The Carnegie Image Tube Committee

and the Development of Electronic Imaging Devices in Astronomy, 1953-1976

by

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ABSTRACT

This dissertation examines the efforts of the Carnegie Image Tube Committee (CITC), a group created by Vannevar Bush and composed of astronomers and physicists, who sought to develop a photoelectric imaging device, generally called an *image tube*, to aid astronomical observations. The Carnegie Institution of Washington's Department of Terrestrial Magnetism coordinated the CITC, but the committee included members from observatories and laboratories across the United States. The CITC, which operated from 1954 to 1976, sought to replace direct photography as the primary means of astronomical imaging.

Physicists, who gained training in electronics during World War II, led the early push for the development of image tubes in astronomy. Vannevar Bush's concern for scientific prestige led him to form a committee to investigate image tube technology, and postwar federal funding for the sciences helped the CITC sustain development efforts for a decade. During those development years, the CITC acted as a mediator between the astronomical community and the image tube producers but failed to engage astronomers concerning various development paths, resulting in a user group without real buy-in on the final product.

After a decade of development efforts, the CITC designed an image tube, which Radio Corporation of American manufactured, and, with additional funding from the National Science Foundation, the committee distributed to observatories around the world. While excited about the potential of electronic imaging, few astronomers used the Carnegie-developed device regularly. Although the CITC's efforts did not result in an overwhelming adoption of image tubes by the astronomical community, examining the design, funding, production, and marketing of the Carnegie image tube shows the many and varied processes through which astronomers have acquired new tools. Astronomers' use of the Carnegie image tube to acquire useful scientific data illustrates factors that contribute to astronomers' adoption or non-adoption of those new tools.

To

Andrew Overhiser

and

Mike Janicek,

for keeping me alive.

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INTRODUCTION

Introduction

In 2013, *Smithsonian Magazine* published their "101 Objects that Made America."[1] The list included artifacts representing some of the greatest accomplishments and discoveries in American history, from Meriwether Lewis' silver-plated compass used by the explorer to map the Rocky Mountains, to a gold nugget uncovered during California's Gold Rush, and a vial that once contained Jonas Salk's polio vaccine. One object listed, a three-and-a-half foot tall instrument enclosed in a case of metal, as seen in Figure 1.1, a fair example of what historians of technology would appropriately call a 'black box,' was used by an astronomer to revolutionize our understanding of the composition of the universe.[2]

From the late 1960s to the early 1980s, astronomer Vera Rubin and her colleague, physicist Kent Ford, who had only a few years earlier designed and built this instrument, travelled to several observatories, attached their new observing aid to telescopes, and recorded the internal motions of several dozen spiral galaxies, ones much like our own Milky Way. Rubin and Ford discovered that the outer arms of each galaxy were rotating at speeds that should not have been possible given the amount of visible mass, primarily in the form of stars and dust. Rubin argued that the only possible explanation was that some unknown material, that did not shine or reflect light the way stars or dust do, had to be present in the galaxy. This study provided the strongest evidence yet found for the existence of *dark matter*, a non-luminous material that was

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[1] Dan Winters, "Smithsonian," *Smithsonian*, November 2013. Smithsonian Collections Online, http://tinyurl.galegroup.com/tinyurl/9T8me0.

[2] For an example relevant to the technology discussed in this dissertation, see Robert W. Smith and Joseph N. Tatarewicz, "Counting on Invention: Devices and Black Boxes in Very Big Science," *Osiris* 9 (1994): 101-123.

detectable by the gravitational forces it exerted on the material around it, which, by 1980, was believed to comprise 90% of the total mass in the universe.[3]

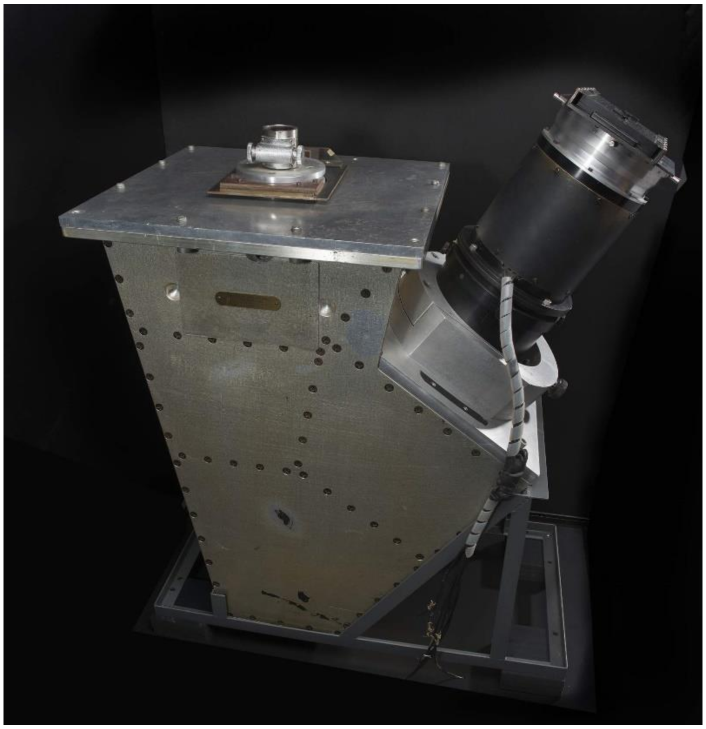

Figure 1.1. Image Tube Spectrograph built by W. Kent Ford, Jr.[4]

Vera Rubin was able to find evidence of dark matter in part because of the research project she pursued and in part because of the instrument she employed. Rubin noticed that few other astronomers were interested in the rotational dynamics of galaxies, which attracted her to the problem.[5] In the male-dominated field of astronomy, Rubin chose a project with little

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[3] Vera C. Rubin, *Bright Galaxies, Dark Matters* (New York: American Institute of Physics Press, 1997) and Vera C. Rubin, "Dark Matter in Spiral Galaxies," *Scientific American* 248, no. 6 (1983): 96. Today, astronomers believe that the universe contains roughly 27% dark matter and 68% of a similarly unknown dark energy.

[4] Photo by Mark Avino, Smithsonian National Air and Space Museum (TMS A20050006000_PS1). Reprinted with permission.

[5] Vera Rubin, oral history interview by Ashley Yeager and David DeVorkin on 20 July 2007, Smithsonian National Air and Space Museum, particularly page 28.

competition, that she could develop on her own, and that she could tackle at her own pace. [6] As Rubin was forming an interest in the outer bands of galaxies, she was hired at the Carnegie Institution of Washington's Department of Terrestrial Magnetism, where Kent Ford was looking for a research program that would push his instrument to its limits.[7] With Ford's instrument, which used a new technology to more efficiently observe very dim objects, Rubin could record the motion of fainter stars, with shorter exposure times, without the need for observing time on the largest telescopes. Rubin began her investigation intending to study the dynamics of spiral galaxies, but was surprised by the result.[8] Though Rubin could not observe dark matter directly, by studying the motion of distant galaxies, she inferred that most galaxies must contain about ten times as much dark as visible mass.[9]

While the benefits of using an instrument that could amplify the light from a distant object were apparent to much of the astronomical community, as seen in conference proceedings and correspondence with image tube developers, astronomers' initial uptake of the device was limited. Though a few astronomers did attempt to use Ford's instrument in the late 1960s and throughout the 1970s, with varying degrees of success in acquiring scientific data, the technology failed to gain widespread support. In this dissertation I examine the reasons – from the lack of technical skill required to operate this new device to a lack of buy-in on the final product – the astronomy community neglected, and sometimes refused, to adopt this instrument as a regular part of their observing toolkit.

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[6] Rubin, oral history interview.

[7] Rubin, oral history interview.

[8] Vera C. Rubin and W. Kent Ford Jr., "Extended Rotation Curves and Mass Distributions in Sc I, Sc II, and Sc III Galaxies," *Bulletin of the American Astronomical Society* 11 (1979): 430.

[9] Rubin, "Dark Matter in Spiral Galaxies," 96.

Background

Observation is a critical component of astronomical research, but the methods by which astronomers have carried out and understood those observations have changed greatly over time.[10] Ancient astronomers could only observe the brightest stars and planets, those visible to the naked eye. With the invention of the telescope in the early seventeenth century, astronomers could see further into the universe and observe fainter objects. Gradually astronomers built larger telescopes, capable of gathering more light from distant objects, increasing the limits of magnification, and providing better resolution of those objects.

During the first half of the twentieth century, telescope design appeared to approach a limiting size, restricted largely by funding and material constraints. In 1948, two decades after George Ellery Hale secured $6 million (the equivalent of roughly 90 million in 2019 dollars) from the Rockefeller Foundation to construct a 200-inch telescope on Mount Palomar in southern California, the telescope saw “first light.” Jointly operated by the Carnegie Institution of Washington and the California Institute of Technology (Caltech), Hale’s telescope was lauded for its observing power, but even as it was being constructed, astronomers questioned the usefulness of investing resources in such large-scale projects. In his 1943 presidential address to the American Astronomical Society (AAS), astronomer Joel Stebbins, a pioneer in electronic detection at the University of Wisconsin, raised the issue of the law of diminishing returns in the field of astronomy.[11] Stebbins noted that a telescope twice in size may cost ten-times as much to build, but the resulting gain in light-gathering power and resolution would not necessarily be proportional to the size or cost.[12] In 1956, Washburn Observatory astronomer and Stebbins protégé, A.E. Whitford, similarly argued that

> the astronomical telescope has long since reached a state of perfection where the tranquility of the atmosphere, rather than the quality of the optics, determines the image

[10] For an account of the changing role of observation in science, see Lorraine Daston and Elizabeth Lunbeck, ed., *Histories of Scientific Observations* (Chicago: University of Chicago Press, 2011), particularly parts 1 and 2.

[11] Joel Stebbins, “The Law of Diminishing Returns,” *Science* 99 (1944): 267-271.

[12] Stebbins, “Law,” 267-268.

> quality. The astronomer may, in theory, gather more information by increasing the aperture, but the engineering difficulties and the cost both rise steeply for any considerable increase in size over that of existing telescopes. [13]

Only a select group of astronomers would have access to a large telescope like Hale's privately operated 200-inch, and few, if any, other astronomers or institutions could afford to devote the resources to constructing a rival instrument. The apparent size limit of optical telescopes restricted astronomers' potential opportunity to see further and more distant.

Some astronomers and physicists believed an alternative to constructing larger telescopes was to amplify the incoming light or increase the sensitivity of the telescope's recording device. Whitford argued that

> The final link in the information chain, the radiation detector at the focus of the telescope, is therefore the element which must be scrutinized for possible lack of efficiency, If the efficiency is low, improvements can be counted as equivalent to increasing the aperture of existing telescopes.[14]

If offered the money for a 100-inch telescope, many astronomers, Stebbins asserted, would have the "moral courage" to say that they prefer to build an 80-inch telescope and use the remainder of the funds for improved instruments and better operations, arguing that, "if the law of diminishing returns seems to prevent us from doing something better, we can always try to do something different."[15] Combining advanced instrumentation with modest-sized telescopes could have the effect of giving more astronomers access to adequate observing resources. Only small improvements in instrumentation were needed, Stebbins and Whitford concluded, to open new research opportunities for a wider field of astronomers.

Early astronomers could only sketch what they saw, drawing what their eyes detected through the lens of the telescope.[16] In the late nineteenth century, astronomical research

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[13] A.E. Whitford, "Photoelectric Astronomy," *Smithsonian Contributions to Astrophysics* 1 (1956): 25-29.

[14] Whitford, "Photoelectric," 25.

[15] Stebbins, "Law," 271.

[16] For more on the role of drawing in astronomical research, see Omar W. Nasim, *Observing by Hand* (Chicago, University of Chicago Press, 2013); Owen Gingerich and Albert van Helden, "From *Occhiale* to Printed Page: The making of Galileo's *Sidereus Nuncius*," *Journal for the History of Astronomy* 34 (2003): 251-267; Owen Gingerich and Albert van Helden,"How Galileo Constructed the Moons of Jupiter,"

underwent a transformation in observing practice when photographic plates replaced hand-drawn images of the sky. In the late nineteenth-century, newly available dry, gelatin-based photographic emulsions revolutionized astronomy.[17] Photography not only provided a permanent record, but also allowed for integration over extended exposures, accumulating light from faint objects. The change from hand-drawn image to photographic plate increased astronomers' ability to gather more light, helping them detect dimmer objects and those further away.

In the early twentieth century, Joel Stebbins and a small group of specialists began exploiting photoelectric principles to measure stellar brightness. In 1887, Heinrich Hertz discovered the photoelectric effect, a phenomenon where electrons are produced when light shines on a material. It was further explained by Albert Einstein and Robert Millikan in 1905 and 1923, respectively, each earning a Nobel Prize for his discoveries. Astronomers were interested in this method because it allowed them to transform light from a single point source object into a proportional number of electrically charged particles that produced a measurable electric current. The accuracy of this method far exceeded that of photographic methods, where the response was nonlinear and therefore required constant calibration.

After World War II, astronomers became increasingly interested in photometric studies (measuring the apparent brightness of an object) to determine the apparent magnitudes (a unitless measure of brightness) of celestial objects. Astronomers interested in photometric studies began using commercially-produced and widely-available photomultiplier tubes, which

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Journal for the History of Astronomy 42 (2001): 259-264; Albert van Helden, "Telescopes and Authority from Galileo to Cassini," *Osiris* 9 (1994): 8-29; Albert van Helden, "Galileo and Scheiner on Sunspots: A Case Study in the Visual Language of Astronomy," *Proceedings of the American Philosophical Society* 140, no. 3 (Sep., 1996): 358-396; and Mary G. Winkler and Albert van Helden, "Representing the Heavens: Galileo and Visual Astronomy," *Isis* 83, no. 2 (June 1992): 195-217.

17 For cases of the practical application of photography to astronomy, see Dorrit Hoffleit, *Some firsts in astronomical photography* (Cambridge, Harvard College Observatory, 1950); John Lankford, "Photography and the Long-focus Visual Refractor: Three American Case Studies, 1885-1914," *Journal for the History of Astronomy* 14, no. 2 (June 1983): 77-92; John Lankford, "The impact of photography on astronomy," in *Astrophysics and Twentieth-century Astronomy to 1950*, ed. Owen Gingerich (Cambridge: Cambridge University Press, 1984): 16-39; and Daniel Norman, "The Development of Astronomical Photography," *Osiris* 5 (1938): 560-594.

amplified the light coming from a single point source object. These photomultipliers were more sensitive, could detect fainter light sources than their predecessors, and provided a more precise measurement of an object's brightness.[18] Astronomers Edwin Hubble and Walter Baade of the Mount Wilson and Palomar Observatories had been conducting spectroscopic observations, attempting to determine the distances to galaxies. Their work relied heavily upon an accurate magnitude scale that astronomers had performed photographically, but many astronomers believed these photographic magnitude measurements were erroneous, especially at the faint end, because of the calibration techniques employed and they pushed to acquire more accurate scientific measurements with improved photoelectric techniques.[19]

While astronomers used photomultiplier tubes to increase the accuracy on their observations, one disadvantage of photomultipliers was that only one measurement could be made at a time. For example, with a photomultiplier, astronomers could only measure Mars or a galaxy as a single point of light, whereas, with a photograph, astronomers could sense variations over the entire disk, capturing the contrasting areas of light and dark across its surface. At the end of the nineteenth century, astronomers' research interest in stellar structure evolved to include galaxies and the nature of the spiral nebulae. The discovery of "island universes," other galaxies, opened up a new field of galaxy studies during the beginning of the twentieth century. Astronomers had employed photometric methods to determine stellar spectra but were beginning to seek to understand the dynamics and composition of galaxies, which required spatial observations. Photomultipliers were ideal for point-source studies but could not produce a two-dimensional image like a photograph, needed, for example, to understand the components of a galaxy.

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[18] David H. DeVorkin, "Electronics in Astronomy: Early Applications of the Photoelectric Cell and Photomultiplier for Studies of Point-source Celestial Phenomena," *Proceedings of the IEEE* 73, no. 7 (July 1985): 1205-1220.

[19] Ira Bowen, oral history interview by Charles Weiner on 26 August 1969, Niels Bohr Library & Archives, American Institute of Physics, College Park, MD (AIP). See also, David H. DeVorkin, "The Changing Place of Red Giant Stars in the Evolutionary Process*," Journal for the History of Astronomy* 37, no. 4 (Nov. 1, 2006): 429–469, especially pp 446-453 and Donald Osterbrock, *Walter Baade: A life in astrophysics* (New Jersey: Princeton University Press, 2001): chap. 5.

In developing the all-electronic television camera in the early twentieth century, physicists similarly exploited the photoelectric effect but used it to produce a two-dimensional image, like a photograph, as a result. The primary consumers of television cameras were broadcast television networks and the military. While broadcast television users appreciated television's ability to transform an optical image into an electrical signal that could be sent far distances onto home television sets, the military valued television for its ability to see in the infrared, making it possible to detect, for example, the exhaust coming from enemy aircraft at night. Television-producing companies were eager to expand their consumer base and actively searched for other arenas, like science, to make use of their products.[20] The military continued to push for more resources into the electronics television industry, resulting in the appearance of an increased number of industrial laboratories with electron-optical capabilities.[21] These industrial labs specialized in developing materials and devices that could more efficiently transform light from a spatial object into an electric signal that could then be manipulated and re-formed into a two-dimensional image.

Astronomers saw this development and became interested in the possible uses of television and its growing resources of technical talent and material. After a 1933 meeting of the American Association for the Advancement of Science, during which astronomers discussed using television to extend the range of telescopes, newspapers throughout the United States printed articles detailing the new reaches of space that would be made observable through the

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[20] Vladimir K. Zworykin and E.G. Ramberg, *Television in science and industry* (New York: Wiley, 1958)

James D. McGee, "Television Technique as an Aid to Observation," *Journal of the Royal Society of Arts* 100, no. 4869 (March 21, 1952): 329-349.

[21] For a discussion of the military's interest in television, see Albert Abramson, *Zworykin, Pioneer of Television* (Chicago: University of Illinois Press, 1995),: chapts. 5-7 and Jennifer Burton Bannister, "From Laboratory to Living Room: The Development of Television in the United States, 1920-1960" (PhD diss., Carnegie Mellon University, 2001): chapts. 3 and 5.

use of television.[22] American newspapers described the hype, awareness, and excitement of television's potential use in astronomy through headlines like, "'Electronic Telescope' Developed; Equals 2,000-Inch Lens in Power," "Reaching Out Still Further," "New Telescope May Bring Stars Closer to Earth," and "Television and the Telescope."[23] With a television camera, astronomers saw the potential to increase the light-gathering capability of a telescope, making dim stars appear brighter and reducing the amount of time required to make an image of that star. Those astronomers imagined they could use a technology like television to make more efficient use of the light available rather than building a larger telescope. During the middle of the twentieth century, while some astronomers continued to campaign for even larger telescopes, some chose to look for ways to advance recording techniques to better use the light collected from modest-sized telescopes and they were optimistic about the ability of television tubes to help in that pursuit.[24]

By the 1950s, there were several methods employed or proposed to electronically amplify the light coming from an object. Devices which used the photoelectric effect to convert photons into electrons that could be easily multiplied to produce a brighter image of the original object, were collectively called *image tubes*. Television tubes were a type of image tube and, like others, had advantages and disadvantages for astronomical work [refer to Appendix A for the distinction

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[22] Meeting abstract found in F.C. Henroteau, "Electronic telescope," *Publications of the American Astronomical Society* 8 (1936): 11. Based on article F.C. Henroteau, "The Electronic Telescope," *Journal of the Royal Astronomical Society of Canada* 28 (1936): 59-62.

[23] William Laurence, "'Electronic Telescope' Developed; Equals 2,000-Inch Lens in Power*," The New York Times*, Dec. 30, 1933, g1; "Reaching Out Still Further," *Green Bay Press-Gazette*, Jan. 9, 1934; "New Telescope May Bring Stars Closer to Earth," *The Montgomery Advertiser*, Jan 2, 1934, 7; and "Television and the Telescope," *The Brooklyn Daily Eagle*, Jan 4, 1943, 20.

[24] For any given telescope, there is a finite amount of observing time available to astronomers. Because the 200-inch telescope was jointly operated by Caltech and the Carnegie Institution, both private institutions, access to observing time was limited to their staffs. As a remedy, some astronomers proposed developing a nationally-funded large telescope. This would increase the amount of total observing time available for all astronomers by adding additional telescopes, but would also give more chance for astronomers not associated with Caltech or Carnegie to have access to a large telescopes. For more, see Patrick McCray, *Giant Telescopes* (Cambridge: Harvard University Press, 2006) and Patrick McCray, "'Beautiful and Cantankerous Instruments': Telescopes, Technology, and Astronomy's Changing Practice," *Experimental Astronomy* 25 (2009): 79-89.

between types of image tubes]. Though television tubes had the potential to combine the technical advantages of photomultipliers with the spatial information provided by photography, they also had, for example, poor resolution and difficulty resolving scenes with small differences in contrast.[25] In an effort to explore their possibilities, some astronomers experimented with electronic image tubes already successfully employed in commercially-available television cameras, which were not designed for the extremely low light levels required in astronomy.[26] Others, however, chose to develop instrumentation specifically for astronomical use. In this dissertation, I trace the development of an image tube that was designed specifically for astronomical application. I have chosen the image tube used by Vera Rubin and Kent Ford because it proved to be one of the most successful and persistent of the image tubes available for astronomers' adoption before all image tubes were replaced by solid state devices in the 1980s.[27]

To be clear, there were numerous efforts to employ image tube technology to amplify and record two-dimensional signals, each with different resources, different design philosophies, and different audiences. The devices they proposed also ranged widely in feasibility and usability. One example neatly illustrates the frustration some harbored over the problem. In 1950, Yerkes Observatory astronomer W. Albert Hiltner consulted with RCA engineer George A. Morton about the possibility of developing an image tube to aid astronomical research.[28] After considering the problem, Morton suggested that the quickest answer for astronomers was to purchase one-hundred photomultiplier tubes, which RCA also produced and sold, and situate them in an array

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25 Carnegie Institution of Washington, Year Book 59: July 1, 1959 – June 30, 1960, 293-306.

26 One group, for example, in England used commercially-available television tubes to conduct planetary studies. See, for example, B.V. Somes-Charlton, "Television as an aid to Astronomy," *New Scientist* (May 1, 1958): 8-11.

27 As historian Robert Smith recounts in his history of the Hubble Space Telescope. Robert W. Smith, *The Space Telescope (Cambridge: Cambridge University Press, 1980)*, See also, Robert W. Smith and Joseph Tatarewicz, "Replacing a Technology: The Large Space Telescope and CCDs," *Proceedings of the IEEE* 73, no. 7 (1985): 1221-1235.

28 As told in William C. Livingston, "Image-tube Systems," *Annual Review of Astronomy and Astrophysics* 11 (1973): 95.

to provide spatial data. This would have resulted in an unusually large detector and would have required extensive engineering work to calibrate the device into a uniform detector. This rather odd story demonstrates the perceived challenges that astronomers and industrial engineers alike saw in the development of image tubes for astronomical purposes and highlights the reaction astronomers faced when they inquired if commercial companies would support the development of astronomical instrumentation. Like many electro-optical companies, RCA wanted to expand their consumer base and sell more products, but they did not want to invest the resources required to design a device for the specific needs of every interested party.

It was not until two decades after RCA brushed aside Hiltner's request that several astronomers at the world's largest observatories successfully applied image tubes in limited capacity. At Kitt Peak National Observatory in 1973, for example, astronomer William Livingston calculated that for the final quarter of 1972, 26% of the observing time on the Steward Observatory 225-cm telescope (roughly 89-inch) and 45% of the observing time on the Kitt Peak National Observatory 210-cm telescope (roughly 83-inch) were assigned for image tube-aided observations.[29] Because the Kitt Peak National Observatory was publicly-funded, the large percentage of observing time dedicated to image tube aided observations supports the argument that astronomers without access to large telescopes at their home institutions valued access to electronic instruments on large telescopes. This was particularly important for astronomers interested in investigating new areas of research opened up or made easier with the equipment, like the study of the physical properties of distant, dim galaxies.

The Carnegie Image Tube Committee

The Carnegie Image Tube Committee (CITC), which operated from 1954 to 1976, was the highest funded group seeking to develop an image tube to aid and advance astronomical observations. The committee was created by Carnegie Institution president Vannevar Bush who,

[29] Percentages given in Livingston, "Image-tube," 95.

during World War II, led nearly all of the United States' civilian-military research and development efforts from the U.S. Office of Scientific Research and Development (OSRD) and after the war articulated a highly influential vision for the relationship between science and government.[30] Bush brought together a group of astronomers, physicists, and engineers to meet the challenge. The project was coordinated through the Carnegie Institution of Washington's Department of Terrestrial Magnetism and included members and collaborators from observatories and laboratories across the United States and England. The initial goal of the CITC was to "explore the possible use of electronic techniques, supplanting or supplementing present photographic methods, to increase the range of telescopes."[31] The Committee believed that an image tube would be useful in any astronomical observing program and should replace direct photography as the primary means of astronomical imaging. The Committee hoped their exploration of devices and techniques would lead to the development of a "manufacturable device for general astronomical use at observatories everywhere."[32] The committee envisioned a device with enough gain to be beneficial for astronomers engaged in any scientific research program, but whose operation was simple enough to be employed by any astronomer at any observatory. During its first decade of operation, the CITC worked with industrial and military laboratories, private and public observatories, and individual astronomers to develop an image tube that they could market to the astronomical community. By 1964, after a ten-year period of research and development, the CITC decided they had developed an image tube that was ready for astronomical research, and though they wished to make further improvements to the device, they believed it was time to release the results of their efforts and receive the credit they believed they

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[30] Vannevar Bush, *Science--The Endless Frontier: A Report to the President on a Program for Postwar Scientific Research* (Washington, D.C., National Science Foundation, 1980) Bush advocated for government support of basic science as an important piece of national security and national prosperity. For a biography of Vannevar Bush, see, for example Zachary G. Pascal, *Endless Frontier: Vannevar Bush, Engineer of the American Century* (New York: Free Press, 1997).

[31] Carnegie Institution of Washington, Year Book 52: July 1, 1952 – June 30, 1953, 39.

[32] Report of the Committee on Telescope Image Converters, "The Development of Image Tubes for Astronomy," 22 January 1958, Carnegie Telescope Image Tube Converter papers, Carnegie Institution of Washington, Department of Terrestrial Magnetism archives, Washington, D.C.

had earned from the astronomical community. Their tube did receive some modest use and helped astronomers acquire ground-breaking scientific results, but the technology was never fully adopted by the astronomical community.

Scope

By placing the Carnegie Image Tube Committee's effort in context with other non-adopted technology stories, I can better identify how this story fits into a larger narrative of how scientists, more broadly, adopt and do not adopt new tools. I take into account the role of trained specialists and the overlapping of disciplines, how users determine if a technology is successfully adopted by a community, and the role of the military in twentieth century instrumentation development.

Historians of twentieth century science have explored how astronomy responded to changes in the field, brought on by new instrumentation, new techniques, and access to new sources of funding.[33] The inclusion of electronics in astronomy, and the need to consult physicists and engineers, brought about an era astronomer Jesse Greenstein called the "de-astronomization of astronomy."[34] In an account of the emergence of radio astronomy in the mid-twentieth century, David Munns argues that the field of radio astronomy was born from new

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33 For the emergence of new fields within astronomy, brought on by the adoption of new technologies, see David Edge and Michael Mulkay, *Astronomy Transformed: the Emergence of Radio Astronomy in Britain* (New York: Wiley, 1976); Ron E. Doel, *Solar System Astronomy in America: Community, Patronage, and Interdisciplinary Research, 1920-1960* (Cambridge: Cambridge University Press, 1996); and Richard F. Hirsh, *Glimpsing an Invisible Universe: The Emergence of X-Ray Astronomy* (Cambridge: Cambridge University Press, 1983). For cases of instrumentation adoption causing a split in scientific disciplines, generally, see, for example, Cyrus C.M. Mody, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology* (Cambridge, MIT Press, 2011). Nicolas Rasmussen, *Picture Control: The Electron Microscope and the Transformation of Biology in America, 1940-60* (Stanford: Stanford University Press, 1997) and Timothy Lenoir and Christophe Lécuyer, "Instrument Makers and Discipline Builders: The Case of Nuclear Magnetic Resonance," *Perspectives on Science* 3 (1995): 276-345.

34 Jessie Greenstein, interview by Rachel Prud'homme on 16 March 1982, California Institute of Technology Archives, 37. For more on the inclusion of electronics in astronomy and its effects on the astronomy profession, see DeVorkin, "Electronics;" Smith and Tatarewicz, "Replacing;" and W. Patrick McCray, "How Astronomers Digitized the Sky," *Technology and Culture* 55, no. 4 (2014): 908-944.

instrumentation and the insertion of physicists and engineers into the field of astronomy, creating a new sub-discipline of radio astronomy.[35] If astronomers wanted to take advantage of the newest technologies available, they either needed to learn new skills or bring trained specialists into their field. While the field of radio astronomy prospered, the simultaneous development of image tubes languished. Both episodes in astronomical history required astronomers to adjust the way they performed their work, but only one succeeded in receiving long-term use.[36]

As opposed to radio astronomy, the short-lived, limited use of image tubes provides a unique case of technology adoption in astronomy, but similar stories can be found in the relationships between producers and users of technology. In his account of the failure of the electric automobile, historian Gijs Mom begins his introduction with a quote from German sociologist Werner Rammert: "A technology does not succeed because it is technologically superior, but is considered technologically superior because it has sociologically succeeded." [37] This quote set the stage for Mom's argument that the triumph of the gasoline car was not inevitable but due to the cultural construction of these technologies. He argued that the competition and flow of ideas and innovations among builders of bicycles, trams, and all forms of cars stimulated improvements. Ultimately, the electric car contributed much to the design of the

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[35] David Munns, *A Single Sky: How an International Community Forged the Science of Radio Astronomy* (Cambridge: MIT Press, 2012).

[36] The adoption of instrumentation in space astronomy and the adoption of computers also succeeded in receiving long-term use in astronomy. For more on instrumentation in space astronomy, see Smith, *The Space Telescope* and Hirsh, *Glimpsing an Invisible Universe.* For the adoption of computers, see McCray, "How Astronomers Digitized," and *Giant Telescopes*.

[37] Quoted in Gijs Mom, *The Electric Vehicle: Technology and Expectations in the Automobile Age* (Baltimore: The Johns Hopkins University Press, 2004). Historians of technology have examined reasons technologies failed to be adopted by a community. For other accounts of technological failure, see, for example Arwen P. Mohun, *Steam Laundries: Gender, Technology, and Work in the United States and Great Britain, 1880-1940 (Baltimore: Johns Hopkins University Press, 1999)*, David Kirsch, *The Electric Vehicle and the Burden of History* (New Brunswick, Rutgers University Press, 2000), and Eric Schatzberg, *Wings of Wood, Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914-1945* (Princeton: Princeton University Press, 1999). For more on the path dependence view of technological choice, see, for example, Paul A. David, "Path Dependence and the Quest for Historical Economics: One More Chorus of the Ballad of QWERTY," *University of Oxford, Discussion Papers in Economic and Social History* 20 (Nov. 1997): 1-48.

gasoline car, including gearing systems, cord tires, and electric starters. Although the electric car did not beat out its rivals, parts of its design, those favored by the users of each piece of technology, can be seen in the triumphant vehicle.

Robert Smith addresses this issue of technological choice in his account of the development of the Hubble Space Telescope.[38] Astronomers had to choose between competing imaging technologies to serve as detectors in the telescope's cameras. Since no detector could satisfy the needs of every astronomer, astronomers could not agree on which technology provided the better image because better meant different things to different sub-communities in astronomy. Instead, the scientists, engineers, and administrators involved had to compromise and consider non-scientific concerns, like the engineering schedule, cost, and required maintenance. The CITC operated as a conduit between the user and producer and as a result, effectively directed Carnegie's entire development path of image tubes for astronomers.[39] Through my dissertation, I show that, as with the case of the Hubble Space Telescope, the historical process by which image tubes failed to secure regular use cannot be explained solely by addressing the technical concerns of the astronomical community, but must simultaneously consider the efforts of the producer group to engage its users, the astronomical community, and that community's social resistance towards change.

In attempting to serve as a conduit between the producers of image tube technology and the potential users of that technology, the CITC had to compete for commercial resources. The military formed a much bigger user group for image tube technology and Carnegie could not

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[38] Smith, *The Space* Telescope, 104.

[39] Accounts of user-directed technological developments like those found in Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch, ed. *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology* (Cambridge: MIT Press, 2012), especially Edward Yoxen, "Seeing with Sound: A Study of the Development of Medical Images," 273-295, Nelly Oudshoorn and Trevor Pinch, ed., *How Users Matter: The co-construction of users and technology* (Cambridge: MIT Press, 2005), Ronald Kline and Trevor Pinch, "Users as Agents of Change," *Technology and Culture* 37, no. 4 (Oct., 1996): 763-795, and David Noble, "Social Choice in Machine Design: The case of automatically controlled machine tools," in A. Zimbalist, ed., *Case Studies on the Labor Process* (New York, Monthly Review Press, 1979): 18-50, and Ronald Kline, *Consumers in the Country: Technology and Social Change in Rural America* (Baltimore: Johns Hopkins University Press, 2000).

compete with their defense budgets. Robert Smith has examined the ways historians have looked at detectors, made increasingly sensitive in and beyond the visible portion of the electromagnetic spectrum, and largely advanced by a push from military and national defense needs.[40] Because the CITC could not compete with defense spending, they attempted to find common problems that the military was interested in, in order to benefit from their development efforts. Though they were able to work alongside military scientists in some capacity because of their interest in extending the range of detectors beyond the visible, their goals were too different to sustain collaboration.

This story is part investigation of a group of innovators, part biography of a technology. This is not a survey of how image tubes work, but I will provide technical detail to the extent that such information reveals relevant information regarding the potential scientific use and methods of operation. Analyzing a technology in this way can illuminate the relationships between the technology and its producers and users, in this case, the technology being the combination of the object and the knowledge required to operate that object. The debate whether to adopt this technology is a debate over whether to adopt the system as a whole.

Chapter elements

This dissertation is divided into five chapters, the first examining the history of astronomical imaging and the following four each chronicling a period of the Carnegie Image Tube Committee's efforts to develop image tubes. Each chapter explores historiographical themes that together build to inform the central question of how astronomers acquire new tools

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40 Robert W. Smith, "Engines of Discovery: Scientific instruments and the history of astronomy and planetary science in the United States in the Twentieth Century," *Journal for the History of Astronomy* 28 (1997): 56. For more on how historians have examined how national security, more than the quest for scientific knowledge, have funded postwar science and technology, see, notably, Paul Forman, "Behind Quantum Electronics: National security as a basis for physical research in the United States, 1940-1960," *Historical Studies in the Physical Sciences* 18 (1987): 149-229 and Walter A. McDougall, …*the Heavens and the Earth: A Political History of the Space Age* (New York: Basic Books, Inc., Publishers, 1985).

and how the adoption or non-adoption of new instruments transformed the profession. In the first chapter, “Imaging in Astronomy: The adoption of new technologies and techniques,” I present the history of astronomical imaging and explore the effect of new technologies on astronomers’ understanding of what was considered a subjective record. As new imaging technologies were adopted by astronomers, the astronomical community had to redefine what activities constituted astronomical research. I use this chapter to provide context for how image tube technology fits into this long legacy of astronomical imaging and to examine episodes of astronomers’ successful adoption of new tools.

In the second chapter, “From Physicist to Astronomer: Ira Bowen and William Baum and the push for electronic imaging,” I argue that because older astronomers were hesitant about adopting new technologies and lacked the technical training to utilize newly discovered electronic techniques, physicists were needed to move into the field of astronomy to direct advances in astronomical instrumentation. In this chapter, I look at the stories of two physicists at the Carnegie Institution of Washington’s California observatories, who both became important figures in the Carnegie Image Tube Committee. Examining the background of both men helps me show the reader that both had experience pushing for new instrumentation in astronomy, but because of their different roles and responsibilities, only one, William Baum, could actively press for the immediate development of electronic imaging at the Carnegie Institution.

Baum gained much of his experience in electronics working for the military during and immediately following World War II. This common theme in twentieth century science has been written about by several historians and notably summarized by Robert Smith in his 1997 article, “Engines of Discovery: Scientific instruments and the history of astronomy and planetary science in the United States in the twentieth century.”[41] Smith highlights the change in the division of labor in instrument development, particularly how specialists, who did not consider themselves to be astronomers, were required for technical work. In this chapter, I argue that young astronomers

[41] Smith, “Engines,” 56-70.

and physicists stimulated the conversation in the astronomical community for the development of electronic instrumentation and blurred the line between physicist and astronomer.

In the third chapter, "Vannevar Bush and the establishment of the Carnegie Image Tube Committee," I examine major decisions that set up the subsequent two decades of image tube development. I argue that Vannevar Bush's belief in the promotion and development of American science led him to locate resources with the intention that the Carnegie Institution would take a leading role in development efforts, so that role would not be left to commercial enterprise. Bush decided to form a committee to begin work investigating the potential benefit of image tubes in astronomy and made Merle Tuve, director of Carnegie's Department of Terrestrial Magnetism, chairman of the committee. Tuve, I argue, was another physicist chosen because of his prior experience directing a laboratory and his experience with electronics.[42] In this chapter, I show how the CITC established goals for its development project and opted to design a device that could be used by any astronomer, in any sub-field. In "Users and Producers: The role of user groups in the CITC's examination, selection, and promotion of image tubes," I demonstrate how the CITC, with funding from the recently established National Science Foundation, was able to contract the production of image tubes for testing.[43] In this chapter, I explore the interplay

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42 Michael Dennis has shown how Tuve adapted and expanded DTM's scientific program to include sustained laboratory research while maintaining his own anti-market ideology. Michael Aaron Dennis, "A change of state: The political cultures of technical practice at the MIY Instrumentation Laboratory and the Johns Hopkins University Applied Physics Laboratory, 1930-1945" (PhD diss., Johns Hopkins University, 1990), especially chapter 2, "Between the Magnet and the Marketplace: Merle Tuve at the Department of Terrestrial Magnetism." Tuve's additional development of electronic instrumentation during World War II, namely the improvement of the proximity fuze, an alternative to the less-reliable contact and timed fuze, helped Tuve transform DTM into a premier laboratory after the war.

43 For further discussion of the National Science Foundation as a piece of Big Science funding, see Stuart Leslie, *The Cold War and American Science: The Military-Industrial-Academic Complex at MIT and Stanford* (New York: Columbia University Press, 1993); Daniel J. Kevles, *The Physicists: The history of a scientific community in modern America*, 2nd edition (Cambridge: Harvard University Press, 1995), chapters 21-23; Robert W. Seidel, "A home for big science: The Atomic Energy Commission's laboratory system," *Historical Studies in the Physical and Biological Sciences* 16, no. 1 (1986): 135-175; Paul Forman, "Behind quantum electronics: National security as basis for physical research in the United States, 1940-1960," *Historical Studies in the Physical and Biological Sciences* 18, no. 1 (1987): 149-229; Peter Galison and Bruce Hevly, eds., *Big Science: The growth of large-scale research* (Stanford: Stanford University Press, 1992); James Capshew and Karen Rader, "Big science: Price to the present," *Osiris* 7 (1992), 3-25; and, for the

between technology and user groups by examining a ten-year effort by industrial laboratories, the CITC, and the astronomical community as they jointly endeavored to construct a device that would meet the needs and goals of all three groups.[44] Throughout this process, the Carnegie group attempted to disseminate information about image tube technology and their progress through publications and conference presentations. Through these promotional efforts, the Committee attempted to form a relationship between the builders and the potential users of this technology, but they struggled to provide an avenue for two-way communication that was acceptable to many astronomers. Their failure to engage the astronomical community in a dialogue, rarely listening to feedback concerning various development paths, I argue, resulted in a user group without real buy-in on the final product.

In 1976, Phillip Abelson, who became director of the Carnegie Institution in 1971, argued that the CITC ushered in a new era of astronomical imaging. I explore his claim in Chapter 5, "Reception of the Carnegie Image Tube: Scientific use and non-use," where I examine the results of the CITC's efforts to develop an image. The CITC contracted RCA to manufacture image tubes to be allocated to selected astronomers for use. Of the Carnegie image tubes that were allocated, some were used actively by astronomers, some garnered intermittent use, and some were largely neglected. Vera Rubin, most famously, used a Carnegie Image Tube to find evidence for the existence of dark matter. In this chapter, I examine astronomers' use and non-use of the Carnegie Image Tube in order to assess the success of the CITC. They were unsuccessful, I argue, at meeting the goals they had established at their formation, but they laid the groundwork for a new era in observational astronomy by showing that there was a need in the astronomical community for more sensitive and efficient detectors.

In this dissertation, I show how the backgrounds of several key physicists influenced the direction of image tube research at the Carnegie Institution and I examine how the concern of

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interwar period, see J.L. Heilbron and Robert Seidel, *Lawrence and his laboratory: A history of the Lawrence Berkeley Laboratory* (Berkeley: University of California Press, 1989).

44 The role of users in technology development has been written about, most notably in Oudshoorn and Pinch ed., *How Users Matter*.

scientific prestige led the Carnegie Institution president to decide to form a committee to investigate image tube technology. I detail how the increase in federal funding helped this effort sustain itself through two decades of development and, finally, I show which astronomers used the Carnegie image tube and examine the many reasons why most astronomers chose not to employ the new way of observing. While the CITC's efforts did not result in an overwhelming adoption of image tubes by the astronomical community, by examining how the Carnegie image tube was produced, funded, and marketed, I hope to have shed light on the many and varied processes through which astronomers have acquired new tools. By additionally investigating how, where, and by which astronomers employed the Carnegie image tube to acquire useful scientific data, I hope to have provided an account of the ways in which producers introduce new technologies or techniques can influence astronomer's adoption of those new tools.

CHAPTER 2

IMAGING IN ASTRONOMY: THE ADOPTION OF NEW TECHNOLOGIES AND TECHNIQUES

Introduction

> "While my aim in this work has been to combine scrupulous fidelity and accuracy in the details, I have also endeavored to preserve the natural elegance and the delicate outlines peculiar to the objects depicted; but in this, only a little more than a suggestion is possible, since no human skill can reproduce upon paper the majestic beauty and radiance of the celestial objects."
> Étienne Léopold Trouvelot, 1882[45]

From 2000-2001, the New York Public Library ran an exhibit called, *Heavens Above: Art and Actuality*, a comparison of astronomical imaging across technological eras. In *Heavens Above*, the exhibit designers situated the nineteenth century celestial drawings of French-American artist and self-taught astronomer E.L. Trouvelot alongside images from NASA's spacecraft and telescopes.[46] Though Trouvelot intended his illustrations to represent actual celestial phenomena, "as they appear to a trained eye…through the great modern telescopes," one could observe, as a reviewer of the exhibit noted, the sense of elegance and charm which Trouvelot sought to preserve.[47] The exhibit designers differentiated between what they saw as Trouvelot's artistic work and the more accurate representation by NASA instrumentation (see Figure 2.1 for an example of the comparison of Jupiter). As one reviewer noted, the show, "compare[d] how astronomy was depicted in the 19th century with our own technological take on

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45 Étienne Léopold Trouvelot, *The Trouvelot Astronomical Drawings Manual*, vol. 15 (New York: Charles Scribner's sons, 1882), v.

46 "Heavens and Above: Art & Actuality" New York Public Library online exhibit, accessed February 20, 2019, http://web-static.nypl.org/exhibitions/trouvelot/index.html.

47 Fred Benheim, "The art and science of Etienne Trouvelot," *The Lancet* 357, no. 9272 (Jun 16, 2001): 1983-1984.

Trouvelot quote in Trouvelot, *The Trouvelot Astronomical Drawings Manual*, iv.

the heavens."[48] In both cases, an astronomer produced the astronomical image as a pictorial representation of observational data.

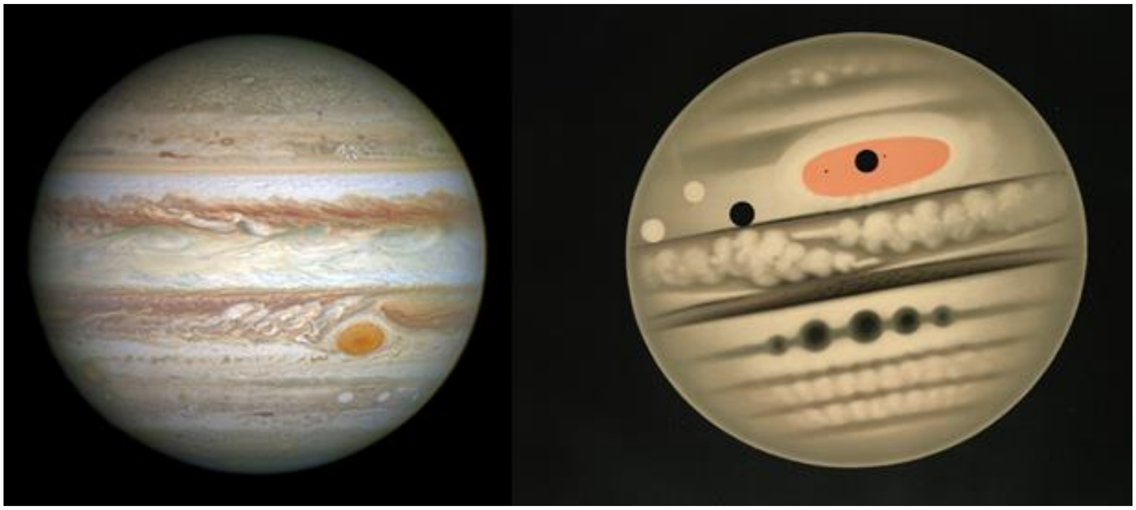

Figure 2.1. Comparison of Jupiter images. Hubble Space Telescope (left) Trouvelot drawing (right)[49]

Historians like Elizabeth Kessler, Mary Winkler, and Albert van Helden have noted that in both eras of astronomical imaging, hand-drawn and computer-generated, astronomers produced a subjective record that required written explanation to accompany the visual representation.[50] Galileo, the first astronomer to use images to represent observational data, always accompanied a hand-drawn image with a written description. He valued the written word over an image, but acknowledged that both were useful in convincing other astronomers and the public of his scientific claims.[51] In the case of NASA's Hubble Space Telescope, astronomers have used Hubble data to create images by adjusting various parameters, including color and contrast, into

48 Benheim, "The art and science," 1983-1984.

49 NASA, ESA, and A. Simon, "Jupiter, WFC3/UVIS," NASA/GSFC, April 21, 2014

E.L. Trouvelot. "The planet Jupiter: Observed November 1, 1980, at 9h. 30m. P.M.," *The Trouvelot astronomical drawings: Atlas* (New York: C. Scribner's Sons, 1881-1882).

50 Elizabeth A. Kessler, *Picturing the Cosmos: Hubble Space Telescope Images and the Astronomical Sublime* (Minneapolis: University of Minnesota, 2012).

Winkler and van Helden," Representing the Heavens."

51 Winkler and van Helden, "Representing the Heavens," 210.

an aesthetically pleasing final product that represented the original data.[52] In both cases of technological use, astronomers needed to learn to use different skills than had been required of the prior generation in order to adopt the newest tool or technique.

Historians have investigated the changing landscape of imaging and the role of observation in science and have asked how scientists' and the public's understanding of and trust in observation changed with new techniques and instrumentation.[53] Additionally, historians have addressed the relationship between the change in astronomical practice and the adoption of new instrumentation.[54] In this dissertation, I examine the adoption story of electronic imaging, which differs from that of other major forms of astronomical imaging in its uptake and reception. However, the story of the Carnegie Image Tube Committee's attempt to introduce electronic imaging into astronomy shares common themes with past eras of imaging technologies. Historians have examined how, for example, the authority of or trust in the observer, the role of trained assistants, the further separation of the astronomer from the objects they study, and the objectivity of the produced image affected astronomers' uptake of prior technologies. In this chapter, I will briefly examine the adoption of observational techniques and instrumentation through four technological phases of imaging in astronomy, discuss common issues addressed by historians in recent literature, and compare how each technology entered the astronomical field:

(1) the eye and the application of the telescope;

(2) the use of hand-drawn images as scientific evidence;

(3) the application of photography to add objectivity and sensitivity;

(4) and early attempts to develop electronic imaging devices.

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52 Kessler, *Picturing the Cosmos,* 7.

53 Lorraine Daston and Peter Galison, *Objectivity* (Cambridge: MIT Press, 2007).

54 For the effect of photographic techniques, see Lankford, "The impact of photography," for photoelectric photometers, see DeVorkin, "Electronics in astronomy," and for solid-state devices, see Smith and Tatarewicz, "Replacing a technology." For instrumentation changes in radio astronomy, see Munns*, A Single Sky* and for x-ray astronomy, see Hirsh, *Glimpsing an Invisible Universe*.

Through this exercise, I will argue that astronomers had to contend with issues of authority and objectivity in adopting technologies prior to the twentieth century, but those concerns were largely absent with the introduction of electronic techniques. This may have been the result of electronic imaging first finding use by the military, legitimizing the technology for astronomers. Present during all eras were issues of the training required to operate the new devices and the further separation of the astronomer from the telescope. An examination of these episodes and the common issues astronomers encountered before adopting each new tool or technique is important to understand under what circumstances astronomers moved past their concerns and made the choice to adopt a new way of recording observations. Furthermore, as a result of the discussions in this chapter, I can in later chapters show the unique hurdles the Carnegie Image Tube Committee encountered in their attempt to disseminate a new technology.

The astronomer's eye and the telescope

Well into the nineteenth century, imaging was not a common activity in astronomy. The aim of a majority of astronomers was to map the sky, noting the position and motion of celestial objects. The introduction of instruments like the telescope, that could increase the input of light into the astronomer's eye, was a major component in the development of modern science, but in the seventeenth and eighteenth century, mainly served to assist astronomers in the cataloging of the positions of celestial objects. Most astronomers sought to determine where an object was, but did not attempt understand what it was. However, a few astronomers, like Galileo, used the telescope to further their understanding of the *nature* of celestial objects. Historian Harold Brown has discussed the early conflict brought about by discrepancies between telescopic and unaided views of the moon, sun, planets.[55] Brown argues that telescope users like Galileo had the burden of showing why instruments provided a better approximation of nature and were more reliable

[55] Harold Brown, "Galileo on the Telescope and the Eye," *Journal of the History of Ideas* 46, no. 4 (Oct.-Dec. 1985): 487-501. See also, Harold Brown, *Observation and Objectivity* (Oxford: Oxford University Press, 1987).

than observations without the aid. The optical principles underlying the telescope, stemming from the invention of eyeglasses and the advances in lens making that followed, were initially not entirely understood by astronomers nor the public and astronomers often kept their techniques for making lenses secret but they needed the public to trust the resulting image they produced.[56] Astronomers like Galileo built their own telescopes with crudely shaped lenses, but slowly a group of skilled workers emerged, specialized in lens-grinding and polishing techniques, who astronomers relied upon to make higher quality lenses for their telescopes. Though few astronomers were using the telescope to capture the image of an object, the community had to prove the accuracy of the telescope.

Historian Albert van Helden has discussed how telescopic observations were a private activity, with only one person viewing through the eyepiece at a time, making it difficult to compare observations.[57] Often astronomers hyped the quality of their telescope or their skill as an observer, with a trained eye. As a result, astronomers' sought methods to explain the value and trustworthiness of the telescope.[58] While some astronomers debated the quality of their telescope, Galileo argued that the human eye was also an instrument whose output needed to be evaluated, interpreted, and at times, corrected.[59] However, astronomers like Galileo sought to maintain the authority of their profession and the objectivity of the observational experience, despite their reliance of a subjective sense. Furthermore, van Helden has discussed how astronomers lacked a visual language that they could use to effectively communicate their work to the public and that the public could use to describe their experience at the eyepiece of a telescope, resulting in a major hindrance in their belief of the output of a telescope. Given that the eyesight of each person varied, and without a strong common visual language to use,

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[56] van Helden, "Telescopes and Authority," 10. For more on the general theme of cultivation of trust and laboratories as a place of secrecy, see Steven Shapin and Simon Schaffer, *Leviathan and the Air Pump: Hobbes, Boyle and the Experimental Life* (Princeton: Princeton University Press, 1985).

[57] van Helden, Albert. "Telescopes and Authority," 8-29.

[58] Brown, "Galileo on the Telescope."

[59] Brown, "Galileo on the Telescope."

seventeenth century astronomers had to use a variety of tactics to convince the public of their observations trustworthiness. This included public demonstrations, where telescopic images were projected directly from the telescope and viewed by multiple people at once, though this only worked for demonstrations of the sun's surface. Astronomers also attempted to appeal to the superiority of individual astronomers' observing skills and equipment and relied on the prestige or trust in the individual astronomer.[60] While some astronomical discoveries could be verified by other astronomers, because of differences in telescopic equipment, eyesight, and observing condition, many could not. There was no easy solution to this problem so astronomers' and the public's acceptance of claims often relied on the prestige of the individual astronomer and their equipment.

Observation is a vital aspect of astronomical research but because the telescope put more distance between the observer and the object observed astronomers had to contend with issues of authority, trust, and objectivity. Astronomers had to rely on their own prestige and that of their telescope to convince others of the trustworthiness of the telescope's output. The reliance on prestige would become important again with the arrival of each new imaging technology.

Sketching and painting the sky

Historian Omar W. Nasim and others have described the revolutionary transformation in how Galileo's and his contemporaries' astronomical drawings came to represent data and not merely representational diagrams.[61] The first use of images in astronomy were diagrams, often showing the motion of the planets and stars. Galileo's first use of images were meant to be representational diagrams more than exact renderings.[62] Drawing was useful for conveying

60 van Helden, "Galileo and Scheiner."

61 Nasim, *Observing by Hand*, Gingerich and van Helden, "From Occhiale," Gingerich and van Helden, "How Galileo Constructed," van Helden, "Galileo and Scheiner," and Winkler and van Helden, "Representing the Heavens."

62 Nasim, *Observing by Hand*.

shapes, forms, and areas of light and dark through the use of shading to give the general view of an object. When Galileo (1564-1642) began sketching the craters of the moon, he wanted to evoke a sense of a changing landscape as the sun's rays hit the surface with a changing angle, but these images were meant to convey a general shape, not exact detail. Galileo's observations and accompanying drawings made the universe physical and other astronomers began to use a pencil or brush to create an accurate portrait of the objects they discovered through their telescopes.

While Galileo used his own artistic talent, though limited in skill, to sketch what he observed, other astronomers relied on experienced artists and engravers. The need for a trained assistant became more important as astronomers' required new skills to carry out their work. Because of the added distance between the observer and the image that was created when an assistant produced the final image, some astronomers viewed that product as more subjective. Astronomer Johannes Helvelius (1611-1687) argued that the work produced by an astronomer who was both observer and sketcher was more valuable than that produced by two specialists working together.[63] The artistic skill of the astronomer became an important part of the observing process, giving the claims of one who could both perform astronomical observations and sketch or paint those observations more authority.

Though astronomy was largely non-image based through much of the nineteenth century, two areas of telescopic astronomy were becoming so: planetary and nebulae studies. From the late eighteenth through the nineteenth century, astronomers William Herschel (1738-1822) and Lord Rosse, born William Parsons, (1800-1867), produced "working images" of nebulae, a series of drawings of the same object over many nights, through increasingly powerful telescopes.[64] Herschel used a reflecting telescope with a 48-inch mirror and a 20-foot focal length and Lord

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[63] Dieter Hermann, "Astronomers as sketchers and painters: the eye – the hand – the understanding," *Contributions, Section of Natural, Mathematical and Biotechnical Sciences* 39, no.1 (2018): 5-14.

[64] Nasim, *Observing by Hand*, 10.

Rosse used a 72-inch telescope. Both telescopes were built by their observers.[65] Rosse employed a trained artist and observer, Samuel Hunter, to assist in his observations and Herschel worked alongside his sister, Caroline Herschel. These series of nebulae images, Nasim argues, were part of the astronomers' process to become familiar with each celestial object in order to illustrate it more accurately.

William Herschel's son, John Herschel (1792-1871), a talented astronomer and artist himself, contended that "what occurs on paper is not only an inscription of an object but also a reflection of the mind's activity of construction."[66] An excellent case in point was Étienne Léopold Trouvelot (1827-1895) whose astronomical drawings and paintings were printed and exhibited more like art than scientific evidence. His eye for detail, however, attracted the attention of contemporary astronomers. Trouvelot, for example, painted structure in the rings of Saturn that would not be rediscovered for 100 years with a NASA spacecraft. Many of these observer/artists similarly sought to dedicate as much time as possible viewing a single object through a telescope. Through this familiarization, they hoped to approach accuracy, still, whether an astronomer's claim was accepted as truth largely depended on the prestige of the observer and their instrument.

Photography and objectivity

Astronomers' reliance on the prestige of the observer in determining the trustworthiness of astronomical drawings as evidence for scientific claims became critical with the debate over the canals of Mars that a few astronomers claimed to have observed at the turn of the twentieth century.[67] The debate over the nature of Martian canals began in 1877, after Giovanni

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65 48 and 72 refer to the diameter of the primary lens or mirror in the telescope. This is commonly how astronomers refer to telescope size.

66 Nasim, *Observing by Hand*, 159.

67 William Sheehan, *Planets and Perception* (Tucson: University of Arizona Press, 1988), Martin Willis, "Optical Shattering: Percival Lowell, Mars, and Authorities of Vision," in *Vision, Science and Literature, 1870-1920: Ocular Horizons* (Pittsburgh: University of Pittsburgh Press, 2011).

Schiaparelli used an 8-inch telescope to observe Mars and reported a system of *canali* that covered most of the Martian surface. Other astronomers, most vocally Percival Lowell, reported seeing the same features, but many criticized their drawings of straight, narrow lines (see Figure 2.2). Astronomers using larger telescopes could not see the features described by Schiaparelli and Lowell, leading some to wonder if telescopes of larger diameter were unable to revolve planetary features.[68] American astronomer Edward Emerson Barnard quipped:

> I have carefully observed, drawn, and measured the surface markings of this planet with the thirty-six-inch during the past two oppositions. I have also examined a great many drawings made of t with all kinds of telescopes, and must confess that I have been amazed at some of the details shown on many of these drawings. I must confess also that in many respects it seems proved, if we are to take the testimony of the drawings themselves, that the smaller the telescope the more peculiar and abundant are the Martian details.[69]

To dispense with the skepticism, Lowell set to photograph Mars: "To make the canals of Mars write their own record on a photographic plate, so that astronomers might have at first hand objective proof of their reality."[70] Photographing Mars was challenging and Lowell had to contend with disturbances in the earth's atmosphere, which caused the light from Mars to slightly move. The eye could account for this movement, but slow photographic emulsions could not, resulting in a blurry image (see Figure 2.2). Consequently, Lowell often accompanied his photographs with drawings of Mars to better explain the features in the photographs.[71] While photographs of Mars

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[68] Pedro Ruiz-Castell, "Priority claims and public disputes in astronomy: E. M. Antoniadi, J. Comas I Solà and the search for authority and social prestige in the early twentieth century," The *British Journal for the History of Science* 44, no. 4 (December 2011): 520.

[69] E.E. Barnard, "Micrometrical measures of the ball and ring system of the planet Saturn, and measures of the diameter of this satellite Titan, made with the 36-inch refractor of the Lick Observatory in the year 1895. With some remarks on large and small telescopes," *Monthly Notices of the Royal Astronomical Society* 55 (1895-1896): 166-167. Quoted in Ruiz-Castell, "Priority claims," 519.

[70] Percival Lowell, "First Photographs of the Canals of Mars," *Proceedings of the Royal Society. Series A, containing Papers of a Mathematical and Physical Character* 77, no. 515 (8 Feb. 1906): 132.

See also, Jennifer Tucker, *Nature Exposed: Photography as Eyewitness in Victorian Science* (Baltimore: Johns Hopkins University Press, 2013): 207-233.

[71] Tucker, *Nature Exposed*, 220-221.

were seen as more trustworthy than drawings, they were not objective and both those who supported and opposed the idea of canals used photographs as evidence for their claim.

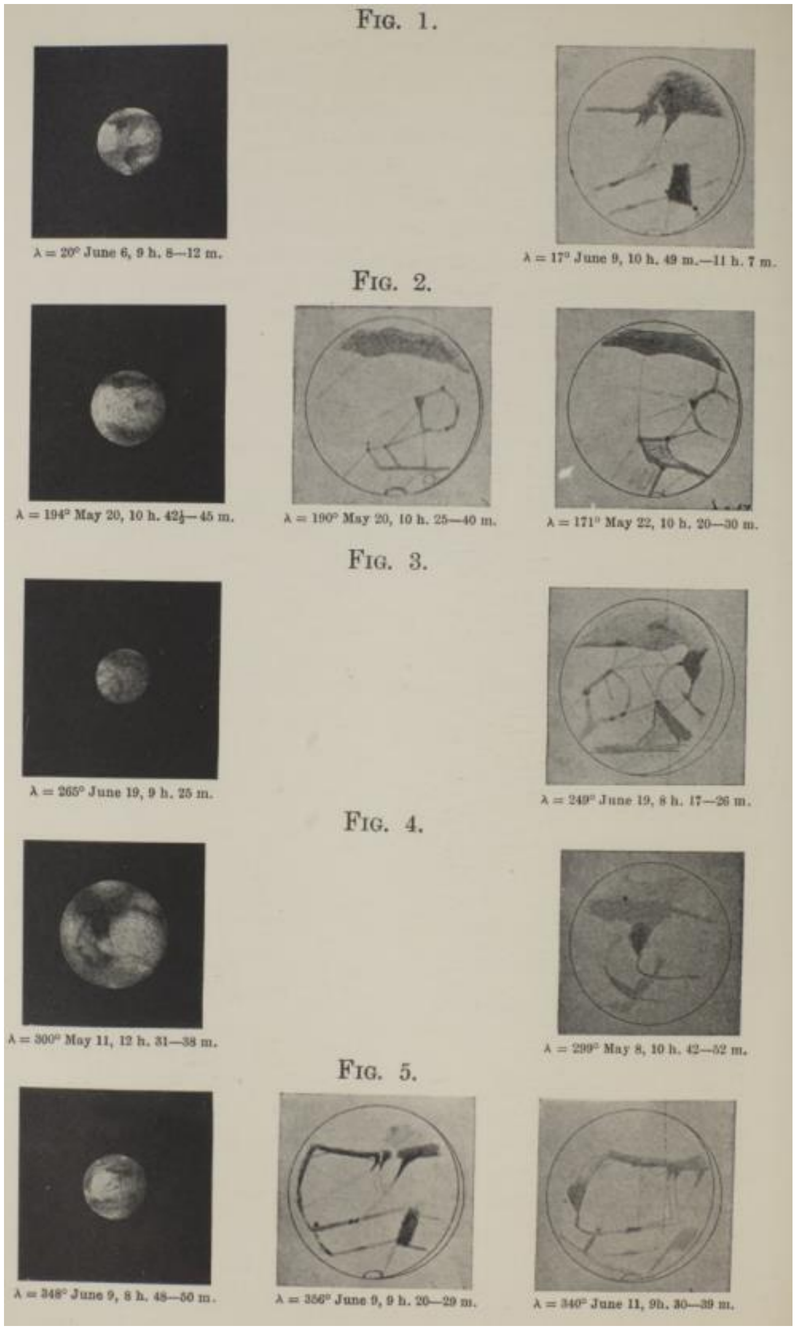

Figure 2.2. Percival Lowell's "First Photographs of the Canals of Mars."[72]

72 Percival Lowell, "First Photographs of the Canals of Mars," 134.

In the late nineteenth century, before Lowell directed his staff to photograph Mars, astronomers began to trust photography to provide a more objective record than the seemingly subjective record of the hand-drawn image because the production of a photographic image did not rely on the interpretation of the observer.[73] Historian Daniel Norman has argued that the development of photography in astronomy is “one of the infrequent cases in science where a new method and instrument of research is immediately accepted and employed to the limits of its capabilities.”[74] The early pioneers in the development of photography were wealthy amateurs, largely by necessity because of the prohibitive costs of the equipment and supplies involved. Photography was transformed during the mid-nineteenth century in the “informal, convivial networks that assembled around the empirical study and drawing of the natural world in genteel circles.”[75] The photographic process became available at a time when *science* came into common language and ideas about empiricism and the inductive method were highly valued.

John Lankford, Peter Galison, and Lorraine Daston, in writing about the role of photography in science, concluded that what gave photographs authority and a supposed objectivity was the method in which they were done and by whom they were made.[76] In the case of Lowell’s Mars photographs, astronomers who opposed the idea of canals did not discredit photography, but the photographer. Historian Jennifer Tucker has compared disbelief in photographs of Martian canals to photographs of spirits and ghosts.[77] Photographs were

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73 For histories on the use of photography in astronomy, including the role of amateurs, see Hoffleit, *Some firsts in astronomical photography*; John Lankford, “Amateurs and Astrophysics: A Neglected Aspect in the Development of a Scientific Specialty,” *Social Studies of Science* 11 (1981): 275-303; Lankford, “Photography and the Long-focus;” Lankford, “The Impact of Photography;” C.E. Kenneth Mees, *From Dry Plates to Ektachrome Film, A Story of Photographic Research* (New York: Ziff-Davis Publishing, 1961): chap. 21; Norman, “The Development of Astronomical;” G. Rayet, “Notes sur l’histoire de la photographie astronomique,” *Extract from Bulletin Astronomique* 4 (1887): 344-360.

74 Norman, “The Development of Astronomical,” 560.

75 Tucker, *Nature Exposed*, 19.

76 Daston and Galison, *Objectivity*, 115-173 for the role of trained judgement and mechanical objectivity in viewing photographic evidence and objective and trustworthy.

77 Tucker, *Nature Exposed*, 119, 233.

supposed to prove their existence, but they did not. Each observer saw what they chose, or wanted, to see in the photograph. French astronomer Camille Flammarion, who had argued for the existence of Martian canals, refused to believe that photographs proved the canals were an illusion because, as one astronomer supposed, Flammarion wished to "remain the great Martian authority."[78] Opposing groups used photographs as evidence for their argument, showing that while astronomers viewed the photographic image as objective, the interpretation of that image was still seen as subjective, with their trustworthiness largely resting on the authority and prestige of the observer.

Applying the photoelectric effect

Nineteenth and early twentieth century astronomers were able to use photography to measure the brightness of celestial objects, but because photographic emulsions were not linear (i.e., there was not a linear relationship between the number of photons that struck a grain of emulsion and how dark that emulsion became), this method required constant calibration. Astronomers in the 1930s experimented with photoemissive materials to develop a detector that was linear and therefore did not require collaboration. As early as 1934, French astronomer André Lallemand attempted to record astronomical images with his camera électronique.[79] Lallemand employed the electronographic method, where light from an object hit a photoemissive surface, releasing photoelectrons, which were magnetically focused to strike an electron-sensitive emulsion. In this method, the end result was very similar in appearance to that of conventional photography – an image on emulsion. Lallemand's camera was successful in its ability to retain a maximum amount of information by minimizing the amount of image degradation. When used by

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78 Quoted in Ruiz-Castell, "Priority claims," 521.

79 André Lallemand, "La Photographie Photoelectronique," L*'Astronomie* 51 (1937):300-304. In English in, André Lallemand, Maurice Duchesne, and G. Wlérick "La Photographie Electronic," *Advances in Electronics and Electron Physics* 12 (1960): 5-16. Also, summarized in Livingston, "Image-Tube Systems," 101 and George R. Carruthers, "Electronic Imaging Devices in Astronomy," *Astrophysics and Space Science* 14 (1971) 346-347.

an observer, nearly every photoelectron was recorded, making it more efficient than traditional photographic emulsion, and therefore reduced the effects of disturbances in the atmosphere which caused an image to appear blurry.

Lallemand's camera (shown schematically in Figure 2.3) consisted of a glass enclosure containing a photocathode, an electrostatic focusing system, and an electron-sensitive plate cartridge. The main weakness of this instrument was its complicated operation. Formerly routine observing nights suddenly required astronomers to conduct a complex science experiment at the telescope. Before each evening's observing session, astronomers first needed to prepare the photocathode. Only after careful cleaning, sealing, and outgassing, could the astronomer position the glass ampoule that contained the photocathode over the electron optics. Lallemand designed an elaborate system of refrigeration using liquid air to prevent contaminants outgassing from the electrographic emulsion into the plate magazine. Though the photocathode could be preserved for many days in the system, the astronomer had to break the glass ampoule and destroy the photocathode in the process of recovering the photographic plates for development. Preparing the tube for exposures with a new photocathode required the astronomer to commit a day's labor. Despite the cumbersome preparation and operation required to use Lallemand's camera, the results obtained showed potential to provide more contrast and better sensitivity than direct photography and astronomers were eager to learn from Lallemand's successes and failures.[80]

[80] B.V. Somes-Charlton, "Photo-Electric Image Techniques in Astronomy," *Journal of the British Institution of Radio Engineers* 19, no. 7 (July 1959): 417-435.

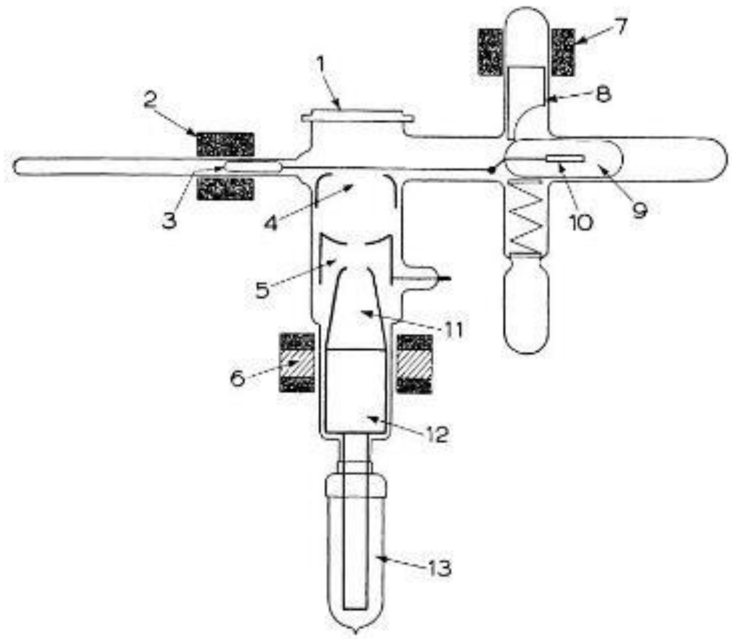

Figure 2.3. Lallemand caméra électronique. Illustrating (1) the entrance window, (2) and (3) the electromagnet and iron plunger used to position the photocathode (10), after breaking the glass ampoule (9) with an iron hammer (8) and electromagnet (7). The electron lenses (4), (5), and (11) electrostatically focus the photoelectrons and the cartridge (12) carries the electron-sensitive plates. The cartridge can be rotated by the electromagnet (6) to change plates. Both the cartridge and the plates are kept cool with liquid nitrogen in the dewar (13).[81]

As Lallemand was developing his electronographic camera, television companies like the Radio Corporation of America (RCA) in the United States and Electric and Musical Industries (EMI) in England had poured extensive funds into developing television camera tubes and receivers in the first half of the twentieth century. Consequently, television research and development were highly competitive and little information was shared across companies and countries. RCA and EMI aspired to make the most profitable television system and neither limited themselves solely to the entertainment or military uses of television technology. Both companies, and their engineers, pushed for a wider use of television tubes, from closed-circuit television systems for security purposes, educational live viewings of surgical procedures, and cameras designed to explore depths of the ocean never before explored. In 1940, RCA engineer, Vladimir

81 Carruthers, “Electronic Imaging,” 346.

Zworykin, sometimes referred to as the inventor of television for his invention of the iconoscope tube (Figure 2.4), took out a patent on a *telelectroscope* (Figure 2.5), a device designed to combine the capabilities of a telescope and television camera to view events at a distance.[82]

Commercial companies used professionally trained physicists to run their television development labs. During World War II, these same physicists were used in efforts to build television-type detectors that could detect heat exhaust from enemy planes, allowing them to be spotted at night. Television detectors used for the military and by broadcast television stations were mass produced and readily available to other groups who might be interested in their use.

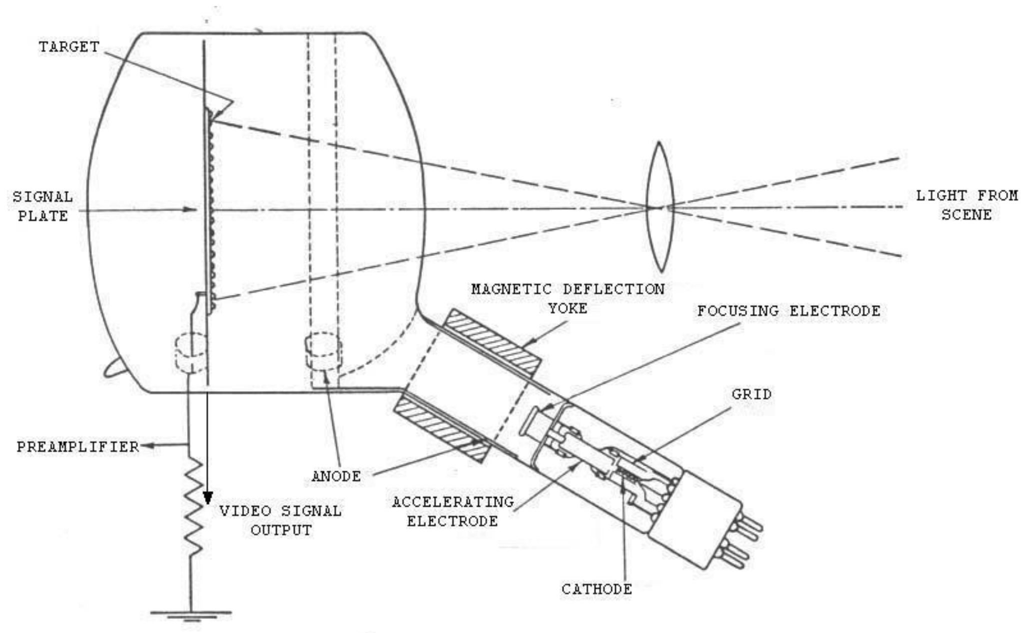

Figure 2.4. The Iconoscope.[83]

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[82] Abramson, *Zworykin, Pioneer of Television*.

Vladimir K. Zworykin, Telelectroscope. U.S. Patent 360,797 filed October 11, 1940, and issued December 8, 1942.

[83] A. Rose, "Television Pickup Tubes and the Problem of Vision," Advances in Electronics and Electron Physics 1 (1948): 152.

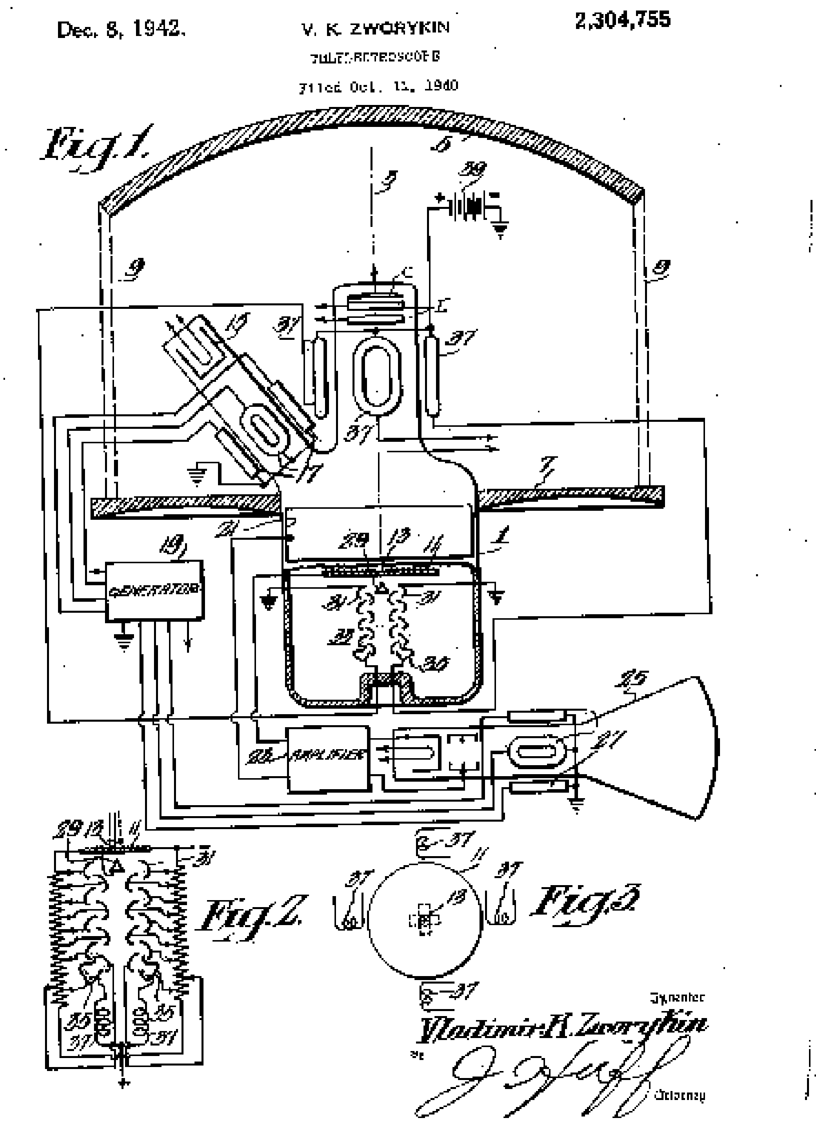

Figure 2.5 Telelesctroscope. Zworykin 1942 patent, combining a television camera (center) with a telescope mirror (5) and correcting lens (1)[84]

[84] Vladimir K. Zworykin, Telelectroscope. U.S. Patent 360,797 filed October 11, 1940, and issued December 8, 1942.

Encouraged by the military's confidence in companies like RCA in particular, beginning in the mid-1950s, astronomers purchased off-the-shelf image orthicon camera tubes, RCA's most recent and successful camera, to test for potential use in astronomy. Astronomers wanted to determine how faint an object could be detected by RCA's mass-produced camera. A television camera tube, in its simplest form, was made up of a photocathode and an electron multiplier. The electron multiplier provided a major increase in sensitivity by raising the level of the output signal well above the amplifier noise. An image orthicon tube, diagrammed in Figure 2.6 and photographed in Figure 2.7, had the added benefit of a secondary target, which further amplified the incoming signal of light.[85] The final output was a video signal derived from the unused portion of the scanning beam.

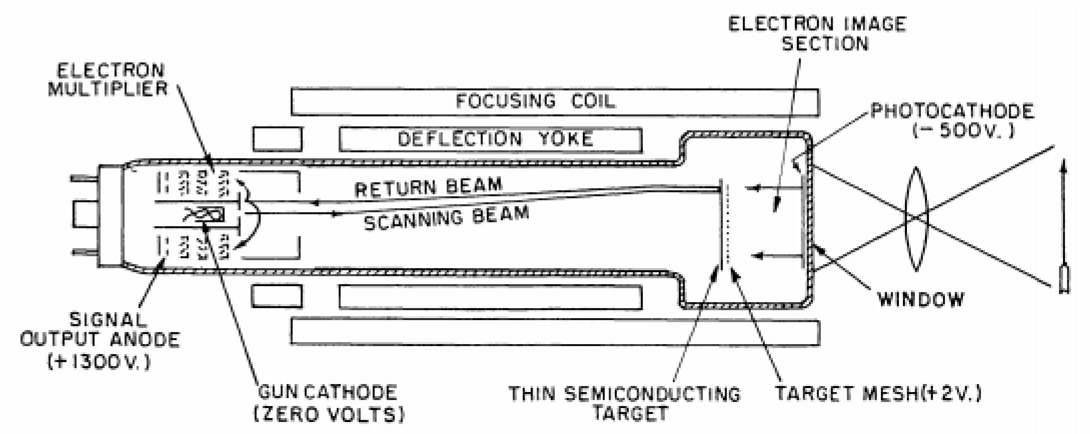

Figure 2.6. Image orthicon tube (diagram). In this diagram, the telescope is represented schematically by a lens on the right hand side and the ray traces are notional. Technically, it is overly simplified since the photocathode would need to be placed at the focal point of the lens.[86]

85 When light from an image was projected onto the transparent photocathode located on the inside of the faceplate of the tube, photoelectrons were emitted from this surface in a number proportional to the intensity of incident light at each point on the surface. These electrons were then focused onto a corresponding position on the target, which was made up of a fine mesh and a thin glass membrane. The mesh allowed most of the photoelectrons through, which resulted in the production of secondary electrons. The resulting secondary electrons were collected by the mesh and maintained at a potential slightly more positive than the target. This caused the target glass to have positive charge and produce an amplification of charge relating to the ratio of secondary electron emission. This image was stored until it was scanned by a beam of electrons produced by an electron gun. This beam deposited enough electrons on the target to neutralize the target charge and drive it down to the potential of the cathode.

86 Carruthers, "Electronic Imaging," 369.

Figure 2.7. Image orthicon (photo). GE-produced image orthicon tube used at Kitt Peak Observatory by William Livingston.[87]

In 1951, astronomer B.V. Somes-Charlton, in collaboration with the Cambridge Observatories, carried out observations with an RCA image orthicon camera tube to ascertain any possible advantages over photography alone.[88] Other astronomers tested image orthicons and published results at the Symposium for Photoelectric Devices, but Somes-Charlton published his results to a wider audience.[89] In these test observations, the glass faceplate (right side of Figure 2.6 and 2.7), was attached to the backend of a telescope, see Figure 2.8. Somes-Charlton produced images by sending the video signal output from the image orthicon tube to a television receiver, producing an image on the screen, which he then photographed using a film camera. Somes-Charlton found initial results, using the moon as the subject, very encouraging.[90] When

87 Photo by author, personal collection.

88 Somes-Charlton, "Photo-electric Image."

89 G.A. Morton and J.E. Ruedy, "The Low Light Level Performance of the Intensifier Orthicon," *Advances in Electronics and Electron Physics* 12 (1960): 183-193; R.K.H. Gebel and Lee Devol, "Some Early Trials of Astronomical Photography by Television Methods," *Advances in Electronics and Electron Physics* 12 (1960): 195-201; Edwin Dennison, "An Isophote Converter for use with Signal-Generating Image Tubes," *Advances in Electronics and Electron Physics* 12 (1960): 307-310.

90 Somes-Charlton, "Photo-electric Image."

Somes-Charlton compared direct photograph and television aided observations, as seen in Figure 2.9, he could qualitatively see the enhanced contrast of the image by the television technique. Because the Image Orthicon tube amplified the light coming from the moon, less time was required for the recording. This shortened exposure time decreased some of the atmospheric effects, which astronomers call *seeing*, which led to a clearer image. Somes-Charlton performed quantitative tests and determined that television was also superior in sensitivity, resolution, and efficiency.

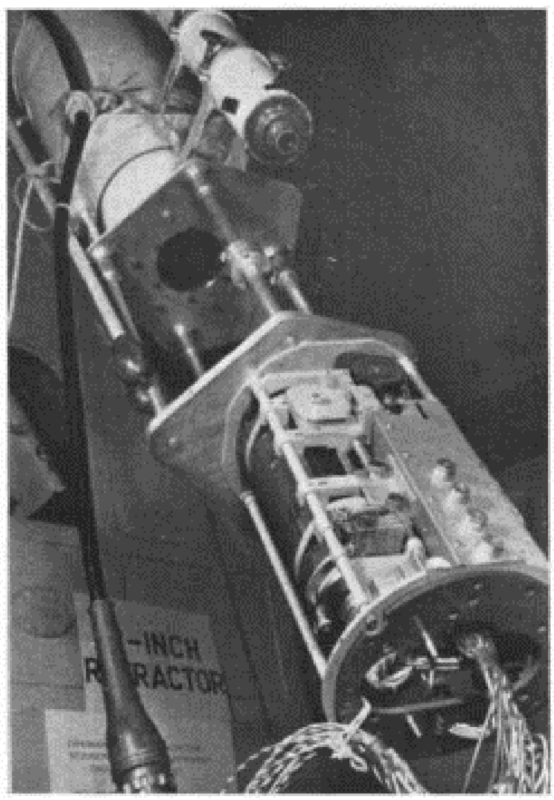

Figure 2.8. Image orthicon assembly attached to Dublin Observatory refracting telescope for demonstrations to the International Astronomical Union in 1955. In addition to the Image Orthicon, the assembly also contained a cooling dewar to maintain the temperature of the detector.[91]

[91] Somes-Charlton, "Photo-electric Image." 429.

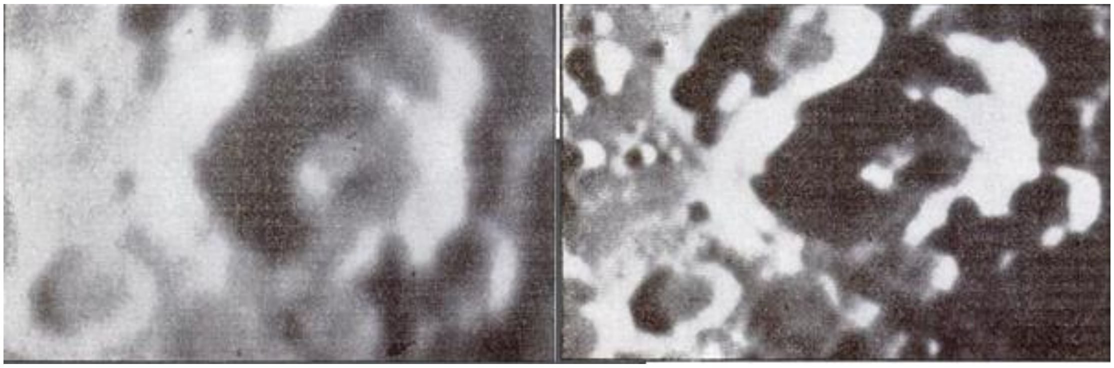

Figure 2.9. Photography vs. the image orthicon. Direct photography recording of the moon at an exposure time of 4 sec. (left) and the moon recorded by an image orthicon, with an exposure time of 0.2 sec, photographed off the screen (right). Both taken with the Cambridge Solar Tunnel Telescope.[92]

Early experimental work with television camera tubes conducted by Somes-Charlton and others proved to the astronomical community that television systems could be employed to the benefit of astronomical observations in limited applications. The promising results of these initial tests encouraged the astronomical community in the potential of the underlying technology but, because most astronomers did not work with objects as bright as the moon, were not considered useful enough to be employed as an off-the-shelf product.[93] Most astronomers needed a modified system to account for the dim objects they hoped to study. The major problem was, how to make a system acceptable and useful for the practicing astronomer.

Unlike prior introductions of new imaging technologies, astronomers did not question the trustworthiness of this device, but not every astronomer could immediately use the new tools. Photographically-recorded observations required some training, but electronically-aided observations required deeper training that not many astronomers typically did not possess. Nineteenth century astronomers had avenues to learn photographic techniques, but twentieth century astronomers were limited in their access to electronic training. Many of those with the

92 Somes-Charlton, "Photo-electric Image." 428.

93 Carnegie Institution of Washington, Year Book 59: July 1, 1959 – June 30, 1960, 293-306.

required training acquired the necessary skills during wartime work, limiting the number of astronomers who felt confident using electronic imaging devices.

Conclusion

In reviewing the Trouvelot exhibit at the New York Public Library, a reviewer likened the positioning of the Trouvelot paintings next to NASA-produced imagery "like comparing a horsedrawn carriage with a modern car."[94] Much like the coachman's use of the horse drawn carriage to move people around town, the astronomer's use of hand drawn images to convey scientific accuracy signified a technological change with widespread consequences for its community. Riders' increased use of the horse drawn carriage led to paved roads and astronomers' use of drawn images of celestial objects provided a calibration process for the telescope: hand-drawn images showed astronomers what they should expect to see through the eyepiece of a telescope.

Ancient astronomers could only study the sky with their eyes, but as astronomers adopted new instrumentation, putting more distance between the object of observation and the observer, they had to reevaluate the meaning and authority of astronomical images. The inclusion of new instruments in astronomy not only expanded the observable universe, but redefined the field of astronomy. It combined questions like what constitutes astronomical data, with what skills are required of professional astronomers. Questions of authority led astronomers to develop better telescopes and eventually methods whose goals were to free the scientist from reliance on sensory perceptions and obtain an objective record. Each of these phases in astronomical imaging brings attention to a new way of observing that coincided with a change in the field of astronomy, both in professional activity and the type of research performed with the access to fainter and more distant objects.

A full discussion of image tube technology has not previously been undertaken, leaving a serious gap in our understanding of the progression of astronomical imaging, an inherently vital

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94 Benheim, "The art and science," 1983-1984.

aspect of the astronomical field, because of its reliance on observational data. I cannot give a full account of image tube development in this dissertation, but instead present a case study that draws on similar themes in the history of astronomical imaging and applied to the era of image tubes.

CHAPTER 3

FROM PHYSICIST TO ASTRONOMER: IRA BOWEN AND WILLIAM BAUM AND THE PUSH FOR ELECTRONIC IMAGING

Introduction

> "we decided that we could probably train a physicist in astronomy better than we could train an astronomer in electronics. And consequently we went to Caltech and got one of their very good young graduates who was especially strong in instrumentation—namely, Dr. William Baum."
> - Ira Bowen, oral history interview, 1969[95]

Before the Carnegie Image Tube Committee was established and the potential benefits of electronic imaging enticed a faction of astronomers, many astronomers were still interested in further exploiting photoelectric techniques for point-source measurements. In 1952, Ira Bowen, director of the Carnegie Institution of Washington's Mount Wilson Observatory in southern California, sought a young, skilled scientist, with a background developing instrumentation, who could develop photoelectric photometers for the Observatories' staff. Bowen presumed that it was not worth the time to train his older astronomers to operate or further develop electronic equipment and instead believed the staff could benefit from the assistance of someone already trained in electronics instrumentation.[96]

Though Ira Bowen worked as the director of a major observatory, he had not received a formal education in astronomy. Rather, he was trained as a physicist, specializing in spectroscopy (the analysis of dispersed light, ie. electromagnetic radiation, into its constituent wavelengths).[97] Bowen eventually became highly adept in observational astronomy and

95 Bowen, oral history interview.

96 Bowen, oral history interview.

97 Ira Bowen biographical information from Bowen, oral history interview; Horace Babcock, "Ira Sprague Bowen, 1898-1973: A Biographical Memoir," *The National Academy of Sciences*, Washington, D.C. (1982); Allan Sandage, *Centennial History of the Carnegie Institution of Washington: Volume I The Mount Wilson Observatory* (Cambridge: Cambridge University Press, 2005): 529-535; and Donald E. Osterbrock,

recognized that it would likely be more efficient to teach an instrument-builder, like himself, astronomy than to teach an astronomer how to build instruments.[98] Bowen opted to hire recent PhD William Baum, educated in physics, but with practical experience building electronic and optical instrumentation for the Naval Research Laboratory during World War II. That experience gave Bowen the confidence that Baum could help his astronomers with photometric studies by developing a more sensitive photometer that could detect dimmer objects.[99]

After only a few years on the Observatory staff, Baum designed a photometer that was successfully employed by astronomers Edwin Hubble, Walter Baade, Allan Sandage, and Halton Arp.[100] Baum's photometer was used to acquire more precise brightness data, leading to more accurate magnitude measurements across a large range of wavelengths, which ultimately helped astronomers revise their estimates for the distances to other galaxies. In the process of developing his photometer, Baum corresponded with James McGee, a physicist with the British television firm EMI, a large producer of photomultiplier tubes.[101] Because EMI's primary efforts were towards the development of television cameras, Baum and McGee discussed the potential benefits of applying television technology to astronomy. Bowen had hired Baum to assist the astronomical staff with photometric measurements but Baum sought to advance the technology further.

"The Appointment of a Physicist as Director of the Astronomical Center of the World," *Journal for the History of Astronomy* 23 (1992): 155-165.

98 Bowen, oral history interview.

99 Bowen, oral history interview.

100 William A. Baum, "A photon counter," *The Astronomical Journal* 60 (1955): 25; William A. Baum, "Counting Photons – One by One I," *Sky and Telescope* 14 (May 1955): 264."; Bowen, oral history interview.

101 Samantha M. Thompson, "The Best is the Enemy of the Good: The story of James Dwyer McGee and the forgotten technology that helped shape modern astronomy" (MSc diss., Imperial College London, 2009).

Both Bowen and Baum agreed that image tube technology could be potentially beneficial to astronomers, but they disagreed about the direction that development should take.[102] Bowen believed that commercial industry should be relied upon to develop a solution for astronomers, but Baum argued that astronomers' needs would not garner enough interest from commercial firms.[103] Baum urged Carnegie Institution of Washington President Vannevar Bush to direct Carnegie resources toward the development of image tubes, to the consternation of Bowen, who did not want to see Carnegie resources redirected away from current projects.[104] In this chapter, I look at the story of two physicists, Ira Bowen and William Baum, who both became important actors in the formation of the Carnegie Image Tube Committee. Both attempted to use their background in optics and instrumentation for the benefit of astronomers but they disagreed about what role the Carnegie Institution should play in the development of electronic imaging.

Ira Bowen was a pioneer of ultraviolet spectroscopy and skilled in optical instrumentation. He successfully transitioned from physicist to astronomer, using his laboratory experiments to assist astronomical observations at the telescope and becoming director of the combined Mount Wilson and Palomar Observatories. As the first physicist in this role, Bowen faced the additional challenge of needing to earn the trust and respect of traditional astronomers and maintain his authority while also pushing for his belief in the ability of advanced instrumentation to propel astronomy forward. Like Bowen, William Baum was not formally trained in astronomy. Baum began graduate school in physics at the California Institute of Technology (Caltech) at the start of World War II, but left to complete his service with the Navy, where he eventually became involved with building optical devices with electronic parts, used to study the sun from rockets. Baum

102 Bowen, oral history interview and William A. Baum, oral history interview by David DeVorkin on 18 June 2004, AIP.

103 Vannevar Bush to Ira Bowen, 4 August 1953, Ira Sprague Bowen Papers, Box 24, Folder 229, The Huntington Library, San Marino, California (HEH); Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, Box 24, Folder 229, HEH; Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, Box 24, Folder 229, HEH; Ira Bowen to Vannevar Bush 21 August 1953, Ira Sprague Bowen Papers, Box 24, Folder 229, HEH.

104 Baum, oral history interview (2004).

returned to Caltech with a strong training in electronics and a new interest in astronomy and Bowen likely saw a familiar character who could learn astronomy on the job while using his background to advance instrumentation for astronomers.

I examine Bowen's background to show he chose to hire Baum because of his similar background in instrumentation and his trust in the ability of physicists to apply their skills to astronomical problems. In this chapter, I also look at Bowen's subsequent tenure as director of the Mount Wilson and Palomar Observatories, which provided the necessary background to understand the reasons he was hesitant to burden his staff with the responsibility of developing image tubes, as I will discuss further in the following chapter. Though Baum came from a similar background, moving from physics into astronomy, I argue the additional training he received during World War II led him to believe that observatories needed to be active in the development of new instrumentation for astronomers. Baum became a key figure in the Carnegie Image Tube Committee and his background speaks to the choices he made in that effort.

I additionally show that Baum was not the only young physicist interested in advancing electronic devices in astronomy. In this chapter, I describe a conference organized by astronomers and physicists who wanted to push for a cooperative observatory dedicated to photoelectric observations. I use this conference to show that there was a community interested in advancing astronomical imaging, but that there was pushback from older astronomers who preferred to build bigger telescopes over more sensitive and precise instrumentation.

This chapter speaks to how astronomers acquire new tools by looking at the role of specialized workers, with technical talent to offer. I build on the work of David DeVorkin, who argued that unlike the fields of radio and space astronomy, whose development was largely driven by physicists and engineers, the application of electronic technology to point-source measurements was led by those in the astronomical community, many of them educated in physics.[105] In the case of two-dimensional electronic instrumentation at the Carnegie Institution, I argue that development was guided by two physicists who became astronomers by choosing to

105 DeVorkin, "Electronics in Astronomy."

solve astronomical problems from an observatory. The first, Ira Bowen, recognized the advantage of bringing in a trained specialist who was not an astronomer, but was needed for the kind of observational instrumentation and techniques that astronomers should be employing. The second, William Baum, had acquired a specific background to be hired by Bowen at an institution where he had access to other influential actors like Vannevar Bush, who had the power to begin development efforts. During this era of astronomical imaging, physicists transitioned into astronomers and stimulated the conversation in the astronomical community for the development of electronic instrumentation and blurred the line between physicist and astronomer.

Ira Bowen: physicist and spectroscopist

Ira Bowen began studying physics at Oberlin College and there collaborated with his professors on research projects, leading to scientific publications.[106] He enlisted in the Army before the end of World War I and taught students in the Army Training Corps. In 1919, he entered graduate school at the University of Chicago, where he received training in classical physics from Albert Michelson and in modern physics from Robert Millikan. Michelson had received a Nobel Prize in physics in 1907 for his "optical precision instruments and the spectroscopic and metrological investigations carried out with their aid" and, in 1919, was actively developing instrumentation to determine the diameter of stars using stellar interferometry with Mount Wilson instrument-specialist Francis Pease.[107] In 1923, Robert Millikan would receive a Nobel Prize for, "his work on the elementary charge of electricity and on the photoelectric effect," research which quickly found applications in a variety of fields from a variety of users.[108] Bowen's

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106 Babcock, "Ira Sprague Bowen," 85.

107 For Nobel Prize information, see "The Nobel Prize in Physics 1907," NobelPrize.org. Nobel Media AB 2019. 1 March 2019, https://www.nobelprize.org/prizes/physics/1907/summary/. For the development of the stellar interferometer at Mount Wilson, see Walter S. Adams, "Francis G. Pease," *The Publications of the Astronomical Society of the Pacific* 50 (1938): 119.

108 "The Nobel Prize in Physics 1923," NobelPrize.org. Nobel Media AB 2019. 1 March 2019. https://www.nobelprize.org/prizes/physics/1923/summary/

experience in the University of Chicago's physics department, the contacts that he made, and the exposure he had to a variety of problems in physics and their applications in astronomy, likely affected his views on scientific research.

In 1921, at the request of Mount Wilson Observatory founder George Ellery Hale, Robert Millikan transferred from the University of Chicago to Caltech to serve as director of the newly established Norman Bridge Laboratory of Physics. Hale convinced Millikan to make the move with the promise of access to the community and instruments growing on Mount Wilson. Millikan was particularly interested in new diffraction gratings, optical elements that separate light into its wavelength components, which were being produced for spectroscopic work by Mount Wilson staff.[109] As early as 1905, Millikan was interested in investigating the extreme ultraviolet spectrum and began using a vacuum spectrograph to record the spectrum of a hot spark of light between metallic electrodes.[110] Millikan and his co-investigator, Ralph Sawyer, after both being called into military service for nearly three years, returned in 1919 and published their first results obtained with this method.[111] At about the same time, physicists made significant improvements to diffraction gratings, the only part of Millikan's spectrograph needing improvements.[112] With a potential for enhanced spectrographic instrumentation in Pasadena, Millikan accepted the offer to join the staff at Caltech.

In 1919, the year Millikan returned from service and Ira Bowen joined the Chicago physics department, Millikan assigned Bowen to the extreme ultraviolet spectroscopic research program. When Millikan transferred to Caltech in 1921, Bowen followed and continued his doctoral program at Caltech. There, Bowen assisted Millikan in studies of cosmic rays using high

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109 Babcock, "Ira Sprague Bowen," 87.

110 Lee. A. Du Bridge and Paul A. Epstein, "Robert Andrews Millikan, 1868-1953: A Biographical Memoir," *The National Academy of Sciences, Washington, D.C.* (1959): 259-260.

111 Robert A. Millikan and R.A Sawyer, "Three-fourths of an octave farther in the ultraviolet," *Science* 19 (1919):138 and Robert A. Millikan, "The Extension of the Ultra-Violet Spectrum," *Astrophysical Journal* 52 (July, 1920): 48-49.

112 Millikan, "The Extension."

altitude balloons, but returned to ultraviolet spectroscopy when Mount Wilson's J.A. Anderson built a greatly improved grating spectrograph, giving much higher resolution than Bowen had previous obtained.[113] Though Bowen was often left on his own to conduct experiments, he collaborated with Millikan on writing and publishing scientific papers.[114] In 1926, Bowen graduated from Caltech having published 19 papers, 18 of them co-authored with Robert Millikan.

Bowen was made an assistant professor of physics at Caltech in 1926 and a full professor in 1931. He continued to teach undergraduate physics courses, eventually taking over the teaching of graduate coursework in optics and spectroscopy. In 1927, Bowen read a paper by Henry Norris Russell, noting a mystery in the seemingly "forbidden" lines in nebula spectrum.[115] Bowen was able to explain the troublesome lines as transition between known energy levels caused by the ionization of oxygen that is not typically seen on earth.[116] From this discovery, astronomers invited Bowen into the astronomical community. For many years after, Bowen continued to study nebular spectra, trying to understand the elements present. In 1938, William H. Wright, the Lick Observatory director, was particularly interested in spectra observations of planetary nebula, but had obtained some abnormal results, so invited Bowen to be a summer research associate to assist with the project.[117] There Bowen performed his first observational work in astronomy, producing a paper, applying his laboratory studies of nebula elements to observational data. In 1939, Bowen was elected to the National Academy of Sciences on the

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113 For more on Robert Millikan's efforts to fly automated instruments aboard balloons, pulling from his prior experience during the war with balloons and the Signal Corps, see David H. DeVorkin, *Race to the Stratosphere: Manned Scientific Ballooning in American* (New York: Springer-Verlag, 1989).

114 Babcock, "Ira Sprague Bowen," 89.

115 David H. DeVorkin, *Henry Norris Russell: Dean of American Astronomers* (Princeton: Princeton University Press, 2000): 228.

116 Donald E. Osterbrock, "The Appointment of a Physicist as Director of the Astronomical Center of the World*," Journal for the History of Astronomy* 23, no. 3 (Aug. 1992): 155-165.

117 Osterbrock, "The Appointment," 158 and Babcock "Ira Sprague Bowen," 93-94.

nomination of astronomers, cementing his transition from physicist to astronomer in the view of most of the astronomical community.[118]

By the early 1940s, the 200-inch telescope, which George Ellery Hale had secured funding for during the 1930s, was still in development due to delays by the entry of the United States into World War II. Hale's 200-inch telescope was being designed by Caltech staff in collaboration with Mount Wilson Observatory and because of Bowen's expertise in optics and instrumentation, he was active in the development of the telescope and its instruments. Bowen's responsibilities grew until progress was brought to a halt when many of the involved scientists and engineers were given new responsibilities, directly useful to the war effort. Vannevar Bush, in addition to serving as President of the Carnegie Institution, had been made head of the Office of Scientific Research and Development (OSRD). The OSRD had been established by the United States Federal Government to direct scientific research towards military purposes during World War II, giving Bush the power and funds to start an ordnance rocket program at Caltech.[119] Bowen was placed in the optics division, developing motion picture cameras to record and study the behavior of rockets in flight.[120] According to Ira Bowen, Bush did not feel it was appropriate to give such a large project to his home institution, so several Mount Wilson scientists had to go to Caltech to assist in the efforts.[121] For four years, from 1941 to 1945, Bowen and many Caltech scientists were taken away from their pre-wartime research, focusing all efforts on OSRD projects.

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118 In 1940, several young astronomers at Lick Observatory preferred Bowen to take on the vacant director position at Lick, but the older staff preferred a "traditional astronomer." Osterbrock, "The Appointment," 159.

119 Conway W. Snyder, "Caltech's *Other* Rocket Project: Personal Recollections," *Engineering & Science, Caltech magazine* 53, no. 3 (Spring 1991): 2-13.

120 Babcock, "Ira Sprague Bowen," 97; Osterbrock, "The Appointment," 159. Bowen specifically oversaw the study of exterior ballistics. He developed instrumentation, like special cameras, to follow rockets during flight and measure how they moved. This was helpful when, for instance, a rocket exploded, and engineers on the ground wanted to know if that was due to a change in atmospheric pressure or a faulty part, which could often be determined by measuring the rocket's acceleration immediately before it was destroyed.

121 Bowen, oral history interview.

In August 1945, after Vannevar Bush in his role as head of the OSRD witnessed the Trinity Test in New Mexico, he continued directly on to Pasadena in his role of Carnegie President to inform Ira Bowen that he had selected Bowen to replace Walter Adams as director of Mount Wilson Observatory. Donald Osterbrock, in his article “The Appointment of a Physicist as Director of the Astronomical Center of the World,” details the long path Bush took before hiring Bowen.[122] Adams had planned to retire in 1944, but Bush asked him to stay on while wartime activities increased. Mount Wilson astronomer Edwin Hubble, likely the most well-known astronomer in America, was expected by many in the astronomy community, including himself, to become director, following Adams’ retirement, but Bush did not expect him to excel in an administrative role. Many other seemingly potential candidates were excluded for lacking “solidity” or “generosity.”[123] Astronomers Otto Struve, director of the Yerkes and McDonald Observatory, Bart Bok of Harvard, and Walter Baade and Rudolph Minikowski of Mount Wilson were not considered because they were foreign-born and Adams and Bush agreed that a non-American would have difficulty adjusting to American ways of collaboration and diplomacy.[124]

Noting the deficiencies in the possible candidates, Vannevar Bush acknowledged he might opt for a physicist instead. Bush, who had been educated in engineering and was an avid inventor, was enthusiastic about the work done by physicists during the war, but was skeptical about the capabilities of the older Mount Wilson astronomers, who Bush saw as ineffective during that period.[125] Osterbrock quotes a letter between Bush and Adams in which Bush made the argument for hiring a physicist: “It would be startling in some ways, but physics and astronomy are so close together in many ways that I do not believe it would be at all out of the question to do

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122 Osterbrock, “The Appointment.”

123 Osterbrock, “The Appointment,” 156-157 for Bush’s comments on Theodore Dunham Jr and Harlow Shapley.

124 Osterbrock, “The Appointment,” 157.

125 Osterbrock, “The Appointment,” 156.

so if the right individual were found."[126] Adams suggested Bowen, and while Bush inquired with other physicist candidates, they too suggested Bowen for the position. Bush consulted with many American astronomers and physicists about Bowen's ability to direct the world's largest observatory. Ernest O. Lawrence, University of California Radiation Laboratory director, suggested that Bowen might lack the "social graces" to work with wealthy Carnegie trustees and may not be up for the task of directing proud, stubborn scientists like Hubble, but others suggested he could be up for the task once freed from Millikan's shadow.[127]. Though Adams acknowledged that it would appear strange to not offer the position to Hubble, he realized that most of the Mount Wilson staff like Bowen and disliked Hubble, viewing him as an outsider, a southerner who affected an English accent. Bush was convinced Bowen was the most fitting candidate and in August 1945, offered Bowen the position of director of Mount Wilson Observatory, the first physicist to hold the post.

On January 1, 1946, Bowen commenced his role as director, outlining his goals for Mount Wilson's research programs. Bowen wanted to focus on the radial-velocity program but push forward on new research questions. Astronomy, Bowen argued, needed to advance with the help of physics.[128] Bowen hired Horace Babcock, an astronomer with a strong background in electronics. Everyone on the staff seemed happy, except Edwin Hubble, who was irate at being passed over and determined not to let an "administrator" dictate his research programs.[129] Bowen promised Hubble that he would remain in charge of extragalactic research, while Bowen would take the lead in spectroscopy. In his first years as director, Bowen had the difficult task of balancing his own, physicist-driven goals for the Observatory with the demands of Hubble.

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[126] Vannevar Bush to Walter S. Adams, 23 October 1944, Walter S. Adams Papers, HEH, as quoted in Osterbrock, "The Appointment," 157.

[127] Osterbrock, "The Appointment," 161.

[128] Osterbrock, "The Appointment," 163.

[129] Babcock, "Ira Sprague Bowen," 163.

Photoelectric devices at Mount Wilson Observatory

The Mount Wilson Observatory staff began using photoelectric photometers in 1931 when astronomers Joel Stebbins and Albert Whitford, from Washburn Observatory at the University of Wisconsin, arrived photometer in hand. In terms of output of photometric results during the 1930s and early 1940s, Stebbins and Whitford were amongst the most successful photometrists. Paul Guthnick of the Berlin Observatory and John S. Hall of Yale University were similarly prolific, and it is worth noting that all three collaborated with physicists on the design on the photocells each used in their photometer.[130] Mount Wilson observers largely benefited from having trained photometrists available to assist with using the newest, but challenging-to-operate, technology to determine stellar magnitudes.

Walter Adams appointed Stebbins and Whitford as research associates, providing a stipend to cover the costs of travel to Pasadena. For over a decade Stebbins and Whitford traveled to southern California, primarily during the summers, to assist Mount Wilson astronomers with observations with the best photoelectric photometers.[131] However, as World War II came to a close and Caltech and Mount Wilson staff could continue work on the Palomar Mountain 200-inch telescope, Vannevar Bush had to make a decision concerning the fate of the visiting research associate program. Palomar Observatory was to be merged with Mount Wilson Observatory, turning the larger observatory system into a joint effort from Caltech and the Carnegie Institution. Bush feared that the debate over who to allocate visiting astronomer funding to would cause too much discord between the observatory staffs and instead decided to disband the program.[132] Bush asked newly appointed director Ira Bowen to deliver the news to Stebbins. Allan Sandage recalled, in his history of Mount Wilson Observatory, that whether Bowen was too “abrupt in his

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[130] *IAU Colloquium, International Astronomical Union* (Cambridge: Cambridge University Press, 12 August 1993): 18-20.

[131] For more on the research projects Stebbins and Whitford engaged in, see Sandage, *Centennial History of the Carnegie Institution of Washington: Volume I The Mount Wilson Observatory*, 436-441.

[132] Sandage, *Centennial History of the Carnegie Institution of Washington: Volume I The Mount Wilson Observatory*, 441.

phrasing," "Stebbins vowed never to set foot on Mount Wilson again."[133] Whether this story is factual, Stebbins stopped observing at Mount Wilson and began conducting research at Lick Observatory, maintaining his research associate status there for the following 15 years.

When Bowen outlined his scientific goals for Mount Wilson, just six months prior to the elimination of the visiting research program, he highlighted the need to incorporate advances in physics into astronomical practice. Without Stebbins and Whitford as a resource, Bowen suggested both Mount Wilson and Palomar Observatories would benefit from having an instruments technician on-staff, trained in electronics to assist with photoelectric studies.[134] A few young physicists and astronomers, those in graduate school or in their early careers during World War II, had received electronics training while in service on military research projects. Bowen chose to hire a young physicist, William Baum, who did not consider himself to be an astronomer prior to completing his doctoral work, but like Bowen was well-versed in optical and electronic instrumentation, making him, in Bowen's opinion, the perfect candidate to bring physics into the observatory.

William Baum: World War II and electronics training

Born in 1924 and raised on a small farm near Toledo, Ohio, William Baum received a full-tuition scholarship to study physics at the University of Rochester where he showed an early interest in optics and optical instrumentation. In 1940, during Baum's first year at Rochester, the United States Congress passed the Burke-Wadsworth Act, establishing the Selective Service and imposing a peace-time draft. During Baum's three years at Rochester, he saw men his age drafted and, after the United States entered World War II in 1941, leave school for active military duty. Even as Baum graduated, he was not certain if it would be possible to continue with his

133 Sandage, *Centennial History of the Carnegie Institution of Washington: Volume I The Mount Wilson Observatory*, 441.

134 Bowen, oral history interview.

education.[135] Still unclear how the draft would affect him, Baum applied to graduate school at Caltech, was accepted, and in the fall of 1943, only three years after he began at the University of Rochester, moved to California.

During his tenure at Rochester, Baum had proven he could succeed academically, but World War II complicated his academic plan. Baum had only just arrived at Caltech when the Selective Service began to pursue him.[136] Robert Millikan was still the director of the Norman Bridge Laboratory of Physics at Caltech when Baum arrived. Given the ongoing draft and the United States' need for more military personnel, Millikan actively tried to retain his teaching assistants and became concerned about the Selective Service's pressure on Baum. As the director, Millikan was responsible for assembling his staff of graduate student teachers, which were covered under Caltech's V-12 Navy College Training Program. This teaching program was designed to supplement the force of commissioned officers in the United States Navy during World War II. Between 1943 and 1946, more than 125,000 participants were enrolled in 131 college and universities in the United States. Millikan depended on this program and his enrolled graduate students. He needed students to be teaching assistants in his labs, and consequently took on Baum as a test case. Millikan tried to convince the Draft Board that his students were performing essential war work. He argued that through the V-12 program, his students had the required training to conduct technical work and it was important for the university to retain them. Millikan attempted to utilize his political ties, which were considerable because of his role as Vice Chairman of the National Research Council, helping to develop anti-submarine and meteorological devices. Millikan spent months working with Baum and the Draft Board. For Baum, this was a rare and fruitful opportunity for him to have regular contact with Millikan, a man of great prestige and influence. During these months, Baum continued his studies at Caltech became involved lightly with the Caltech ordnance rocket program and took an optics course with

135 William A. Baum, oral history interview by David DeVorkin on 12 January 1983, AIP.

136 Baum, oral history interview (1983).

Ira Bowen.[137] Ultimately, Millikan failed in his quest to keep Baum protected from the Selective Service. Baum and others realized they would not be able to escape military duty, so Baum volunteered for service in the Navy.[138]

Though Baum was unsuccessful in his effort to evade military duty, working with the Navy provided him training in electronics and exposed him to the kind of astronomical research that could be carried out with electronic instrumentation. The projects Baum executed during these years taught him how to approach instrumentation development, while balancing the needs of scientists and the work flow of technicians in contracted laboratories. Though originally avoided, Baum's military efforts provided experience that would shape his career trajectory in electronics and astronomy.

After completing his required Naval basic training, Millikan succeeded in having Baum reassigned back to Caltech in Naval uniform, but unfortunately for Millikan, Baum was not allowed to teach. Instead, Baum was assigned to the local Navy Liaison Office, where he was given some freedom to engage in a research project of his choosing. Baum began to experiment with radio direction finding, creating devices to help determine the direction to a radio source. Though Baum thought this research would be beneficial to the Navy, he later remarked that he did not think he accomplished anything substantial.[139] However, he did gain practical experience with electronics and designing and building instruments, key skills that he would utilize during his time with the Navy. Though he could not teach and continue his graduate education, he gained valuable skills conducting research for the Navy.

For unclear reasons, in early 1945, Baum was reassigned to the Naval Research Laboratory (NRL) in Washington, D.C. He was first sent to the Fire Control Division, who were responsible for controlling the aiming of guns aboard ships. Though this research and

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137 For more on Caltech/JPL rocket program, see Clayton R. Koppes, *JPL and the American Space Program: A History of the Jet Propulsion Laboratory* (New Haven: Yale University Press, 1982).

138 Baum, oral history interview (1983).

139 Baum, oral history interview (1983).

development did not interest Baum, it did provide him his first opportunity to operate electronic computers. Shortly after beginning work, Baum applied for a transfer to the Optics Division, where he hoped to find a more scientifically-focused group of people. After successfully joining the Optics Division, Baum was placed under the direction of physicist Richard Tousey, who was initially unsure about how to best utilize the young ensign.

At the close of the war, about 100 unused German V-2 rockets, a full supply of parts, and some scientists and specialists were relocated to White Sands Proving Grounds, an installation in the New Mexico desert. The V-2, a liquid-fueled missile about 14 meters tall and 2 meters in diameter, reached its target via a parabolic trajectory above most of Earth's atmosphere. Scientists at the Naval Research Laboratory realized they could use the V-2's ability to reach Earth's upper atmosphere, coupled with the rocket's appreciable payload capacity to house a spectrograph, to explore the ultraviolet spectrum of the sun, the part of the solar spectrum blocked by ozone and oxygen in the atmosphere. Because Baum had experience with machine tools and a strong background in optical instrumentation from his undergraduate years at Rochester, Tousey assigned him to the spectrograph project.[140] Within this project, Baum was able to combine his interest and experience with optics with a burgeoning interest in instrumentation. Additionally, he was further intrigued by the possibility of exploring unknown scientific territory through advanced instrumentation. Later in his life, Baum remarked, "it was the adventure of exploring the unknown…If you were a budding young scientist and wanted to do something exciting, you would want to go after just such a project."[141] Baum's excitement for developing new technologies at the NRL stimulated him to later become an advocate for electronic imaging devices in astronomy, using new methods to solve new problems.

[140] Baum, oral history interview (1983). Baum states in his OHI that he was added to the spectrograph project because of his background in optics, but Tousey never says this explicitly in his OHIs. He says he originally didn't know what to do with Baum when he was assigned to the optics division, but since he had Baum to use, he used him.

[141] Baum, oral history interview (1983).

Ultimately, Baum's practical experience with the logistics of developing a technology certainly sensitized him to the challenges of technological development. Through trial and error, Baum and Tousey designed the first ultraviolet spectrograph to photograph the sun. Baum later recalled, "this was not a time when things went through careful engineering scrutiny with designs being carefully reviewed, discussed, and flight qualified. There wasn't anything like that at all. The modus operandi was simpler: if we could get something ready in a matter of weeks, we could take it out to White Sands, install it in a rocket, and off it would go."[142] Though the original prototype was designed and built at NRL, the final design of the flight instrument was developed at Baird Associates (later Baird Atomic), a commercial company located in Cambridge, Massachusetts. Baum spent several months in Cambridge with Baird engineers and technicians, monitoring the production of the first instruments. Tousey chose Baird Associates primarily because he was well acquainted with Baird president Walter Baird. Baum saw in practice how once a well-funded group of scientists had theorized, prototyped, and tested an instrument, commercial companies were integral to producing the final product, in quantity. This early experience demonstrated to Baum how a development project, free from rigorous oversight, could be fruitful and, additionally, the role that industry could successfully play in the development of new instruments.

Though he fought hard to avoid active service, Baum's work with the Navy had a positive impact on his education and career, especially making him particularly valuable as an experienced instrumentalist with a command of optics. While serving, he had his first contact with computers, designed, built, and tested optical instruments, and worked with a commercial company to produce a final, working product. All these experiences shaped how he approached and used instrument development to solve scientific problems.

Beginning in the fall of 1946, Baum returned to Caltech as a graduate student, working with Millikan, part-time, while still retaining his position at the NRL. For his thesis project, Baum decided to investigate refiguring the spectrograph being used by Tousey. The United States'

[142] Baum, oral history interview (1983).

supply of V-2 rockets was quickly being depleted, so Baum aimed to design a smaller instrument that would fit into a smaller rocket. Working at the newly established Jet Propulsion Laboratory (JPL), operated under contract by Caltech, Baum set out to design this new instrument. He worked closely with Penn Optical, a company located in Pasadena, who he had hired to polish the delicate pieces of lithium fluoride that would serve as prisms for the spectrograph. Unfortunately, the partnership did not operate smoothly. The production of prisms was habitually delayed, with no reasonable excuse provided by Penn Optical.[143] On one occasion, the polishing equipment accidently crashed down onto two of the prisms. Within a few months, though not without headache, these issues were resolved, and Baum had his prisms. The device itself was a specialized concoction of circuits, motors, and a vacuum tube system with store-bought coffee cans to hold the batteries. Though Baum had experience contracting technical work to industrial labs, he found that the process did not always advance as planned. Through his thesis project, Baum expanded his NRL introduction to large-scale research and the advantages and disadvantages of working with a commercial firm.

Photoelectric devices at Mount Wilson Observatory II

In 1950, as Baum completed his thesis, Ira Bowen offered him a job to operate and develop photoelectric instrumentation for the Mount Wilson and Palomar Observatories. Baum was initially hesitant about accepting a position at an observatory because his astronomical education had been extremely limited, but Bowen convinced him to take on the challenge, joking, "Don't worry about it, I don't know any astronomy either."[144] Through lunches and meetings with astronomers, Baum quickly became proficient in astronomical issues and began to investigate methods to improve photometric instrumentation so astronomers could more accurately measure stellar magnitudes, without the complicated calibration process required in photographic studies.

[143] Baum, oral history interview (2004).

[144] William A. Baum, oral history interview by David DeVorkin on 14 January 1997, AIP.

Baum pursued a type of photometer employing a pulse-counting technique that had been continually developed since the 1930s, before the development of the photomultiplier.[145] With a pulse counting photometer, physicists could detect individual photons, but these photometers were only useful for bright sources. In 1946, Gerald Kron argued that newly developed photomultipliers could help astronomers detect photons coming from distant stars and the first pulse-counting stellar photometers were built at the Cook Observatory of the University of Pennsylvania and at the Cambridge Observatories.[146] Both photometers used photomultipliers, built by the RCA, as their intensifying instrument. Photomultipliers helped detect fainter light sources, but the weak signals were often lost in the noise produced by the amplifying photomultiplier. Baum first set out to determine a method for integrating, or adding up, the signal coming out of the photomultiplier in the photometer to make the signal more detectable.[147]

In developing his pulse-counting photometer, Baum mostly worked on his own, though he collaborated occasionally with other physicists since they had been developing the technology for two decades and were better acquainted with its limits and potential. Baum worked with high-energy physicists at Caltech, who were interested in pulse counting for recording tracks made by high-energy particles in crystals. The main difference between the two applications was in the amount of light each had available. Astronomers wanted to measure dim objects, which meant counting pulses that resulted from single electrons coming off photocathodes whereas high-energy physicists were getting bursts of photoelectrons. Though Baum could learn from high-energy physicists, the astronomical problem was technically more demanding because of their limited light sources.

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145 J. B. Hearnshaw, *The Measurement of Starlight: Two Centuries of Astronomical Photometry* (Cambridge: Cambridge University Press, 1996) 417.

146 Gerald Kron, "The application of the multiplier phototube to astronomical photoelectron photometry," *Astrophysical Journal* 103 (1946), 326; E.B. Wood ed., *Astronomical Photoelectric Photometry* (Washington, D.C.: American Advancement of Science, 1953): 64; and, Gilbert Yates, *Monthly Notices of the Royal Astronomical Society* 108 (1948) 476.

147 Baum, oral history interview (1997).

By 1953, Baum had developed a pulse-counting photoelectric photometer, an instrument capable of counting individual photoelectrons that was used for long exposures with the 200-inch telescope at Palomar. While Baum's detector approached the same limits in magnitude as photographic emulsions, the benefit of the photon-counting system was its linearity, meaning astronomers could use it to precisely calibrate stellar magnitudes across wavelength ranges.[148] While further study is needed to determine how astronomers like Edwin Hubble felt about working alongside Bowen's young hire, Baum's photometer helped Mount Wilson and Palomar astronomers better calculate the entire distance scale of the universe.

A conference to investigate a cooperative photoelectric observatory

During the late 1940s – early 1950s, while Ira Bowen and William Baum pushed for the investigation of photoelectric aids for observational research, a small group within the astronomical community, largely with a physics or instrumentation background, were also interested in developing photoelectric devices for astronomers. The Mount Wilson and Palomar Observatories operated the world's largest telescopes, but the Carnegie Institution and Caltech were privately owned, making it difficult for astronomers working from other institutions to be granted observing time on the best telescopes. In 1952, John Irwin, an astronomer from the Goethe Link Observatory at Indiana University, advocated for publicly-owned, cooperative photoelectric observatories, calling on the astronomy community to build a series of observatories, whose primary use was photoelectric-aided observations. Irwin argued that several medium-sized (16- to 36-inch) telescopes with photoelectric capabilities would provide astronomers with the equipment needed to access dimmer objects in the sky without the need to build larger telescopes of their own to compete with astronomers who had access to the largest telescopes in California.[149] By establishing a coalition of observatories, whose purpose was to

148 DeVorkin, "Electronics in Astronomy," 1218; Baum, oral history interview (1997).

149 Frank K. Edmondson, *AURA and its US National Observatories* (Cambridge: Cambridge University Press, 1997); Frank K. Edmondson, "AURA and KPNO: The Evolution of an Idea, 1952-58," *Journal for the*

conduct photoelectric observations, Irwin would also create a collaborative central staff with the expertise and interest to continue to develop electronic devices. Without this partnership, astronomers, scattered through the United States, would likely continue to work in isolation. Though people like Baum and Bowen had access to financial and material assets at Carnegie, not all astronomers were as fortunate and a cooperative observatory had the potential to combine their resources.

Irwin's proposal for a publicly-owned series of observatories required public funding and, after World War II, there were new sources of funding available, primarily through the Office of Naval Research. Some astronomers had concerns about the dangers of becoming wholly dependent on government and particularly military funding.[150] Only a few astronomical sites were entirely funded by federal sources in 1951, primarily, the United States Naval Observatory and Sacramento Peak Observatory.[151] The University of Michigan astronomy department had the highest number of faculty (5) supported by federal money, including the department's director, Leo Goldberg.[152] Astronomers at observatories like Mount Wilson-Palomar and Yerkes retained dominance in their field due to their access to large telescopes in good observing locations, all without the aid from government or military funding.

In 1952, the National Science Foundation (NSF), created by President Harry Truman, appointed a special committee to advise on the funding needs of and proposals from the astronomical community. During their first meeting, this panel, consisting of leaders from the

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History of Astronomy 22, (Feb. 1991): 68-86; and Frank K. Edmondson, "How AURA, KPNO, and CTIO got Started," *Publications of the Astronomical Society of the Pacific* 98 (Nov. 1986) 1110.

150 Beginning in 1948, the Office of Naval Research conducted basic research in astronomy and astrophysics where the results produced could have been beneficial to the Navy. Research programs included, for example, astro-ballistics, solar terrestrial relationships, upper atmosphere research, navigation, position finding, and improvement of techniques and instrumentation. G.F. Mulder, "The Office of Naval Research Program in Astronomy," *Astronomical Journal* 59 (Aug. 1954): 271-272; For more on post-World War II federal funding of astronomical research, see David H. DeVorkin, "Who speaks for Astronomy? How Astronomers Responded to Government Funding after World War II," *Historical Studies in the Physical and Biological Sciences* 31, no. 1 (2000): 55-92.

151 Edmondson, "AURA and KPNO," 69-70.

152 Edmondson, "AURA and KPNO."

astronomical community, discussed Irwin's proposal for a cooperative photoelectric observatory. Irwin proposed that the involved universities would cover the operating costs of the new facility and that the NSF would provide the capital funds. Though the panel ultimately rejected the proposal, unsure if funds should be devoted to advanced instrumentation or large telescopes project, there was lingering interest in a photoelectric observatory.[153] Because of this interest, an *ad hoc* Panel on Astronomical Facilities was appointed by the NSF Program Director for Physics and Astronomy, Raymond Seeger. The Panel, consisting of Robert McMath (chairman), Albert Whitford, Ira Bowen, and Otto Struve set out to investigate the feasibility of a specialized, cooperative observatory, which had the potential to direct resources, funding and experienced staff, towards a common goal of advancing astronomical detectors.[154] The final report and recommendations suggested that a conference on photoelectric methods be held to assess the need and feasibility of establishing a new facility to carry out this type of observation.[155]

In 1953, the National Science Foundation sponsored an "Astronomical Photoelectric Conference" at Lowell Observatory in Flagstaff, Arizona with the help of an appointed organizing committee: Whitford (Chairman), Irwin (Secretary and Editor of the Proceedings), Gerald Kron, and Seeger, all whom had been involved in either the original proposal or review by the NSF. Whitford, Irwin, and Kron were all vocal advocates for the use and further development of photoelectric photometers in astronomy.[156] Flagstaff was chosen in part at the urging of Lowell Observatory trustee Roger Lowell Putnam, though many astronomers expressed their concern over the chosen location of Flagstaff for the conference. It appeared to them to show early favor of the northern Arizona town for a future site of a photoelectric facility. Lowell Observatory had a

153 Edmondson, "AURA and KPNO," 71-73.

154 Edmondson, *AURA and its US National Observatories*. For more on McMath's role in astronomy, see DeVorkin, "Who Speak for Astronomy?"

155 John B. Irwin ed., *Proceedings of the National Science Foundation astronomical photoelectric conference, held at Lowell Observatory, Flagstaff, Arizona, August 31 – September 1, 1953* (Bloomington, Indiana, October 1955): 107-108.

156 John Irwin to Al Wilson, 6 January 1954, Al Wilson Papers, Lowell Observatory Archives, Flagstaff, Arizona (LOA)

long history of developing instrumentation for many research programs. Whitford defended the decision in a letter to McMath, writing, “I must say that I can see objections to putting the telescope at any other place that might be considered as alternatives to Flagstaff.”[157] He continued, “My own feeling is that Flagstaff is about as good a suggestion as has been made when one compares the climate and the local maintenance facilities with that at alternative sites.”[158] Lowell Observatory staff argued for their home location, but Irwin disagreed on the choice of Flagstaff: “I remember I was very busy, and my whole thinking was, well, Flagstaff, Arizona, was outside the center of the optimal location as far as I was concerned. It was beyond the pale. Some astronomers at Lowell tried to correct my impression on that and pointed out that some very, very good work had been done in the so-called rainy season at Flagstaff, say, in the middle of August when they have thunderstorms, and so on… and some big discoveries were made, and so on and so on.”[159] Flagstaff would become a primary hub for the development and testing of photoelectric devices, both point-source and imaging, and this early debate is important in understanding astronomers’ attitude toward the Arizona observatory.

The conference directly followed the summer meeting of the American Astronomical Society in Boulder, Colorado. The close proximity, partnered with NSF funding astronomers’ travel expenses, encouraged astronomers from throughout the United States to attend. There were representatives from all the big universities that had astronomy departments from the East Coast, the Midwest, and from the Pacific coast. Though, as Irwin recalled, representation from the Pacific coast was not as strong as was hoped, with only Baum, Kron, and Stebbins, who had recently began research at Lick Observatory, representing California Observatories. Still, there were representatives from the smaller schools too, like Amherst and the University of Kansas. In

157 McMath to Whitford, quoted in Edmondson, *AURA*.

158 Frank Edmonson and John Irwin interview, 1978, Frank Edmondson History of AURA interviews and documentation, 1978-1991, AIP.

159 Frank Edmonson and John Irwin interview, 1978, Frank Edmondson History of AURA interviews and documentation, 1978-1991, AIP.

all, Lowell Observatory hosted 35 astronomers, represented all the major observatories in the United States.[160]

This was an impressive turnout to discuss the future of a developing technology. The committee outlined three main goals for the conference:

> (1) To consider the present status of that part of observational astronomy where photoelectric methods are being used or could be used to advantage; (2) To consider the various observational methods now in use, to evaluate the limitations imposed by the apparatus and by the atmosphere, and to discuss possible new techniques and their astronomical potentialities; (3) To consider the question of whether an additional telescope of moderate size in a good site would facilitate the photoelectric research in progress or contemplated at observatories in unfavorable climates.[161]

The conference program ultimately was divided into four sessions dealing with (1) present and potential fields in photoelectric astronomy; (2) instrumental and observational techniques; (3) atmospheric and climate effect; (4) a possible cooperative telescope. The NSF asked Struve to chair the session on a cooperative telescope, but he was unable to attend due to an already-scheduled observing run. McMath's declining heath prevented him from traveling to the high-altitude town of Flagstaff so Whitford suggested Leo Goldberg as chair. Goldberg's acceptance would have a great impact on the direction of the conference, as he had his own goals for the meeting. Goldberg wrote to Seeger, "I am afraid, however, that my thinking is much more ambitious than the proponents of the photelectric telescope, and if you think it proper I should like to express my views at Flagstaff."[162] The fourth session was included largely due to pressure from Leo Goldberg, who insisted that a discussion of a cooperative observatory, separate from its instrumentation, was needed. At the close of this session, Leo Goldberg offered his concluding opinion, like a rallying-cry:

> For a cooperative photoelectric telescope to be set up in a perfectly transparent atmosphere with conditions of perfect seeing, is fine, but I think that other groups could

[160] Irwin, *Proceedings of the National Science Foundation Astronomical Photoelectric Conference, held at Lowell Observatory, Flagstaff, Arizona, August 31-September 1, 1953*.

[161] Anonymous, "Astronomical Photoelectric Conference: Introduction," *Astronomical Journal* 60 (Jan., 1955): 17-18.

[162] Leo Goldberg to Joel Stebbins, 18 August 1953, Leo Goldberg personal files (copy in Frank Edmondson History of AURA interviews and documentation, 1978-1991, AIP) and quoted in Edmondson, "AURA and KPNO," 72.

> make equally good cases – such as the stellar spectroscopists, for example. As I look around the room here, I count about twenty competent researchers who do not now have access to first class instruments, to say nothing of a large telescope. If you went around the country and included other areas in astronomy, you could conservatively get that number up to fifty. The difficulty seems to be that there are many telescopes, but there is a shortage of the right kind of telescope time. A few years ago it was said that you didn't need more telescopes, that Mt. Wilson was hard up and didn't have enough astronomers to operate their instruments and what was needed was travel money so the people could go west or southwest. I don't think that that argument would hold up any longer. It is obviously impossible for every observatory to have optimum observing facilities and the fact that is that at present such facilities are concentrated in relatively few areas.
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> The Mt. Wilson system of guest investigators has been very generous and has taken care of some of the need but not enough of it; and it is very probable that in the future the number of guest investigators there will decline rather than increase. I think what this country needs is a truly National Observatory to which every astronomer with ability and a first class problem can come to on leave from his university…I would not settle for anything less, even though quite a lot of useful work can be done photoelectrically, with relatively poor seeing. We ought not to be as much concerned with doing useful work as with the real need to do great work.
>
> We do not want an observatory that would just keep astronomers busy in their spare time; we want first-class results…Now if we are going to confine ourselves to a relatively small photoelectric telescope then I would say that the potential demand for such and instrument would be relatively small…we would not get an influx of astronomers on a national scale, and I don't think we should confine our thinking to a small photoelectric telescope.[163]

Goldberg continued for several minutes, but by the time he concluded, the direction of the conference had changed course.[164] Leo Goldberg advocated for a larger telescope that could be used by university astronomers without access to large telescopes, like those at Mount Wilson-Palomar and Lick Observatories. He did not think it should be confined to a single type of instrumentation. Goldberg received support from the conference attendees, but Whitford, a supporter of a photoelectric observatory, commented that the scale of the competing projects, one small and focused and one large and encompassing, was enough reason to support the more manageable project.[165]

[163] Irwin, *Proceedings of the National Science Foundation astronomical photoelectric conference, held at Lowell Observatory, Flagstaff, Arizona, August 31 – September 1, 1953*, 107-108.

[164] Frank Edmonson and John Irwin interview, 1978, Frank Edmondson History of AURA interviews and documentation, 1978-1991, AIP.

[165] Edmondson, *AURA.*

The original purpose of the conference had been to consider the need for new photoelectric facilities but given Goldberg's argument and his status within the astronomical and NSF community, it was the ultimate consensus of the participants, and eventually the NSF, that if a collaborative observatory could be built, it should not be limited to photoelectric investigations.[166] Baum, in attendance, would have noticed the shift in direction away from instrumentation and the lack of investment from the astronomy community, at large. An observatory dedicated to photoelectric technology would have created a natural home for advances and new developments in photoelectric technology. Instead, with the focus pulled from better detectors to bigger telescopes, astronomers interested in advancing electronic instrumentations had to move forward without the support of federal funding.

Electronic imaging as an aid to astronomy

Yerkes Observatory astronomer W.A. Hiltner presented a paper at the 1953 Flagstaff conference on astronomical photoelectric devices that was different from the others.[167] Hiltner focused his talk on image tubes, rather than photometers. Both image tubes and photomultipliers operated via the photoelectric effect, resulting in a linear output between the intensity of photons coming in and the electrical signal coming out, which could be amplified, but image tubes provided spatial information. When used in conjunction with a telescope, the operator could use an image tube to produce an image through three possible methods, all by transforming the light into an electronic signal and suitably amplified: the image could either be recorded onto an electron-sensitive emulsion (electronography); use a phosphorescent screen to transform photons into photoelectrons, which could them be amplified and recorded on a photographic

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166 For a complete discussion of how the Flagstaff Conference played a pivotal role in the establishment of AURA and the National Observatory, see, Frank Edmondson, *AURA and Its US National Observatories*.

167 W.A. Hiltner, "Image tubes for astronomical purposes," reprinted in *Astronomical Journal* 60, (Jan., 1955): 26.

emulsion (phosphor screen output); or transformed into a scanning electric signal and directly sensed as such (television, or signal-generating). As Hiltner explained, "the subject of image tubes does not rightly belong in a discussion of photoelectric photometry, because image tubes considered the spatial distribution of light and not just the one-dimensional measurement of brightness," but, he argued, a discussion on this "possible solution to more efficient observations of spatial distribution of radiation" was needed in astronomy.[168]

In the discussion following Hiltner's presentation in Flagstaff, University of Wisconsin astronomer Art Code, three years out of his graduate degree and working for the Albert Whitford-directed Washburn Observatory, commented that "this is indeed an exciting region of photoelectric measurements" and that "Dr. Hiltner and others who are worried about such things should be much congratulated."[169] Code further predicted that these tubes will, "usher in a new era in astronomy and perhaps new astronomers too, because once we have such things as image tubes, then the fully automated telescope, with the astronomer sitting at a desk quite remote from his telescope would be a practical thing."[170] With his photon-counting photometer and with EMI-produced photomultipliers, Baum had firmly shown that astronomers could observe fainter point-sources than by using photography alone. For Baum, like Hiltner and Code, the next logical step was to endeavor to extend the photoelectric method to imaging, by creating an area detector that could replace inefficient photographic plates.

Baum, Hiltner, Kron, and others were aware of French astronomer André Lallemand's early attempt to record astronomical images using his *camera électronique*, but Lallemand's

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[168] Irwin, *Proceedings of the National Science Foundation astronomical photoelectric conference, held at Lowell Observatory, Flagstaff, Arizona, August 31 – September 1, 1953,* 69.

[169] Irwin, *Proceedings of the National Science Foundation astronomical photoelectric conference, held at Lowell Observatory, Flagstaff, Arizona, August 31 – September 1, 1953,* 72.

[170] Irwin, *Proceedings of the National Science Foundation astronomical photoelectric conference, held at Lowell Observatory, Flagstaff, Arizona, August 31 – September 1, 1953,* 72.

camera required a trained operator and days of preparation to use.[171] A few astronomers, like Kron and Merle Walker of Lick Observatory, used the device with some success, attracted by its increased sensitivity over photography alone, but it did not gain wide acceptance because of the practical difficulties associated with its use.[172] Though Baum was aware of Lallemand's device, he believed that the direction being pursued was not likely to produce any practical applications for observers.

After consulting with James McGee, who developed both television tubes and photomultipliers for EMI, Baum believed television might be a more appropriate device for astronomers than the Lallemand camera. In 1952, while consulting with McGee about photomultiplier tubes, Baum invited McGee to California to use EMI-manufactured photomultipliers during an observing run on the Mount Wilson 100-inch telescope. McGee found the experience thrilling and the two began to discuss ways to apply signal-generating television technology to the problem of astronomical imaging.[173] While Baum was interested is using McGee's expertise in electro-optical instrumentation to aid astronomers, McGee was partly motivated by the television industry's interest in expanding their consumer base by making their products useful to a wider group, beyond the for-entertainment users.[174]

As I discussed in the preceding chapter, television camera tubes could be useful because they produced an electrical signal, which astronomers could have processed directly to provide quantitative measurements of intensity and spectral distribution, whereas film records had to be scanned with a densitometer in order to transform the information into a quantitative form.

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171 André Lallemand, M. Duchesne, and G. Wlerick, "La Photographie Electronique," First Symposium on Photo-Electronic Devices, Vol. 12 in: *Advances in Electronics and Electron Physics*, (1960): 5.

172 See "SEC Camera Tubes". Westinghouse Electric Corporation. Presented at the Third Symposium on Photoelectronic Image Devices at Imperial College, London, September 20-24, 1965. Reprinted in *Advances in Electronic and Electron Physics* 22 and Livingston "Image-tube Systems," reprinted from *Annual Review of Astronomy and Astrophysics*. Vol 11, 1973.

173 B. L. Morgan, "James Dwyer McGee. 17 December 1903-28 February 1987," *Biographical Memoirs of Fellows of the Royal Society* 34 (Dec, 1988), 529.

174 McGee, "Television Technique," 329.

Moreover, the electrical signals were linear and could be amplified, or intensified, to make the output easier to detect and measure. Baum was not the only observatory staff member to pursue electronic detectors in the early 1950s. Astronomers, with experience developing photoelectric photometers like Kron, Whitford, and Stebbins were similarly drawn to the problem. They used that experience and interest to push for advanced electronic instrumentation in astronomy at their home institutions.

The push for image tube development at the Carnegie Institution

Working from the Mount Wilson Observatory Santa Barbara Street offices in Pasadena, Baum pursued photoelectric imaging. He told Director Bowen that he wanted to discover a way to take advantage of the photoelectric method in an imaging mode, and there must be a better way than the Lallemand approach.[175] Baum felt fortunate that he could have this conversation with Bowen, who understood the physics behind the proposed instrument and valued the use of advanced instrumentation in astronomy. Bowen similarly appreciated having these kinds of conversations with Baum, who, according to Baum could not have had this discussion with Edwin Hubble, Baum saying "Hubble just didn't understand instrumentation. Baade either for that matter…They weren't instrument people. They used what was already handed to them as far as technique at the instruments was concerned."[176] Baum felt confident he could convey his ideas to a more receptive Bowen, who had a strong background in and appreciation for instrumentation.

Unfortunately for Baum, Bowen was not as receptive as he had hoped. Bowen held a strong position on how instrumentation should be developed, believing that large firms and industries would develop for their own needs first, and if there was an impetus for building such devices for commercial television, all that astronomers needed to do was sit back and wait for

175 Baum, oral history interview (2004).

176 Baum, oral history interview (2008).

development to reach a point where devices were good enough for astronomical use.[177] During their conversations, Baum likely did not realize the responsibilities placed on to keep astronomers like Hubble happy and did not have the funding to devote staff time to an instruments project as large as Baum was suggesting.[178] After several conversations on the subject, Baum had to accept that he would not get permission to tackle the problem himself. Baum felt strongly that industry would never manufacture image tubes at a quality that would be acceptable for astronomy, because the two groups had different objectives. Baum realized that astronomers would need to cool their device to observe faint objects, a worry not likely shared with the commercial television industry.[179]

Baum had to wait until the fall of 1953 to propose image tube development to Carnegie Institution president Vannevar Bush, when he made his annual visit to Pasadena. The "Coming of the Great White Father," as Santa Barbara Street staff referred to Bush's annual visit, provided an opportunity for Baum to further discuss his thoughts on image tubes.[180] During these trips, Bush would casually visit with the scientists and technical staff, getting updates on work and offering to listen to advice or complaints. When Bush stopped at Baum's office, Baum updated him on his photoelectric photometer and argued that the next step should be to expand this principle to imaging. Baum told him about Lallemand's work and ways they could improve upon that method. Bush seemed interested in the idea, but did not say much until the following day, when Baum was called to Bowen's office. As Baum recalled decades later, he walked in to find Bowen and Bush facing him. Bowen asked, "Now what's all this talk about a photoelectric image device?" As Baum remembers, "of course he knew perfectly well we'd been discussing it. So, I went through my spiel again and said that I felt that there was a big advantage here…It was the equivalent to

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177 Baum, oral history interview (2004).

178 Ira Bowen and Vannevar Bush correspondence, August 1954, Ira Sprague Bowen Papers, Box 24, Folder 229, HEH.

179 Baum, oral history interview (2008).

180 Baum, oral history interview (2008).

building much bigger telescopes if you could pull it off."[181] Bowen replied with his same argument for letting industry tackle the problem first. He said, "these are very expensive things and beyond our engineering capacity and we have to let firms like RCA develop them to a later stage before we should get our feet wet." But then, to his surprise, Bush interrupted Bowen declaring: "Ike, you're dead wrong." The matter seemed to rest there, but as Baum would later learn, Bush took his proposal back to Washington, D.C. to see what might be done to organize sufficient talent to make it happen. This episode was critical in the formation of a committee devoted to developing image tubes in astronomy. Baum was confident in his assessment of the opportunity for technical advances and believed Carnegie should play a role in that process. By sharing these beliefs directly with Bush, he was able to successfully spur on the development of image tubes for astronomy.

Conclusion

The addition of new electronic technology into the observatory often required the assistance of a new set of skilled workers. Vannevar Bush had unintentionally pushed out Stebbins and Whitford, who had assisted Mount Wilson astronomers with photoelectrically-enhanced photometric studies so Ira Bowen had to seek out an instrument specialist that would be dedicated to electronic instrumentation. Because Bowen had learned astronomy, he trusted that he could hire another physicist who could learn the astronomy side of things on the job.

Here, I have presented the case of two physicists who were pulled into the field of astronomy, by astronomers, who felt they could use their background and experience to aid astronomical research. Ira Bowen and William Baum had similar backgrounds, studying physics and developing optical instrumentation and both believed that electronic instrumentation, which had been spurred on in development by wartime needs and resources, could be used to push astronomical observations deeper and dimmer. They differed, however, in how they viewed the

[181] Baum, oral history interview (2008).

role of the Carnegie Institution in taking a larger leap in the development of electronic imaging. Bowen was restricted by the environment in which he became director and the pressure put upon him by his staff to focus astronomers' research on using the world's largest telescope, Palomar's 200-inch. According to Bowen, development efforts should be left to commercial industry, but Baum, on the other hand, was influenced by the relaxed nature of technological development he encountered developing instrumentation during World War II and understood the disadvantages of working with contracted, privately-owned commercial companies.

CHAPTER 4

VANNEVAR BUSH AND THE ESTABLISHMENT OF THE CARNEGIE IMAGE TUBE COMMITTEE

Introduction

By the mid-1950s, a few groups had the interest, drive, and resources to begin developing image tubes for astronomers.[182] By February 1954, Vannevar Bush had secured funding for a Carnegie-directed research and development program on image tubes for astronomy, writing to William Baum, "It will be a difficult and challenging program and I shall follow it with much interest."[183] Less than a year had passed since Baum first proposed to Bush that Carnegie should investigate the possible uses of image tube technology in astronomy. In this chapter I argue that during that time, Vannevar Bush made four major decisions that defined the course of the Carnegie effort in the development of image tubes in its earliest stage. First, a month-long debate between Bush and Ira Bowen led to an expanded project which was centered in Washington, D.C. Second and third, Bush sought and was awarded funding from the Carnegie Corporation for the research and development of image tubes through its first two years and selected Merle Tuve, director of the Carnegie Institution of Washington's Department of Terrestrial Magnetism to manage the funds and oversee the new project. Lastly, with input from Tuve and William Baum, Bush brought together astronomers, physicists, and engineers to form a committee, which became known as the Carnegie Image Tube Committee (CITC), whose members' expertise and connections shaped the ultimate goal of the committee and directed its progress. Bush acted over the course of only a few months but directed the scope of work at Carnegie that would last for several decades.

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[182] See, for example, discussions of image tubes in Zdenek Kopal, ed., *Astronomical Optics and Related Subjects, Proceedings of a symposium held 19-22 April, 1955 at the University of Manchester* (Amsterdam: North Holland Publishing Company, 1956).

[183] Vannevar Bush to William A. Baum, 18 February 1954, William A. Baum papers, LOA.

In 1953, at the start of the summer, William Baum recommended to Vannevar Bush and Ira Bowen that the Carnegie Institution invest resources into the development of image tubes for astronomers.[184] Given he had an established professional relationship with EMI physicist James McGee, Baum initially suggested that Carnegie collaborate with EMI and take advantage of the resources available to the British television firm.[185] Bowen's priority was the traditional observational programs and the instrumentation development already underway at Mount Wilson and Palomar Observatories.[186] Bowen argued that the majority of the work should be conducted by EMI, preventing the burden of research and development from falling on the Observatories' staff and budget constraints.[187] Bush acknowledged the value of forming international collaborative relationships, but took Baum's suggestion a step further and suggested that the United States and the Carnegie Institution should play a leading role in such an important astronomical and technological development.[188] World War II was a defining moment for American science, both in the need for output and on the availability of funding.[189] As the head of the Office of Scientific Research and Development (OSRD) during World War II, Bush saw the value of independent scientific investigation and the close link between fundamental research and practical applications. In his 1945 report *Science – The Endless Frontier*, Bush argued that scientific progress was essential for the nation's health, prosperity, and security and that, "we

184 Baum, oral history interview (2004); Bowen, oral history interview (2007); W. Kent Ford Jr., oral history interview by David DeVorkin and Shaun Hardy on 25 October 2013, AIP.

185 William Baum to Vannevar Bush, 27 May 1953, Ira Sprague Bowen Papers, HEH; Baum, oral history interview (2004); William Baum to Ira Bowen, August 1953, Ira Sprague Bowen Papers, HEH; Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

186 For Bowen's priority of traditional astronomy, Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

187 Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

188 Ira Bowen to Vannevar Bush, 19 August 1953, Ira Sprague Bowen Papers, HEH.

189 Standard work, Kevles, *The Physicists*.

cannot any longer depend upon Europe as a major source of this scientific capital."[190] A country or person's perceived supremacy in science has been linked not only to the output of their scientific research, but in the superiority of their instruments.[191]

Over the course of the summer, these two highly respected, powerful men debated the right course of action. Their correspondence details arguments for and against various paths, but ultimately resulted in Bush's decision to pull together a Washington-based committee to investigate the possible advantages of image tubes as aids to telescopic observation and assess the scope of work required to carry out development.[192] This expanded project would be much larger than Baum anticipated and would not include collaboration with EMI. It would, however, be operated from Carnegie's Department of Terrestrial Magnetism (DTM) in Washington, D.C., Bush's primary location, which pleased Bowen and served as a convenient compromise for Bush.

By forming a committee, Bush brought together experts in a variety of fields, each coming to the problem with their own interests, connections, and experiences. The Carnegie Image Tube Committee's four members represented four institutions: William Baum of the Mt. Wilson and Palomar Observatories, John S. Hall of the United States Naval Observatory, Ladislaus L. Marton of the National Bureau of Standards, and Merle Tuve, director of Carnegie's Department of Terrestrial Magnetism and the CITC's chairman. Bush selected members based on their experience in key areas he targeted, but also considered their physical location (all but Baum were located in Washington, D.C.), their ability to work well as part of a team, the need to create a multi-institution effort, and, for a chairperson, the ability to manage a project that would elicit input and buy-in from many in the astronomy and physics communities.[193] The Committee

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190 Bush, "Science – The Endless Frontier." For further assessment of Bush report, see Daniel Kevles, "The National Science Foundation and the Debate over Postwar Research Policy," *ISIS* 68 (1977): 5-26.

191 For examples of the link between instrumentation and prestige, see Heilbron and Seidel, *Lawrence and His Laboratory* and Shapin and Shaffer, *Leviathan and the Air Pump*.

192 Ira Bowen and Vannevar Bush correspondence, Ira Sprague Bowen Papers, HEH, particularly, 4 August 1953; 12 August 1953, 19 August 1953, 21 August 1953.

193 Ira Bowen to Vannevar Bush, 4 November 1953, Ira Sprague Bowen Papers, HEH.

members worked independently, investigating different types of image tubes based on their institution's resources, their physical location, and their professional contacts, but they corresponded regularly and met occasionally to discuss their findings.

Social, political, and economic forces acted within each of these episodes of inflection and altered the progression of Carnegie's image tube development. By examining these periods and the choices made by Bush, we can discern how the backgrounds, knowledge, resources, and motivations of individual actors guided the Carnegie image tube project through its exploratory phase from an international collaboration with the television industry to a U.S.-based effort, using resources from several private and government laboratories. Carnegie Image Tube Committee members and Carnegie administrators each influenced the scope of the project which would take them into the next phase of development.

Vannevar Bush and Ira Bowen, debating a path forward

During one of Bush's annual trips to Pasadena, Baum presented his argument for astronomers' need to be actively engaged in the development of image tubes for astronomical research to Ira Bowen and Vannevar Bush. Using technical information provided by James McGee from his research with EMI, Baum requested support from Bowen to dedicate part of his time to this project, but Bowen was hesitant.[194] Both Bowen and Bush accepted Baum's reasoning that image tubes were worth developing, but they differed on the course that should be taken. Bowen worried about the time his staff would need to commit to the development efforts and was therefore cautious about committing resources to Baum's proposed project. After their meeting and Bush has returned to Washington, D.C., Bowen wrote, "Any hesitation that may have appeared in former discussions is solely due to the local problems connected with wonderful new equipment that is already seriously under staffed particularly on the instruments side."[195] In

[194] Baum, oral history interview (2004); Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

[195] Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

contrast, Bush saw a chance for Carnegie, and therefore, the United States, to become a major player in a new, developing technology, writing that “astronomy is a central part of our affairs. If there is going to be another advance in astronomical methods I think we should use every effort to see that our thinking is in advance of developments, and that we do not just trail along.”[196] They debated the best path forward for image tube research, each coming to the problem with their own priorities and needs. Their correspondence reveals the influence each had on the scope and direction of Carnegie’s involvement with image tube development, which resulted in a collaborative project with institutions primarily located in Washington, D.C., close to Bush’s office, but distant from Bowen’s staff in California.

After Baum suggested collaborating with EMI, Bush sought the advice of English chemist Henry Tizard, who Bush suspected might be more knowledgeable of the British firm’s capabilities and reputation.[197] Though Tizard admitted he was not familiar with astronomers’ interest in using image tubes to extend the range of telescopes and did not yet understand why the use of photoelectric methods in astronomical observations was fundamentally better than photographic methods, he was able to offer his support of EMI’s work. He argued that the EMI photomultiplier tubes were better than RCA’s and their development was no longer classified, so collaboration should be easy.[198] Bush forwarded Tizard’s assessment to Bowen, commenting, “Apparently the British group we have been in touch with is an excellent one.”[199] Bush further acknowledged that while they could work with RCA and their head engineer Vladimir Zworykin, he was, “not at all

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196 Vannevar Bush to Ira Bowen, 19 August, 1953, Ira Sprague Bowen papers, HEH.

197 In 1940, during Bush’s tenure as director of the Office of Scientific Research and Development, he met with a British delegation who offered the still neutral United States valuable scientific work they hoped the U.S. could exploit. The delegation, named the Tizard Mission after its instigator, established a system encouraging an open international exchange of scientific and technological ideas. Though Tizard has been described by historians as a “second-rate” scientist, his success as a scientific manager and administrator gave Bush reason to trust his assessment of British scientific endeavors; For a detailed account of Henry Tizard, a “second-rate scientist” but an effective manager, see David Zimmerman, *Top Secret Exchange: The Tizard Mission and the Scientific War* (Montreal: McGill- Queen's University Press, 1996).

198 Henry Tizard to Vannevar Bush, 14 July 1953, Ira Sprague Bowen papers, HEH.

199 Vannevar Bush to Ira Bowen, 4 August 1953, Ira Sprague Bowen papers, HEH.

sure they are entirely easy to work with."[200] Bush's hesitation toward cooperating with RCA may have stemmed from an effort he had initiated as part of the OSRD. In 1944, Bush set up a Committee on Sensory Devices, largely for the purpose of rehabilitating blind soldiers but intended to assist all blind Americans. [201] Bush had approached RCA and Zworykin to lead the project, but Zworykin declined Bush's offer to lead the OSRD program, likely due to his reservations concerning patent rights while conducting research under government contract.[202] Bush's trust in Tizard's knowledge and credibility, even though Tizard was not a specialist in the field of photoelectronics, combined with Bush's personal experience with Zworykin, led him to agree with Baum, that EMI would make an excellent collaborator on the image tube project.

Bowen, like Bush, supported the use of a British firm for development. His support, however, was not centered around his trust for the performance of the British firm, but rather because, Bowen reasoned, if a British company were to take on the bulk of the technical design and manufacture work, British astronomers would take on the responsibility of testing the devices produced, freeing his staff from the commitment. Though the potential of image tubes for astronomical work was exciting, Bowen did not want to commit his staff to undertake a project which they could not devote resources to adequately. Bowen appealed to Bush, writing, "the present inflation has imposed such financial limitations on supporting institutions that we are having to operate both Observatories with a scientific staff which is actually smaller than the one which formerly operated Mount Wilson alone."[203] While the scientific staff had decreased, Bowen was able to rely on an increase in guest investigators to keep the telescopes in regular use, but the Observatory staff could not rely on guest investigators to help with instrumental problems. Staff like Horace Babcock and Baum had to bear additional burden, "as each new guest

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200 Vannevar Bush to Ira Bowen, 19 August, 1953, Ira Sprague Bowen papers, HEH.

201 James Scott Hauger, "Reading machines for the blind: A study of federally supported technology development and innovation" (PhD diss., Virginia Polytechnic Institute and State University, 1995).

202 Hauger, "Reading machines," 21.

203 Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

investigator require[d] a certain amount of instruction in the use of present instruments."[204] Requiring Babcock and Baum to additionally work on new instrumentation, according to Bowen, would have been impossible given their other responsibilities.

With the proposal to develop a new technology, Bowen became concerned about the point in which his staff would be called upon to assist, the duties that would be required of them, and how those requirements would distract them from their research.[205] Bowen was confident in the direction his observatory was headed and the science his astronomers were pursuing. The 48-inch and 200-inch telescopes on Palomar Mountain had only been in operation for a few years and, Bowen argued, were only beginning to realize their full potential. Bowen emphasized that a small telescope should be used for testing, suggesting that time on larger telescopes was too valuable and should be delayed until a reliable tube had been produced. Additionally, Bowen wanted his staff to utilize their current auxiliary instruments, like the spectrograph and microphotometer that were only just beginning to help astronomers reveal new details about the universe, before investing resources into the development of new instrumentation.

Bowen believed the addition of too many new instruments tempted astronomers to conduct too many observational programs, which ultimately could reduce their production of scientific results. "Because of the very wealth of exciting new problems which the Palomar equipment ha[d] opened up," Bowen feared that they would "fail to carry out any of them through to the point where final permanent conclusions [could] be reached."[206] "All of this makes me hesitate," Bowen wrote to Bush, "to ask Baum to undertake another major instrumental development in the immediate future before the completion of the problems now underway and for which expensive instrumentation has just been provided."[207] "In any case," Bowen maintained,

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[204] Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

[205] Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH. "The only question in our mind is concerned with the exact stage at which our group here should start actively to participate in the scientific development."

[206] Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

[207] Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

“these factors as you know have caused me rightly or wrongly to ‘drag my feet’ when major new instrumental developments, such as radio astronomy or image tubes have been proposed. This has been especially the case if I could not see a way to pass much of the development over to another group.”[208] Bowen preferred to provide quality maintenance to his staff’s current research programs and instrumentation and did not want to distract an already limited staff with new instrumentation that had not yet been proven to work at the level Bowen required for his largest telescopes.

For Bowen, the simplest path forward was to rely on British engineers and astronomers for the development of image tubes and the Carnegie Observatories would follow the development closely and “be in a position to take over immediately when tubes ha[d] been developed to the point where they [were] and effective astronomical tool.”[209] British astronomers would be in close proximity to consult with EMI engineers, and EMI engineers could even be present at test observations. Additionally, Bowen argued his case in terms of practicality, writing “Quite aside from the shortage of instrumental help at Mount Wilson and Palomar the difficulty of shipping delicate experimental equipment back and forth over 6000 miles distance each time having to pass through customs would I believe be quite insurmountable.”[210] Bowen proposed that Carnegie help secure funding for EMI to pursue development of image tubes for astronomical use and for arrangements to be made for a British observatory to collaborate with EMI during the testing phase of development.[211] The Mount Wilson and Palomar Observatories, primarily through Baum, would follow the development closely, so that they would be in a good position to take over immediately once tubes could be guaranteed to be an effective astronomical tool, operate reliably, and provide substantial advantages over photographic plates. Bowen’s plan would have allowed him to continue to direct his Observatories the way he wished, allowed his

208 Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

209 Ira Bowen to Vannevar Bush, 12 August 1953, Ira Sprague Bowen Papers, HEH.

210 Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

211 Ira Bowen to Vannevar Bush, 21 August 1953, Ira Sprague Bowen Papers, HEH.

astronomers to continue their research programs, and make certain that Baum, though he wished to play an active role in the development of image tubes, would devote most of his time to the new auxiliary equipment already in use at the Carnegie Observatories.

Initially, Bush was inclined to agree with Bowen's proposal. He realized that they had three courses they could pursue: two extreme cases and a spectrum of middle ground.[212] First, they could follow Bowen's plan to do nothing but provide financial backing and encouragement, and, in Bush's words, "stand ready for the appropriate time when they can try out the devices with the Hale [telescope]."[213] At the other extreme, the Carnegie Institution could take on the whole of the program, building tubes to their astronomers' needs and specifications, testing tubes at their facilities, and being responsible for the success or failure of the project. Realizing that many variations in between these two extremes existed, Bush eventually argued that if this project was important, Carnegie should be active in its development. Bush opposed Bowen's wait-and-see mentality, arguing that, "we should not let any grass grow under our feet on what may involve new and very powerful instrumentation for astronomy. If we take our time, as I believe you were inclined to do, someone will beat us to it."[214] Bush feared that by waiting for a final product, Carnegie and the United States would not play any role in the development of the next great technology in astronomy.

Bush appealed to a very recent moment in astronomy history: the development of radio astronomy.[215] The study of cosmic radio signals began in the United States during the 1930s, but British, Dutch, and Australian groups soon took over as the lead developers. After World War II, the Carnegie Institution, as well as a few other U.S. laboratories and universities, began limited attempts at developing a radio program. In 1950, Ira Bowen and Merle Tuve, director of

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[212] Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

[213] Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

[214] Vannevar Bush to Ira Bowen, 4 August 1953, Ira Sprague Bowen Papers, HEH.

[215] Munns, *A Single Sky*, Edge and Mulkay, Astronomy Transformed, and Allan Needell, "The Carnegie Institution of Washington and Radio Astronomy: Prelude to an American National Observatory, Journal for the History of Astronomy 22, no. 1 (Feb., 1991): 55-67.

Carnegie's Department of Terrestrial Magnetism, agreed to undertake an interdepartmental collaboration, utilizing the Mount Wilson-Palomar staff's knowledge of astronomy and DTM's expertly-staffed laboratories. By 1952, developments stalled, however, largely due to Bowen's fear that the development of radio astronomy would result in fewer resources for traditional observational astronomy and Tuve's aversion to government funding. Carnegie's unenthusiastic interest in radio could not compete with the interest and connections of physicists who hoped to exploit radio technology rather than establish a scientific program, eliminating Carnegie scientists from the early development of radio astronomy.[216]

One year after attempts to develop a radio astronomy program at Carnegie failed, Bush argued that development image tubes differed from radio astronomy, because in radio astronomy, physicists could work independently of astronomers, only requiring occasional visits for consultations. Because image tubes were an addition to the telescope, Bush reasoned, there needed to be active participation from all sides; astronomers could not rely solely on physicists to develop the technology for them. The users and developers needed to form a close relationship and a more intimate collaboration process was needed. The realization that Carnegie and the United States had missed out on the development of radio astronomy, had left a mark on Bush:

> I have a feeling that radio astronomy rather crept up on us; it did on me certainly. It was a going affair in various places before we were fully alert. Yet astronomy is a central part of our affairs. If there is going to be another advance in astronomical methods I think we should use every effort to see that our thinking is in advance of development, and that we do not trail along.[217]

Carnegie, Bush argued, could not idly wait like they did with the development of radio astronomy.

By the end of the summer of 1953, Bush, in correspondence with Bowen, had rationalized his way through multiple possibilities, acknowledging the arguments for and against each proposal. Because of Bush's role as director of OSRD, a science advisor to the president, and his concerns for diplomacy, he saw the benefits of both international cooperation and

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216 For a detailed account of CIW's role in the development of radio astronomy, see Needell, "The Carnegie Institution of Washington and Radio Astronomy."

217 Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

relinquishing control of a scientific project to another country. Bush thought it was a positive thing that Australians took a leading role in the development of radio astronomy. For Bush, it was good for science and good for international relations. Bush cautioned that "we should, I think, use some care to be sure our scientific friends in other countries do not conclude that we are trying to monopolize all of science by the weight of the dollar."[218] However, though he was wary of monopolizing the whole of science, Bush believed because the British were more advanced in the field of science, compared to Australians, the U.S. did not need to acquiesce the development of image tubes to them alone. Bush acknowledged that, additionally, there were groups in the U.S. also working on similar problems. Competition, he accepted, could be very good for astronomy.[219]

Though Bush found many reasons in support of international cooperation, he acknowledged, "proceeding in this way leaves me unhappy. We have the greatest observatory in the world by far. Along comes a method that may have possibilities comparable to those that inspired Hale. And we are content to sit back and let others do it!"[220] Bush felt an obligation, as the maintainers of the world's greatest observatory, to lead the way in all aspects of astronomy. Though Bush acknowledged Bowen's fear of limited staff resources and disregarding ongoing scientific programs (he begrudgingly accepted that he could not prove Bowen's fears were not rooted in fact and had to, therefore, accept Bowen's judgement), Bush hoped that if they began development in collaboration with a either a company or a private institution, federal funding might become available later to support the extra staff Bowen would require. Bush was sympathetic to Bowen's concerns, but made the case for a more active participation on the part of Carnegie.

218 Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

219 Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

220 Vannevar Bush to Ira Bowen, 19 August 1953, Ira Sprague Bowen Papers, HEH.

Bush locates resources: appoints a chairman and secures private funding

During the closing months of 1953, Bush proposed to Bowen that Carnegie collaborate with EMI while simultaneously establishing a U.S. group, but suggested that the U.S.-based group be led by Department of Terrestrial Magnetism director, Merle Tuve. While Bush and Bowen debated possible paths forward, Bush simultaneously acquired a more complete understanding of the problems astronomers wished to address through the development of image tubes, namely (1) the amplification of an astronomical image for the purpose of shortening the exposure time and (2) an increase in the signal-to-noise ratio in attempt to eliminate the limit on imaging set by the brightness of the background sky. With devices capable of achieving these goals, astronomers could study the properties of faint galaxies. Bush concluded that these problems could be solved with adequate financial resources and the right combination of specialists.

Bush and Bowen had worked with Merle Tuve in their attempt to establish a radio astronomy program at Carnegie and, though they initially failed in that attempt, Bush similarly called on Tuve to investigate the extent to which DTM laboratories staff could assist in the development of image tubes for astronomy. Formed in 1904, the mission of Carnegie's Department of Terrestrial Magnetism was to study the earth's magnetic field, including how it changed across the globe and over time.[221] The changing geomagnetic field produced inconsistencies in the compass readings of sailors so the DTM staff coordinated several land- and sea-based expeditions, acquiring data used by scientists to determine correct navigational charts. With their mission fulfilled, the DTM staff had to turn to other problems to keep the department operational.

In 1925, physicists Merle Tuve and Gregory Breit explored the theoretical ionosphere, directing pulsed radio waves into the upper atmosphere, observing the echoes, and confirming the ionosphere's existence. In the process, they discovered the principles of radar. In the 1930s

[221] For a thorough examination of the history of the Department of Terrestrial Magnetism, see Louis Brown, *Centennial History of the Carnegie Institution of Washington, Volume II: The Department of Terrestrial Magnetism* (Cambridge: Cambridge University Press, 2004).

and 1940s, DTM staff made fundamental discoveries of atomic forces, making DTM a premiere center for nuclear physics. During World War II, DTM scientists, like most scientists at American institutions, were brought into the war effort by the OSRD. Tuve led a project on the development of the proximity fuze, one of the largest projects, after the Manhattan Project and the MIT Radiation Laboratory.[222] It was from this project management that Bush likely had confidence that Tuve could run a smaller, but still instrument development program, like the image tube project. Additionally, DTM housed a well-equipped laboratory and he preferred a slow, methodical approach to the problem. Tuve, additionally, was based in Washington, D.C. and was well-acquainted with other laboratories with electro-optical capabilities. Bush wanted the primary efforts to be done from Carnegie, but if EMI wanted to support their own development, the two groups could independently test their devices on small telescopes, but eventually join to observe with the Hale 200-inch telescope.

Tuve, like Bowen, was hesitant about overburdening his staff with a new venture, but rather than dismissing the project, he offered to help, given the ability to add a few staff members to assist. Bush believed they would need someone from the television industry, with knowledge of scanning systems, but Tuve suggested any devoted technician, who was competent in photoelectric performance of materials and their construction would be an acceptable substitute. Tuve recommended that they additionally acquire an individual familiar with electrostatic and magnetic focusing, similar to those employed in electron microscopes, and an astronomer, even during the early stages, who could be available for consultations. Likely at Tuve's suggestion, Bush investigated possible partnerships with staff from the United States Naval Observatory (USNO) and the National Bureau of Standards (NBS), both located in Washington, D.C, who had knowledgeable staff and well-equipped labs. Bush sought a plan that included limited involvement from Bowen's staff, yet still contained active involvement from Carnegie and Tuve's staff.

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222 Brown, *Centennial History of the Carnegie Institution of Washington, Volume II: The Department of Terrestrial Magnetism*, 114.

With Tuve invested in assisting with image tube development, Bush was confident that the combined Carnegie Institution of Washington, the United States Naval Observatory, and the National Bureau of Standards would be able to apply for and receive federal funding through an agency like the recently-formed National Science Foundation, but he thought it safe to have a reserve of private funds.[223] Building a multi-institution committee was important for Bush, partially because he believed funding agencies were more likely to award grants to collaborative efforts. Additionally, it is likely Bush believed, recognizing Tuve's distaste for federal funding, that securing private funds during the early years was vital to maintaining Tuve's support.[224] In November 1953, Bush wrote to John Gardner, a staff member of the Carnegie Corporation of New York, inquiring if the Corporation would support Bush's proposed collaborative effort in astronomy. Bush requested $50,000 to cover two years of work, a modest amount compared to other grants given by the Carnegie Corporation, which extended into the hundreds of thousands of dollars.[225]

Andrew Carnegie established the Carnegie Corporation of New York as a philanthropic trust to provide grants to worthy causes and, though he typically chose to support causes related to education and international peace, he gave the Corporation freedom to change priorities in grantmaking as needs in society changed. Following Carnegie's death in 1919, the Corporation trustees decided it was important to increase the nation's scientific expertise and provided large grants to several organizations, including the Carnegie Institution of Washington.[226] In 1939, Bush became president of the CIW and began serving on the Carnegie Corporation Board of Trustees. With a connection to the Corporation staff, Bush inquired, "whether the Corporation would care to

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223 Vannevar Bush to Gardner, Carnegie Corporation papers, Columbia.

224 Dennis, "A change of state."

225 Vannevar Bush to John W. Gardner, 4 November 1953, Carnegie Corporation of New York records, Series III.A. Grants, Box 469, Folder 7 Columbia University Rare Book & Manuscript Library.

226 See Patricia Rosenfield, *A World of Giving: Carnegie Corporation of New York: A Century of International Philanthropy* (New York: Public Affairs, 2014). Also, the Carnegie Corporation of New York website https://www.carnegie.org/about/our-history/ and Andrew Carnegie. *The Gospel of Wealth*. (New York: Carnegie Corporation of New York, 2017) (first published in 1889).

support a rather extraordinary piece of collaborative research in the field of astronomy?"[227] In his request to Gardner, Bush felt strongly that, if this endeavor was to be the next great development in astronomy, then Carnegie should assuredly be a part of it. "It appears," Bush wrote in his concise grant application to the Carnegie Corporation of New York, "that through the use of this technique one might make a 36-inch telescope capable of producing results now attainable only through the 200-inch Hale instrument…Such an advance, if accomplished, would be of major significance to astronomy as a whole."[228] In January 1954, the Carnegie Corporation granted Bush $50,000 to support the CIW's research into image tubes meant to extend the range of telescopes.

This funding became increasingly more valuable when, at the end of 1953, EMI decided not to collaborate with Carnegie nor any British astronomers on the development of image tubes for astronomical research. While McGee was still eager to carry out work for Baum, the management at EMI could not be persuaded to accept a project of limited commercial application.[229] Baum believed EMI's rejection of their proposal was not due to a short-term financial concern, but because the project did not have enough future commercial value. Baum presumed that they, "wish[ed] to avoid diverting limited staff and facilities from commercially pressing projects."[230] Bush and Baum had both hoped EMI would be a good partner for an international collaboration towards the development of new technology in astronomy, but for EMI, astronomers did not constitute a large-enough market to warrant investment of their time.

When Baum proposed to Bowen and Bush that Carnegie invest resources into the development of image tubes for astronomy, both understood the need for more sensitive

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227 Vannevar Bush to John W. Gardner, 4 November 1953, Carnegie Corporation of New York records, Series III.A. Grants, Box 469, Folder 7 Columbia University Rare Book & Manuscript Library.

228 Vannevar Bush to John W. Gardner, 4 November 1953, Carnegie Corporation of New York records, Series III.A. Grants, Box 469, Folder 7 Columbia University Rare Book & Manuscript Library.

229 William Baum to Merle Tuve, 2 March 1954, William A. Baum papers, LOA. Baum references a letter from McGee to Tuve: "…this Company was unable to accept you offer to do this work."

230 William Baum to Merle Tuve, 2 March 1954, William A. Baum papers, LOA.

instrumentation. Bowen believed image tubes could be a significant aid to observational astronomy, but he did not want the center of that development to be located in Pasadena, where it would drain his staff resources and divert energy away from established research programs. In image tubes Bush saw the next great technological advance in astronomy and wanted to ensure Carnegie played an active role. After failing to secure a role for Carnegie in the development of radio astronomy, Bush was determined to find a role for Carnegie in the development of image tubes. The correspondence between Bush and Bowen reveals the deference they held for each other, while also highlighting their priorities with respect to the role and purpose of the Carnegie Institution and its observatories. The conversation between Bush and Bowen that took place during the second half of 1953 resulted in a project much larger in scope that either had originally intended. Bush secured funding for to a group devoted to research and development in Washington, D.C., under the advisement and management of Merle Tuve. This solution gave Bush the Carnegie involvement he craved while also removing any major hardships from falling on the staff at the Mount Wilson and Palomar Observatories, which pleased Bowen.

Bush constructs a committee

Without EMI as a partner and without EMI's team of experts in television and photoelectronic systems, Bush investigated possible alternatives sources for the experience and knowledge he required. He learned that Yerkes Observatory had entered in to an arrangement with RCA to investigate the potential use of RCA's television tubes in astronomy. While off-the-shelf television tubes worked well for bright objects like the sun or moon, for most astronomical programs, the tube would have needed to be adapted to the needs of the astronomer. Yerkes invested $200,000 into a collaboration with RCA which yielded, according to both Bush and Bowen, no useful results.[231] Bush believed this was probably because the Yerkes project was a

231 Vannevar Bush to Ira Bowen, 4 November 1953, Ira Sprague Bowen papers, HEH. Further research is needed to unpack the nature of this collaboration and who was involved.

"sideshow" for RCA and was never seriously pursued by their best people.[232] RCA, like EMI, likely realized the commercial value of this project did not justify using their best resources.

In the fall of 1953, engineers from DuMont Laboratories, a builder of television cameras, visited the Pasadena offices of the Carnegie Observatories, eager for astronomers to use their image tubes, but they did not want to address astronomers' specific needs. According to Bowen conversations between Baum, Babcock and the DuMont engineers revealed a complete lack of understanding and appreciation of the real problems facing astronomers.[233] The solutions DuMont suggested were not useful for astronomers' hope of detecting and measuring fainter objects like galaxies. While a commercial company could have provided insight into the development of scanning methods like those employed in television, Bush conceded that a television expert would not necessarily have the required understanding of the problems facing astronomers and, concluded, with Tuve's urging, that a television expert was not necessarily required.[234]

To find astronomers and physicists who could assist with the project, Bush looked throughout Washington, D.C., where the Carnegie Institution headquarters were located. He likely consulted Tuve, who would have known other individuals, groups, and labs in the region with the capabilities Bush sought. To ensure that the committee always considered the needs and requirements of the astronomical community, Bush wanted an astronomer actively involved with the project. He hoped to find someone who had a background in electronics and who also had an interest in the development of image tubes for astronomy. At the United States Naval Observatory (USNO), Bush found John S. Hall, an astronomer who had the right experience and characteristics. Hall earned his PhD in astronomy from Yale University and became director of the Astronomy and Astrophysics division of USNO in 1948. Beyond being skilled in electronics work and having an interest in electronic imaging, Bush specifically noted that Hall was a

232 Vannevar Bush to Ira Bowen, 4 November 1953, Ira Sprague Bowen papers, HEH.

233 Ira Bowen to Vannevar Bush, 9 November 1953, Ira Sprague Bowen papers, HEH.

234 Vannevar Bush to Ira Bowen, 4 November 1953, Ira Sprague Bowen papers, HEH.

“delightful individual to work with,” a quality seemingly important to Bush as he assembled his team.[235] Additionally, the commandant of the Naval Observatory was willing to collaborate with Carnegie, even offering space and technical aid. In John Hall and the USNO, Bush found a very willing and capable partner for Carnegie. Bush also inquired with Washburn Observatory director Albert Whitford about having one of his skilled astronomers, Art Code, spend up to a year at DTM, “with the idea that Code might be the man to really embrace this project.”[236] Code declined the offer, though the reasons for this require further investigation. With Hall, Tuve and Bush were happy with their astronomer and the potential collaboration with the USNO.

At the nearby National Bureau of Standards (NBS), Bush located a physicist, Ladislaus (Bill) L. Marton, who was becoming well known for his work in electron microscopy. Marton was an engineer at the RCA research laboratories in Camden, New Jersey before founding the Electron Physics Section at NBS. Bush noted that Marton was also interested in using his knowledge of electrostatic focusing methods and applying them to the problem of electronic imaging for astronomy. NBS, like USNO, was happy to collaborate with Carnegie on the development of image tubes for astronomers. By attaching an astronomer to the project which also had one of the leading authorities in electron microscopy, Bush gave the pursuit increased credibility in the astronomical community.

With these key pieces in places, Baum would only be needed to act as a liaison for the Carnegie Observatories in order to be kept abreast of the development status.[237] This was a fine solution for Bowen, who feared, “spreading Baum’s efforts too thinly.” Baum, who instigated this

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235 Vannevar Bush to John W. Gardner, 4 November 1953, Carnegie Corporation of New York records, Series III.A. Grants, Box 469, Folder 7 Columbia University Rare Book & Manuscript Library.

236 Merle Tuve to William Baum, 21 January 1954, Carnegie Telescope Image Tube Converter papers, Carnegie Institution of Science, Department of Terrestrial Magnetism, Washington, D.C.

237 Vannevar Bush to Ira Bowen, 4 November 1953, Ira Sprague Bowen papers, HEH. “It seems to me that if a group here were working on the subject, and if liaison could be kept alive at all times through Dr. Baum, we would have the elements of a very interesting program.”

program, was not content to watch from the sidelines.[238] In a 2004 interview, Baum acknowledged that he believed Bush had overlooked him as committee chairman because he was young, relatively inexperienced and did not have the recognition in the community of someone like Tuve.[239] Though Baum was content to serve as a committee member, he wanted to maintain a more active role than mere liaison. Ultimately, Bush had brought together four members who, after Bush retired as president of Carnegie Institution in 1955, would solely direct the Committee's activities.

Research and Development: Year one

When Bush formed the CITC, he charged them with investigating the possibility of using image tubes to extend the range of telescopes, assessing the technical requirements for astronomical observations, and determining the best routes to producing an image tube that would satisfy the needs of astronomers. The CITC members first conducted a literature review and began testing signal-generating image tubes available directly from industrial labs, who were already investigating image tubes primarily for entertainment television and military use. CITC members believed that the military projects had the potential have goals that overlapped with their own, but those development efforts were often classified. Additionally, other astronomical groups at Lick Observatory and the Paris Observatory, were simultaneously investigating electronographic image tubes. Because the Committee preferred to not overlap development efforts and Baum had been inspired by the potential of signal-generating tubes from McGee, the CTIC focused their efforts on television tubes.[240]

The Committee encouraged and supported image tube development already in progress, but they found most efforts would not satisfy astronomers' low-light level requirements. Through

238 Vannevar Bush to Ira Bowen, 12 August 1953, Ira Sprague Bowen papers, HEH; Baum, oral history interview (2004).

239 Baum, oral history interview (2004).

240 Carnegie Institution of Washington, Year Book 54: July 1, 1953 – June 30, 1954, 39-41.

these early discussions with commercial firms, however, CITC members realized they would need to direct the course of development efforts if they hoped to find a device that would help astronomers detect fainter objects. Many factors contributed to the first avenues the CITC members pursued. Each type of image tube had the potential to solve the problems astronomers were interested in – such as analyzing dim galaxies. Technical concerns appeared most prominent in early Committee discussions, but arguments about technical specifications were often compounded with social and economic concerns. In deciding on which tube system to develop, the CITC had to consider the availability and location of resources, most importantly, technical staff.

After a visit to Farnsworth Laboratories in Fort Wayne, Indiana, John Hall returned to Washington, D.C. and reported to the Committee that Farnsworth was happy to take on the manufacture of image tubes for the CITC to test, but Hall was told, "the more money set aside for a Farnsworth contract the better the chance of success." Farnsworth requested a contract of $10,000, but John Hall responded that they likely could not go over $5,000. Farnsworth managers, knowing Carnegie's proposed contract was small compared to what the military could offer, tried to leverage a higher compensation, but the CITC had an alternative plan to strengthen their offer. Hall had requested bids from multiple companies and used the competition to astronomers' advantage, Baum adding that competition "and prestige are factors which we should not fail to take advantage of."[241] Though the CITC was able to acquire small contracts to have prototype tubes fabricated, they still had to rely on development efforts already being explored for commercial television and military uses.

Bill Marton at the National Bureau of Standards used $5,000 allocated from the $50,000 initial funds to hire an assistant, Edward Dayhoff. The two physicists visited RCA scientists at their Princeton laboratories on several occasions to discuss mutual technical problems encountered with electronic imaging. They "apparently aroused a spirit of cooperation" at RCA, according to Hall, but discovered that not much quantitative work had been done at the very low

241 William Baum to John Hall, 31 December 1954, William A. Baum papers, correspondence, LOA.

light levels required for astronomical observations.[242] Within a few months, NBS had carried out a literature review of television storage tubes, tested image orthicon tubes, consulted with RCA and the Vacuum Tube Section at the Bureau of Ships. They did not find any development close to their desired outcome and realized they had to look farther, physically, to find a better match.

Marton and Dayhoff would often ask for and receive tubes from RCA that had been discarded for not being manufactured at the quality required by RCA. Because NBS was testing imperfect tubes, their results from television tubes did not result in any outcomes which encouraged them to further test signal-generating devices.[243] By 1954, the CITC determined that television storage tubes would require too much time and money to bring to a point where they could be useful to most astronomers.[244]

Concurrent studies

During their first year of operation, the Carnegie Image Tube Committee narrowed their scope of work based on several factors. While Marton with NBS investigated the potential of television tubes, Baum sought out astronomers who were investigating other types of image tubes in astronomy. They acquainted themselves with the work of other groups for two reasons: first, they could learn what others had determined were technical successes and failures, providing the committee with potential avenues to explore and knowledge of which paths would not be fruitful, and second, the CITC did not want to overlap development efforts. The CITC agreed, with so many possible directions to explore, if another capable group was already exploring one, they would not compete, and adjusted their focus accordingly.

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[242] John Hall to William Baum, 2 March 1954 William A. Baum papers, correspondence, LOA.

[243] Edward Dayhoff to William Baum, John Hall, Bill Marton, Merle Tuve, 12 March 1954, William A. Baum papers, correspondence, LOA.

[244] Carnegie Institution of Washington, Year Book 55: July 1, 1955 – June 30, 1956, 39.

Baum traveled to Yerkes Observatory, where they had attempted to work with RCA, without any success.[245] At Lick Observatory, astronomers attempted to use Andre Lallemand's electronographic camera.[246] Baum noted that "the image resolution [was] excellent," but the device was difficult to operate.[247] Baum corresponded with Lallemand to see if his electronographic method might be worth pursuing and invited him to meet with the Carnegie committee during a trip to the United States.[248] Despite the cumbersome preparation and operation required to use Lallemand's camera, the results obtained showed potential and members of the CITC were eager to learn from Lallemand's successes and failures. Though few astronomers, like those at Lick Observatory, thought Lallemand's device could be practicably used by astronomers, Lallemand's visit sparked interest in electronography as an operating method for image tubes. The CITC was impressed by the potential of the electronographic method and decided to concentrate their efforts on a modified Lallemand system.[249]

During Lallemand's trip, he visited astronomer Lyman Spitzer at Princeton University. In the fall of 1954, Spitzer wrote to Merle Tuve, expressing his newfound interest in applying electronography to astronomical spectrophometry:

> It seems to me that his image tube, while perhaps somewhat impractical for direct photography of two-dimensional surfaces, is, in principle, ideal for spectrophotometry, where a one-dimensional image is needed. I am convinced that development of a practical image tube for this purpose would completely revolutionize astronomical spectrophotometry, and I believe that a program of development along these lines is urgently needed.[250]

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245 Vannevar Bush to Ira Bowen, 4 November 1953, Ira Sprague Bowen papers, HEH.

246 André Lallemand, "The Electronic Camera, Its Installation, and Results Obtained with the Lick 120-inch Reflector," *Publications of the Astronomical Society of the Pacific* 72, no. 427 (Aug., 1960): 268-284.

247 William A. Baum, "Image Tubes in Astronomy," *Science* 154, no. 3745 (Oct. 7, 1966) p 115.

248 William Baum to André Lallemand, 17 May 1954 William A. Baum papers, correspondence, LOA.

249 James McGee to William Baum, 21 February 1955, William A. Baum papers, correspondence, LOA.

250 Lyman Spitzer to Merle Tuve, 19 August 1954, Carnegie Telescope Image Tube Converter papers, DTM.

Spitzer was aware of Carnegie's efforts to develop image tubes and wrote to the committee's chairman hoping that Tuve would "place the spectrographic image tube high on [their] priority list."[251] In spectroscopy, the astronomer was only interested in a single stream of light that could then be broken into its spectral lines. Whether in attempt to appease Spitzer, and other astronomers like Jesse Greenstein and Martin Schwarzschild, who had also expressed interest in this development, the CITC added another goal to the project, which they described in Carnegie annual reports.[252]

Tuve forwarded Spitzer's request to the CITC members. They acknowledged that this is likely a problem they would have attended to after the initial phases of the program, but pressure from prominent members of the astronomical community encouraged them to advance their program more quickly. Tuve suggested that Hall and the USNO contingent focus solely on the spectrographic problem to "show that [they] mean business about the opportunity as a whole."[253] Baum argued that they would have likely included spectrophotometry in their development efforts regardless of Spitzer's request, which was, "in fact identical to what Hiltner [at Yerkes Observatory] already has underway."[254] The CITC emphasized that their goal was in contrast to the goals of other astronomical groups interested in image tube development, which, according to the CITC, were "directed toward the personal research of one or two individuals."[255] They preferred to design a tube that could be used by most of the community, a general use tube that could be manufacturable and be used in any project. Still, the CITC added a new goal, and aimed

251 Lyman Spitzer to Merle Tuve, 19 August 1954, Carnegie Telescope Image Tube Converter papers, DTM.

252 Jesse Greenstein and Martin Schwarzchild were carbon-copied on Lyman Spitzer's August letter to Merle Tuve; Carnegie Institution of Washington, Year Book 55: July 1, 1955 – June 30, 1956, 65.

253 Merle Tuve to William Baum, 19 September 1954, Carnegie Telescope Image Tube Converter papers, DTM.

254 William Baum to Merle Tuve, 22 September 1954, William Baum papers, correspondence, LOA.

255 January 22, 1958 Carnegie Image tube Committee Report, "The Development of Image tubes for Astronomy."

to extend the measurement of spectra to much fainter objects, down from the current 12th magnitude, to the 16th magnitude, roughly 40 times dimmer.[256]

In a grant report for the Carnegie Corporation, the CITC wrote, “The requirement for a manufacturable device necessitated the interest and participation of commercial firms from the start,” but they struggled to find a company whose staff understood the needs of astronomers.[257] Baum hoped McGee and EMI would be the group to appreciate the technical requirements the CITC sought, but EMI refused to collaborate on the project. Baum urged McGee to serve as a consultant on the project to whatever degree he could manage. Baum even asked Merle Tuve to request that Vannevar Bush write a personal plea to McGee for his continued support.[258] McGee agreed to serve as a consultant, with EMI’s approval, corresponding with each CITC member, offering suggestions and advice where he could.[259] After twenty years working with EMI, McGee had growing concerns about the limitations put upon his research by working for a commercial company.[260] This feeling became even more apparent as he spent more time in correspondence with Baum, writing “Naturally it was somewhat of a disappointment to me that this company was unable to accept your offer to do this work, as I would very much have liked to have a crack at the problem at much closer quarters.”[261] McGee found Baum’s excitement infectious and could no longer ignore his frustration with his inability to pursue the projects he found interesting.[262]

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256 Carnegie Institution of Washington, Year Book 55: July 1, 1955 – June 30, 1956, 65.

257 Carnegie Image Tube Committee Report, “The Development of Image Tubes for Astronomy,” 22 January 1958, Carnegie Telescope Image Tube Converter papers, DTM.

258 Merle Tuve to William Baum, 25 February 1954 Carnegie Telescope Image Tube Converter papers, DTM.

259 James McGee to William Baum, 10 February 1954, William A. Baum papers, correspondence, LOA.

260 Morgan, “James Dwyer McGee.”

261 James McGee to William Baum, 10 February 1954, William A. Baum papers, correspondence, LOA.

262 Morgan, “James Dwyer McGee.”

Fortunately for McGee, renowned physicist Patrick Blackett, who occasionally consulted with EMI and served on McGee's PhD dissertation committee, had become Head of the Physics Department at Imperial College London and Blackett had been promised the freedom to rebuild the department as he wished. Upon his arrival in London, Blackett discovered that the University of London (which Imperial College was still a part) held funds for a chair in the department of Instrument Technology that were not being used. Blackett decided to reactivate the post and offered the job to McGee. McGee took on this post with 'the object of establishing a group to work on photoelectric devices that appeared to be required for scientific purposes, in particular astronomy," acknowledging that specialized image tubes were required for scientific progress, "but in such small numbers that commercial laboratories were not interested to develop and make them."[263] In September 1954, during his inaugural lecture as Professor of Instrument Technology, McGee quoted Mount Wilson Observatory founder George Ellery Hale, who said, "No method of advancing science is so productive as the development of new and more powerful instruments and methods of research."[264] The belief that applied physics was far superior to theoretical physics in its applicability, guided McGee's actions and his view on his new role in academia.

At Imperial, McGee devoted his lab and staff to producing an image tube employing the electronographic method. To realize the benefits of electronography and produce an image tube that would be useful to astronomers conducting spectroscopic observations, McGee began with Lallemand's camera, but developed a simpler, single-stage image tube. The problems he encountered were mainly technical, as opposed to the managerial struggles faced at EMI, but with sufficient time and resources now to devote to the problem, he steadily made progress. This tube retained all of the advantages of the Lallemand system without the difficulty of operation and

263 James McGee to C. M. Hutt (16 June 1972), McGee papers, K/PB/1/1, Imperial College Archives.

264 Joel L. Fleishman, J. Scott Kohler, and Steven Schindler, *Casebook for the Foundation: A Great American Secret* (New York: PublicAffairs, 2007): 38.

expendability of the photocathode.[265] McGee intended this tube to satisfy Spitzer and others interested in spectroscopy and so became known as the Spectracon.

McGee's move to a university enabled him to formally work with the Carnegie committee. Correspondence increased between the CITC members and McGee as they consulted each other on their developments and progress. When McGee's team began to investigate their own version of a tube employing the electronographic method, the CITC were happy to relinquish development of that type of system to Imperial College.[266] Though McGee led that development, John Hall, in his annual reports to the Carnegie Institution, considered those efforts to be a part of the CITC's work. McGee's move away from industry and into academia expanded the CITC's abilities by adding the resources of an additional committee member and his laboratory.

With McGee's move to Imperial, and his dedication to the development of an electronographic image tube, the group working from Washington, D.C. was able to abandon that effort and moved on to a third possible method of electronic imaging: image intensifiers, or image converters, which will be discussed further in the following chapter. All three methods (television, electronography, and image converters) offered the same potential advantages over photography alone, but for the CITIC members, image converters seemed to offer a more immediate promise over television for low-light level applications and they were confident that an electronographic solution was being capably developed at Imperial College London.[267]

In December of 1954, the CITC met and concluded their exploratory phase. Though much of the CITC's first year had been devoted to the investigation of television-type image tubes, the Committee decided to move away from concentrating on electronic read-out devices. In annual reports of the Carnegie Image Tube Committee, John Hall often referenced other

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265 McGee realized that if the thickness of the target mica could be reduced to a sufficient thickness and if the accelerating voltage applied to the electrons could be raised high enough, then roughly 75% of the photoelectrons could pass through the mica with enough energy to blacken a grain on the electron-sensitive emulsion.

266 Carnegie Institution of Washington, Year Book 62: July 1, 1958 – June 30, 1960, 336-339.

267 Carnegie Institution of Washington, Year Book 62: July 1, 1958 – June 30, 1960, 333-334.

endeavors being explored by groups in the United States, England, and France. Hall, and the other members of the CITC, however, did not see these endeavors as competition, but as complementary pieces. No single astronomical group could acquire the necessary resources to investigate all avenues so the CITC was happy to allow the few interested groups to share the workload. The delineation of projects was sometimes arbitrarily determined by whomever embarked on a path first but was also decided by each group's goals and access to resources. Though each group worked towards its unique goals, its decisions were often guided by the work of others.

Conclusion

By spring 1954, Bush had secured two years of funding and composed a multi-institution committee consisting of the specialists he believed the project required. The committee members Bush choose exerted their influence on the project, directing the team towards solutions based on their home institution's resources and physical location and their own area of expertise. By choosing to invest time and resources into the image tube project initially, overriding Ira Bowen's concerns, Bush gave the project credibility. In selecting Merle Tuve to coordinate the project, Bush furthered the credibility by attaching an esteemed physicist to the project. The individuals Bush chose to fill out the committee each exerted their own influence on the direction of work. The addition of the Naval Observatory and the National Bureau of Standards brought an additional level of expertise and opinion and, as the committee grew, awareness of their work also grew.

Many factors contributed to their decisions. Technical concerns appear most prominent in early Committee discussions, but arguments about technical specifications were often compounded with social and economic concerns. In deciding which tube system to develop, the CITC had to consider the availability and location of resources, most importantly, technical staff. In attempting to work with commercial companies, the CITC learned the military was also actively engaged in research with the same companies on similar projects, though they were often classified. Though the Committee set out to work prioritizing technical concerns, the obstacles they encountered changed the direction of their research. Understanding how individual interests can direct a multi-institution, collaborative project helps us appreciate the non-linear progression of technological development.

CHAPTER 5

USERS AND PRODUCERS: THE ROLE OF USER GROUPS IN THE CITC'S EXAMINATION, SELECTION, AND PROMOTION OF IMAGE TUBES

Introduction

> "The primary aim in the development of the devices which we have considered so far has been the creation of tools for a satisfactory broadcast television service. Yet their usefulness, and the usefulness of apparatus which may be readily derived from them, goes far beyond this…In particular in the scientific field television techniques can often be applied to great advantage. It is true that the requirements of science and entertainment are so different, often even diametrically opposed to each other, that our attitudes and methods in the two fields must need be quite different. We shall indicate some ways in which television methods may find application in the field of astronomy."[268]

Thus began Vladimir Zworykin, television pioneer and RCA Laboratories head engineer, in this 1950 article in the *Journal of the Society of Motion Picture and Television Engineers*, proposing alternative uses for commercial television equipment. In the years immediately following the invention of the all-electronic television system, and the subsequent development of a variety of photoelectric imaging devices, astronomers became enthusiastic about the potential benefits of adding electronic aids to astronomical imaging. Concurrently, the growing number of companies with electro-optical capabilities realized the potential gain in revenue if they expanded their consumer base beyond broadcast television and several military units and appealed to a new base of users.

Astronomers, however, represented a small consumer group with limited financial resources and, therefore, those who were interested in technological advances often struggled to convince commercial companies that they had value as a potential buyer, worthy of investment in the development of products that satisfied their specific needs. Initially, those astronomers piggybacked on military projects, hoping to benefit from their seemingly limitless budgets. The military's goals, however, were markedly different than astronomers' and their development

[268] Vladimir K. Zworykin, "New Television Camera Tubes and Some Applications Outside the Broadcasting Field," *Journal for the Society of Motion Picture and Television Engineers* 55 (September, 1950): 237-239.

efforts quickly diverged. Luckily, as the marketplace of companies with electro-optical capabilities swelled, instrument developers were able to use commercial competition to the astronomical community's advantage. Additionally, once the federal government granted money to the Carnegie Institution to fuel commercial development of astronomical-grade image tubes, competition between companies for astronomers' business intensified. The producers of electronic image tubes stimulated the formation of a new group of users, astronomers interested in advanced instrumentation, and that group of newly-formed users, leveraging competition and funding, simultaneously drove producers to adapt their products to astronomers' needs.

In this chapter, I explore the interplay between technology and user groups by examining a ten-year effort by industrial laboratories, the Carnegie Institution's Image Tube Committee, and the astronomical community as they jointly endeavored to construct a device that would meet the needs and goals of all three groups. This decade-long struggle began with the Committee's hiring of a young technician dedicated to their image tube project, continued through a decade of development and testing, which saw the addition and subtraction of resources, and concluded with the allocation of image tubes to 20 observatories around the world. Throughout this process, the Carnegie group attempted to disseminate information about image tube technology and their progress through publications and conference presentations. Through these promotional efforts, I argue, the Committee attempted to form a relationship between the builders and the potential users of this technology, the astronomy community as a whole, but they struggled to create a productive avenue for two-way communication. I will show that some members attempted to engage the astronomical community in a dialogue, but the astronomical community was not always an enthusiastic nor helpful participant, and the CITC's chairman, Merle Tuve, was often hostile toward feedback concerning various development paths. I argue this resulted in a product without a user group.

The production of image tubes for astronomers offers a different perspective in the history of technology because this complex process transpired across two technology-user interactions. In this case, the CITC can be seen as the mediator in a "consumption junction," originally described by Ruth Schwartz Cowan.[269] I'll use it here in the context described by Ronald Kline as "the mediation – by advertisers, sales people, and other – between groups we call consumers of technology and those we call producers of technology, such as inventors, engineers, managers, and workers."[270] The consumption junction in this case is the professional sphere of astronomers actively involved in the development of image tube technology for the specific use in astronomy, including the Carnegie Image Tube Committee and other groups of technically skilled staff at institutions like Lick Observatory, Yerkes Observatory, and Imperial College London.

This interpretative scheme is helpful in understanding the development of astronomical image tubes because it describes the way in which consumers "respond to mediators of technology, how consumers help construct all aspects of technology by using it, and how the actions of these groups help to create social change."[271] This perspective gives mediators and consumers agency in the development of technology. Here, the Carnegie Image Tube Committee acted as a mediator by serving as promoter and distributer, attempting to bridge communications between the producer (electro-optical manufacturing companies) and the user (the larger astronomical community).

However, this story is complicated because the CITC also directed the course of technological development, providing requirements, material, and guidance on technical specifications to the producer. Kline wrote, "The line between producers and consumers is, of course, blurred and dependent on one's perspective. One industrial group (such as automobile

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[269] Ruth Schwartz Cowan, "The Consumption Junction: A Proposal for Research Strategies in the Sociology of Technology," in *The Social Construction of Technological Systems*, ed. Wiebe E. Bijker, Thomas P. Hughes, and Trevor Pinch (Cambridge, Mass., 1989).

[270] Ronald R. Kline, *Consumers in the Country: Technology and Social Change in Rural America* (Baltimore, 2000), 9. See also, Joy Parr, *Domestic Goods: The Material, the Moral, and the Economic in the Postwar Years* (Toronto, 1999). Carolyn M. Goldstein, "From Service to Sales: Home Economics in Light and Power, 1920-1940," *Technology and Culture* 38 (1997): 121-152. Karin Zachmann, "A Socialist Consumption Junction: Debating the Mechanization of Housework in East Germany, 1956-1957." *Technology and Culture* 43, no. 1 (2002):73-99.

[271] Kline, *Consumers in the Country*, 9.

manufacturers) consumes the products of another industrial group (such as steel companies), workers use technology to make products, and consumers became producers when they engage in paid or unpaid labor."[272] John Hall, the CITC's designated astronomer, likely saw himself as a consumer of this technology, but he was also actively engaged in its development and production. Kent Ford, a young physicist hired by the CITC to assist in the development of image tubes, began his tenure as a producer, making parts that were used in the production of Carnegie's image tube, but eventually used the device for scientific research. Because of the flawed relationship between the CITC and the astronomical community, the producer manufactured a device for the CITC, not their goal prospective user. Using this framework, I will show the forms of conflict between the astronomical community and the CITC causing the CITC to struggle in their role as mediator.

After the formation of the Carnegie Image Tube Committee in 1954, the Committee members set to test image tube prototypes, working with commercial, university, and government laboratories. With funding from the Carnegie Corporation, the Committee hoped to first explore the potential of television-type devices, hoping to benefit from the resources already directed towards commercial television development. After abandoning that method (see Chapter Four), the CITC pursued an electrostatically-focused design of interest to the military. The CITC consulted with military engineers and worked together collaboratively until they reached a point of development where their end goals forced them to divergent paths of development. In the following years, the CITC lost resources, primarily through staff departures, but also saw resources added, in the form of specialized staff, financial support, and new, dedicated facilities. They transformed from a group, reliant on spillover technology from other better-funded and better-staffed groups, to a self-reliant faction who were able to embark on a ten-year effort to contract a commercial lab to manufacture an image tube specifically for astronomers.

Given the CITC's role as conduit between the builder and the user, the CITC believed they needed to promote their work within the astronomical community, to both elicit buy-in and

272 Kline, *Consumers in the Country*, 9.

stoke confidence. At the 1955 International Astronomical Union meeting in Dublin, Otto Struve organized a special session devoted to the application of television and allied techniques to astronomy, increasing interest from astronomers.[273] I will show that CITC members attempted to sustain that interest by publishing reports on their development efforts, though many astronomers saw those efforts as largely one-sided. When a few astronomers approached the CITC and inquired if they would consider adding an advisory board of outside astronomers who could help guide decisions in the development process, Committee members, particularly Committee Chair Merle Tuve, became outraged at the idea that they needed the input of those who were not actively engaged in development activities. In this chapter I will examine Mere Tuve's refusal to incorporate more of the astronomical community into CITC activities and examine the astronomical community's actions, which gave Tuve reason to be hostile.

Over a decade of development and testing concluded when the CITC partnered with RCA to produce an image tube they believed was simple to use and would be beneficial to a majority of the astronomical community. In this chapter, I will show that because conversations regarding the testing, choice, and allocation of tubes was seen as insular by the groups in the astronomy community, many astronomers were less invested in the final product, believed that the device was too broad in scope to be effective in any specific research project, and that the allocation process only considered those with a high-level of technical knowledge and ability. I will also show how each of these beliefs or effects was either a purposeful decision by the CITC or reaction to perceived resistance from the astronomical community. As a bridge between user and builder, the CITC failed to incorporate the needs of their user, according to the user, which ultimately led to a final product that did not receive widespread use.

[273] Plans for session discussed in William Baum to Merle Tuve, 20 April 1954, William A. Baum papers, correspondence, LOA.

Barrier-membrane image converters

In December 1954, CITC members concluded their exploratory phase and decided to direct their attention away from television tubes and toward the development of a barrier-membrane, also called a thin-film, converter. The barrier-membrane tube was a type of electronographic image tube, like the Lallemand camera, in which the electronic device was mainly used to amplify the light and intensify the image, resulting in an image on photographic emulsion.[274] Electrons ejected from the photocathode of a tube of this type could be directly recorded when they struck a very fine-grained emulsion, in theory providing a high quantum efficiency. Gerald Kron at Lick Observatory, Albert Hiltner at Yerkes Observatory, James McGee at Imperial College London, and André Lallemand at the Paris Observatory were all investigating various forms of electronographic image tubes, and though the CITC originally did not want to overlap efforts, the CITC members believed electronographic method seemed the most promising.

The barrier-membrane converter, first developed by Albert Hiltner and Peter Pesch at Yerkes Observatory, had a very thin film stretched across the end (see Figure 5.1).[275] After the operator mounted the tube in a vacuum chamber and placed the system so that the photocathode sat at the focal point of the telescope, the operator then evacuated the area around the tube, removed the glass break-away cap, and moved the photographic plate behind the thin film with a mechanical plate changer. The operator removed the protective glass cap by placing a tungsten wire around the cap, sending a surge of current through the wire, making it hot, and cracking the glass. The photoelectron beam could pass through this film, but gas molecules could not, meaning the electronic image formed outside the tube while the high-quality vacuum inside the tube was preserved. This solved the biggest problem with the Lallemand camera because the vacuum seal did not need to be broken each time a new photograph was taken, but the plate

[274] George Carruthers, “Electronic Imaging,” 344.

[275] W.A. Hiltner and Peter Pesch, “Image Tube Research at Yerkes Observatory,” *Advances in Electronics and Electron Physics*, ed L. Marton 12 (1960): 17-20.

changer was still difficult for an astronomer to operate. Nevertheless, the CITC was optimistic about this type of tube and hoped, with this system, to help astronomers obtain photographic plates with regularity and ease and without the hassle of breaking the vacuum.[276]

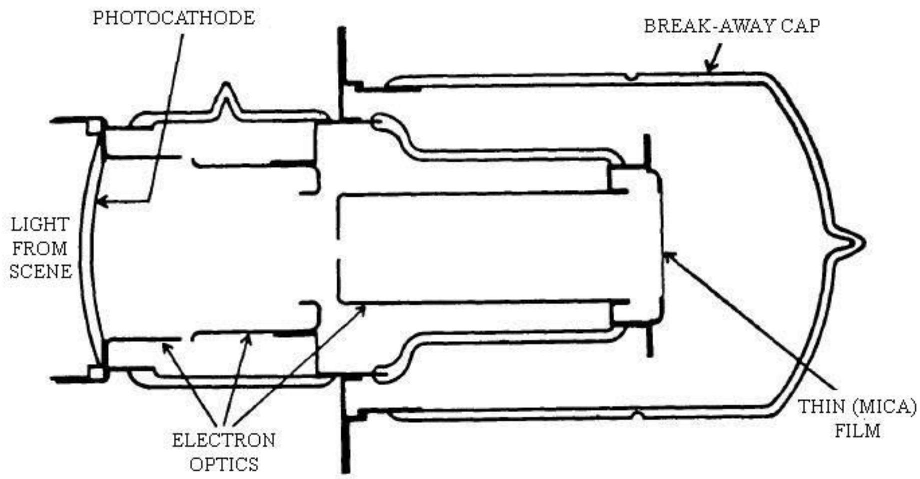

Figure 5.1 Barrier-membrane image converter.[277]

The most challenging part of manufacturing barrier-membrane converters was the production of the thin films used as the membrane.[278] William Baum and John Hall attempted to facilitate the production of tubes and thin films by commercial laboratories, but commercial companies "did not want to have the responsibility of making the films" which were fragile and difficult to produce without being porous, which caused leakage of gas molecules.[279] Instead, Edward Dayhoff at the National Bureau of Standards, with assistance from Stuart Sharpless at the United States Naval Observatory, made experimental films that an engineer in a commercial laboratory would place in their manufactured vacuum tubes. Dayhoff was still partially paid from

276 John Hall to William Baum, 5 January 1955, William Baum papers, correspondence, LOA.

277 J.S. Hall, W.K. Ford, Jr., and W.A. Baum, Astronomical Tests of Barrier-Membrane Image Converters," *Advances in Electronics and Electron Physics*, ed L. Marton Volume 12 (1960): 23.

278 John Hall to William Baum, 29 January 1955, William A. Baum papers, correspondence, LOA.

279 John Hall to William Baum, 29 January 1955, William A. Baum papers, correspondence, LOA; Hiltner and Pesch, "Image Tube Research at Yerkes Observatory," 17.

CITC funds and Hall was able to direct Sharpless' efforts at USNO. By the spring of 1955, Dayhoff and Sharpless had produced useable thin films, which they sent to commercial labs to insert into their commercial image converters.

Kent Ford and Thin Films: new technical talent with an increase in funding

From 1956 to 1958, the CITC saw a period of increased activity as the group managed staff arrivals and departures, an increase in funding, and with that, an increase in workload. In June of 1957, Kent Ford, a recent physics graduate of the University of Virginia, with a proven record of constructing electronic devices and delicate materials for the CITC, was hired as full-time, permanent staff at the Carnegie Institution's Department of Terrestrial Magnetism. By the end of 1958, CITC members John Hall, Bill Marton, and Edward Dayhoff either left the Carnegie group or took on reduced roles due to other responsibilities. During this time, the CITC received a grant from the National Science Foundation, the first major grant the Carnegie Institution accepted from a non-Carnegie entity, worth $255,000 (equating to $2.2 million in 2019 dollars). The NSF funding and the addition of Kent Ford greatly increased the CITC's resources to continue the development of image tubes.

> "By far the largest number of films (many hundreds) have been made with numerous variations of technique by immediate members of the Committee group, particularly by Mr. Kent Ford, Jr., of the Department of Terrestrial Magnetism, now working with a grant from the Joint Committee at the University of Virginia."[280]

In the 1955-1956 Carnegie Image Tube Committee annual report, John Hall brought attention to the immediate benefit of hiring a technician devoted to the image tube project. W. Kent Ford, Jr. first began working for the Carnegie Image Tube Committee from the DTM labs during the summer of 1955, while still a graduate student at the University of Virginia in Charlottesville, a few-hour's drive from DTM's offices in Washington, D.C. Edward Dayhoff left the

[280] Carnegie Institution of Washington, Year Book 55: July 1, 1955 – June 30, 1956, 66.

National Bureau of Standards at the beginning of the summer and Marton was “not personally sold on the thin-film method,” leaving the NBS less active in the CITC programs.[281] As a result, the CITC needed someone dedicated to the image tube project and, though he had no formal training in astronomy, Ford had proven to his graduate advisors to be highly skilled at working with delicate materials. It was his advisor’s contact with Merle Tuve that helped secure him the job at DTM.[282]

Ford’s first task was to evaluate the thin-film tube program.[283] During that first summer, Ford worked from DTM’s machine shop making thin films with techniques he had learned in graduate school, testing them initially with John Hall at the U.S. Naval Observatory’s 26-inch telescope in Washington, D.C. and a year later at the USNO’s 40-inch telescope in Flagstaff, Arizona.[284] Ford and Hall consulted with engineers and physicists at the United States Army’s Fort Belvoir laboratory in Virginia who were working applying the barrier membrane technique to night vision imaging. The films Ford built met technical specifications that the commercial labs could not meet and were shipped to the Farnsworth and RCA laboratories, where they could be installed in image converter tubes for the CITC. Here, Ford and the CITC acted as the consumption junction, the mediator between the producers and consumers, deciding for the astronomical community that the thin-film tubes were worth pursuing and that thin films needed to be built in a private laboratory, where the CITC could control the technical specifications.

The production of thin films and the manufacture of thin-film tubes represented the main efforts of the CITC from 1955-1957 and was funded by the CITC’s $50,000 grant from the Carnegie Corporation. The CITC immediately benefited from their decision to hire a technician devoted to the image tube project, which enabled members to acquire useful tubes to test first in

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281 William Baum to A.E. Hiltner, 11 July 1955, William A. Baum papers, correspondence, LOA.

282 Ford, oral history interview.

283 In the published and private discussions of the thin-film converter, the terms “thin-film” and “barrier-film” are used interchangeably.

284 Hall, Ford, and Baum, “Astronomical Tests of Barrier-Membrane,” 23.

a laboratory and then in typical observing conditions at the telescope. Ford recalled during an oral history interview in 2013 that he became proficient at producing films and the work eventually became routine, even after he returned to Charlottesville in the fall of 1955.[285] While at school, Ford continued to embed himself in the technical literature and tested various barrier-film tubes. The more work he did on the CITC project, however, the more it seemed to him that thin-film tubes were not going to provide a long-term solution for the CITC, largely because they were delicate, difficult to operate, and restricted the field of view, things the CITC decided were important for a tube that the astronomical community could use.

Even for astronomers highly trained in electronics, this tube proved challenging to operate. During a test observation at the Naval Observatory in Flagstaff, astronomer Gerard de Vaucouleurs who spent a year as a visiting scientist at the nearby Lowell observatory from 1957 to 1958, commented that he would be interested in using the image converter tube if, as quoted by Ford, "it ever was easy to work."[286] Even though Ford was able to build a device that would have provided astronomers the ability to photograph fainter objects, he predicted it would rarely be used if it was not easier to operate. Whether in response to de Vaucouleurs' concerns regarding the usability of the thin-film tube or their own issues of durability, Ford and Baum considered how the average astronomer would use the image tube and attempted to redesign aspects to make them more robust and easier to operate.

John Hall, William Baum, and Kent Ford tested several thin-film tubes at the Naval Observatory 41-inch telescope, some successful.[287] However, the tests also proved problematic because, before exposure, the observer still had to remove the protective glass cap by cracking it with an electrically heated wire. Ford and Baum tried to circumvent this inconvenience by creating

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285 Ford, oral history interview; William A. Baum, W. Kent Ford, Jr., John S. Hall, "Recent tests of thin-film image converters," *Astronomical Journal* 60 (June 1955): 154.

286 Ford, oral history interview.

287 Carnegie Institution of Washington, Year Book 57: July 1, 1957 – June 30, 1958, 91.

a metal cap with a can opener-type device under it over the glass cap in the vacuum chamber.[288] This method worked well on multiple tubes tested at the telescope, but still required additional work for the observer. Additionally, in order to obtain a useful photograph from this tube, the exposure time had to be limited to under 1 minute, determined by the background emission from the photocathode.[289] In order to extend the useful exposure time, they had to cool the cathode with liquid nitrogen, which caused further problems in the observatory, due to flooding from the cooling system.[290] The CITC concluded that these early tests indicated potential good performance by thin-film tubes, even though the method, where the observer was required to ensure that the system was continuously vacuum-pumped, was cumbersome.[291]

In June 1957, Kent Ford completed his PhD in physics and began searching for a permanent position. In 2013, Ford recalled how managers at Westinghouse, who Ford had worked with as a part of his role with DTM, actively pursued him, but the work at Westinghouse did not excite him as much as that with the Carnegie image tube project.[292] He decided to ask Merle Tuve for a permanent position at DTM. Ford had met his wife at DTM that first summer in 1955 and they had since gotten married, had a son. Ford was eager to return to D.C. where they had friends and family.[293] Tuve was enthusiastic about the prospect of hiring Ford as a regular employee, devoted to the image tube project, but was concerned that Ford did not have a strong background in astronomy which Tuve felt was needed to take on a larger role in the project. Tuve recommended that Ford take a year off to study astronomy with Art Code, an astronomer with an interest in electronic imaging, at the Washburn Observatory. Tuve had attempted to hire William

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288 Hall, Ford, and Baum, "Astronomical Tests of Barrier-Membrane," 24.

289 Ford, oral history interview.

290 Carnegie Institution of Washington, Year Book 57: July 1, 1957 – June 30, 1958, 91.

291 Carnegie Institution of Washington, Year Book 58: July 1, 1958 – June 30, 1959, 309.

292 Ford, oral history interview.

293 Ford, oral history interview.

Livingston and a second astronomer but both turned down his offer for a permanent position.[294] Ford acknowledged during the 2013 interview that gaining that astronomy education would have been beneficial, but in 1957, he argued convincingly that his tacit knowledge working on the image tube project for two years was far more valuable. Tuve eventually agreed to bring Ford on without the additional astronomy training, likely helped by the fact that the CITC struggled to elicit interest from young astronomers in CITC work.

In January 1958, the Carnegie Image Tube Committee estimated that they would expend nearly all its funds by the end of the year from the original $50,000 grant from the Carnegie Corporation. The CITC utilized these funds for direct expenses associated with the design, fabrication, and testing of potentially useful image tubes of two basic types (television-type with electronic readouts and barrier-membrane-type with photographic readouts) with five industrial laboratories.[295] With approval from the Carnegie Institution's new president Caryl P. Haskins, who assumed his duties after Vannevar Bush retired in 1955, the CITC applied for funding from the National Science Foundation, hoping an increased revenue source could make their project more competitive for commercial contracts to guarantee image tubes could be regularly produced for testing.[296]

The Committee's grant application reveals many of the concerns and expectations for the "Telescope Image Tube Project," as it had been rebranded, dropping the name Carnegie, suggesting they wanted the committee viewed as a collaborative effort. First, the need for financial resources to compete for industrial lab contracts is highlighted repeatedly. With funding from the NSF, the CITC could ensure that they could have tubes manufactured to the exact specifications they requested, without needing to rely on the bi-products of other research projects. In predicting the trajectory of the image tube project, the CITC never submitted an exact

294 Bill Livingston to Merle Tuve, 15 October 1958 Carnegie Telescope Image Tube Converter papers, DTM.

295 Carnegie Institution of Washington, Year Book 58: July 1, 1958 – June 30, 1960: 312.

296 William Baum to Merle Tuve, 8 February 1958, William A. Baum papers, correspondence, LOA.

schedule, as they realized the unknown timetables for development and production could not be reliably foretold and did not want to commit to a deadline. Still, the CITC hoped, if funding could be provided within the year, they would be able to deliver useful image tubes to astronomers within four years. This is significant because, with a goal release date in mind, the CITC had still not formerly requested feedback from the astronomical community concerning the direction of development it was pursuing. In May of 1958, the NSF awarded the CITC a two-year, $255,000 grant to underwrite the large industrial costs associated with manufacturing image tubes to test at the telescope.

John Hall, who had become the primary contact for collaborative efforts with commercial companies, continued his work with RCA and Farnsworth and brought Ford into those on-site discussions, relaying feedback from the CITC's testing observations to the commercial labs. When Ford began his permanent position, for every collaboration Hall was engaged in, Ford either assisted Hall or took over communications entirely. However, in the fall of 1958, John Hall left his position at the U.S. Naval Observatory and took on the post of director at Lowell Observatory, leaving behind many of the responsibilities he had once had concerning the image tube project. Bill Marton, who had been out of touch since leaving for a research trip in India in 1957, was also disinterested in development avenues pursued by the CITC. With Hall and Marton gone, Kent Ford became the primary contact for their industrial laboratory collaborators and took over writing the CITC annual reports and much of the correspondence.

Phosphor output: mica-window tubes and cascaded intensifiers

The CITC requested funding from the NSF to support their efforts to contract an industrial laboratory to manufacture three types of images tubes: (1) the thin-film tube already actively under investigation at DTM and two types of phosphor output tubes: (2) the mica window tube, best suited for infrared work, and (3) the cascaded intensifier, particularly useful in the blue portion of the spectrum, most often used by astronomers.[297] In phosphor output tubes, the phosphor screen converted the photoelectrons into visible light that could be recorded on a regular photographic emulsion. Phosphor output tubes were used extensively during World War II in infrared cameras because the image produced by the phosphor screen was many times brighter than the original image.[298] However, the observer needed a complicated series of lenses to reproduce the final image, there was limited appreciable gain. This was less of a problem for the military, who wanted to detect things like heat coming from enemy aircraft and did not need a resolved image. This issue was solved by James McGee at Imperial College London, who developed a method where a mica window was placed directly in between the phosphor screen and the photographic emulsion. In this method, the observer could be sure that the image displayed on the phosphor screen would be more efficiently recorded by the photographic emulsion.

The cascaded intensifier contained one or more stages of image intensification, where each stage consisted of a phosphorescent screen on one side and a photocathode on the other. This system of image intensification multiplied the photoelectrons inside the tube, increasing the brightness of the image on the phosphor screen, which further counteracted the inefficiency of photographing the screen with traditional photographic emulsions. Ford worked directly with Myron (Mike) Klein, a physicist with the Army's Night Vision Laboratory at Fort Belvoir. Klein and Ford studied the use of the electrostatic phosphor output screen tubes for night vision, but the two groups had different requirements for the device, which would affect the design of the tube. "The military," Ford later recalled, "just wanted a soldier to be able to see something through the night vision device and recognize it as a tank, or a person, or a rabbit. Our interests were always in

[297] "A Proposal for the development of Photoelectric Image Tubes," draft grant proposal to the National Science Foundation, 30 January 1958. Carnegie Telescope Image Tube Converter papers, Carnegie Institution archives.

[298] Carnegie Institution of Washington, Year Book 59: July 1, 1959 – June 30, 1960: 309.

trying to measure something."[299] Ford also collaborated with the Atomic Energy Commission, but their goals were too different to pursue extensive collaboration.

Testing at Lowell Observatory

In 1952, Naval Observatory administrators were looking for a new home for its 40-inch telescope, no longer producing useful science from its Washington, D.C. site. John Hall embarked on a site testing trip to Flagstaff, Arizona, his first trip to the high desert. After the telescope was eventually moved to the USNO Arizona site in 1955 Hall made repeated trips to use the telescope for his own research. During those visits he became friendly with the astronomers and trustee at nearby Lowell Observatory. The Lowell astronomers, who had hosted the Flagstaff photoelectric conference in 1953, had been interested in the possible advances that could come from the use of photoelectric detectors and collaborated often with the CITC. On September 1, 1958, Hall took over the reins of director at Lowell Observatory.

John Hall was not able to perform the same duties he had previously undertaken as a member of the CITC, but did immediately set out to find a telescope, of moderate size, that could perform as a useful test laboratory for available image tubes. In the winter of 1959, Lowell Observatory purchased a 24-inch reflecting telescope and precision mounting from a Ben O. Morgan, of Odessa, Texas. The telescope, which became known as the Morgan telescope would take nearly a year before it could be shipped from Texas and installed in a new building on the Lowell Observatory grounds. Kent Ford designed a grating spectrograph that could be used on the Morgan telescope in conjunction with experimental image tubes for spectroscopic studies.

Baum, Ford, Hall, and occasionally James McGee, tested many tubes at the Morgan telescope. The CITC's plan was to first put any potentially useful experimental tubes through a preliminary check at the Morgan telescope. If they provided useful data and were deemed by the Committee to be worthy of further use, they were then moved to Mount Wilson where they were installed on the Coudé spectrograph on the 100-inch telescope. During an early test of a

[299] Ford, oral history interview.

magnetically-focused tube, Baum and McGee found encouraging results in Flagstaff, but found the same tube useless when moved to Mount Wilson. The difficulties occurred largely because McGee neglected to consider disturbances in the magnetic focusing field caused partly by the steel structure of the spectrograph and pier, but also by changes in the local magnetic field when the massive steel dome of the 100-inch telescope was rotated. McGee's lack of background in astronomy led him to not take into consideration the non-laboratory conditions of astronomical research. Having access to the Morgan telescope for these real-world testing sessions, helped the Committee better understand how an astronomer would practically use the new device.

The thin-film tube, mica-window, and cascaded tubes were well-suited for industrial manufacture and had been used with varied success in tests at telescopes in Flagstaff.[300] Of the five industrial labs already under contract, the CITC moved forward with production with two (RCA and ITT/Farnsworth). The CITC contracted with ITT Laboratories (formerly Farnsworth Laboratories) to develop a simple mica window tube, which the members then tested on the Morgan telescope. This mica window tube was the simplest form of the phosphor output screen and only had a very small effective field of view where good resolution could be attained. "Although the resolution of the device leaves much to be desired," Ford wrote in the Carnegie annual Year Book, "this represents a reduction in exposure time by a factor of 30 as compared with direct photography….For a limited group of applications this mica-window tube may prove of value despite its inherent low resolving power."[301] By the end of 1958, the Committee decided to abandon their efforts towards the thin-film tube design, rejecting it because of its difficulty in practical use.[302] The CITC was happy with the results gained by the mica-window tube, but acknowledged it was not a general use device.

As the Committee's interest moved away from the electrostatically-focused tubes and towards magnetically-focused image intensifier tubes, they could no longer rely on any remaining

[300] Carnegie Institution of Washington, Year Book 59: July 1, 1959 – June 30, 1960, 297-299.

[301] Carnegie Institution of Washington, Year Book 58: July 1, 1958 – June 30, 1959, 310.

[302] Ford, oral history interview.

cooperation from the military. Magnetically-focused tubes allowed for a larger field of view, compared to the electrostatically-focused barrier-film tube, but disinterested the military because these tubes were too heavy and bulky due to their required magnets. They could have theoretically been used by tank commanders, but the staff at Fort Belvoir's laboratories were interested in developing something for field use. While the CITC occasionally experimented with a new mica-window tube or television scanning tube, they focused mainly on image-intensifying cascaded tubes with an internal phosphor screen.

Attempts to increase awareness

The CITC's research and development of image tubes was a largely insular endeavor, but they were not entirely to blame and did attempt to act as a mediator between the astronomical community and the producers of image tubes. There was, however, a discrepancy between the CITC's attempts at creating awareness of their efforts, the pushback from other groups of astronomers, and the kind of back-and-forth communication that some in the astronomy community desired. Occasionally, CITC members would present at conferences of the American Astronomical Society or publish short articles in the Publications of the Astronomical Society of the Pacific. Beginning in 1955, International Astronomical Union general meetings contained a session devoted to advances in photoelectric detectors, which had the potential to reach a wider group of astronomers. In 1958, James McGee organized the first symposium on photoelectronic image devices, but the attendees were largely physicists or astronomers directly involved in the development of image tubes for astronomy. In this section, I examine attempts by the CITC to act as a conduit between their assumed ultimate user group, the astronomical community, and the producers of the technology, and why they failed in these early years to listen to any useful feedback.

In the years immediately following the establishment of the CITC, William Baum was the most active promoter of CITC activities, primarily through publications in astronomical journals. At Mt. Wilson, he worked directly with visiting astronomers, gaining firsthand knowledge of astronomers' misunderstandings, questions, and fears regarding the development of electronic aids at the telescope. In 1954, at the start of the CITC's operation, Baum wrote to Tuve, outlining the benefits of promoting the CITC's work:

> "it seems to me that it would be very worth our while to create a wider awareness in astronomical circles of exactly what it is that we are trying to do. Astronomical interest in the problem, and a correct understanding of it, will go a long way toward promoting both the development and the acceptance of new picture techniques. If I can manage to attend the forthcoming meeting of the American Astronomical Society at Ann Arbor this June, there would be an opportunity to present a paper outlining the fundamentals of the image-receiving problem very much as they were stated in the first half of my report to you last December. I'd also like to emphasize the cooperative nature of the present project, put in a plug for the Bureau of Standards, and in general seek to stimulate active interest."[303]

Tuve responded that he and the rest of the Committee were "glad" to have Baum give a talk, adding, "You may also tell them whatever you wish about our activities in the hope that others may be stimulated."[304] While supportive of Baum's dissemination of information, there was no notion that Tuve was interested in hearing the astronomers' response to Baum's talk.

Between 1954 and 1956, Baum authored, or co-authored with his fellow Committee members, four articles arguing for the importance of investing in the investigation and development of electronic image devices.[305] From 1957 to 1964, the Committee published just six articles detailing testing results of various tube designs.[306] These articles served as one-way

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[303] William Baum to Merle Tuve, 20 April 1954, William A. Baum papers, correspondence, LOA.

[304] Merle Tuve to William Baum, 30 April 1954, William A. Baum papers, correspondence, LOA.

[305] William A. Baum, "Application of television techniques to astronomy," *Astronomical Journal* 59 (Oct., 1954): 314; William A. Baum and John S. Hall, "Present status of the joint image-converter project," *Astronomical Journal* 60 (June, 1955): 154; William A. Baum, "Electronic Photography of Stars," *Astronomical Society of the Pacific Leaflets* 7, no. 326 (1956): 209; William A. Baum, "Electronic Photography of Stars," *Scientific American* 194, no. 3 (Mar., 1956): 81-92.

[306] William A. Baum, W. Kent Ford Jr., and John S. Hall, "Recent astronomical tests of thin-film image converters," *Astronomical Journal* 63 (Feb., 1958): 47; Merle Tuve, W. Kent Ford Jr., John S. Hall, and William A. Baum, "Results of Preliminary Tests of Cascaded Image Converters," *Publications of the Astronomical Society of the Pacific* 70, no. 417 (Dec., 1958): 592; Merle Tuve, W. Kent Ford Jr., John S. Hall, and William A. Baum, "Speed gains obtained with a cascaded image converter," *Astronomical Journal* 64 (Oct., 1959): 346-347; William A. Baum, W. Kent Ford Jr., and John S. Hall, "Recent Tests with Image Tubes," *Publications of the Astronomical Society of the Pacific* 71, no. 422 (Oct., 1959): 382; W Kent Ford Jr., Laurence Fredrick, John S. Hall, Ted F. Houch, William A. Baum, "Evaluation of Mic-Window Image

communication, as the Committee dispensed information. When they did present oral presentations at astronomical meetings, their sessions were not well-attended.[307] They believed they had given astronomers the opportunity to voice their feedback, but that astronomers did not take advantage of the opportunity. Baum, and later Ford, actively promoted the CITCs work through journal publications, but they failed to learn much of their consumer's needs through this process.

There clearly was interest in the the community. In 1954, Otto Struve, Yerkes Observatory director and president of the International Astronomical Union, was interested in including a symposium on image reception problems in astronomy at the 1955 IAU meeting in Dublin, Ireland. William M.H. Greaves, chairman of the commission on stellar photometry and organizer of the image tube session, invited representatives from the CITC, other observatory-based groups exploring photoelectronic devices, and representatives from the electronics industry to attend at present at the session. Tuve suggested Baum and Hall give talks because of Baum's work at Palomar and because Hall as an astronomer could best represent the CITC's goals. After the conference, the primary news discussed amongst astronomers was not the CITC's work, but those still working on adapting television tubes for astronomical problems.[308] Baum attempted to curtail expectations of image tubes, especially those of television tubes, suggesting that it was likely that the technical specifications being dispensed by members of the electronics industry were "ideal" numbers. Baum, the CITC, and other similar groups were more focused on numbers most likely to be obtained in routine observations under observatory, not laboratory conditions.[309] The 1955 IAU meeting sparked interest in the possibilities of image tube technology but had the unfortunate result of setting astronomers' expectations too high.

Tubes" *Astronomical Journal* 70 (March, 1961): 43; William A. Baum, "Facts and Myths Concerning Image Tubes," *Astronomical Journal* 69 (1964): 532.

307 Citations to published abstracts are very low >= 1.

308 Somes-Charlton, "Television as an aid;" Somes-Charlton, "Photo-electronic Image."

309 Baum, "Facts and Myths."

In 1958, McGee convened the first symposium on 'Photo-electronic image devices as aids to scientific observation' to spread his ideas about the benefits of image tubes to many scientific fields. His symposium opened up an international dialogue, attracting a substantial number of men from academia and industry and from a variety of disciplines to present their efforts to incorporate image tubes into their respective fields. McGee was extremely proud of this symposium, which would occur five times during his life.[310] This symposium provided a central place of communication and collaboration that was unrestricted by commercial or military secrecy, where research could be carried on and students trained in this field of Applied Physics.[311] In 1961 McGee organized the second symposium, attracting twice as many contributors as the first. The growing success of the symposium reflected McGee's growing reputation in the international community of astronomers and applied physicists. Unfortunately, the symposium did not reach the astronomy community as the other CITC members had hoped. The proceedings of the symposium were published in Advances in Electronics and Electron Physics, not a journal often read by astronomers. McGee's symposium created a dialogue amongst developers of image tube technology, but the astronomy community did not engage in the conversation.

First signs of pushback: The Moscow episode

The lack of communication between the CITC and the astronomy community came to a head after the 1958 International Astronomical Union in Moscow. Like the 1955 meeting, a special session was devoted to photoelectronic imaging and the CITC presented their status, along with members of the other groups from the United States, France, and Russia. After the meeting, Leo Goldberg, in a report on the IAU, expressed his concern that the French and

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310 Morgan, "James Dwyer McGee."

311 J. D. McGee, Notes on the opening of the fourth symposium on photoelectronic image devices, Imperial College, 16 September 1968, James Dwyer McGee papers, KPB/1/3 Imperial College Archives.

Russians were further along in development compared to the U.S.-based groups.[312] Tuve replied directly to Goldberg, expressing his own frustration with Goldberg's response and "others he had seen" to the development of image tubes.[313] Since Lallemand had produced his first tube two decades prior, some astronomers thought image tube development should have been more advanced. Tuve defended his group against the accusation of being too slow in their progress, arguing that there was nothing stopping any astronomer from using Lallemand's camera even though it was the CITC's impression that his camera would be "suitable only for enthusiastic specialists."[314] The CITC, Tuve argued, was directing their efforts towards an image tube "more generally useful."[315] The CITC had established at their start that they wanted to design a robust, easy-to-use image tube that could be used by any astronomer, but astronomers, as implied by Goldberg's report, wanted something sooner.

At the IAU meeting, Russian scientists presented tests performed with mica-window tubes, which were not, as Tuve informed Goldberg, a new device. The CITC had investigated mica-window tubes and described their development efforts in the annual Carnegie Year Books, a publication which likely did not attract a wide astronomer readership. The mica-window tubes were, in fact, available for immediate use by astronomers, but the CITC abandoned further development, as described in Carnegie Year Books #55-57, because of their poor resolution.[316] Tuve contended with Goldberg, suggesting,

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312 Reference to this report in Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter, Carnegie Institution archives; Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM. Report could be in Goldberg's papers at Harvard University.

313 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

314 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

315 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

316 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

> "If we supply you with a tube such as the Russians used, I honestly believe you would test it for half a day or so and set it aside. If we supplied you or your colleagues with a Lallemand tube, with sealed-off cassettes of fresh cesium surfaces, I am confident its best use would be as an exhibit on the Observatory shelves."[317]

"Our Committee, Tuve argued, "was not endeavoring…to make any grandstand plays" but was interested in producing a "genuinely useful astronomical tool for wide regions of the spectrum."[318] Though frustrated by the dissatisfaction of astronomers, Tuve did conclude his letter, however, with a diplomatic request for feedback:

> I write this somewhat reluctantly, as I feel rather immune to criticism of astronomers regarding image tubes, but I recognize that our committee is vulnerable, and especially the two astronomers on it. If you can help us make the United States astronomical leaders, somewhat less discontented with the present situation, I will appreciate your suggestions."

There were no response letters to Tuve from Goldberg in the archives I visited, but further work should be done at the Goldberg papers at Harvard. Merle Tuve appears to have kept a pristine record of CITC activities and if Goldberg did respond, there was no evidence of any change in the way the CITC approached the astronomical community at large.

Tuve was relatively reserved in his letter to Goldberg in comparison to his plea to Ira Bowen, writing, "I suppose our committee should be content to be lambasted by our American friends, but I am strongly tempted to throw the ball right back at them with the reminder that no great help was forthcoming from the ranks of astronomers either for our efforts or for [Albert] Hiltner's."[319] Tuve was frustrated that the CITC could not secure the services of a young astronomer to assist with the tedious labor of testing tubes at the telescope. In every attempt they made to recruit a young astronomer, they chose to work for Aden Meinel at the University of Arizona, who could outbid the CITC with an offer of a permanent position.[320] "The gist of my

317 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

318 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

319 Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter papers, CIW.

320 Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter papers, CIW.

position," Tuve wrote, was "that we deserve to be spanked if we have been slow-pokes, but the spankers would be more constructive if they would find us at least one young astronomer willing to take a job with our committee."[321] Instead, the CITC has had "raise [their] own man," in Kent Ford to take on the work.[322]

In his response, Bowen acknowledged that he had received several reports from astronomers after the Moscow meeting. Though he did not specify which astronomers had approached him he suggested to Tuve that either the CITC had not been fully promoting their own accomplishments like the French and Russian groups or American astronomers "apparently [did] not realize just what the problem [was]; namely, that the attainment of large intensity amplification is relatively easy in certain cases."[323] While creating an image tube that can produce large amplifications of light was relatively easy to accomplish, Bowen recognized that the CITC's goal was bigger; they hoped to create a tube that would result in a large application of the light intensity, while also maintaining resolution of the original image, and be easy to operate in an observatory setting. Bowen questioned whether the "above reactions from the Moscow meeting [did] not point to the desirability of appointing an advisory group of perhaps a half dozen or more astronomical consultants to [Tuve's] group. One of the main purposes would be to educate these astronomers concerning the problems of image tubes."[324] Bowen's suggestion of an advisory committee implies a search for advice, but his focus on education again shows the focus on the dissemination of information rather than having a dialogue. Both Bowen and Tuve seemed to suggest that if astronomers knew the true state of affairs in the development of image tubes generally, and at the CITC, they would be satisfied with the suggested destination and the progress.

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321 Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter papers, CIW.

322 Merle Tuve to Leo Goldberg, 5 December 1958, Carnegie Telescope Image Tube Converter papers, DTM.

323 Ira Bowen to Merle Tuve, 10 December 1958, Carnegie Image Converter papers, CIW.

324 Ira Bowen to Merle Tuve, 10 December 1958, Carnegie Image Converter papers, CIW.

Suggestions of ways to improve the CITC's outreach were not received with much consideration by Merle Tuve. In response to Bowen's letter, and the astronomers who had turned to him, Tuve asserted that he had heard from astronomers too and that, "many of them are now aware of the possible developments in this field and have many problems in connection with their own programs to which they are very anxious to apply the new tubes once they are available in practical form."[325] Though not enthusiastic praise for the CITC's work, Tuve took their comments as proof that they understood the efforts being tackled at DTM and would be interested in using the final product. Furthermore, Tuve argued that the outcry from astronomers was not due to their frustrations with the U.S. group's lack of progress, but their eagerness to use one of these devices as soon as possible. Because of this, Tuve concluded, there was no need to consult with astronomers as to the direction of development. Instead, he argued, time should be dedicated solely to the rapid development of an image tube they can get into the hands of astronomers.[326] This assessment contradicts Tuve's letter to Goldberg, which insinuates that a large problem is that Goldberg and other astronomers do not have a good grasp on the problems facing image tube developers. Instead, Tuve seems to be arguing that the CITC was on a good path and did not need to be slowed down by communicating directly with astronomers beyond occasional published articles, conference presentations, and yearly Carnegie reports. There was no response from Bowen in the archival record, but, again, Tuve nor the CITC changed their outreach plan in any way in the subsequent years.

The resistance from both groups of users, the CITC and the astronomical community, to work together to determine a common goal and plan is evident in this correspondence.[327] Though

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325 Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter papers, CIW.

326 Merle Tuve to Ira Bowen, 5 December 1958, Carnegie Image Converter papers, CIW.

327 In a 2007 oral history interview, DTM astronomer Vera Rubin recounted how Merle Tuve passed her a folder with a report from Mount Wilson astronomer Horace Babcock detailing his strongly-held belief that astronomy was only done on the West coast, implying DTM was not a respected astronomical research facility. This may have worked into Tuve's defensive nature, but that report was not written until after 1964, and I have no direct evidence to how DTM was viewed by West Coast astronomers in the late 1950s.

the non-leaders, astronomers like Hall and Baum or others scattered across the country, may have felt differently, the relationship was decided by the elite, who had risen to the dual role of administrator and astronomer. As a result, the CITC did not formally engage the astronomical community, though Baum and Ford continued to present at conferences and learn from astronomers as they passed through observatories, conducting test observations. In development efforts, the CITC continued to work towards their goal without any sway from the astronomical community.

The Early 1960s: final development efforts

Throughout the early 1960s, Kent Ford continued to work with physicists in industrial labs, facing new challenges. Because the National Science Foundation funds were government funding, they could only be used to pay for staff time, materials, labor, and other supplies, from which no patentable ideas could arise. Like the thin-film tubes, the cascaded tubes used thin films, but these were easier to produce and were already manufactured easily by commercial labs.[328] Ford had to use caution when working alongside these labs because they did not want their techniques to be shared with rival companies the CITC also collaborated with on the image tube project. When the Committee pushed companies for thinner films, companies were successful, but did not inform the CITC how that was accomplished.

During these early 1960s developments and test observing runs, the CITC continued to publish updates in astronomical journals, but some astronomers still felt excluded. In 1961, Caltech astronomer Jesse Greenstein wrote to Merle Tuve again asking if it would be possible to hold a meeting with the CITC and others engaged in the development of image tubes with a group of outside astronomers where they could discuss the state of tube development.[329] Greenstein's goal for this meeting was to have the two groups come to an agreement on the best

[328] Ford, oral history interview.

[329] Jessie Greenstein to Merle Tuve, 26 December 1958, Carnegie Image Converter papers, CIW.

path forward in tube design because he was “definitely of the opinion that the present work has gone at too low a rate [and he was] not sufficiently aware of the results to know that it has gotten far enough to start ordering tubes for the rest of the country.”[330] Again, Tuve resisted the proposition that the CITC needed to consult with outside astronomers. Tuve felt that the astronomers in attendance during image tube sessions at the IAU meetings were still enthusiastic about using CITC image tubes when made available and there was therefore no reason to take the time to appeal to them in a specialized setting like Greenstein, and others previously, suggested. Tuve argued that, “as a measure of policy or desire on the part of working astronomers everywhere, these sessions were not useful.”[331] Tuve and the CITC had made it their goal early in the process to design a tube that could have general use and be easy to operate to serve the greatest number of astronomers. They feared that astronomers would want specialized tubes for individual research projects, an endeavor that would be too costly and time consuming to be useful in the near future.

With mounting pressure from astronomers and development reaching a plateau, the CITC acknowledged they had to move forward and test them in the real world. The most successful of the two designs was an RCA-produced cascaded tube, model number C-33011 tube, which came to be known as a “Carnegie tube.” Several C-33011 tubes were produced and tested on the Morgan telescope. When Ford brought an early model to Flagstaff to test, Bill Baum quickly realized that Ford had neglected to incorporate a mechanism to focus the image. Ford’s lack of astronomical training again led to not appreciating the act of observing at a telescope, but because of his technical ability, he was able to remedy the problem on site. Eventually, number 107 met the demands of the CITC and, in 1963, they decided that tube would be the version that would be dispersed to astronomers to use for research.

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330 Jessie Greenstein to Merle Tuve, 26 December 1958, Carnegie Image Converter papers, CIW.

331 Merle Tuve to Jessie Greenstein, 4 January 1962, Carnegie Image Converter papers, CIW.

Conclusion

The CITC began their development into image tubes with the goal of providing astronomers an image tube that would aid telescopic observations for any astronomer, regardless of their ability to operate electronic equipment and regardless of their research topic. The CITC members learned, however, that those goals did not line up with the most vocal American astronomers. Merle Tuve was often accused running a lagging operation, which frustrated him greatly. Part of the problem seems to have been in the ineffectiveness of the CITC in educating astronomers about the development of image tubes generally and the specific efforts of the CITC. Tuve placed some of the blame on astronomers, who wanted a useful product out of the CITC's efforts, but were not willing to assist the project in terms of staffing. Though Tuve often suggested to the Committee that they hire a full-time astronomer, by the time they were ready to, none would take up the offer. The inability of the CITC to act as a productive mediator between the producers of image tubes and the astronomical community led to a user group without buy in on the final product. In the following chapter, I will examine the repercussions of that failure.

CHAPTER 6

RECEPTION OF THE CARNEGIE IMAGE TUBE: SCIENTIFIC USE AND NON-USE

Introduction

In his 1976 annual report as president of the Carnegie Institution, Philip H. Abelson discussed what he saw as a revolution in electronics.[332] Americans were increasingly bringing electronic devices into their home and were incorporating the new machines into their everyday life, from commercial radios to television sets. More important, but less evident to the average American, Abelson argued, was the application of electronics to commerce, manufacturing, defense, and science. The addition of electronics to scientific research, including new electronic tools, altered the way scientists gathered and analyzed data.[333] By 1976, electronic instrumentation had already permeated most aspects of research at the Carnegie Institution, such as the nuclear physicists' use of an image tube spectrograph to determine the lifetime of energy level states.[334] In astronomy, for example, Abelson lauded the ability of electronic tools to increase the sensitivity and accuracy of measurements and credited the new devices for astronomers' ability to extend the volume of the measurable universe.[335] At Carnegie's Department of Terrestrial Magnetism, scientists had shifted from research concerning the earth and its environment, determining the earth's magnetic field first through expeditions then with magnetic observatories, to the burgeoning field of radio astronomy and the development of image tubes for astronomical observations.[336] The success of the Department of Terrestrial Magnetism's

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[332] Carnegie Institution of Washington, Year Book 75: July 1, 1975 – June 30, 1976: 3.

[333] Smith, "Engines of Discovery," 56.

[334] G.E., Assousa, L. Brown, and W.K. Ford, "Mean Life measurement of 4p and 4p' levels in argons II using an image tube spectrograph," *Nuclear Instruments and Methods* 90 (Dec., 1970): 51-54.

[335] Carnegie Institution of Washington, Year Book 75: July 1, 1975 – June 30, 1976: 3.

[336] Brown, Centennial History of the Carnegie Institution of Washington, Volume II: The Department of Terrestrial Magnetism; Gregory Good ed., *The Earth, the Heavens and the Carnegie Institution of Washington, History of Geophysics Volume 5* (Washington, D.C.: America Geophysical Union: 1994); James

programs show, Abelson wrote, that "a training in physics is particularly useful as a preparation for problem solving."[337] "Since the department is for the most part staffed by physicists," Abelson continued, "it is not surprising that they have invented, developed, or adapted many items of electronic equipment," including the Carnegie Image Tube Committee's development and distribution of 34 image tube systems to observatories around the world.[338] Their international use, Abelson argued, "opened a new era in observational astronomy" and was further proof that the electronic revolution had infiltrated all aspects of society, to great benefit.[339]

In this chapter, I examine the results of the Carnegie Image Tube Committee's efforts to develop an image tube to aid and advance astronomical observations and investigate Abelson's claim that Carnegie opened a new era in observational astronomy. By examining correspondence and published articles, I show that of the 34 image tubes that were allocated, some were used actively by astronomers, some garnered intermittent use, and some were largely neglected. I examine astronomers' use and non-use of the Carnegie's image tube in order to assess the success of the Carnegie Image Tube Committee. Astronomers who successfully used the Carnegie's image tube (i.e., used data from image tube-aided observations in a scientific publication) were able to do so because they had experience operating electronic equipment. Astronomers without this experience had to rely on the assistance of a technician, trained to operate the device on the telescope. This created further separation between the astronomer and the telescope and added an additional component to image tube technology: the role of the trained assistant. The CITC were unsuccessful, I argue, at meeting the goals they had established at their formation, because their device could not be used by any astronomer at any observatory. However, through the examination of research projects astronomers carried out with

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Trefil and Margaret Hindle Hazen, *Good Seeing: A Century of Science at the Carnegie Institution of Washington*, 1902-2002 (Washington, D.C.: Joseph Henry Press, 2002).

337 Carnegie Institution of Washington, Year Book 75: July 1, 1975 – June 30, 1976: 3.

338 Carnegie Institution of Washington, Year Book 75: July 1, 1975 – June 30, 1976: 10.

339 Carnegie Institution of Washington, Year Book 75: July 1, 1975 – June 30, 1976: 10.

this image tube, I argue they succeeded in launching a new era in observational astronomy by showing that there was a need in the astronomical community for more sensitive and efficient detectors that could help them see further into the universe. Even though the Carnegie Image Tube Committee's efforts did not result in an overwhelming adoption of image tubes by the astronomical community, their limited success does show how image tubes could help astronomers study the dimmest galaxies and uncover new details of the universe. The Carnegie tube may not have survived its competition, but several groups relied on the CITC-developed device to advance their field.

The Carnegie Image Tube Committee was managed from Carnegie's Department of Terrestrial Magnetism offices in Washington, D.C., but its members were located at, and often relocated to, observatories and laboratories throughout the United States. The CITC's chairman, Merle Tuve, retired from his post as DTM director in 1966, allowing John Hall to take over the position as CITC Chairman. Hall, who left his role as U.S. Naval Observatory astronomer and became director of Lowell Observatory in 1958, was joined in Flagstaff by William Baum, who took on Lowell's Planetary Patrol Program in 1965. L.L. Marton became an inactive member of the Committee by 1958, but was still listed as a member, while Kent Ford was never listed as a Committee member, but took over most of the CITC's operations after Hall left Washington, D.C.

The original CITC members had established their goal in 1954 to develop a rugged electronic device, with enough gain to be beneficial for astronomers, but whose operation was simple enough to be employed by any astronomer at any observatory, particularly those with access to only modest-sized telescopes. "The purpose of the original Carnegie Corporation grant," the CITC members conveyed in a 1959 report, rested in the "hope that telescopes of modest size may become roughly as effective in studying the far reaches of space as is the present 200-inch telescope used with photographic plates."[340] By the start of 1964, after a decade

340 Carnegie Institution of Washington, "The Development of Photoelectric Image Tubes for Use with Astronomical Telescopes," report to the Carnegie Corporation (2 March 1959).

of research and development efforts by scientists and engineers at DTM, Mt. Wilson and Palomar Observatories, Lowell Observatory, the U.S. Naval Observatory, the National Bureau of Standards, RCA, the International Telephone and Telegraph Company (ITT), and Imperial College London, the CITC believed they achieved that goal. Through their RCA collaboration, RCA produced two image tubes that the CITC believed were ready for regular astronomical use: a mica-window converter and a cascaded image intensifier. The mica-window converter was particularly useful for astronomers wishing to observe in the infrared, but the cascaded image intensifier was Carnegie's general-use image tube, which was particularly useful in the blue portion of the spectrum, most often used by astronomers. The cascaded intensifier was produced in higher quantity than the mica-window converter, and became known as the Carnegie Image Tube.

Merle Tuve requested funding from NSF to purchase a "limited production run" of image tubes from RCA to dispense to astronomers. Because of the federal government's restrictions on granted funding, RCA retained the patents for the image tubes developed with the CITC. RCA could, therefore, produce the Carnegie Image Tube for any interested party. Tuve urged the NSF to approve funding for the CITC to purchase the first run of these devices, arguing that a "simple purchase order to RCA by any other agency or group…will unavoidably eclipse the contributions and steady efforts Carnegie and NSF an RCA have made together the past few years to bring these tubes up to the specifications of sensitivity, resolving power and low background during long exposures which are required for astronomical use."[341] Tuve feared that the RCA's production of an astronomy-quality image tube would be difficult to separate from RCA's efforts with the Air Force, Atomic Energy commission, and Army engineers. Those efforts resulted in the production of image tubes with very high gains, which were not suitable for astronomers' long exposures and Tuve was concerned that Carnegie would not receive credit amongst the astronomical community for their efforts if they did not deliver image tubes themselves. Tuve

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[341] Merle Tuve to H. Leland J. Haworth, Randal M. Robertson, Geoffrey Kelly, Gerard F.W. Mulders of the National Science Foundation, 24 January 1964, Carnegie Telescope Image Tube Converter papers, DTM.

hoped to gain "public recognition of accomplishments on behalf of pure science" and link the image tube with the Carnegie Institution.[342]

The National Science Foundation granted the CITC funding to purchase 20 cascaded image tubes to dispense to astronomers. In September 1964, the Carnegie Institution issued a press release informing the astronomical community that they had developed an image tube "capable of tripling power of telescopes," with a production run of the first 20 available to interested astronomers.[343] In this announcement, the CITC appealed to astronomers, arguing that the CITC's image tube, given its gain in the rate of recording data by a factor of 10 over the best photographic emulsions, could extend the range of a telescope, making it the equivalent of an unaided telescope of three times the diameter. By enabling astronomers to effectively increase the light-recording power of a telescope by a factor of nearly 10, they were hoping to help observatories with moderately-sized (i.e., 60- to 80-inch) telescopes compete with astronomers who had access to the 200-inch Hale telescope on Palomar Mountain.

The first run of Carnegie Image Tubes each cost $5,000 (roughly $40,000 given inflation) to manufacture, but would be provided free of charge to astronomers, through the grant from the National Science Foundation. Because the CITC used NSF grant funds to purchase the RCA-manufactured tubes and compile the necessary auxiliary image tube equipment, a joint committee was created with members representing the CITC and the NSF to determine which observatories would be provided image tubes. The CITC compiled a list of 35 observatories and institutions who had inquired about the availability of the CITC tubes and the Joint Allocations Committee made a call for applications to those interested parties.[344] The application was simple,

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342 Merle Tuve to H. Leland J. Haworth, Randal M. Robertson, Geoffrey Kelly, Gerard F.W. Mulders of the National Science Foundation, 24 January 1964, Carnegie Telescope Image Tube Converter papers, DTM.

343 Carnegie Institution of Washington, "Carnegie Committee Now Has "Image Tube" Capable of Tripling Power of telescopes; Production Order Placed for First Twenty; Press release (26 October 1964).

344 Merle Tuve to Gerard F.W. Mulders of the National Science Foundation, 22 June 1965, Carnegie Telescope Image Tube Converter papers, DTM.

but the Joint Committee was able to prioritize a list of applications, focusing on the astronomical problem each institution wished to tackle with the new equipment.

Between 1965 and 1968, the CITC loaned Carnegie Image Tubes to 34 observatories around the world. As RCA produced each tube, the CITC granted the first available to Yerkes Observatory, Lick Observatory, Kitt Peak National Observatory, Lowell Observatory, and Mt. Wilson Observatory in the first round of allocations. The CITC members chose these observatories because they all employed trained technical staff with experience working with a variety of image tube systems and who could evaluate the allotted image tubes. As RCA produced the second, third, and fourth wave of tubes, the CITC and NSF allocated them based on applications by their respective observatory staff. Some astronomers, with less skill and experience, received image tubes, but, as I will show in the chapter, encountered problems in the maintenance of the image tube, while others found the device too troublesome to use regularly, especially for visiting observers. Through the examination of the allocation process and subsequent use of image tubes at receiving institutions, I will show how the inability of RCA to standardize the Carnegie Image Tube to the CITC's high specifications, the need for local staff to be highly trained in operating the apparatus, and the frequent requirement of each observatory to adapt their observing equipment to the new image tube resulted in a disappointed reception amongst astronomers.

After the CITC allocated their image tubes, Kent Ford was tasked with helping several observatories set up their image tube systems and for years continued to field questions concerning their operation.[345] Ford partnered with Carnegie astronomers to put his image tube system into practical use at large telescope facilities like Mount Wilson and Palomar in California, Kitt Peak National Observatory in Arizona, and Cerro Tololo Inter-American Observatory in Chile, but also worked directly with astronomers at institutions with moderately-sized telescopes, those whom the CITC hoped image tubes would be most beneficial. Some astronomers with

345 Ford, oral history interview. Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM.

moderately-sized telescopes at their disposal, now faced with the reality of the situation, and its comparatively low cost, leapt at the chance to add a Carnegie Image Tube to their arsenal of instrumentation when they first became available.[346] However, as the only CITC representative engaged in this service, Ford could not provide adequate help to all observatories and observers in need.

Because observatories employed different varieties of equipment, astronomers were required to adapt the Carnegie tube to their observing equipment and needs. For some, this added more difficulty to the installation process.[347] After the Carnegie Committee's inventory of image tubes had been dispersed, Ford wanted to turn his focus to the improvement of the equipment required to use the image tube at the telescope, to help astronomers get the most out of their Carnegie device, but he also made himself available to assist in the installation process.[348] Ford intended to help other observatory staff develop proficiency in the use of new image tubes, but each observatory needed to have someone on staff who would take ownership and responsibility over the equipment on a daily basis. Frequently, only one staff person was properly trained, and if that person was not available, or was difficult to work with, the image tube equipment could not and would not be used for long stretches of time.[349] To further complicate the process for astronomers and the CITC, RCA was unable to completely standardize the manufacturing process and some tubes became degraded if they were not maintained

[346] A.B. Meinel to Merle Tuve, 6 November 1964, Carnegie Telescope Image Tube Converter papers, DTM. "The extension of this new equipment to other observatories would be possible at minimum cost in time and dollars since the development work has been paid for."

[347] Ford, oral history interview; Ford 1966-1968 correspondence with Tokyo Observatory and the Vatican Observatory, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM; William N. Dove to Kiyateru Osawa, 20 April 1967, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM; W. Kent Ford, Jr. to Fr. Martin F. McCarthy, 3 October 1968, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM.

[348] Ford, oral history interview.

[349] Ford, oral history interview.

properly.[350] By requiring that astronomers adapt their equipment to the requirements of an image tube, the need for local staff to be highly trained in operating the apparatus, and the inability of the CITC and RCA to guarantee each tube would be produced at the same high standard, I show that astronomers were left wondering whether the image tube's increased sensitivity and efficiency was worth the difficulty of its use.

From the 34 individuals and institutions who were allocated image tubes, roughly one-third published articles in scientific journals or presented at academic conferences using data collected with a Carnegie Image Tube, but the majority of those papers were an assessment of the image tube and not scientific research data. Other astronomers did publish scientific results using a Carnegie Image tube, but they did so while working as a visiting scientist at a larger observatory, who had also been granted a Carnegie Image Tube, with a Carnegie Image Tube spectrograph designed by Kent Ford attached to a larger telescope than the individual had access to at their resident observatory. Through the allocation process, astronomers interested in using image tubes were able to gain experience conducting research with the new device but most preferred to use them on larger telescopes. This was significant for two reasons. First, observatories like Kitt Peak National Observatory (KPNO) and the Cerro Tololo Inter-American Observatory (CTIO) often required visiting astronomer to have experience using the instrumentation as to not be a burden on the local telescope operator, but Kent Ford spent two years on sabbatical at KPNO, from 1973 to 1974 and was able to assist visiting astronomers with observations.[351] The CITC had hoped image tubes would create a more democratic process of acquiring data if 60-inch telescopes could perform similarly to the 200-inch telescope, unaided, but astronomers using that 60-inch, even aided, could not compete with the data from an aided 200-inch telescope. Astronomers still benefited from having access to an allocated image tube at their home institution, though not in the way, I argue, the CITC had originally intended.

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350 Tom D Kinman to W. Kent Ford, Jr., 8 December 1967, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM; W. Kent Ford, Jr. to Tom. D. Kinman, 26 June 1968, Carnegie Telescope Image Tube Converter papers, DTM.

351 Ford, oral history interview.

Second, and equally important in assessing the success of the CITC, is an examination of how this action by astronomers, choosing larger observatories over their own moderately-sized telescopes, defied the original goal of the CITC. In 1954, the CITC was established to provide tubes that would allow astronomers who mostly only had access to moderately-sized telescopes. Astronomers' choice to acquire data using electronically-aided observations at the world's largest telescopes, rather than using an image tube to make their local telescope the equivalent of a large telescope is revealing, especially given the kind of astronomical research that was becoming popular, where observations of the dimmest objects were important and there was great competition to see who could acquire that data first. This period shows that astronomers were eager to have observational aids that would allow them to measure the dimmest light source possible, but the Carnegie Image Tube did not solve the major problem of telescope access.

The most proficient user of the Carnegie Image Tube was DTM astronomer Vera Rubin, who, by working directly with Kent Ford, was able to employ the new instrument to its fullest potential. Rubin and Ford found particular success in the measurement of radial velocities of spiral galaxies. Their data led Rubin to conclude that galaxies contained much more mass than observable, providing the strongest evidence for the existence of dark matter. Rubin was successful in part due to her partnership with the device's designer, Kent Ford and in part due to her pursuit of a research project that did not interest her male colleagues. Rubin chose her research project because it interested her and, "no one else was doing it," but she was aided by Kent Ford who was actively looking for a research project which would stretch the limits of his recently developed image tube spectrograph.[352] I use Rubin's success to show how the Carnegie Image Tube had the potential to advance scientific research if the right combination of research project, skilled astronomer, and technical assistant were present.

From the 1950s through the 1970s, while the Carnegie Committee developed their system, a few groups around the world had simultaneously been developing image tube systems of their own. While the Carnegie Committee had set out to design a device that would receive

352 Rubin, oral history interview.

general use and could be adapted to a variety of research projects, other astronomers focused their efforts toward a specific research program. Astronomers from different sub-fields had different needs from an imaging device and some devices had been specifically designed to address those needs. As a result, astronomers had the choice between competing technologies and could select the one better suited to their needs. Additionally, larger trends in astronomical technology, like simultaneous advances in the efficiency of photographic emulsions, the launch of several space-based observatories, and the development of devices that allowed for data to be born digital and fed immediately into a computer, I argue, all lessened the CITC's impact on astronomical imaging.

Although Carnegie's tube received modest use, image tube technology was never fully adopted by the astronomical community. Throughout this chapter, I look at how and why astronomers chose to adopt or not adopt the newest-available technology. Although much of the astronomical community was initially excited about the potential of electronic imaging, in practice, new devices required that astronomers learn new skills, which deterred many from utilizing the new technology. Astronomers had the choice between photography, an established technology, inefficient, but familiar, and image tubes, a new technology, technically superior, but required training. Several of the astronomers who applied to borrow and use a Carnegie Image Tube produced groundbreaking science with the instrument, but they received thorough training first.

The Carnegie Image Tube: potential uses and operation

In the CITC's 1964 press release, Merle Tuve expounded the benefits of image intensifying tubes, saying, "Image intensifiers are of importance because of the exceedingly low light levels with which astronomers must work."[353] The CITC claimed exposures of many hours' duration could be made with the device, opening up possible applications where astronomers sought to measure faint light sources. "The first application that comes to mind," Tuve offered, "is

353 CITC press release 1964, 6.

the photographing of fields of faint stars," but "perhaps the most important application of image intensifiers…will be in obtaining stellar spectra."[354] Because of the relatively high efficiency of photographic emulsions in the blue region of the spectrum, astronomical spectroscopy was typically done in this region and the Carnegie cascaded tube had gains of 10 times that of the best available photographic emulsions in the blue region. This tube also has an extended sensitivity into the red region of the spectrum and greater gains over photographic techniques were possible than in the blue.

The Carnegie cascaded tube, diagrammed in Figure 6.1, consisted of two stages coupled by an intensifying screen and a system of magnets to focus the photoelectrons. The tube itself was three inches in outside diameter, five inches in length, and with its magnets, weighed about forty pounds.[355] The operator would place the image tube system at the focus of the telescope's optical system or spectrograph so that they directed the light from a celestial object or from a spectrum onto the photocathode at the end of the image tube. This image, impinging on the photocathode, drove photoelectrons out, which were accelerated by the magnets, intensified in the first stage, and reimaged as a brighter image on the output screen. The operator could then photograph the final image with conventional optics and emulsions.[356] The performance of the tube was partly limited by the quality of the optical system used in conjunction with them and Ford attempted to develop auxiliary equipment to help overcome or lessen those challenges.[357] Astronomers additionally encountered problems trying to maintain the voltage which ran to the system, which could limit the resolution if not managed. The resolving power of the tube was also affected by the motion of the tube through the earth's magnetic field during long exposures, as

354 CITC press release 1964, 6. Tuve explained further that, "To see fainter stars a longer-focal-length telescope is required, but with present instruments this involves going to focal ratios too large for the rather low quantum efficiency of photographic plates, and the exposure times become impossibly long. With image intensifiers, long-focal-length telescopes too slow for photography can be used effectively to record still fainter images against the background of the night sky."

355 CITC press release 1964, 5.

356 CITC press release 1964, 5.

357 Ford, oral history interview.

the telescope and tube had to move to track an object in the sky. This limited the length of exposures, which had been a major advantage of the image tube system.

The CITC warned potential users they should suppress their expectations of image tubes in general.[358] In the 1940s, astronomers predicted gains over 100 could be reached over photographic plates, but they discovered in the early 1960s that older photographic emulsions, when baked in an oven, could be five or six times more efficient than previously realized.[359] Therefore, image tubes could really only be 20-25 times more efficient than previously thought. But technical and operational difficulties made these high values unrealistic according to the CITC. The use of electronographic image tubes, which used electron-sensitive emulsions, offered the best hope of reaching that theoretical limit of performance, but electronographic image tubes like Andre Lallemand's camera or James McGee's Spectracon were unwieldy to use. The Carnegie Image Tube was still far from achieving this theoretical performance, but "since the present cascaded tubes achieve much of the gain that could be obtained with the best possible devices using modern photoelectric surfaces," the CITC argued, "the Carnegie Committee is emphasizing the immediate application of these tubes to current observing programs."[360] Far from a strong endorsement, the CITC wanted to emphasize the realistic expectations of their image tube and highlight that theoretical efficiency values were not yet attainable by any group with any device.

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[358] CITC press release 1964, p 6. Baum, "Facts and Myths," 532.

[359] CITC press release 1964, 7. For more on advances of baking plates, Mees, *From Dry Plates to Ektachrome Film*.

[360] CITC press release, 9.

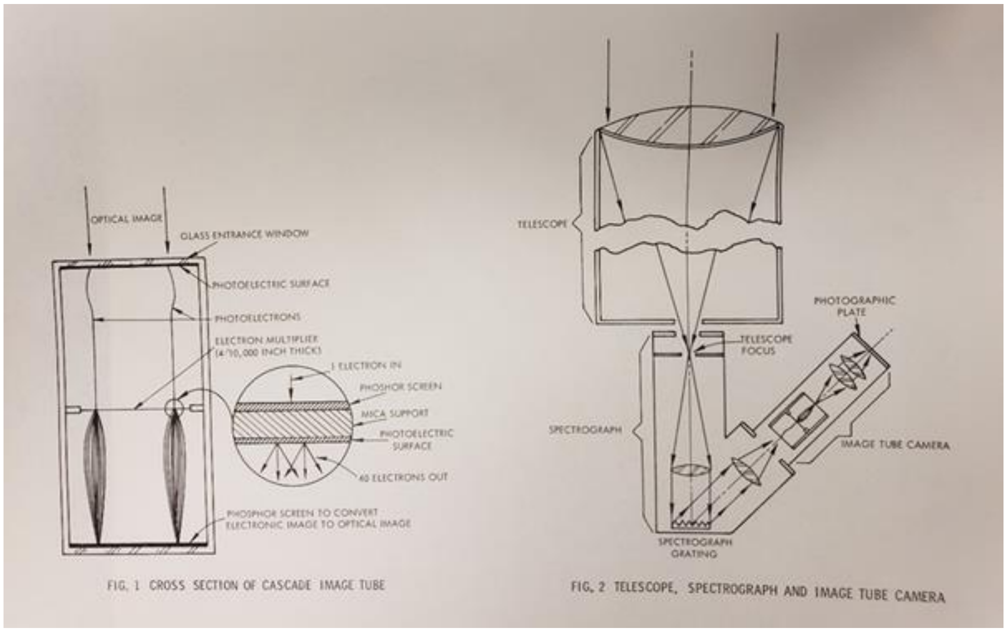

Figure 6.1. Carnegie cascaded image tube. Structure (left) and placement on the telescope (right).[361]

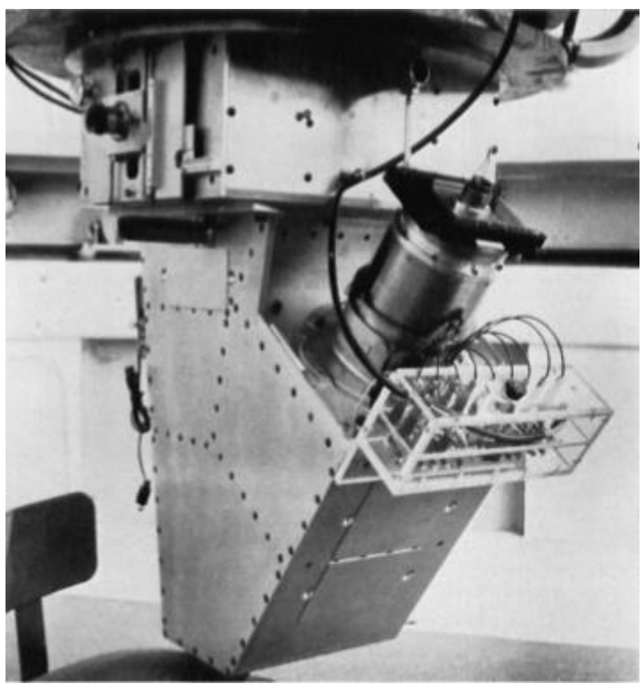

Figure 6.2. The DTM image tube spectrograph with attached Carnegie Image Tube.[362]

[361] CITC press release, 9.

[362] W. Kent Ford, Jr. “Astronomical Uses of Cascade Intensifiers,” *Advances in Electronics and Electron Physics* 22B ed. L. Marton (1966): 700.

Even though increased gains in sensitivity were possible for spectrographic studies, for many observers, this was not helpful because image tube systems were too bulky to be substituted directly for photographic plate holders in many spectroscopic cameras. Many observatories with spectrographic cameras were fast Schmidt systems with the focus located inside the camera and therefore inaccessible for bulky image tube equipment. Ira Bowen designed a Cassegrain Schmidt spectrograph camera specifically designed for image tube use after he retired as director of the Mount Wilson and Palomar Observatories in 1964.[363] This solution was wonderful for observatories who had access to the proper resources, financial and material, needed to construct a new spectrograph, but many observatories were frustratingly left looking for a way to adapt their current equipment.

First round of allocations: testing by experts in the field

The first five Carnegie Image Tubes were sent to observatories all chosen because their staff was active either in the development or testing of image tubes and whose judgement the Committee valued during this advanced state of evaluation of the cascaded tube.[364] The first system was put into place at Yerkes Observatory by staff astronomer W.A. Hiltner with help from Gerald Kron of the Lick Observatory and Alois Purgathofer of DTM. Kron, who had been developing his own electronographic camera, assisted in the initial evaluation at Yerkes.[365] The system was primarily used with a spectrograph for stellar spectral classification, but also proved successful in obtaining direct sky photographs with the Yerkes 40-inch refractor.[366] Despite these early successful tests from a highly trained group of astronomers, the Yerkes Observatory

363 E.E. Dennison, M. Schmidt, and I.S. Bowen, "An Image Tube for the Hale 200-in, Telescope, *Advances in Electronic and Electron Physics* 28B ed. L. Marton (New York: Academic Press), p 767-771.

364 Merle Tuve to Gerard F.W. Mulders of the National Science Foundation, 22 June 1965, Carnegie Telescope Image Tube Converter papers, DTM.

365 Carnegie Institution of Washington, Year Book 64: July 1, 1964 – June 30, 1965.

366 Carnegie Institution of Washington, Year Book 64: July 1, 1964 – June 30, 1965.

director, C.R. O'Dell, reported that their allotted tube produced an intermittent high background flash that they were unable to correct.[367] Ford sent Yerkes a replacement tube, but given no Yerkes staff or visiting astronomer published scientific results crediting use of the Carnegie tube, I am unable to confirm the extent to which the Carnegie tube continued to find use at Yerkes.

A second system was installed by Ford, Pugathofer, and Tuve at the Kitt Peak National Observatory and left in the capable hands of Bill Livingston and Roger Lynds of the Observatory staff, who had been testing image orthicon tubes on the KPNO telescopes for several years. A few years earlier, Merle Tuve had tried to hire Livingston to assist with the Carnegie program, but Livingston chose to take on a permanent position in Arizona instead.[368] The group made initial observations on the Kitt Peak 60-inch solar telescope, using the solar spectrograph to obtain high dispersion stellar spectra. Livingston continued to test a variety of image tubes, including the Carnegie Image Tube, at Kitt Peak through the mid-1970s, but was eventually forced by the KPNO director to redirect his attention away from instrumental developments and toward producing scientific results himself.[369] Given Livingston's research primarily concerned the nature of the sun, the brightest object in the sky, the slight gain in efficiency did not outweigh the added trouble of operating an image tube.[370] The Carnegie Image Tube did, however, find significant use from visiting observers after tubes had been allocated to a wider field of astronomers, which I will discuss further in the following section.

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[367] W. Kent Ford, Jr. to C.R. O'Dell, 2 January 1968, William Baum papers, correspondence, LOA.

[368] Merle Tuve to Bill Livingston, 4 August 1958, Carnegie Image Converter papers, CIW; William Baum to Merle Tuve, 7 October 1958, Carnegie Telescope Image Tube Converter papers, DTM; Bill Livingston to Merle Tuve, 15 October 1958, Carnegie Telescope Image Tube Converter papers, DTM; Merle Tuve to Bill Livingston, 14 November 1958, Carnegie Telescope Image Tube Converter papers, DTM; In future work, I'd like to re-interview Bill Livingston and question him concerning his refusal of the CITC job offer to hopefully get a better sense of how young astronomers, even those particularly interested in image tubes, viewed the CITC efforts.

[369] Bill Livingston, interview by Samantha M. Thompson, October 2015, personal files.

[370] Bill Livingston, interview by Samantha M. Thompson, October 2015, personal files.

Gerald Kron installed a third system at Lick Observatory, bench testing it first, then attaching it to the 160-inch camera of the 120-inch telescope Coudé spectrograph.[371] Kron left Lick Observatory in the fall of 1965 to take up the director position of the Flagstaff Station of the U.S. Naval Observatory, but fellow Lick staff astronomers Merle Walker and George Preston, who also had extensive experience working with electronic imaging devices, took over the tube's testing and maintenance after Kron's departure. Hyron Sprinrad, an astronomer at the nearby University of California Berkeley, used the Carnegie Image Tube at Lick Observatory to collect planetary spectra and was "most favorably impressed" with the results he obtained.[372] Though Kron told Kent Ford that Spinrad intended to use the device in the future, Spinrad never published any scientific results from data collected with the Carnegie Image Tube.[373] In December of 1967, Lick Observatory astronomer Tom Kinman requested a replacement tube after their tube began to produce too much spurious background noise, becoming useless for any observational program.[374] Kinman wrote, "We have tested it in the same spectrograph as the other Carnegie tube which we possess and find that the background is quite excessive even at 17,000 volts. Apparently, the background is so bad that the test spectrum was swamped and we do not know whether a focus is obtainable. The tube has therefore been packed ready to return to you…Needless to say I was very disappointed in the performance of this tube and I hope that it will be possible for another tube to be made available."[375] Ford responded quickly, equally

[371] Gerald Kron to William Baum, 8 February 1964, William A. Baum papers, correspondence, LOA; William Baum to Gerald Kron, 26 February 1964, William A. Baum papers, correspondence, LOA; William Baum to Gerald Kron, 26 February 1964, William A. Baum papers, correspondence, LOA; W. Kent Ford, Jr. to Gerald Kron, 7 February 1968, Carnegie Telescope Image Tube Converter papers, Allocations Folder, DTM.

[372] W. Kent Ford, Jr. to Gerald Kron, 7 February 1968, Carnegie Telescope Image Tube Converter papers, Allocations Folder, DTM.

[373] William Baum to Gerald Kron, 5 June 1965, William A. Baum papers, correspondence, LOA; Gerald Kron to William Baum, 8 June 1965, William A. Baum papers, correspondence, LOA.

[374] Tom D Kinman to W. Kent Ford, Jr., 8 December 1967, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM.

[375] Tom D Kinman to W. Kent Ford, Jr., 8 December 1967, Carnegie Telescope Image Tube Converter papers, Allocations folder, DTM.

disappointed at the tube's failure, but suggested it was "inevitable that an occasional one should build up an excessive background."[376] Kinman was frustrated again when, within six months of receiving his replacement tube, the new tube again began to produce spurious background noise, limiting any possible benefits to the tube's use.[377] Ford was sympathetic and likewise frustrated, noting that Kinman's tube was producing backgrounds unlike any he had ever encountered, sarcastically exclaiming, "A new and different problem!"[378] Ford could not find a reason for the tube's failing and recommended that Kinman look to purchase a tube directly from RCA, as the CITC had no additional spare tubes to lend.[379] It is unclear whether Kinman purchased additional tubes from RCA, but he never obtained scientific results with the Carnegie Image Tube from which he was able to publish any scientific results. This episode highlights that even a skilled operator encountered problems with image tubes in practice, likely in part due to the inability of the RCA laboratories to produce a standardized tube to the CITC's specifications.

The fourth system was installed at Lowell Observatory, under the direction of John Hall, and tested primarily by Laurence Fredrick on the 24-inch Morgan telescope.[380] After Kent Ford developed a full equipment apparatus for the image tube, including a spectrograph, Ford and DTM astronomer Vera Rubin used the Carnegie Image Tube primarily on the 72-inch Perkins telescopes at Lowell Observatory, described further in a subsequent section. At the Hale Observatories, which the Mount Wilson and Palomar Observatories had become collectively called, William Baum, Kent Ford, and Vera Rubin had intended to install a Carnegie image tube

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376 W. Kent Ford, Jr. to Tom D. Kinman, 12 December 1967 Carnegie Telescope Image Tube Converter papers, DTM.

377 W. Kent Ford, Jr. to Tom D. Kinman, 26 June 1968, Carnegie Telescope Image Tube Converter papers, DTM.

378 W. Kent Ford, Jr. to Tom D. Kinman, 26 June 1968, Carnegie Telescope Image Tube Converter papers, DTM.

379 W. Kent Ford, Jr. to Tom D. Kinman, 26 June 1968, Carnegie Telescope Image Tube Converter papers, DTM.; Tom Kinman, "Spectroscopic Observations of Nineteen Quasi-Stellar Radio Sources," Astrophysical Journal 148 (May 1967): L59-:L63.

380 Carnegie Institution of Washington, Year Book 68: July 1, 1968 – June 30, 1969.

system on the 100-inch telescope at Mount Wilson, but Hale Observatories director Horace Babcock requested additional image tube systems for the 200-inch telescope at Palomar.

The purpose of these original five installations was to test the RCA-produced tubes in the field, but the CITC discovered that astronomers, like Babcock, quickly wanted systems designed to accommodate their specific research project. Babcock hoped to use the Carnegie tubes immediately for research, but was told by Tuve that they were restricted to observations that included a member of the Carnegie Image Tube team.[381] However, likely due to their Carnegie affiliation, the Hale Observatories were, in the first round of allocations, granted a loan of three image tubes to use on three instruments. Ford and Baum installed the first image tube system on the 73-inch camera at the Coudé focus of the 100-inch on Mount Wilson in July 1965, and allowed the complete system to remain there for use by the Carnegie and Caltech staff astronomers.[382] The second unit was installed on the 72-inch camera at the Coudé focus of the 200-inch telescope on Palomar Mountain later that fall. A third installation was planned for a Cassegrain nebular spectrograph at the Cassegrain focus of the 200-inch telescope in early 1966 but was initially delayed because it required Ford to make adjustments to his DTM spectrograph to fit the Cassegrain focus (see Figure 6.2 for a visual comparison of the Cassegrain vs Coudé focus of a reflecting telescope.[383] The Hale Observatories instrument shop staff eventually built a Cassegrain nebular spectrograph before Ford could adapt his instrument. It was installed on the Hale telescope in 1973.[384]

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[381] Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

[382] The Coudé focus of a telescope sits independent of the telescope's motion, allowing heavy instruments to be mounted without affecting the telescope's balance; Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

[383] Horace Babcock to William Baum, 5 November 1965, William A. Baum papers, correspondence, LOA; Merle Tuve to Horace Babcock, 11 June 1965, William A. Baum papers, correspondence, LOA.

[384] California Institute of Technology, "Prime Focus Nebular Spectrograph Log Book," Caltech archives, forward, https://authors.library.caltech.edu/29181/2/Prime_Focus_Nebular_Spectrograph_Log_Book-ocr.pdf

The first two image tube installations were of high interest to many Mt. Wilson and Palomar Observatories astronomers, chiefly Olin Wilson, Guido Munch, Bob Kraft, Armin Deutsch, and Babcock, whose work on interstellar lines, special emission lines, and the Zeeman effect of special lines was especially suited to image tube aided observations.[385] Babcock informed Tuve that while Olin Wilson's attitude toward image tube work had been merely "tolerant [or] even skeptical," he had been completely converted by the recent results obtained by the other image tube systems at Mt. Wilson and had become an enthusiastic proponent.[386] The third installation carried a greater degree of urgency for Maarten Schmidt's work on the redshifts of quasi-stellar objects (QSOs). Even more pressing for Babcock's team of astronomers was the work by Allan Sandage, who had shown that there were about four quasi-stellar galaxies (QSG) per square degree brighter than the 19th magnitude.[387] Astronomers had acquired redshifts for only a few of these sources and were in desperate want for a device that could help them measure more. "It is pretty obvious," Babcock contended, "that the whole subject of cosmology is undergoing a break through, and that redshifts of large numbers of QSG's are going to be needed. It is extremely important to employ the most efficient means of getting these redshifts, and this indicates that nebular spectrographs with image tubes will see a great deal of use on large telescopes in the next few years."[388]

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[385] Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

[386] Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

[387] Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

[388] Horace Babcock to Merle Tuve, 28 May 1965, William A. Baum papers, correspondence, LOA.

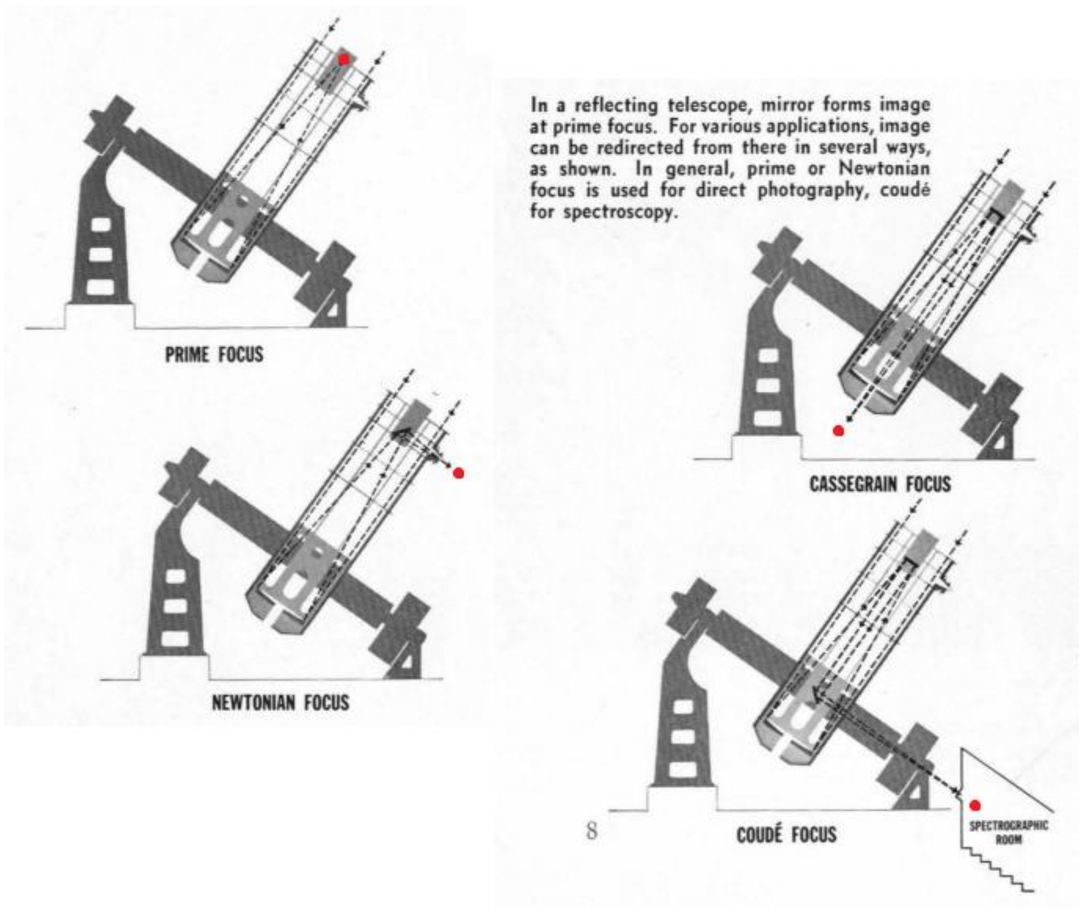

Figure 6.3. The Prime, Newtonian, Cassegrain, and Coudé focus of the 100-inch reflecting telescope.[389]

Kent Ford had built a spectrograph specifically designed to accommodate the Carnegie Image Tube and Babcock wanted to borrow one while the Hale Observatories worked to build a spectrograph of their own.[390] Tuve reminded Babcock that Ford would also need to make adjustments to DTM's spectrograph to fit onto the 200-inch telescope. In the end, the Hale Observatories optical laboratory completed their own spectrograph, designed by Ira Bowen,

389 Adapted from California Institute of Technology, *Frontiers in Space*, Official Publication of the Mount Wilson and Palomar Observatories. Jointly Operated by the Carnegie Institution of Washington and the California Institute of Technology, 8.

390 W. Kent Ford, Jr., "Astronomical Uses of Cascade Intensifiers," Advances in Electronics and Electron Physics 22A (1966): 697-704.

before Ford could make the time to make changes to the DTM spectrograph.[391] A couple of years later, Bowen wrote to Tuve to inform him that Maarten Schmidt had used the image tube spectrograph on the 200-inch for the first time. Schmidt, Bowen wrote, was "jubilant over the gains the new spectrograph was providing compared to the old nebular spectrograph…The Observatories are greatly indebted to you and the Image Tube Committee for this very great extension in the capabilities of the 200 inch."[392] Because Maarten Schmidt had access to the world's largest telescope, a Carnegie Image Tube to aid his observations, and the technical knowledge and experienced staff available to utilize the equipment to its fullest potential, he was able to obtain valuable data for his research program.[393]

From 1964-1965, six Carnegie Image Tubes with complete tube apparatus were sent to Yerkes Observatory, Lick Observatory, Kitt Peak National Observatory, Lowell Observatory, and the Hale Observatories. The purpose behind these early assignments of instrumentation was to have those with demonstrated interest and prior experience with image tubes evaluate the RCA-manufactured tubes, and they did so with varying degrees of success. Because of Bowen's spectrograph camera, astronomers were able to use the Hale 200-inch telescope to study the faint, "star-like" quasi-stellar objects, first discovered in the late 1950s. Yerkes and Lick Observatories, however, had to contend with faulty image tubes.

Tubes allocated via application

After the initial loan of Carnegie Image Tubes, the remainder were allocated to observatories and observers who had made requests to the Committee for assistance in establishing intensifier systems for their own observing problems. A Joint Allocations Committee

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391 E.E. Dennison, M. Schmidt, and I.S. Bowen, "An Image Tube for the Hale 200-in, Telescope, Advances in Electronic and Electron Physics, ed. L. Marton 28B (1968): 767-771.

392 Ira Bowen to Merle Tuve, 9 August 1967, Carnegie Telescope Image Tube Converter papers, DTM.

393 John L. Lowrance, Donald C. Morton, Paul Zuccino, J.B. Oke, and Maarten Schmidt, "The Spectrum of the Quasi-Stellar Object PHL 957," *The Astrophysical Journal* 171 (15 January 1972): 233-251.

was formed from two members of the CITC (John Hall and William Baum) and two members of the National Science Foundation who, after the first 20 tubes had been delivered from RCA, and six were immediately allocated to the initial group of testing observatories, allocated another 10-11 tubes and holding on to some as a reserve. Tuve and the CITC compiled a list of active image tube users, they called the “Carnegie Associated Group” and sent applications to all potential candidates.[394]

The application was simple, as shown in Figure 6.3, and the Joint Committee announced that they would prioritize applicants based on the needs of their research program.[395] However, in correspondence between the CITC members and the NSF representatives, with heavy input from Kent Ford, the Joint Committee heavily weighed the technical abilities of the local staff, their access to the auxiliary equipment needed to operate the image tube system, and, most importantly, the ability of the telescope to carry the weight of the entire apparatus.[396] The CITC did not intend to provide tubes in perpetuity, but instead offered to serve as the purchasing agency for the initial supply, manufactured to strict specifications for use with telescopes for the best feasible resolution for research programs requiring long exposures.[397] The CITC hoped to provide auxiliary equipment, such as focusing mounts with plate holders, lenses, magnets, to a few users, but could not promise to be able to provide equipment to every observatory who received a tube. Likewise, the CITC offered Kent Ford’s services to train users, but given he was the only staff person available to undertake this training, he could not be made available in a timely fashion to all users. Applications, therefore, needed to be assessed given the resources of the CITC.

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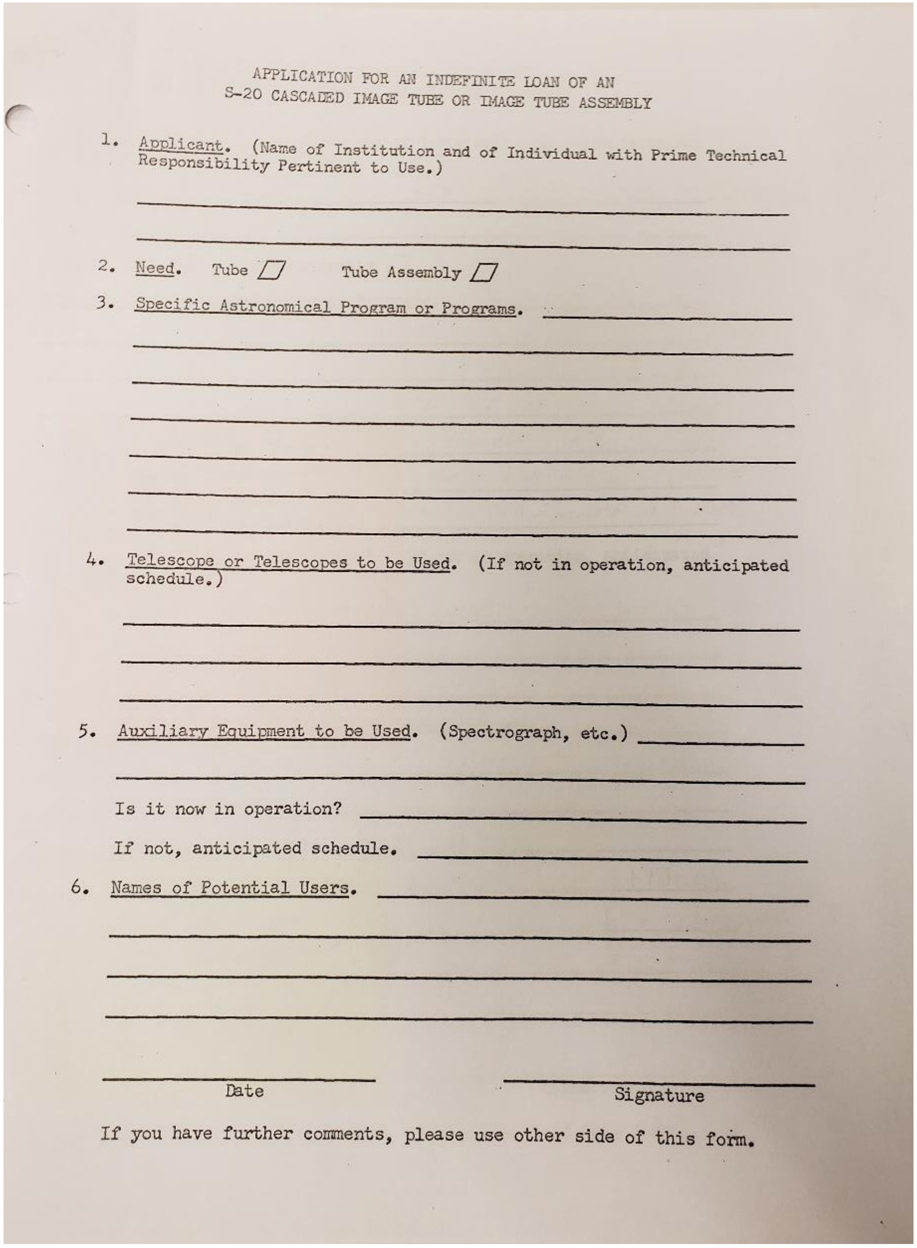
[394] Merle Tuve to Gerald Mulders, 22 June 1965, Carnegie Telescope Image Tube Converter papers, DTM.

[395] Carnegie Institution of Washington. Carnegie Image Tube Committee 1964 press release Carnegie Telescope Image Tube Converter papers, DTM.

[396] Ford, oral history interview.

[397] Merle Tuve to Gerald Mulders, 22 June 1965, Carnegie Telescope Image Tube Converter papers, DTM.



APPLICATION FOR AN INDEFINITE LOAN OF AN
S-20 CASCADED IMAGE TUBE OR IMAGE TUBE ASSEMBLY

1. Applicant. (Name of Institution and of Individual with Prime Technical Responsibility Pertinent to Use.)

2. Need. Tube ☐ Tube Assembly ☐

3. Specific Astronomical Program or Programs.

4. Telescope or Telescopes to be Used. (If not in operation, anticipated schedule.)

5. Auxiliary Equipment to be Used. (Spectrograph, etc.)

Is it now in operation?

If not, anticipated schedule.

6. Names of Potential Users.

Date

Signature

If you have further comments, please use other side of this form.

Figure 6.4. Application for loan of a Carnegie Image Tube.[398]

Despite having an established application process, before the Joint Committee could prioritize the applicants, image tubes were sent to:

Gerald Kron of the U.S. Naval Observatory, Flagstaff Station, Arizona

[398] Carnegie Image Tube Committee papers, Allocations, DTM

Harlan Smith of the McDonald Observatory at the University of Texas

Theodore Dunham of Mount Stromlo Observatory in Australia

When Gerald Kron was hired to direct the USNO Flagstaff Station (USNOFS), he inquired with Tuve if a Carnegie Image Tube could be sent for his use on the Naval Observatory 61-inch telescope for nebular spectroscopy.[399] Kron informed Tuve that USNO astronomer Jim Christy was also interested in using the Carnegie tube to investigate the possibility of "increasing his limiting magnitude" in stellar spectrophotometry studies on the Naval Observatory 40-inch.[400] Tuve responded that the Image Tube Committee had, "taken the position that [they would] not wait for action of a formal Allocations Committee in providing initial image tubes to interested astronomers at our major U.S. observatories" and would gladly ship a tube to Kron when he arrived in Flagstaff.[401] That tube was delayed because Kron was in between observing trips and would not have time to prepare a shipment to Kron until his return.[402] In February of 1968, Ford sent Kron a new image tube system.[403] It is unclear if this was a replacement for a faulty tube, an additional tube, or the tube originally promised to USNOFS, but Ford diligently checked it's technical specifications, writing, "I have checked the tube for gain and for photocathode sensitivity and find it good in both respects. The cathode is more sensitive in the blue and violet than any of the tubes we currently have available, including the tube that Vera and I have been using. (I will remind you of this again when you make us the loan of one of your modified-Lallemand camera!)." It is unclear when Kron received his tube, but he never published any results with the

[399] Gerald Kron to Merle Tuve, 20 March 1965, Carnegie Telescope Image Tube Converter papers, DTM.

[400] Gerald Kron to Merle Tuve, 3 September 1965, Carnegie Telescope Image Tube Converter papers, DTM.

[401] Merle Tuve to Gerald Kron, 12 March 1965, Carnegie Telescope Image Tube Converter papers, DTM.

[402] Gerald Kron to Merle Tuve, 14 September 1965, Carnegie Telescope Image Tube Converter papers, DTM.

[403] Kent Ford to Gerald Kron, 7 February 1968, Carnegie Telescope Image Tube Converter papers, DTM.

Carnegie tube, likely because he was busy developing his own image tube, based on the Lallemand system.[404] Christy eventually published results on the relative spectrophotometry of low-luminosity stars acquired with a Carnegie Image Tube.[405]

Harlan J. Smith, Director of McDonald Observatory at the University of Texas, Austin, immediately began using his allotted Carnegie Image Tube on the Coudé spectrograph on the 82-inch telescope and, "immediately upon installation...the new Carnegie Image Tube worked very well indeed."[406] However, they did encounter difficulties, as Smith described, "the people using it were unfortunately not the same who had done the careful testing and focusing in our laboratory here in Austin, and so did not appreciate fully that they were getting a degradation in resolution perhaps arising from the proximity of the steel girders in the Coudé spectrograph. In other words, prior to the next use of the Coudé image tube, some work must be done on improving its focus under field conditions. The speed gain is around the expected 10 to 15 times over the IIa-0 plates we have been using, normally unbaked."[407] Smith did present one paper and publish one paper on the, "Use of an Infrared Image Tube for High-Dispersion Planetary Spectroscopy" and "An Upper Limit for Atmospheric Carbon Dioxide on Mercury," but this episode of use highlights an important aspect of the skill required to operate an image tube.[408] The

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404 G.E. Kron, H.D. Ables, and A.V. Hewitt, "A Technical Description of the Construction, Function, and Application of the U.S. Navy Electronic Camera," *Advances in Electronics and Electron Physics* 28A (1968): 1-17.; Merle F. Walker and Gerald E. Kron, "The Determination of Stellar Magnitudes by Electronography," *Publications of the Astronomical Society of the Pacific* 79, no. 471 (December 1967): 551-568.

405 Jams W. Christy, "Spectrophotometry of Low-Luminoisty Stars with the Carnegie Image Tube," *Proceedings of the Astronomical Society of the Pacific* 90 (April 1978): 207-215.

406 Harlan Smith to Merle Tuve, 26 April 1966, Carnegie Telescope Image Tube Converter papers, DTM.

407 Harlan Smith to Merle Tuve, 26 April 1966, Carnegie Telescope Image Tube Converter papers, DTM.

408 Harlan J. Smith, Louise Gray, Edwin S. Barker and Ronald A. Schorn, "Use of an Infrared Image Tube for High-Dispersion Planetary Spectroscopy," *Astronomical Journal* 72 (October 1967): 829; Jay T. Bergstralh, Louise Gray, Harlan J. Smith, "An Upper Limit for Atmospheric Carbon Dioxide on Mercury," *The Astrophysical Journal* 149 (September 1967): 137-139.

technician believed the tube was working properly, but it took someone like Harlan Smith, with a better grasp of the expectations of the tube, to realize it was not set up correctly.

At Mount Stromlo Observatory, located near Canberra, Australia, interest in the Carnegie Image Tube came largely from Theodore Dunham, who had worked at Mount Wilson Observatory developing spectrographic instrumentation. Kent Ford traveled to Australia to assist in the installation of the image tube system and, according to a 2013 interview with Kent Ford, Dunham was more interested in vetting the image tube assembly than using the device for scientific research.[409] Fort trained both Dunham and Kurt Gottlieb, the Observatory's instruments manager. Ford noted that he had no issues training Dunham nor Gottlieb, but had heard later that Gottlieb, "rubbed some people the wrong way," which created issues with the use of the image tube at Mount Stromlo.[410] Whether it was a result of the instruments technician being difficult to work with, only one scientific paper was published with the equipment in Australia, though that paper was highly cited (82 times).[411]

On November 29, 1966, the Joint Committee Allocations Committee sent out letters requesting applications for a Carnegie Image Tube.[412] From the received applications, the Joint Committee divided the applicants into three categories, those receiving an "A" or "B" score, with a field of potential grantees. The list of five observers receiving an "A" rating included:

Richard Woolley of the Royal Greenwich Observatory in England

F. Bertola of the Asiago Observatory in Italy

P.L. Byard of the Ohio State University Perkins Observatory

Kiyoteru Osawa of the Tokyo Observatory

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409 Ford, oral history interview.

410 Ford, oral history interview.

411 Leonard Searle, J.G. Bolton, "Redshifts of fifteen Radio Sources," *The Astrophysical Journal* 154 (December 1968): 101-104.

412 Carnegie Image Tube Committee, Joint Allocations Committee form letter, 29 November 1966, Carnegie Telescope Image Tube Converter papers, DTM.

Stuart Sharpless of the Mees Observatory at Rochester.[413]

In addition, the Joint Committee thought it paramount to reserve one assembly for the 200-inch and the other for the newest telescope in the southern hemisphere at the Cerro Tololo Inter-American Observatory in Chile.[414] Kent Ford travelled to London to help install the Carnegie system at the Royal Greenwich Observatory (RGO), but base on papers presented as James McGee's Symposium on Photoelectronic Devices, RGO astronomers preferred the electronographic cameras being developed by Gerald Kron and James McGee.[415] The Joint Committee selected the Asiago Observatory as a recipient, in hopes that they could accommodate visiting European astronomers.[416] Bertola was satisfied with the results, publishing a paper on the "First Results with the Carnegie Image Tube at Asiago" in the Observatory's reports, though, no scientific publication was made with results using that image tube, neither by a staff nor visiting astronomer.[417] Astronomers at the Ohio State University, Tokyo Observatory, and the Mees Observatory did not publish scientific results with equipment allocated to their home institution.

Ten observatories received a "B" rating and the Committee recommended that tubes be placed on loan with those institutions only after the requirements for tube assemblies had been fulfilled.[418] S. Jeffers of the David Dunlap Observatory at the University of Toronto received an image tube in June of 1968 and two years later published a paper comparing the performance of

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413 John Hall to Merle Tuve, January 1967, Carnegie Telescope Image Tube Converter papers, DTM.

414 John Hall to Merle Tuve, January 1967, Carnegie Telescope Image Tube Converter papers, DTM.

415 James D. McGee, H. Bacik, C.I. Coleman, and B.L. Morgan, "Extended Field Spectracon," *Advances in Electronics and Electron Physics* 33A (1971): 14; D. McMullan, J.R. Powell, and N.A. Curtis, "Electronographic Image Tube Development at the Royal Greenwich Observatory," *Advances in Electronics and Electron Physics* 33A (1971): 37-51.

416 Merle Tuve to F. Bertole, 23 February 1967, Carnegie Telescope Image Tube Converter papers, DTM.

417 F. Bertole, "First Results with the Carnegie Image Tube at Asiago," *Contributi dell'Osservatorio Astrofisica dell'Universita di Padova in Asiago* 203 (January 1968): 3-9.

418 John Hall to Merle Tuve, January 1967, William A. Baum papers, correspondence, LOA.

the Carnegie Image Tube on a 24-inch telescope with direct photography on a 74-inch telescope.[419] Jeffers reported that the two systems were comparable in limiting magnitude and resolution and concluded, “On the basis of these results the 24-inch telescope-image tube system may be proposed as an alternative technique to the 74-inch direct photography system for research in globular clusters.”[420] No astronomer used the system at Toronto for scientific research, on either the 24-inch or 74-inch telescopes.

The Vatican Observatory staff encountered multiple problems with their image tubes and Kent Ford had to send two replacements. Ford was “distressed” that their tube unaccountably “slumped” and mentioned that this was “quite unusual, particularly if there was no sign of excessive ion scintillation.”[421] The only two possible difficulties that Ford could think were causing the problem were”(1) that somehow the transfer lens was stopped down accidently, or (2) that the high voltage was connected to the wrong part of the voltage divider, but,” he added, “I trust that both of these possibilities have been checked by now,” alluding to possible user error while attempting to not insult his users.[422] Other observatories encountered various problems as well. Olaf Lindblad of the Stockholm Observatory had difficulty attaching the image tube to their spectrograph without causing bad definition over long exposures.[423] However, most of the observatories allotted image tubes either used them to test the image tube or did not use them at all.[424]

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419 S. Jeffers, “Direct Photography with a Carnegie Image Tube,” *The Journal of the Royal Astronomical Society of Canada* 64, no. 3 (June 1970): 121-128.

420 Jeffers, “Direct Photography,” 128.

421 Kent Ford to Martin F. McCarthy, S.J., Specola Vaticana, Castel Gandolfo, 3 October 1968, Carnegie Telescope Image Tube Converter papers, DTM.

422 Kent Ford to Martin F. McCarthy, S.J., Specola Vaticana, Castel Gandolfo, 3 October 1968, Carnegie Telescope Image Tube Converter papers, DTM.

423 S. Lindlblad to Kent Ford, 29 November 1967, Carnegie Telescope Image Tube Converter papers, DTM.

424 Images tubes were sent to William Liller, Harvard College Observatory, Benjamin F Peery, Indiana University; L.H. Allet, UCLA, James P. Rodman, Mount Union college, Ohio, T.A. Matthews, University of Maryland.

Department of Terrestrial Magnetism astronomer Vera Rubin was the most frequent user of the Carnegie Image Tube, working alongside Kent Ford to use the technology to its fullest. A further extensive examination of Vera Rubin and her role in image tube development is now possible with the very recent release of her personal papers at the Library of Congress. In this section, I will briefly summarize her image tube work with Kent Ford as it relates to the larger issue of astronomer use of the Carnegie Image Tube, acknowledging that further work is required.

In 1965, Merle Tuve hired astronomer Vera Rubin onto the DTM staff. After receiving a bachelor's degree in astronomy from Vassar College and a master's degree astronomy from Cornell, she entered Georgetown University graduate school at the age of 23. While at Georgetown, Rubin worked with external colleagues George Gamow, Margaret and Geoffrey Burbidge, and Gerard de Vaucouleurs. By 1964, the astronomy program at Georgetown had begun to fall apart and Rubin began looking for other employment.[425] She approached Bernie Burke, an instrument developer at DTM working in radio astronomy, and inquired if he thought she could get a job at DTM. This came as a shock to Burke, according to Rubin, because DTM had never hired a female secretary, let alone a female astronomer.[426] Burke invited Rubin to stay for lunch, which was known for being a time for the staff to discuss their work, and Tuve invited Rubin to share her research. A couple of months later, Tuve offered her a job, though at two-thirds the salary she had been making at Georgetown. Still she accepted the position. Rubin later learned that Tuve had set up two desks for her, one in Kent Ford's office and one with Bernie Burke, allowing her to choose with whom she wanted to work. When Rubin first had lunch at DTM, she sat near Ford, who had just come back from Observing at Mount Wilson with the

425 Rubin, oral history interview, 23.

426 Rubin, oral history interview.

Carnegie Image Tube. Rubin was excited by the prospect of adding the image tube to her observing program so she, “walked into Kent’s office and never left.”[427]

Rubin planned observations of galaxies, objects of sufficiently low brightness to challenge image tube capabilities. She and Ford carried out those observations at Lowell Observatory and Kitt Peak National Observatory, often driving the image tube spectrograph back-and-forth, up and down Arizona. Rubin presented their discovery of the flat rotation curve of the Andromeda galaxy at the 1968 American Astronomical Society meeting, which received little notice at the time, but citations of their paper slowly grew throughout the 1970s.[428]

From astronomers’ use of their allotted Carnegie Image Tube, the CITC was able to ascertain certain elements of the tube’s usefulness. They noted that astronomers were using image tubes, “for observations in a wide variety of spectroscopic programs at both high and low dispersions. Problems under study [included] high-dispersion radial velocities of interstellar lines and stars, planetary spectroscopy, classification and line identification in late type stars, moderate- and low-dispersion observations of barred spiral galaxies, peculiar galaxies, radio galaxies, and quasi-stellar objects.”[429] In operation, the CITC held that the RCA tube was reliable and “reasonably rugged,” and that it required the same sort of care as a standard photomultiplier.[430] The CITC did acknowledge that astronomers should use caution when connecting the system to the 20,000 volts required to operate the system and that exposure to a very bright light could damage its sensitivity.[431] The high number of observatories who received image tubes, but whose astronomers did not publish any results, makes sense given these

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427 Rubin, oral history interview.

428 ADS report of citations of Vera Rubin and Kent Ford, “Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions,” *Astrophysical Journal* (February 1970): 379-403; Deidre Hunter, “Vera Cooper Rubin (1928-2016),” *Publications of the Astronomical Society of the Pacific* 129 (April 2017): 1-5.

429 Carnegie Institution of Washington, Year Book 66: July 1, 1966 – June 30, 1967, 136.

430 Carnegie Institution of Washington, Year Book 66: July 1, 1966 – June 30, 1967, 136.

431 Carnegie Institution of Washington, Year Book 66: July 1, 1966 – June 30, 1967, 136.

restrictive guides for operation. Through this process, the CITC discovered that the inability of RCA to standardize the Carnegie Image Tube to the CITC's high specifications, the need for local staff to be highly trained in operating the apparatus and amenable to assisting astronomers in observations, and the frequent requirement of each observatory to adapt their observing equipment, resulted in a tube that many astronomers, even those with a technical background and an interest in the technology, struggled to use.

Looking at the published scientific results, a few astronomers who received allocated image tubes published results using their home instrument, but they had access to telescopes, while still considered moderate in size, on the larger end, around 74-inch. The most frequently used telescopes with an attached Carnegie Image Tube were used by visiting astronomers at Cerro Tololo in Chile and KPNO in Arizona. Kent Ford had installed one of his DTM spectrographs at Cerro Tololo, Kitt Peak, and Lowell Observatory and was on site at Kitt Peak during the early 1970s to assist visiting astronomers with their observations. In evaluating the use of the Carnegie Image Tube, it appears astronomers preferred to use the systems on larger telescopes, with the equipment already in place. However, telescope time at these large observatories was extremely limited and not all astronomers could have easy access to this technology.

Conclusion

From 1964 to 1965, using a new grant funded by the National Science foundation, the CITC ordered 20 cascaded image tubes, to be manufactured by RCA, and to be dispersed to observatories around the world. By the summer of 1964, they considered their goal, first outlined in 1955, to have been reached and the RCA-manufactured device was put into production during the following year. Initially, the CITC supplied half a dozen active astronomers in major U.S. observatories with tubes for actual use on their telescopes for research. They also supplied all necessary auxiliary equipment with each tube allocated, including magnets, high-voltage supply and controls, special lenses, focusing mount, and other items. These RCA tubes operated with a gain or advantage of a factor 10 or 12 above the best modern photographic emulsions used in astronomy. Of the 20 tubes not initially allocated to a select number of observatories, the remainder were distributed according to the Joint Allocations Committee of the Carnegie Institution and the National Science Foundation. The allocation of Carnegie Image Tubes represented the final phase of the Committee's testing program.

Kent Ford traveled to several observatories to help the local staff install the Carnegie tube, with varying degrees of success. Some image tubes were used regularly, while most were not. DTM astronomer Vera Rubin used the Carnegie image tubes frequently and worked closely with Ford to guarantee that the tubes were employed to their fullest potential. The number of astronomers interested in the Carnegie Image Tube helps show that there was interest in a device that could aid astronomical observations, especially from groups interested in investigating newly discovered and extremely dim objects and phenomena. When given the opportunity to use a large telescope, with the equipment already in place, and a trained assistant there to help with observations, astronomers were more likely to take advantage of the new technology.

CHAPTER 7

EPILOG AND CONCLUSION

> "I took my first CCD spectra in '84, and virtually never went back. …that was the end of the image tube." – Vera Rubin[432]

In October 1984, Vera Rubin and Kent Ford traveled to Palomar Mountain to obtain the spectra of a large spiral galaxy (UGC 12591) with a spectrograph attached to the Hale 200-inch telescope. Rubin, Ford, and their collaborators Riccardo Giovanelli and Martha P. Haynes combined this observational data with data they collected from the radio telescopes at Arecibo Observatory to conclude that the outer arms of UGC 12591 rotate at a rate of 500 kilometers per second, the largest rotational velocity that had ever been detected.[433] Significantly, Rubin and Ford's spectrograph was not attached to an image tube but rather, for the first time, to a solid-state detector. This new detector, a charge coupled device, or CCD, eventually became ubiquitous in most imaging devices. One could find a CCD in the cameras on board the Hubble Space Telescope and in the cameras in the earliest smartphones. For astronomers, adopting the new technology meant that they no longer needed to carry home photographic plates from observing runs, but reels of computer tape that could be rapidly analyzed with coded programs. For Rubin, this 1984 observing run at Palomar and her first use of a CCD during an observing run marked the end of the image tube era.

In this final chapter, I will address the end of the image tube era and discuss the role of the Carnegie Image Tube Committee in that technological transformation. I will then draw conclusions from the arguments presented in the prior chapters, concerning the role of specialists, the military, user groups, institutions, and individuals in the ultimate limited use of the

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432 Rubin, oral history interview.

433 Riccardo Giovanelli, Martha P. Haynes, Vera C. Rubin, and W. Kent Ford Jr., "UGC 12591: The Most Rapidly Rotating Disk Galaxy," *Astrophysical Journal* 301 (1 February 1986): L7-L11.

Carnegie Image Tube. I will furthermore present paths and questions to address in future research.

The end of the image tube era

By the early 1980s, most of the scientists and administrators involved in the formation of and the development efforts with the Carnegie Image Tube Committee had passed away, retired, or moved on to other projects. Ira Bowen died in 1973, Vannevar Bush in 1974, Ladislaus L. Marton in 1979, and Merle Tuve in 1982. Before John Hall retired from Lowell Observatory in 1977, he hired William Baum to direct the Observatory's Planetary Research Center and coordinate the NASA-funded International Planetary Patrol Program. Baum continued to develop image tubes in conjunction with his new role until, after being added to the Hubble Space Telescope's instrumentation team in 1976, he began testing CCDs to fly as a part of the space telescope's wide field planetary camera. Around the same time, Kent Ford began investigating ways to digitize astronomical data and images, slowly moving away from developing image tubes for observation. Rubin continued to study the rotation rates of spiral galaxies, but by the early 1980s, had switched to using CCDs instead of image tubes. Only Baum, Ford, and Rubin remained active in the astronomy community after 1980, but their gradual move away from image tubes and towards solid state technology symbolizes the end of the Carnegie Image Tube Committee's work.

In 1965, Baum joined the Lowell Observatory staff and immediately began to coordinate an international photographic planetary patrol network. A NASA grant equipped all stations in the network, which included Lowell Observatory, the Cerro Tololo Inter-American Observatory in Chile, the Republic Observatory in South Africa, the Mount Stromlo Observatory in Australia and the Mauna Kea Observatory in Hawaii, with identical planetary cameras and modified telescopes to capture identically-scaled images of the planets. Lowell Observatory and Baum calibrated, processed, edited, and catalogued the network's images.[434] Though planetary photography was not Baum's research field, he attempted to make the most of his background in instrumentation to advance the field of planetary imaging.[435] At the Planetary Research Center, Baum and his staff conducted photoelectric measurements and developed a device to stabilize planetary images through the aid of a cascaded image tube.[436] Though Baum stopped directly contributing to the Carnegie Image Tube project when he took on his new role at Lowell, he continued to use electronic imaging techniques in new ways.

In 1976, Jim Westphal, the principal investigator of one of the three teams proposing instrumentation for the in-development Large Space Telescope (later named the Hubble Space Telescope) asked Baum to join his instruments team. The scientists and administrators involved in the early development of the Space Telescope had spent many years debating the advantages of the CCD in comparison with television camera tubes for the telescope's wide field and planetary camera.[437] CCDs were small, lightweight, and consumed little power, but they had a narrow field of view and were poor detectors in the ultra-violet, a key part of the spectrum that astronomers hoped to access by flying above earth's atmosphere. The debate was complicated by many factors, but largely stemmed from the different needs of planetary astronomers and stellar astronomers. Planetary astronomers pressured the instrumentation teams to pursue CCDs because they performed better in the red part of the spectrum, a region of particular importance for planetary research. By the time Baum was brought on to Westphal's team, they had already

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[434] William A. Baum, "Planetary Patrol – An International Effort," *Transactions of the International Astronomical Union: Proceedings of the Fourteenth General Assembly* edited by C. de Jager and A. Jappel (1970): 136.

[435] Baum, oral history interview (2004).

[436] William A. Baum, "Activities of the Planetary Research Center of the Lowell Observatory," *Transactions of the International Astronomical Union: Proceedings of the Fourteenth General Assembly* edited by C. de Jager and A. Jappel (1970): 136-137.

[437] For an extensive discussion on the debate of camera detector, see Smith, *The Space Telescope*, 104-110 and Smith and Tatarewicz, "Replacing a Technology." Also see David DeVorkin's discussion of the Smithsonian Astrophysical Observatory's development of a television detector for space-based observing in David DeVorkin, *Fred Whipple's Empire: The Smithsonian Astrophysical Observatory, 1955-1973* (Washington, D.C.: Smithsonian Press, 2018), chap. 21.

decided to pursue CCDs. Because CCDs had only recently been invented NASA, therefore, wanted assurance they would work on the space telescope through testing by astronomers on ground-based telescopes.[438] From the late 1970s through the early 1980s, Baum transitioned from developing image tube technology to testing new CCDs, culminating in the end of image tube development at Lowell Observatory.

At the Department of Terrestrial Magnetism, Ford and Rubin contended with the desire to digitize astronomical data. DTM had first brought computers in during the 1950s and with improved, faster systems in the 1960s, the staff were trained to fully utilize the new tools.[439] The astronomers bought a VAX-750 computer to share with the entire department, which the geophysicists used to read digitized seismic recordings. In 1975, after a two-year sabbatical at the Kitt Peak National Observatory, Kent Ford returned to Washington, D.C. and joined the effort by building a scanning micro-photometer to digitize photographic plates.[440] The device Ford created produced a digitized spectrum on a reel of magnetic tape that the astronomer could insert into a computer and examine. As Ford later recalled, the decision to use digital systems was not a difficult one to make:

> "By that time Vera and I were interested in rotation curves of galaxies at the distance of the Virgo cluster. And, you could see the curves in the spectra. And so, the idea was, 'Do you sit there with your measuring engine and crank along that, that line, or do you build a machine that takes the digitized image and follows it for you?'"[441]

Ford wrote computer code that would find the velocity of a spectrum and automatically move on to the next, simplifying the post-observing process for astronomers.

While the decision to digitize astronomical data was easy, Ford was not convinced by the growing interest in born-digital systems. In 1976, Ford wrote that, "We anticipate that much of our astronomical work in the next few years will continue to be done with photographic recording of

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438 Smith and Tatarewicz " Replacing a Technology," 1233.

439 Brown, *Centennial History of the Carnegie Institution of Washington, Volume II: The Department of Terrestrial Magnetism*.

440 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146.

441 Ford, oral history interview.

the image intensifier output."[442] Even though there had been "great progress" made with direct recording with digital sensors, he wrote, "there are some types of observations for which the size…, stability, and efficiency of the present intensifier systems still give an overwhelming advantage."[443] Though Ford did not believe born-digital systems would not take over immediately, he did investigate the avenues different groups were pursuing. He concluded that while the "intensifier-image dissector scanners at Lick Observatory and at the Kitt Peak National Observatory and the Silicon Intensified Target (SIT) systems at Hale, Kitt Peak, and Cerro Tololo Observatories [were] operating successfully and [were] yielding photometric astronomical data with sky background subtraction…these types of systems [fell] short in performance over what might be achieved with some silicon detectors now in the development stage."[444] The silicon detectors Ford referred to were generally described by the term CCD and had the advantage over traditional camera tubes in the geometrical stability, compactness, and long-term stability of sensitivity.[445] "As a result of the long program of development and evaluation of image tube systems at DTM," Ford wrote in 1976, "we are in good position to analyze and evaluate the characteristics of some of the more promising of these devices."[446] While Ford continued to assist Rubin in her observations with the Carnegie image tube spectrograph, at DTM, he investigated CCDs that were being commercially developed.

Ford retired in 1988 and later commented that while CCDs allowed for easier data collection, something that became more important to him as he grew older, he missed the

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442 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146.

443 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146.

444 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146. "In these detectors an image is read out serially point by point by moving photogenerated charge laterally through the bulk silicon of the device to an output gate. The charge can be accumulated during an exposure or integration period and then moved by manipulating in appropriate phase the potential applied to metallic electrodes insulated from the bulk silicon. These structures are generally described by the generic term charge coupled devices, or more frequently simply CCDs."

445 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146.

446 Carnegie Institution of Washington, Year Book 76: July 1, 1976 – June 30, 1977, 146.

personal contact with the observing process, revealing, “We could bring tapes home and that was great. That was good data and I enjoyed that, and enjoyed working on the data. But, it wasn’t the same thing as having your own spectrograph or your own image tube there. So, I had lost a little bit of contact with that. I was more of a user at the National Observatory, or Palomar, for that matter.”[447] By using a new technology of which he did not drive development, Ford had made final move from producer to user. Though he wished to, “go back to the darkroom or the workbench and build something,” the era of CCDs, with its accompanying formatted system of observing, had arrived.

Reviewing the arguments

In the 1980s, astronomers chose to replace telescopic observations employing electronic image tubes and photographic plates with born-digital data detected with a CCD. In this dissertation, I explored the Carnegie Image Tube Committee’s attempt from the 1950s to 1970s to replace direct photography as astronomers’ chosen observational method. From the proposal to development and from the manufacture to use of the Carnegie Image Tube, astronomers, physicists, instrument-builders, and commercial producers had to re-examine what they considered to be a “better” way of observing. I examined the motivations for and against the pursuit of image tube development, the goals for that development, and the measures of success from the various groups involved in this story, all to better understand how astronomers acquire new tools and how they react to the introduction of new technologies and techniques into their profession. In this section, I will contextualize my arguments and draw conclusions from this assessment to the larger issue of technology adoption in astronomy.

Astronomers had become confident users of photography and only a few eagerly ventured to connect electronic experiment to the telescope to improve data collection. This hesitation may have stemmed from older astronomers’ lack of training in how to operate

[447] Ford, oral history interview.

electronic equipment and their fear of adding a non-astronomer into the observation process. Physicists, with a background in optical instrumentation, or astronomers, with a training in electronics, led the push for instrumentation development in astronomy. This dynamic can be seen in the efforts of Ira Bowen, William Baum, and the dozens of physicists and astronomers who pushed photoelectric aids in the 1940s and early 1950s. Ira Bowen became the first physicist to direct the Mount Wilson Observatory, an accomplishment noted by many of the more traditional astronomers. Though Bowen believed in the value of advanced instrumentation, he did not want to divert resources away from his observatory's research agenda and instrumentation project. The responsibility he had as an administrator outweighed his interest in using physics to further astronomical instrumentation.

Young physicists, those who completed their doctoral degrees during and directly after World War II, entered the field of astronomy with new skills and newly-available financial resources. In 1952, a group of young physicists and astronomers held a conference to investigate building an observatory dedicated to photoelectric observations. Though older astronomers, who preferred not to restrict a new telescope's use to electronically-aided observations, squashed this idea, William Baum pushed for a large-scale project to investigate image tubes at the Carnegie Institution through his access to the open ear of Vannevar Bush. As laid out in his 1945 report, "Science, The Endless Frontier," Bush believed in the importance of advancing scientific instrumentation that could advance scientific research, which would raise the country's prestige. Furthermore, Bush had access to funding that could get a development project up and running. The development of radio astronomy similarly involved a push from physicists, and while Bush also wanted to develop the new field in the United States, and specifically at the Carnegie Institution, he struggled to get the project going before other countries made major developments first. Bush, Bowen, and Baum were excited or hesitant about the prospective development of image tubes for different reasons, each concerned with the group which held them accountable, showing institutions, disciplines, and other organizations shape the development of new technologies through individuals.

Vannevar Bush succeeded in establishing a program to investigate image tubes and with that effort created a consumption junction of technology development, where the Carnegie Image Tube Committee acted as the conduit between the manufacturing companies and the astronomical community. As a conduit, the Carnegie Image Tube Committee made decisions regarding which collaborations with industrial and military labs were worth pursuing, the lowest acceptable limit of technical specification requirements, when the final product was ready for general use, how to best to allocate image tubes, and how to train those who received image tubes. Military labs appear several times in this story due to their scientists' similar pursuit of image tube technology. The Committee members occasionally engaged with military projects but only up until the point where they felt their goals diverged too greatly to benefit from a collaboration. The Committee similarly used various industrial labs as long as their engineers and managers could prove they understood the problems facing astronomers and continued to work toward common goals. When neither industrial nor military labs could help with a particular technical problem, like the production of thin film, the Committee hired a physicist specifically to fulfill that need. The CITC's inability to find an industrial or military partner to collaborate over an extended period of time reveals the specific nature of the CITC's goals, providing further evidence for my argument that, because astronomers were a relatively small consumer group, no producer of technology alone would provide them the solution to the imaging problem.

Kent Ford and William Baum attempted to share information concerning the Committee's efforts with the astronomy community, but some astronomers still expressed their frustrations over their perceived omission in the ongoing conversations. This dynamic may have been due in part to the tension derived from the Department of Terrestrial Magnetism not being viewed by the astronomical community as a place where observational astronomy was done. Without a trust in the science being done and the astronomers connected with the project, the community had little reason to trust the instrumentation developed. This lack of trust is different than that seen in earlier episodes of astronomical imaging. In the case of the Carnegie Image Tube, astronomers trusted what the device produced, but did not trust that it was designed with astronomers' concerns in mind. Though Merle Tuve argued that he had a strong group dedicated to the project, much of the astronomical community did not feel engaged in the process, decreasing their buy-in on the final product.

While the Carnegie Committee struggled to engage in a productive dialog with astronomers regarding their needs and wants in an image tube system, they did recognize that providing image tube systems was not enough and therefore promised to provide help by experienced staff to train observatory personnel in their use. Because the tubes were completely sealed and self-contained, the Committee predicted they would be reliable and stable under actual observing conditions for very long periods of time, once the local staff had been properly trained and they had received assistance with their installation. Unfortunately, the community never reached this honeymoon period with image tubes because of installation delays. Kent Ford was the only person available to assist with training and installation of the image tubes and time limitations prevented him from visiting all observatories eligible for a tube quickly. Furthermore, because the Committee provided image tubes free-of-charge, astronomers had less investment in continuing to use the device.

The development of other image tube devices further complicated the CITC's attempts. In the early stages of development, having other groups developing electronic devices initially pleased the CITC, but once produced, the instruments served as competition for the Carnegie device. The same astronomers were potential users of the Carnegie tube and James McGee and Gerald Kron's electronographic cameras, as well as space-based observatories and television-type image tubes. The Carnegie Committee not only had to compete with photography as the established method of data collection, but they had to contend with the added competition of alternate forms of electronic imaging.

Assessment of the CITC's position as conduit between producers and users of the developing technology shows that ultimately the CITC helped increase development resources and produced a usable device that was employed by several astronomers at the world's largest observatories, producing ground-breaking science. However, they also reduced the devices ultimate appeal by not actively involving the larger community in the development process and decisions. Whether this double edged dynamic of producing a device without a dedicated user group occurs in other instances of technological adoption or non-adoption amongst astronomers should be considered in future studies.

By focusing on the efforts of the Carnegie Image Tube Committee, I was able to examine a specific example of this effort and analyze the relationships between committee members, between institutions, between disciplines, other amongst competing groups of developers. Though image tubes did not succeed as the leading technology, this period transformed the field of astronomy by showing astronomers areas of research opened up by more sensitive detectors, and hopefully helps us better understand how astronomers acquire new tools.

Next steps

In reflecting on this study, additional avenues of investigation could further shed light on the central arguments and questions. First, this dissertation explores one effort to develop image tubes, but other groups developed image tubes in this period also and call for examination. A fuller examination of the archival sources for each group, such as those based at Lick Observatory, Yerkes Observatory, and Imperial College London, could further illuminate their efforts, goals, and comparative successes. The story of the electronographic image tube developed by George Carruthers at the Naval Research Laboratory may be of particular value. It flew on sounding rockets and Apollo 16, and astronauts set it up on the lunar surface to study the earth in the ultra-violet spectrum, the first time the earth had been wholly viewed in that light.[448] The success of astronauts independently operating an imaging device would contrast with astronomers' need for technical assistance to use the Carnegie tube. Because the Carnegie Committee had largely abandoned a television-style image tube, I also did not follow the large efforts of the groups interested in building a television detector for space-based observatories. Historians Robert Smith and David DeVorkin, however, have done important work on these

[448] George Carruthers, "Apollo 16 far-ultraviolet camera/spectrograph: Earth observations," *Science* 177, no. 4051 (1 Sept. 1972): 788-791.

technologies.[449] These stories should be included in a full account of the era of electronic imaging in astronomy.

Additional archival sources could provide insight into the perspectives of different groups involved in the Carnegie group's effort. Notably, the RCA archives at the Hagley library may reveal a deeper understanding of a producer's goal, beyond increasing their consumer base. The Library of congress recently cataloged and opened Vera Rubin's papers. Further examination of her personal correspondence may shed light on the reasons she chose to use the Carnegie Image Tube. Moreover, the papers of an astronomer who adopted the Carnegie Image Tube may reveal other astronomers' view on that use.

I am interested in conducting additional oral history interviews, or re-interviewing, younger astronomers, those who graduated into the professional field just as the Carnegie Image Tube became available in hopes of discovering how that generation viewed image tube technology and why the Carnegie group had difficulty attracting staff members to their project. This additional information would help in my attempt to understand how and why astronomers choose to adopt new tools.

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449 Smith, *The Space Telescope;* DeVorkin, *Fred Whipple's Empire.*

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CU: Columbia University archives, New York, New York

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HEH: The Huntington Library, San Marino, California

ICL: Imperial College London, London, U.K.

LOA: Lowell Observatory Archives, Flagstaff, Arizona

NASM: National Air and Space Museum, Washington, D.C.

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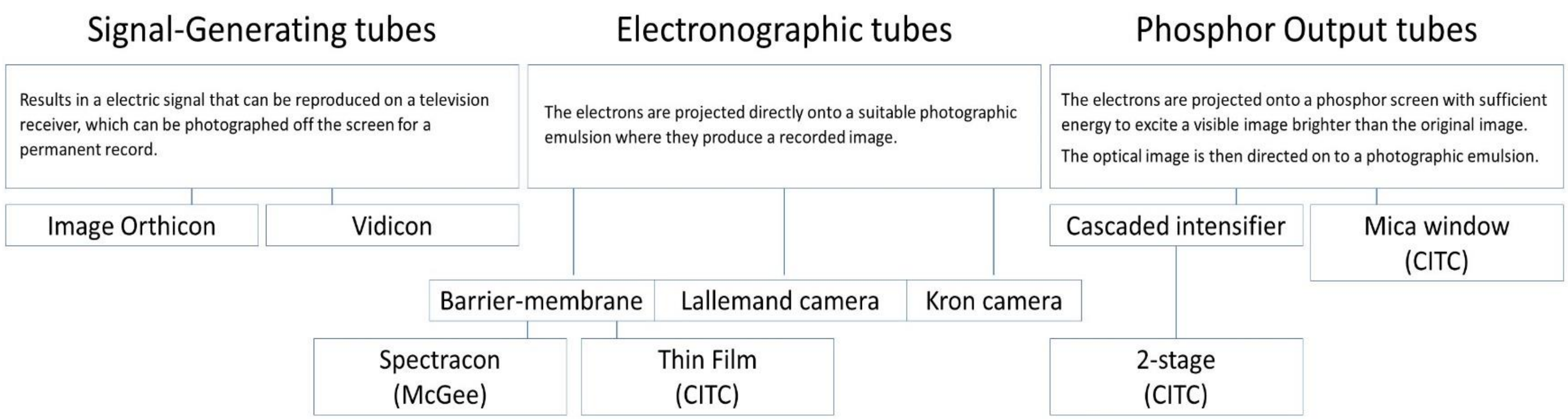
APPENDIX A

IMAGE TUBE DESIGNS

Image Tube Designs

Every type of image tube serves to convert photons into electrons, transforming an optical image into an electron image.
The goal it to then make a permanent record of that electron image with as little loss of image information as possible.
There are the following three main methods by which this is attempted:



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