept for a 25-Meter Telescope: The Rotating Shoe Array"; NGT Report No. 3, "A Concept for a 25-Meter Telescope: The Steerable Dish"; NGT Report No. 4, "A Concept for a 25-Meter Telescope: The Multiple Mirror Telescope"; NGT Report No. 5, "A Concept for a 25-Meter Telescope: The Singles Array." Copies are available in the NOAO library, Tucson.

The National New Technology Telescope Program

The late 1970s and early 1980s were marked by intense discussion in the American astronomical community. At the January 1980 "Telescopes for the 1990s" conference in Tucson, astronomers showed considerable interest in the design of a new generation of very large telescopes. Meanwhile, their discussions with the NSF suggested that some form of coherent effort was needed to build a new, nationally accessible telescope. According to Larry Barr, a Kitt Peak engineer, "it was clear that lots of groups weren't just talking about big telescopes. . . . They had formed groups or teams within their organizations. 1980 and onwards represents to me when serious development work was started."[38]

Shortly after the 1980 conference, Burbidge initiated the National New Technology Telescope program, with the goal of building a 15-meter telescope. Burbidge originally envisioned the NNTT program as a collaborative effort between four institutions: the Kitt Peak National Observatory, the University of Arizona, the University of California, and the University of Texas.[39] All had both previous experience in building telescopes and sufficiently developed proposals for larger instruments. Kitt Peak staff saw the 15-meter size as a more realistic ambition and took the lead in organizing efforts. According to the proposal submitted by to the NSF in 1981, astronomers and engineers from each of the participating institutions would focus their efforts on a specific area of technology, thereby developing the NNTT as a joint enterprise.

Funding for the NNTT program originally came from the core budget of Kitt Peak. A year later, the NSF formally joined the effort by funding a proposal for technology development.[40] With technology development underway and some initial funding secured, the stature of the NNTT project was rising in the eyes of proposal reviewers and the NSF. In January 1982 the NNTT project received another major boost with the publication of the National Academy of Sciences' third decadal survey of astron-

38. Barr interview (n. 32 above); Robinson, "Monster Mirrors and Telescopes" (n. 2 above.)

39. The University of Texas was a minor player in the project from the outset, as it also had plans to build its own 8-meter class telescope, and soon dropped out, leaving Kitt Peak, California, and Arizona as the main players; see Harlan Smith and Thomas Barnes, *Report of the Optical Conference on the 7.6-Meter Telescope* (Austin, Tex., 1982).

40. "A Technology Development Program for a National 15-Meter Telescope: A Joint Proposal by KPNO and the Universities of Arizona, California, and Texas," 1981, NOAO library, Tucson. This gave Kitt Peak an additional six hundred thousand dollars for the fiscal years 1981–83 to further explore design concepts. The Kitt Peak National Observatory and, later, the Advanced Development Program of the National Optical Astronomy Observatories published a series of NNTT Technology Development Program reports between 1982 and 1987.

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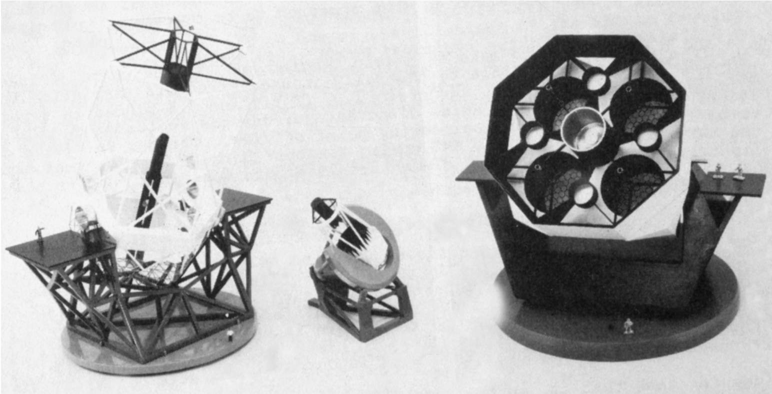

FIG. 3 Segmented-mirror and multiple-mirror designs for the NNTT with a scale model of the Kitt Peak 4-meter telescope, suggesting the grand size of the planned telescope. (Copyright Association of Universities for Research in Astronomy Inc. [AURA], all rights reserved; reproduced with permission.)

omy.[41] These reports play a powerful role in shaping funding priorities for the coming decade. The 1982 survey, chaired by George Field of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts, placed a new-technology telescope of the 15-meter class third on the list of high priority items. The report went on to state: "The Committee finds the scientific merit of this instrument to be as high as that of any other facility considered . . . its priority does not reflect its scientific importance but rather its state of technological readiness. *The design studies needed . . . are of the highest priority and should be undertaken immediately*.[42]

TWO NNTT DESIGN CONCEPTS

Astronomers from Kitt Peak and the other participating institutions soon determined that two telescope designs—a segmented-mirror design and a multiple-mirror design—were the most promising (fig. 3). Both concepts broke away from the traditional design paradigm exemplified by the Hale telescope. The innovative solution adopted by teams from both the University of California and the University of Arizona was to divide the desired 15-meter light-collecting area into smaller pieces. The manner in which the two competing groups proposed to do this, however, was quite different.

41. National Academy of Sciences, *Astronomy and Astrophysics for the 1980s*, vol. 1, *Report of the Astronomy Survey Committee* (Washington, D.C., 1982). See also vol. 2, *Reports of the Panels* (n. 5 above).

42. National Academy of Sciences, *Astronomy and Astrophysics for the 1980s*, vol. 1, *Report of the Astronomy Survey Committee*, 16. Emphasis in original.

Jerry Nelson, of the University of California at Berkeley, was the individual most visibly associated with what became the segmented-mirror telescope (SMT) design for the NNTT. A particle physicist by training, Nelson, after 1977, was increasingly involved in plans to build a 10-meter telescope solely for astronomers from the University of California, lobbying his colleagues and university administrators to accept his design for that telescope, which featured a segmented primary mirror.[43] His plan for the NNTT was basically a larger version of that earlier concept. The primary mirror would be composed of sixty thin, hexagonal glass segments, each 1.8 meters wide. While their thinness would keep the mass of the primary mirror low, extensive effort would be required to fabricate the aspheric segments. Once finished, the segments would be combined, actively supported, and controlled to form a precise parabolic light-collecting surface. Nelson worked closely with Kitt Peak staff in the late 1970s to develop the segmented-mirror technology. Two main challenges faced Nelson and his colleagues on both telescope projects: how to make the mirror segments, and how to control and align them accurately as the telescope moved and pointed across the sky.[44]

Nelson's design provoked strong opposition from some University of California astronomers, who advocated a more conservative approach. In 1980, due to Nelson's persuasive promoting and the concept's potential for expandability beyond 10 meters, the university granted over one million dollars for the design and planning of a 10-meter telescope using the segmented-mirror concept.[45] According to Nelson and his colleagues, the same technology and experience could be used for the benefit of the national NNTT project as well.

Unlike the California group led by Nelson, the University of Arizona already had a working version of their design for the 15-meter NNTT. In the 1970s the university and the Smithsonian Astrophysical Observatory had jointly built a multiple-mirror telescope (MMT) on Mount Hopkins,

43. Plans for making a telescope collecting area out of individual segments date back to 1828, when Lord Rosse built a reflecting telescope whose six-inch spherical primary mirror had two parts. See, for example, Henry King, *The History of the Telescope* (Cambridge, 1955).

44. In developing mirror-segment technology, Nelson drew upon similar efforts in segment fabrication begun at KPNO as part of the NGT program in the 1970s. See Jerry Nelson, interview by Timothy Moy, 2 June 1992, Keck Telescope Interviews, California Institute of Technology Archives, Pasadena.

45. The design was eventually used for two 10-meter telescopes on Mauna Kea in Hawaii. On early versions of the telescope, see Jerry Nelson, "The Proposed University of California 10-Meter Telescope," in Pancini, Richter, and Nelson (n. 10 above), and "The University of California Ten-Meter Telescope Project: The Segmented Design," in Hewitt (n. 6 above). The project was funded by over two hundred million dollars from the William M. Keck Foundation; see Paul Ciotti's "Mr. Keck's Bequest," *Los Angeles Times Magazine*, 24 May 1987.

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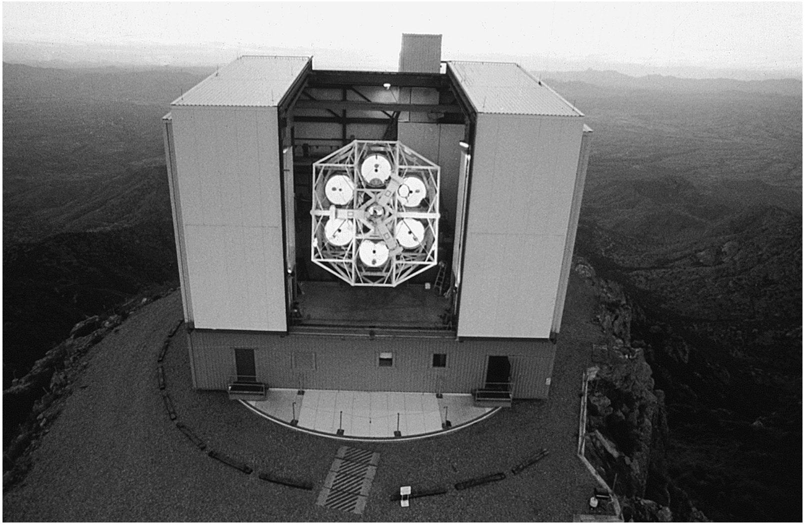

FIG. 4 The multiple-mirror telescope on Mount Hopkins in southern Arizona, shown in its original configuration with six 1.8-meter mirrors. It was converted in the late 1990s to a single-mirror configuration with a 6.5-meter mirror made by the Steward Observatory Mirror Laboratory. (Image by H. Lester, MMT Observatory. Used with permission.)

near Tucson (fig. 4).[46] Finished in 1979, this telescope incorporated several innovations. It employed an altitude-azimuth mount instead of the traditional equatorial mount, as on the venerable Hale telescope. More precise computer-controlled drives for moving the telescope made this type of mounting feasible, and using it meant that the telescope could be housed in a smaller, much less expensive building (the Mount Hopkins telescope is in an unglamorous but efficient square building that rotates with the telescope). At the telescope's heart were six military-surplus, 1.8-meter mirror blanks originally made for space reconnaissance missions. The lightweight mirror blanks were fashioned from pieces of fused silica painstakingly joined together, as George Ritchey had attempted to do decades earlier. The designers of the MMT placed the six mirrors on a single common mount, giving the telescope a combined effective aperture of 4.5 meters.[47]

The University of Arizona's design for the NNTT was a larger version of the Mount Hopkins telescope. It featured four 7.5-meter, lightweight,

46. See Jacques Beckers et al., "The Multiple Mirror Telescope," in *Telescopes for the 1980s*, ed. G. Burbidge and A. Hewitt (Palo Alto, Calif., 1981), 63–128.

47. Despite its name, the MMT, with its six primary and six secondary mirrors, is really a multiple-telescope telescope. When it was commissioned in 1979 it had the third largest equivalent collecting area of any telescope in the world.

monolithic mirrors on a common mount. Each mirror could be used individually or focused in combination, yielding a total light-gathering ability of a 15-meter telescope—a design that became known as the "four-shooter."[48] Roger Angel, an astronomer at the University of Arizona's Steward Observatory in Tucson, Arizona, emerged as the principle spokesman for the multiple-mirror telescope version of the NNTT. The son of an English chemist, Angel had graduated with a degree in physics from Oxford before moving into the nascent field of X-ray astronomy in the late 1960s. Like Nelson, Angel had experience in developing astronomical instrumentation but not in telescope design per se. Encouraged by the success of the Mount Hopkins telescope, Angel and his colleagues at Arizona, including Neville Woolf and Peter Strittmatter, began to consider how to make even larger collecting areas.[49] The Mount Hopkins telescope demonstrated the underlying concept that Arizona astronomers advocated. But what Angel and his colleagues lacked was a way to make large, lightweight mirrors.

The University of California was already funding Nelson's research into segmented-mirror design. Kitt Peak management therefore directed most of their NSF funding for NNTT technology development into Angel's forays into large-mirror manufacture.[50] Beginning in his yard using Pyrex custard cups and a homemade kiln, Angel and his graduate student John Hill soon decided to cast the blanks directly from molten glass. After several months of research and development, they chose a spin-casting process using a massive rotating furnace. The furnace's rotation spun the molten glass into a parabola, and removable ceramic cores created a honeycombed interior.[51] In more than one sense, George Ritchey's ideas for lightweight cellular mirrors reemerged in the University of Arizona's NNTT concept.[52]

48. Earlier plans existed for scaling up the MMT before the NNTT program was begun; see Neville Woolf and Roger Angel, "MT-2," in Hewitt, 1062–150.

49. Roger Angel, interview by author, Tucson, Ariz., 8 October 1998; Angel to George Field, 13 July 1979, file "Correspondence, 1979," Steward Observatory, University of Arizona. For an earlier description of lightweight mirror technology, see E. Loytty and C. F. Devoe, "Ultra-lightweight Mirror Blanks," *Institute of Electrical and Electronics Engineers Transactions on Aerospace and Electrical Systems* 2 (March 1969): 300–305.

50. The NSF proposal requested sixty-five thousand dollars for "mirror blank development" in fiscal year 1981, with funding increasing to one hundred and fifty thousand dollars in fiscal year 1983; see "A Technology Development Program for a National 15-Meter Telescope" (n. 40 above).

51. Roger Angel and John Hill, "Manufacture of Large Glass Honeycomb Mirrors," in *International Conference on Advanced Technology Optical Telescopes: March 11–13, 1982, Tucson, Arizona*, ed. G. Burbidge and L. Barr (Bellingham, Wash., 1982).

52. I base this conclusion on my interviews with Roger Angel at the University of Arizona and on his personal files, which he graciously allowed me to examine. The latter include several publications from the 1960s and 1970s by other authors on various ways to make lightweight, honeycomb-style mirrors, along with comments by Angel; examples include an internal report prepared by Kodak on mirror making for Hughes Aircraft, dated January 1979, titled "Large Primary Mirror Study," and E. Loytty and C. F.

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Despite their different approaches, the two telescope designs shared several features. Both concepts were untried on the scale that Angel and Nelson proposed, and neither was obviously superior to the other.[53] Both designs incorporated weight-saving techniques for the primary mirror to achieve a large and stable collecting area. Both employed a space-saving altitude-azimuth mount like that used for the Mount Hopkins telescope. Both achieved a further reduction in the size of the telescope enclosure by proposing relatively short focal lengths for the primary mirror relative to the aperture (that is, its focal ratio), which would make the telescope "stubbier" than one with a longer focal length.[54] The astronomy community's experience in designing large radio telescopes also influenced design concepts. Jerry Nelson, for instance, acknowledged that his original vision for the segmented-mirror NNTT was something that "looked like a radio telescope but the optical quality would be that of an optical telescope. . . . I read a number of papers on the design and construction of radio telescopes to understand the rules by which they're built. . . ."[55]

Both the segmented-mirror and multiple-mirror concepts for the NNTT drew upon previous research and development efforts at the institutions from which they emanated. Both designs were scaled-up versions of planned or existing telescopes. Both were products of existing traditions in conceptualizing large telescopes, and each had a clearly identifiable technological style of increasing a telescope's collecting area.[56] In the 1970s, scientists from Arizona were involved in building the original MMT, and they collaborated with Kitt Peak staff in developing a scaled-up design for the Next Generation Telescope project.[57] In similar fashion, Nelson and the University of California were already committed financially and technically to the segmented-mirror design as part of their 10-meter telescope project.

The strong commitment of the Arizona scientists and engineers to the

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Devoe, "Ultra-lightweight Mirror Blanks," *IEEE Transactions on Aerospace and Electrical Systems* 2 (March 1969): 300-305.

53. See Larry Barr et al., "The 15-Meter National New Technology Telescope: The Two Design Concepts," in *Advanced Technology Optical Telescopes 2*, ed. B. Mack and L. Barr (Bellingham, Wash., 1983), 37–46, for a general presentation of the two basic concepts.

54. For comparison, the Hale telescope has a slower (i.e., longer) focal ratio of f/3.3.

55. Nelson interview (n. 44 above), p. 17. The designers of the original MMT also acknowledged a debt to the radio telescopes in their efforts to make an larger yet cheaper optical telescope; Carleton interview (n. 23 above).

56. The predisposition for particular telescope designs is similar is similar to the different styles adopted in the design of infrared mosaic detectors; see David Edge, "Mosaic Array Cameras in Infrared Astronomy," in *Invisible Connections: Instruments, Institutions, and Science*, ed. Robert Bud and Susan Cozzens (Bellingham, Wash., 1992), 130–67.

57. The University of Arizona continues to advocate multiple-mirror telescopes; the university is currently building the Large Binocular Telescope, which features two 8.4-meter honeycomb mirrors on a common mount.

multiple-mirror concept and of their California counterparts to the segmented-mirror design raises the interesting question of why those groups favored those particular technical designs. One answer may be found in the resources consumed in building large telescopes; the design and construction of such an instrument is a very lengthy process that may occupy a significant portion of an astronomer or engineer's career. A second may lie in the investment, both of money and of professional reputation, that those institutions and individuals had made in one design or the other; given the depth of their commitment, it is not terribly surprising that they would seek to maintain a certain technological continuity or that the design they favored would have become part of their professional identity.[58]

WEIGHING THE SCIENCE AND TECHNOLOGY FOR THE NNTT

The communities designing the NNTT walked a very thin line. On one hand, the telescope had to appeal to as broad a portion of the astronomy community as possible. Few would support a national telescope costing tens of millions of dollars but designed around a narrow research agenda. On the other hand, the NNTT had to be sufficiently specialized that it did not turn out to be an instrument of mediocre performance and no unique capabilities. It also had to complement other telescopes in progress, such as the Hubble Space Telescope and the University of California's 10-meter segmented-mirror telescope.[59] Astronomers argued that the NNTT, with its 15-meter collecting area, could carry out observations much more quickly than the existing 4-meter national telescopes at Kitt Peak and La Serena. More efficient performance was becoming ever more important as the growing number of astronomers strained KPNO's ability to provide telescope access. Moreover, the light-gathering capabilities and increased observing efficiency of the proposed NNTT would be essential for key research areas, such as star formation and high redshift galaxies.[60]

In early 1983 Geoffrey Burbidge commissioned an advisory committee to help determine what science could best be done with the NNTT and to correlate this with design specifications.[61] Robert Gehrz, a rising star in the

58. Robert Smith has commented on this aspect of designing large, long-term instrumentation as an "act of faith"; see "Engines of Discovery: Scientific Instruments and the History of Astronomy and Planetary Science in the United States in the 20th Century," *Journal for the History of Astronomy* 28 (February 1997): 49–77.

59. This concern that the NNTT be a complementary instrument to the Hubble Space Telescope and others was noted, for instance, in the conclusions of a design workshop for the NNTT held at Flagstaff, Arizona, in June 1982; see "Technology Development Report No. 3: Notes on the NNTT Design Workshop, June 7–9, 1982," November 1982, NOAO library, Tucson.

60. Roger Davies, "The Scientific Potential of the 15m National New Technology Telescope," in Mack and Barr (n. 53 above), 32–36.

61. Geoffrey Burbidge to NNTT Scientific Advisory Committee Members, 9 March 1983; copy in the possession of Robert Gehrz, Department of Astronomy, University of

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field of infrared astronomy from the University of Wyoming, chaired a group of respected astronomers from several institutions, including KPNO, the University of Arizona, and the University of California. The committee was charged with evaluating the research to be done with a national 15-meter telescope, identifying the astronomical techniques to be used to carry out this research, and then determining which of the two designs was best suited to these goals.[62] As Gehrz recalled: "It's like the Army deciding what specs it wants for a Sherman tank. You write down what you want it to do and then you look at your design alternatives."[63]

Between March 1983 and July 1984, the Scientific Advisory Committee heard presentations from advocates of both the segmented-mirror and multiple-mirror designs for the NNTT as well as reports from outside consultants. Nelson, Angel, and other participants in these exchanges kept a certain level of decorum, but each side remained adamant about the superiority of its own approach and the flaws of its competitor's.[64] The committee held a meeting of special importance in Tucson on 3–4 November 1983, at which the twelve members formally ranked the scientific research priorities of the NNTT. With little difference of opinion, they listed spectroscopy and infrared imaging as the most promising scientific research techniques; astronomers on the committee, for example, gave the technique of multiobject spectroscopy very high priority for the NNTT.[65] In order to be able to collect the spectra from fifty to two hundred stellar objects simultaneously, the new instrument would need a field of view of at least half a degree.[66]

Negotiating the performance specifications for the NNTT was an incremental process that took place over several meetings. In addition to input from its members, all of whom were prominent optical and infrared astronomers, the committee solicited feedback from others in the community. While the advisory committee evaluated the science to be done with the NNTT, members of the astronomical community who supported either

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Minnesota, Minneapolis. On the official responsibilities of the committee, see "Charge to the SAC," memorandum, John Jefferies to Robert Gehrz, 9 May 1984, copy in Gehrz's possession.

62. To help them better evaluate the technology being considered, the committee also held technology assessment workshops in early 1984. Outside consultants were brought in to offer their views on the risks and costs associated with the SMT and MMT versions of the NNTT. See "Notes from Consultants for the NNTT/SAC," copy in the possession of Robert Gehrz.

63. Robert Gehrz, interview by author, Minneapolis, Minn., 23 November 1998.

64. See, for example, Jerry Nelson and Terry Mast, "Reasons for Selecting the Segmented Design for the National 15-Meter Telescope," June 1984, with commentary by Roger Angel and Neville Woolf, copy in the possession of Larry Barr, Tucson, Arizona.

65. Jean Goad, "Science with the NNTT," memorandum, 9 November 1983, copy in the possession of Larry Barr.

66. For comparison, the full moon subtends an angular diameter of about a half a degree.

the multiple-mirror or segmented-mirror designs (or no new national telescope at all) wrote letters or attended discussions at national astronomy gatherings.[67] In some cases, astronomers addressed such general concerns as the role of a large, ground-based telescope in an era that would soon see the launch of the much anticipated Hubble Space Telescope. These interactions served several functions: they gave the community of professional astronomers opportunities to have input on the type of research that might be done with a new national telescope and to influence the design selection process, and they served as an indication of overall interest in the project for the funding and management institutions, such as AURA and the National Science Foundation.[68]

Astronomers' negotiations and evaluations, presented in meetings, letters, and memoranda, prioritized the NNTT's scientific capabilities and yielded a detailed list of the telescope's desired performance and design requirements. A vision of the NNTT emerged gradually. Bruno Latour has described similar processes as the creation of a "paper world" in which "[m]achines . . . are drawn, written, argued, and calculated before ever being built" and becoming part of the "messy, greasy, concrete world."[69] As astronomers and engineers created this paper telescope, the boundaries between engineering, science, society, politics, and funding became increasingly indistinct. Members of the Scientific Advisory Committee and others in the astronomy community frequently inhabited the intersections of all these worlds as they negotiated the NNTT's design.

The Great Telescope Shoot-Out

As the Scientific Advisory Committee and the American astronomy community debated the research agenda and design of the new national telescope, other developments were taking place outside the NNTT pro-

67. For instance, one astronomer wrote to Geoffrey Burbidge after a meeting of the American Astronomical Society: "What effect will [NNTT] development have on the high quality support we have experienced at KPNO? With the [California] Ten Meter Telescope . . . and other projects, is the effort in Astronomy as a science properly balanced? . . . After weighing the discussion, I favor the segmented mirror telescope proposal partly out of conservatism, partly intuition, and, to a lesser extent, technical questions. . . ." Malcolm Savedoff to Geoffrey Burbidge, 20 June 1984, copy in the possession of Robert Gehrz. Correspondence such as this was regularly circulated among advisory committee members in preparation for their formal meetings.

68. The committee also drew upon scientific justifications prepared for other large telescope projects, such as the University of California's 10-meter telescope and the Next Generation Telescope program. See Sandra M. Faber, "The Scientific Case for a 10-Meter Telescope," in Hewitt (n. 6 above), 304–28; "The Scientific Case for a Very Large Aperture Ground-Based Telescope," in Hewitt, app. 1.

69. Bruno Latour, *Science in Action* (Cambridge, Mass., 1987), 253. I am grateful to Robert Smith for pointing this passage out to me.

gram. On 1 February 1984, the AURA board of directors officially established the National Optical Astronomy Observatories (NOAO). This action brought together, under one director, the three previously separate national astronomy facilities managed by AURA, including Kitt Peak.[70] The board also created a fourth division, the Advanced Development Program, as part of the newly merged group of national observatories. The primary responsibility of the Advanced Development Program was "to pursue the design, construction, and commissioning" of the NNTT.[71] To lead the Advanced Development Program, AURA chose Jacques Beckers, formerly the director of the Multiple Mirror Telescope Observatory. Meanwhile, in May 1984 the University of California announced that it had received a private donation of thirty-six million dollars for its 10-meter telescope project.[72] This funding made the future of the California project much more secure, and almost certainly aroused envy in those who had to finance their own large telescope projects in a more piecemeal and less secure fashion.

With these developments in mind, the NNTT's Scientific Advisory Committee held its final meeting, in July 1984 in Santa Cruz; some participants called it the "great telescope shoot-out." On the morning of 13 July, Roger Angel and Jerry Nelson made a final pitch for their designs. As Larry Barr recalls it, Angel was pessimistic about the chances for his MMT concept being selected. "I remember talking to Roger Angel the night before the meeting. He was quite discouraged. I think he felt the Berkeley group and the SMT had been presented so well and that the University of California had been funding the Berkeley group for several years now. He thought they were much further along in the 10-meter telescope design, which they were. And that served as a much better model for the 15-meter than we had in the MMT-style."[73]

Astronomers on the committee identified the fabrication of the primary mirror as the greatest risk for both telescopes. In addition to consid-

70. The first director of NOAO was John T. Jefferies, a solar astronomer; he replaced Geoffrey Burbidge as director of the national observatory in 1983. *KPNO Newsletter*, no. 27, 1 June 1983; *KPNO Newsletter*, no. 32, 1 May 1984.

71. *KPNO Newsletter*, no. 34, 1 September 1984. In addition to carrying out research and development for the NNTT, the ADP was also to develop technology associated with adaptive optics and infrared detectors.

72. The circumstances surrounding the funding of this telescope are interesting. The thirty-six million dollars that the University of California was given was not enough to build the telescope, so the university invited the California Institute of Technology to share in the funding and use of the completed facility. In 1984 Caltech announced that it had received its own donation from the Keck Foundation to build its own 10-meter telescope. Eventually the University of California returned its thirty-six-million-dollar gift and became a partner with Caltech in building the two 10-meter Keck telescopes on Mauna Kea. See David Saxon, interview by Shirley Cohen, 29 January 1997, and William Frazer, interview by Timothy Moy, 17 March 1992, Keck Telescope Interviews, California Institute of Technology Archives, Pasadena.

73. Larry Barr, interview by author, Tucson, Ariz., 2 December 1998.

ering the technical aspects of the design, there were scheduling and political factors to weigh. For instance, if the multiple-mirror style were chosen, it had to be done in such a way so as not to damage the existing technical case for California's 10-meter telescope project. But the likely construction of a 10-meter telescope also meant that a segmented version of the NNTT might have to be postponed while the California project was built first. The multiple-mirror design faced similar considerations; the committee knew that a working model of the Arizona design already existed in the Mount Hopkins telescope, and some members questioned the merits of building a larger version of a telescope that had yet to unequivocally demonstrate the validity of the multiple-mirror concept.[74]

The debate continued on 14 July, as committee members evaluated the science capabilities and risk factors associated with the competing design concepts. Robert Gehrz remembers this session as "agonizing. Everyone was soul-searching. . . . All the cases were eloquent. Everyone had good reasons for one over the other. But the majority of them, based mainly on conservatism, were for using the bigger single mirrors. It basically boiled down to a gut-level feeling that controlling thirty or forty segments flying in close formation was going to be very tough."[75] Larry Barr recalls: "All of us chose the MMT concept over the SMT concept as the better choice for a 15-meter telescope. It's important to keep the phrase '15-meter telescope' as part of that statement because any other size would have produced mixed opinions. . . . I felt at ten meters the SMT was a better design. But I worried a lot about building a mediocre monster at fifteen meters."[76]

In weighing the two designs, the advisory committee argued that the multiple-mirror design had a wider field of view, valuable for achieving high efficiency in multiobject spectroscopy. The large baseline and mirror configuration in the MMT style offered the possibility of higher resolution in the infrared spectrum as well as the capability of doing interferometry.[77] For the time being, the planned new national telescope was going to be an Arizona "four-shooter."

By the end of 1986, however, the future of the NNTT project was in doubt. After three years of technological development and promotion to the astronomy and funding communities, support for the project was not overwhelming. Other institutions, including the California Institute of

74. "Minutes of July 1984 SAC Meeting," copy in the possession of Robert Gehrz.

75. Robert Gehrz, interview by author, Minneapolis, Minn., 25 May 1999.

76. Barr interview, 2 December 1998.

77. The press release accompanying the decision stated that, while both concepts could be made to work, "Some of the most important science to be done will require high spectral and spatial resolution and the multiple-mirror concept seemed . . . to offer outstanding and versatile performance in those applications." See "Statement by the NNTT Scientific Advisory Committee," 15 July 1984, copy in the possession of Robert Gehrz; "Scientists Urge NOAO to Build Giant Multiple-Mirror Telescope," NOAO Press Release 84-16, 20 July 1994, copy in the author's possession.

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Technology, the University of Arizona, and the Carnegie Institution of Washington, had plans to build their own large telescopes in the next ten years. Several other very large telescopes would soon be built abroad, as well. While the 15-meter NNTT would have been bigger than any of these, astronomers and administrators questioned its scientific justification when private and international groups were building a new generation of instruments. The NSF was disappointed with the slow progress in scaling up Arizona's mirror-making technology and, at the same time, recognized a political need to build the next big national telescope as an international collaboration. Also, the astronomy community began to express its doubts more vocally about the future of NOAO as a science institution in the world of optical astronomy dominated by privately funded large telescopes and the (still anticipated) Hubble Space Telescope.

In August 1987, the AURA Board formally postponed the National New Technology Telescope.[78] The board and a specially selected committee of astronomers decided that NOAO should direct its efforts toward building two 8-meter telescopes instead of the 15-meter NNTT. What was originally conceived as an instrument for American astronomers became, in the end, two telescopes funded, designed, and built by an international collaboration in which the United States was only a 50 percent partner.[79]

Evaluating Success and Failure

A large telescope is literally a social construction, its final design the outcome of negotiations and compromises between astronomers, engineers, and patrons. Like the decision to build the NNTT as a "four-shooter," the decision to cancel the project was influenced by changing science goals, technological expectations, and the prevailing political and fiscal climate. Prior to 1984, astronomers and engineers had different and competing visions of how the NNTT should be built. Members of the Scientific Advisory Committee developed and agreed upon a list of scientific purposes for the telescope. Science managers at AURA and the NSF considered the needs of American astronomy in conjunction with the telescope's technological challenges and scientific possibilities. These dynamic interactions all occurred in the broader context of political and financial possibilities.

78. The possible cancellation of the NNTT is suggested in earlier reports prepared by AURA, such as the "Report of the Future Directions for NOAO Committee," 15 September 1987, Peter Strittmatter Personal Files, Steward Observatory, Tucson, Arizona. See also Goetz Oertel, interview by author, 23 April 1999. I am at work on a book taking the national telescope project up to the present, which will critically examine the decision to build it as two separate telescopes.

79. On 25 June 1999 the first of two 8-meter Gemini telescopes was dedicated at a ceremony near the summit of Mauna Kea in Hawaii; its twin, located in northern Chile, is expected to begin operation in 2001.

What astronomers viewed as a feasible project in 1984 was seen three years later as too expensive, too ambitious, too risky.

The history of the NNTT complements current scholarly examinations of the meaning of technological success or failure.[80] The NNTT existed only in the paper world of design specifications, committee reports, astronomers' requirements, and scientific research agendas, and in scale models and associated developmental technology. How does one evaluate a project that was advocated, designed, and partially funded, but never built? One way is to consider the NNTT in terms of the project's influence on telescope design and conception.

Popular treatments of astronomy have described the late 1970s and 1980s as a "revolutionary" period for telescope building.[81] Is this description accurate? A "technological revolution," according to one interpretation, is "the professional commitment of either a newly emerging or redefined community to a new technological tradition."[82] The designs offered by Nelson and Angel did represent a break with previous ways of building large telescopes. Between 1980 and 1990 astronomers witnessed the appearance of two viable approaches for achieving more light-collecting power at an affordable cost. These competing technological styles were incorporated into several large-telescope designs in the next decade.[83] Development of the segmented-mirror technology advocated by Jerry Nelson was the basis for two 10-meter telescopes. In 1992, after a long developmental period, Roger Angel and the Steward Observatory Mirror Laboratory began fabricating mirror blanks of 6.5 meters and more. Angel and Nelson's designs were not sterile failures, but rather had a significant influence on telescope design and the international astronomy community in general.[84]

80. Gooday (n. 9 above.) One of the salient points Gooday raises is that the success or failure of a technology is highly subject to interpretation: success or failure according to whom? Also, what may be deemed a "failure" at one point may be seen as a technological "success" at another.

81. See, for example, Malcolm Browne, "New Vistas Open for Earthbound Astronomers," *New York Times*, 11 February 1997; Stephen Maran, "A New Generation of Giant Eyes Gets Ready to Probe the Universe," *Smithsonian*, June 1987; Roger Angel, "The Revolution in Ground-Based Telescopes," *Quarterly Journal of the Royal Astronomical Society* 31, no. 2 (1990): 141–52.

82. Constant (n. 3 above), 19.

83. In addition to these technological traditions, new telescope designs began to incorporate other technologies developed in parallel during the 1980s, such as adaptive optics and larger, charge-coupled, device-based detector arrays.

84. While Nelson and Angel were developing their mirror technologies, commercial firms began to consider the profitability of making large telescope blanks for the astronomy market. Companies such as Corning and Schott soon developed their own response to astronomers' demands for more collecting area. The technological solutions pursued at Schott and Corning entailed the use of a very thin, solid, monolithic "meniscus" made from a glass-ceramic material. Because such a thin blank is unstable with respect to its

The effects of the NNTT program on the astronomy community extended beyond the creation of hardware. Astronomers' experiences with the NNTT altered the process of designing new large telescopes in many ways. Consider the professional backgrounds of Roger Angel and Jerry Nelson. Both men received their formal training in physics, and prior to the NNTT project neither had much experience in the design of large telescopes. Initially they were outsiders in the telescope design community. But, unlike George Ritchey fifty years earlier, Angel and Nelson successfully generated support for their concepts. Both belonged to respected institutions and were able to secure funding from diverse sources—private donors, the NSF, NASA, and research consortia—to support their R&D efforts throughout the 1980s. Historically, they were in the right places at the right time. Ritchey, in contrast, proposed his ideas at a time when astronomers did not believe the technology that would form the basis of the Hale telescope was exhausted.[85]

The NNTT was to be, ideally, an instrument for the entire astronomy community. American astronomers participated as a group in the planning process through public meetings and other avenues of communication opened by the national observatory, through which it offered suggestions concerning both the prioritization of the research to be done with the NNTT and the design that should be followed. The Scientific Advisory Committee, composed of astronomers and not telescope engineers, offered select members of the astronomy community another opportunity to play a major role in the design process. To a great extent their specifications and performance criteria defined the telescope. Moreover, their choice of the multiple-mirror design was the key endorsement that allowed the National Optical Astronomy Observatories to pursue further development of the NNTT between 1984 and 1987. Advising bodies of astronomers, such as the NNTT's Scientific Advisory Committee, would become a common element in the design and political selling of other large telescope projects, both ground and space-based, in the 1980s and 1990s.

The NNTT also had institutional significance. Kitt Peak supported and

own weight as the telescope points across the sky, an elaborate system of controls and actuators must be incorporated into telescopes using this technology. The meniscus approach was used in several very large telescopes built during the 1990s. While a direct causal link between development of primary mirror-making techniques for the NNTT program and the appearance of large corporate R&D efforts for telescope mirror making can not be established, the timing is surely not coincidental. See, for example, W. Lewis and W. Shirkey, "Mirror Blank Manufacturing for the Emerging Market," in *International Conference on Advanced Optical Telescopes*, ed. G. Burbidge and L. Barr (Tucson, Ariz., 1982), 307–9.

85. On the role of outsiders in the innovation process, see Michel Callon and John Law, "On Interests and Their Transformation: Enrollment and Counter-enrollment," *Social Studies of Science* 12 (1982): 615–25; Thomas Gieryn and Richard Hirsh, "Marginality and Innovation in Science," *Social Studies of Science* 13 (1983): 87–106.

funded the segmented-mirror and multiple-mirror designs for the NNTT in conjunction with efforts to make a strong case to the astronomy community and the NSF. The NNTT presented an opportunity for the national observatory to increase the technical sophistication of its facilities significantly, and it devoted considerable resources to the project. Unlike the earlier efforts at Kitt Peak for its Next Generation Telescope program, more detailed attention was paid to funding constraints, project organization, and consensus building in the community. The NNTT project benefited Kitt Peak and, later, NOAO in several ways. It gave the national observatory a technologically challenging and sophisticated project, highly visible to the scientific community and the public. Articles about the project appeared in astronomy journals, popular science magazines, and newspapers. At a time when many private and state institutions were taking steps to build new and larger telescopes, the NNTT project made the national observatory a player among these elite organizations. With its bold, if short-lived, Advanced Development Program, NOAO explored auxiliary telescope technology such as adaptive optics and infrared detectors.

The design process for the NNTT was the product of an increasingly common form of patronage in which large institutions participate in collaborative efforts to build a national or international research facility financed, to some degree, with tax dollars. Astronomers have largely forgotten about the project, and researchers new to the field are largely unaware that plans for it existed. Today, some funding officials and science managers from organizations such as AURA and the NSF consider the NNTT a flawed project that was never really viable. But the design of the NNTT, like any instrument for big science, was situated at the junction of past technological experiences, current and future technological expectations, future research needs, and the political and funding realities. The NNTT was a bold undertaking in ways other than its sheer size. It endeavored to break from the earlier technological paradigm while serving a broader scientific community, and the designs and strategies developed and pursued by supporters of the project had significant effects on the way that large ground-based telescopes are conceived of and built today. Its success or failure must, therefore, be evaluated in terms other than “was it built?”