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# How Astronomers Digitized the Sky

**W. PATRICK McCRAY**

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On 29 September 1989 an astronomer walked into the classically shaped dome sheltering the venerable Hale Telescope atop Palomar Mountain. For decades, this privately owned telescope—only scientists at the California Institute of Technology (Caltech) and the Carnegie Observatories in Pasadena enjoyed regular access to it—stood at the forefront of astronomical research. The scientist settled in at the telescope and did what astronomers before him had done tens of thousands of times: he took a photograph.

For an hour, the telescope's 200-inch mirror reflected a trickle of photons arriving from a supernova remnant in the constellation Cassiopeia to a small piece of glass coated with an ultra-sensitive chemical emulsion. This would be the Hale's last official photographic observing run. As the popular astronomy magazine *Sky & Telescope* described it, astronomical photographs would soon be "things of the past . . . just like oil lamps, pendulum clocks, and slide rules." Instead, light that the telescope gathered would be recorded on solid-state electronic detectors—in other words, the data would be "born-digital."<sup>1</sup>

A technological era can begin and end in many ways. Sometimes it is signaled suddenly by a nuclear explosion's glare or a satellite's chirps; in other cases it is more gradual, such as when the whoosh of turbojets slowly supplanted the familiar drone of propeller-powered airplanes.<sup>2</sup> Although

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1. Described in the "News Notes" section of *Sky & Telescope*, February 1990, 134.

2. An evocative example of this change is given in the opening pages of Edward W. Constant II, *The Origins of the Turbojet Revolution*.

*Sky & Telescope* described this particular break with the technological past as a discrete moment, observational astronomers certainly recognized it as only one marker along a longer path of events stretching back more than two decades. Part of this story involved astronomers' efforts to integrate computers into their research and collect digitized data; another aspect included the creation of innovative instrumentation and the complexities associated with building it. Finally, establishing the means to share digital data among researchers and across national borders had the potential to reshape older norms about data sharing and access.

This article has three primary goals. First, it uses representative historical examples to illustrate how the astronomy community migrated from an analog world to a digital one. This was not simply a matter of astronomers adding electronic computers to their toolkit. As they replaced and supplemented older technologies, astronomers' basic research practices changed accordingly. Operating a competitive modern observatory also required a new workforce whose members possessed a different set of skills. Instead of (or in addition to) expertise in areas like celestial mechanics, stellar spectral classification, and astrometry, the digitization of astronomy required knowledge about solid-state detectors, digital circuits, and computer programming. Looking beyond issues of professional skills, innovation in hardware, and data standards, the digitization of astronomy helped reshape norms and behaviors in the astronomy community—what scholars describe as a “moral economy.”<sup>3</sup> Once astronomical images existed in digital form, as opposed to photographs on glass plates, they could be moved and shared in ways not easily done before.<sup>4</sup>

Second, this narrative shows how the successful digitization of astronomy demanded agreed-on standards, as well as new hardware.<sup>5</sup> By 1980 astronomers routinely collected or converted their data into forms that could be manipulated and analyzed by a digital computer and stored on some sort of magnetic medium. However, in order for scientists to readily share their growing collections of digital data within the same observatory

3. In terms of scientific research, a *moral economy* refers to the often-unstated rules, values, expectations, and obligations associated with the production of knowledge and circulation of resources, although, according to Robert E. Kohler, *Lords of the Fly*, these may change as technologies change. The classic articulation of a moral economy remains E. P. Thompson's “The Moral Economy of the English Crowd in the Eighteenth Century,” as well as his earlier *The Making of the English Working Class*. For the deployment of the idea by historians of science, see Steven Shapin, “The House of Experiment in Seventeenth-Century England”; Lorraine Daston, “The Moral Economy of Science”; W. Patrick McCray, “Large Telescopes and the Moral Economy of Recent Astronomy”; and Bruno J. Strasser, “The Experimenter's Museum.”

4. Astronomers routinely refer to their data as *images*, although they more often refer to astronomical spectra, which yield information about an object's composition, temperature, and other physical conditions.

5. Amy Slaton and Janet Abbate, “The Hidden Lives of Standards”; Abbate, *Inventing the Internet*; Andrew L. Russell, “Standardization in History.”

or, even worse, among institutions located in different countries, it needed a common format. Although not consciously identified as such, the digitization of astronomy is therefore a transnational technological history possessing implications that extend beyond one scientific discipline.

Finally, this article extends the concept of *data friction* to modern observational astronomy. In *A Vast Machine*, Paul Edwards deploys *friction* as a metaphor to explore information and computation as they relate to climate modeling. In his telling, data friction refers to “costs in time, energy, and attention” needed to “collect, check, store, move, receive, and access data.”<sup>6</sup> Whether it was analog or digital, collecting, analyzing, and sharing astronomical data required that work be performed. However, the nature and kind of this work varied with time. At its core, this article examines specific ways in which data-friction points, in keeping with the metaphor, were successfully greased or remained stubbornly sticky.

Data-collection and -sharing practices were more ingrained in the traditional optical astronomy community than in newer subfields like radio astronomy. I have accordingly focused my attention on this more established group.<sup>7</sup> Observational astronomers had used photographic methods to collect data since the mid-nineteenth century; but in a relatively short span of time, between roughly 1965 and 1980, their view of the sky transformed to a digital one. This process implicated a tangled combination of hardware and software, as well as the messy complexities of heterogeneous engineering familiar to historians of technology.<sup>8</sup>

Different means of data collection overlapped during the time period this article addresses. In the *photographic era* astronomical data were collected via photographic means and they remained photographic. Adjoining this was an *electronic era*. Starting as early as 1900, alternative devices like photomultipliers and image tubes augmented established photographic techniques; however, the data output was still mostly recorded in analog fashion on strip charts or punch cards, which an electronic computer might later analyze.<sup>9</sup> Note though that just as *computerization* is not equivalent to *digitization*, data produced via electronic techniques did not

6. Paul N. Edwards, *A Vast Machine*, 84; Edwards et al., “Science Friction.”

7. Traditional observational astronomy using light in the visible or optical part of the spectrum (that is, what we naturally see) is the oldest sub-branch of the discipline, and data collected at optical wavelengths with ground- or space-based telescopes, alone or combined with data from other wavelength regimes like radio or X-rays, still results in the majority of research publications; see Helmut A. Abt, “The Most Frequently Cited Astronomical Papers Published during the Past Decade.” Over the time span that this article addresses, astronomers became less parochial in terms of the wavelength regimes (optical, infrared, radio, and so on) in which they worked; see Abt, “The Growth of Multiwavelength Astrophysics.”

8. John Law, “Technology and Heterogeneous Engineering.”

9. For example, Joel Stebbins, Albert Whitford, and Richard Kron pioneered photoelectric techniques for measuring point sources in the decades before World War II; see David H. DeVorkin, “Electronics in Astronomy.”

necessarily result in a digital format.<sup>10</sup> However, scientists also developed tools to convert both electronic signals and analog photographs into a digital format. Finally, during the 1970s astronomical practice gradually transitioned into a *born-digital era* in which the data were collected in real time in a digital format and transferred into digital data-handling and -manipulation systems. The boundaries between these three eras were blurred and indistinct; older technologies and techniques endured and complemented new ones. The fact that photographs were still being taken at Palomar in 1989, long after astronomers has supposedly moved into the digital era, drives this point home.

The *digital turn* that started in the electronic era and then defined the born-digital era was not the first time that technological innovation disrupted astronomical practice. A century earlier scientists experienced something similar when astronomy took a *photographic turn*. By 1850 astronomers in Europe were producing rudimentary daguerreotypes of the moon, stars, and solar spectrum. A few decades later the advent of dry gelatin plates placed photography in astronomers' essential toolkit.<sup>11</sup> Scientists and observatory directors eventually cultivated relationships with specialists like C. E. Kenneth Mees, a British-born chemist who ran Eastman Kodak's research laboratory where specialized film emulsions were developed.<sup>12</sup> Just as electronic and digital data-recording devices would do in the 1970s, photography disrupted scientific practice, empowered individuals (and their institutions) who mastered the new techniques, and enabled data exchange and archiving in the form of plate libraries. Like digital data-recording techniques, earlier photographic methods raised questions about aesthetic and epistemological issues, as well as the challenges of managing amounts of data that were large for the time.<sup>13</sup> Finally, civilian scientists' deployment of photographic, electronic, and digital means to capture astronomical data benefited from research and development done for military or classified reconnaissance purposes.

The transition from an analog data regime to a digitized one entailed far-reaching social, managerial, and technical issues. One could present

10. Nathan Ensmenger's "The Digital Construction of Technology" highlights the need for historians to make the distinction between *computerization* and *digitization*. As he notes, "not all computers are digital and not all digital devices are computers." Focusing on the process of digitization, besides offering some analytical advantages, also encompasses not just artifacts, but also representations of data.

11. See C. E. Kenneth Mees, *From Dry Plates to Ektachrome Film*, esp. chap. 21; and John Lankford, "The Impact of Photography on Astronomy." Mees also developed film emulsions for particle-physics experiments.

12. Hans T. Clarke, "Charles Edward Kenneth Mees, 1882–1960."

13. Photographic as well as digital images could be manipulated during collection and processing. This generated concerns among some scientists as to the distinction between *images*, *information*, and *artifacts*. See, for example, Michael Lynch and Samuel Y. Edgerton, "Aesthetics and Digital Image Processing"; and Elizabeth A. Kessler, *Picturing the Cosmos*.

OCTOBER  
2014  
VOL. 55

this story in several different ways, focusing, for example, on activities at one institution or on the development of a particular piece of hardware. I have opted instead to present a series of illustrative snapshots that represent a diverse community of actors and institutions: astronomers at elite private observatories in California; a young English scientist shifting from physics to astronomical research; and computer-savvy astronomers working at national observatories in the United States and Europe to create a community-wide standard. Other examples would have yielded a somewhat different yet complementary view. The digitization of astronomy was not delimited to one country or subfield of the discipline; rather, it was a process that all researchers—observers and theoreticians alike—experienced in some way. Nor can one ignore the fact that it was not just astronomers who took the digital turn; similar and sometimes serendipitous parallels can be found in the histories of other scientific disciplines, such as particle physics, meteorology, and biomedical research.<sup>14</sup>

Nonetheless, the examples presented here—selected as representative while taking advantage of available evidentiary materials—are windows into the larger and gradual digitization process that unfolded throughout the entire international astronomy community. This approach allows us to see the transformation at several different scales—from the local context of individual laboratories to the transnational circulation of instruments and data—across these overlapping data eras. Although the examples chosen here depict local processes, the importance of collecting, processing, and sharing digital data transcended specific institutions, individual research questions, and national boundaries. For astronomers, the transition from analog to digital was, in both senses of the phrase, a universal concern.

### Astronomers and Data

Much of astronomy's history, at least where it intersects with technology, has focused on the building of instrumentation and the politics and patronage that made this possible.<sup>15</sup> Less attention has been paid to the production and circulation of astronomical data. But images—once analog in form though now almost always digital—are indispensable for producing new knowledge about the universe.

For centuries, astronomers' view of the night sky was analog. It was

14. Peter Galison, *Image and Logic*; Edwards, *A Vast Machine*; Joseph A. November, *Biomedical Computing*. A much larger project, far beyond the scope of one article, might consider the process and implications of the digitization of scientific research in general.

15. See, for example, Richard F. Hirsh, *Glimpsing an Invisible Universe*; David H. DeVorkin, *Science with a Vengeance*; Robert W. Smith, *The Space Telescope*; Donald Osterbrock, *Pauper and Prince*; W. Patrick McCray, *Giant Telescopes*; and David P. D. Munns, *A Single Sky*.

continuous and infinitely variable, not comprised of discrete values or discontinuous signals. This analog picture—akin to what we see when we observe the stars and planets with our unaided eyes—remained largely unchanged even after the advent of astronomical photography.<sup>16</sup> But starting in the 1960s this analog view of the universe gradually transformed as astronomers introduced digital computers, electronic detectors, and magnetic-recording media into observatory domes and laboratories. After a brief transition period professional astronomy transformed into a scientific practice mediated and controlled by digital technologies. The advantages of this were considerable: once the underlying technical architecture and social practices were in place, digital data could be more easily analyzed, manipulated, transported, and communicated.

Astronomical data differs from other data. James Gray, a computer scientist and expert in data management, often joked with colleagues that he “liked working with astronomers because their data is worthless, in the best possible sense.”<sup>17</sup> By “best possible sense,” he meant that astronomical data have little to no commercial worth nor value as intellectual property. Unlike the massive databases maintained by firms like Walmart or Google, astronomers’ data pose no privacy issues; one can “do all sorts of exercises with them that one has to do with commercial data, but without being sued.” Astronomers’ data, as Gray saw it, have little relevance to national security and, unlike meteorological or climate data, have little to no political valence.<sup>18</sup> For many computer scientists, astronomical data appeared inherently interesting. Thanks in large part to the processes described in this article, one can “take the data and give them to somebody else. . . . [They are] well documented, spatially and temporally.”<sup>19</sup>

Generally speaking, there is no shortage of astronomical data. For example, since its 1990 launch the Hubble Space Telescope has collected and transmitted dozens of terabytes of observational data back to earth.<sup>20</sup>

16. John Lankford, “The Impact of Photography on Astronomy.”

17. Gray, whose January 2007 disappearance while sailing near San Francisco prompted a massive high-tech search, often used this anecdote in public presentations. It appears in a number of places, including a tribute from a colleague; see Alexander S. Szalay, “Jim Gray, Astronomer.”

18. Gray’s comment only applies to *certain* types of contemporary astronomical data. In the past, the military services were keenly interested in certain kinds of astronomical information. (See Deborah Jean Warner, “From Tallahassee to Timbuktu”; and W. Patrick McCray, *Keep Watching the Skies!*) Moreover, statements such as Gray’s are somewhat naïve because the pretense of entirely objective data is hard to maintain; see Lisa Gitelman, ed., “*Raw Data*” *Is an Oxymoron*. This, of course, connects to much broader discussions on the nature of scientific objectivity itself, as discussed by Lorraine Daston and Peter Galison, *Objectivity*.

19. Alexander S. Szalay, “Publishing Large Datasets in Astronomy.”

20. As of August 2012, about 65 terabytes (TB) of data had been acquired and processed for the Hubble Space Telescope (Karen Levay and Robert J. Hanisch, personal communication with the author, 4 August 2012). A terabyte is 1,000 gigabytes (GB). As

OCTOBER  
2014  
VOL. 55

As a result journalists commonly invoke astronomy in their reports about *big data*, a nebulous term used to describe the creation and management of massive data sets and archives, which are then searched in anticipation of finding new patterns and relationships.<sup>21</sup>

The overabundance of data, in fact, had long presented scientific communities with tremendous challenges.<sup>22</sup> But during the 1970s astronomers began commenting on an especially significant discontinuity in the amount of data they found at their disposal. It is here that one begins to see the increasing frequency of phrases like a “flood of data.”<sup>23</sup> A British committee reported, for example, that “data generated by powerful new detectors . . . are overwhelming,” while American astronomers accepted the “potential disruption” of computers into the “quiet austerity of a telescope dome” because scientists simply “cannot cope with the large amount of data produced by electronic detection systems.”<sup>24</sup> Within a decade astronomers routinely spoke with both trepidation and excitement about onrushing “floods” and “deluges” of data, such that one might dare refer to research before the mid-1980s as “antediluvian astronomy.”<sup>25</sup> Where once astronomers complained that they did not have enough data, they started to worry about the data drowning them.

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a point of reference, the size of a typical popular song (such as Nirvana’s “Smells Like Teen Spirit”) downloaded digitally is 10 megabytes (MB) or smaller—less than 0.01 GB, or 0.00001 TB. All of the cataloged books in the Library of Congress equal some 15 TB.

21. A special section in the 27 February 2010 issue of *Economist* called “Data, Data Everywhere” began by referencing astronomers’ growing collections of digital data. A similar treatment appears in Viktor Mayer-Schönberger and Kenneth Cukier, *Big Data*.

22. Even sixteenth-century natural philosophers struggled with the overabundance of information that resulted from various voyages of exploration; see Daniel Rosenberg, “Early Modern Information Overload”; Daniel R. Headrick, *When Information Came of Age*; and Lars Heide, *Punched-Card Systems and the Early Information Explosion*. As Robert Darnton notes in “An Early Information Society,” every age was an “age of information.”

23. Letter, Stephen E. Strom to Peter Boyce, 6 July 1977, in the Donald C. Wells papers, copies of which are in the author’s possession (hereafter DCWP). Looking beyond astronomy, the overall rapid expansion of science after 1945 helped create this looming deluge. In 1959, U.S. senator Hubert H. Humphrey, in fact, noted the “flood of new knowledge” that U.S. researchers were having to contend with; see Humphrey, “Engineers and Information.”

24. “Report of the Panel on Astronomical Image and Data Processing,” March 1979, in the Richard S. Ellis papers, copies of which are in the author’s possession (hereafter RSEP); Lloyd B. Robinson, “On-Line Computers for Telescope Control and Data Handling.”

25. Although this phrasing is mine, terms both aqueous and fiery—*flood* and *explosion*—are typically found. One example of this metaphor spilling over to other fields is in Peter Aldhous, “Managing the Genome Data Deluge.”



## Spanning the Analog/Digital Divide

Like many post–World War II scientists, astronomers were eager to see their research benefit from newly available electronic computers. For example, in 1959 an astronomer at the Mount Wilson and Palomar observatories (MWPO) described how computers could reduce data more quickly than a human.<sup>26</sup> Besides helping scientists avoid the situation where “useful information gathers dust and never appears in the literature,” computers might also become, like telescopes, general-purpose instruments that could perform a variety of tasks.<sup>27</sup>

The growing interest of astronomers in digital computers matured, of course, in the context of rapid changes within the overall computer industry.<sup>28</sup> Much of this change happened during the 1960s, a period that one industry analyst called the “go-go years,” as stock prices of established electronics companies were buoyed by the needs of the space program and the arms race.<sup>29</sup> The 1960s were a period of striking change in the astronomy community’s demographics as well. Membership in the American Astronomical Society increased markedly and, partially in response to burgeoning space-exploration programs, more universities launched astronomy curricula.<sup>30</sup> The influx of individuals from disciplines like physics and electrical and computer engineering was part of what Jesse Greenstein, who directed the astronomy program at Caltech from 1948 to 1972, called “the de-astronomization of astronomy.”<sup>31</sup>

The growing sophistication of electronic instrumentation used to collect data helped drive this shift. By the 1960s it was clear that astronomers’ research would be increasingly intertwined with innovative instruments developed by “gadgeteers” and “electronickers.”<sup>32</sup> These new members of the astronomy community were often self-taught when it came to building instruments or learning to write software code. One challenge they faced was reconciling frictions between older analog ways of doing astronomy

26. *Data reduction* is the transformation of the raw information collected by instruments into a more ordered and simplified form; see Halton C. Arp, “Reduction of Photoelectric Observations by an Electronic Computer.”

27. Marshall H. Wrubel, “The Electronic Computer as an Astronomical Instrument.”

28. Paul E. Ceruzzi, *A History of Modern Computing*; Martin Campbell-Kelly and William Aspray, *Computer*.

29. John Brooks, *The Go-Go Years*.

30. David H. DeVorkin and Paul Routly, “The Modern Society.” In 1960 there were about a thousand AAS members; a decade later the number had climbed to about 2,500.

31. Jesse L. Greenstein, oral-history interview with Rachel Prud’homme, 16 March 1982, Niels Bohr Library and Archives.

32. Letter, Leo Goldberg to Jesse L. Greenstein, 15 October 1958, “Goldberg” folder, box 12; letter, Greenstein to Alec Boksenberg, 17 September 1975, box 4, folder 1—both in Jesse L. Greenstein papers, Archives of the California Institute of Technology, Pasadena (hereafter JLG-P-CIT).

OCTOBER  
2014  
VOL. 55

with newly emerging digital techniques while trying to remain abreast of swiftly changing innovations from the computer industry; another was navigating the twin economies of astronomy: the *political economy* of securing the resources to build increasingly costly and complex instruments, as well as a *moral economy* in which instrument-builders did not always accrue the recognition that they believed they deserved.<sup>33</sup>

A sense of these difficulties can be seen in the professional experiences of one of these electronicers. In 1963 Edwin Dennison was recruited by Horace Babcock, the director of MWPO, to direct a new undertaking called the Astro-Electronics Laboratory (AEL).<sup>34</sup> The lab would, Babcock said, be devoted to the “modernization of existing instruments” as well as the “laboratory development of new devices and techniques,” including “modern equipment for data acquisition and processing.”<sup>35</sup> Trained as an astronomer, Dennison was self-taught though well-versed in instrument design based on traditional electronics, such as vacuum tubes, photomultipliers, and basic circuit diagrams<sup>36</sup> (fig. 1).

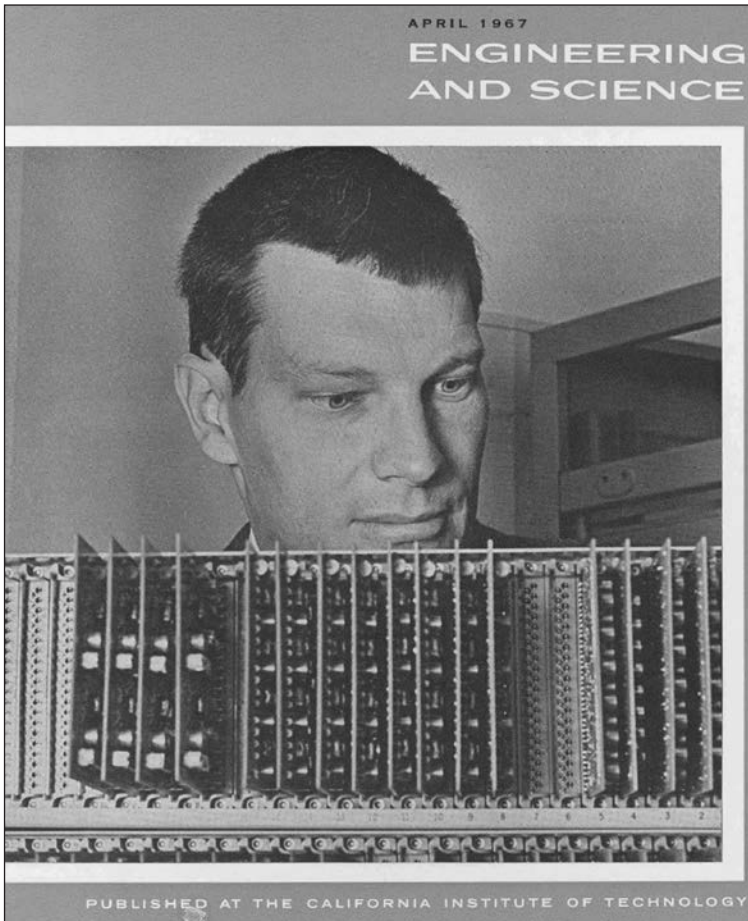
Dennison arrived in Pasadena just as MWPO was making plans to build a new telescope on Palomar Mountain. Its design suggests how the relationship between telescopes and computers was already changing. An architect’s sketch depicted wires and cables leading directly from the telescope to a computer in the observatory dome, where data would be recorded for later processing. Whereas older telescopes had new instruments, digital or otherwise, literally bolted onto them, astronomers anticipated from the outset that this new facility would incorporate the latest electronic and digital instrumentation. When the telescope was commissioned in 1970

33. As late as 1998, this was still an issue; see Judith G. Cohen, “Letter.” Cohen, a Caltech astronomer and instrument-builder, expressed concern about the status and rewards for instrument-builders, something that was becoming more of an issue as the timescale and money needed to build devices increased.

34. Caltech owned the telescopes on Palomar Mountain, while those on Mount Wilson were owned by the Carnegie Institution of Washington, D.C.; they were jointly operated at the time by the two institutions.

35. Letter, Horace W. Babcock to Edwin W. Dennison, 4 May 1963, folder 711, box 39, in Horace W. Babcock papers, Huntington Library, San Marino, California (hereafter HWBP-HL).

36. Photomultipliers were basically evacuated electronic tubes that converted light into measurable electric current. Light from the telescope entered a glass tube and struck a photocathode. Electrons were ejected and traveled toward an anode, striking intermediate photocathodes along the way, a process that caused a cascade of thousands of electrons. Photomultipliers enjoyed a relatively linear relation between the energy of incident light and the electric current it produced. This was an advantage over photographic plates, where the response was nonlinear and therefore required calibration. For instance, while photographic plates could require 300 or 400 photons to darken an emulsion grain, new photomultipliers were much more efficient at recording the light captured by a telescope. These new tools enabled astronomers to do *photometry*, the measurement of a star’s energy output, in a more straightforward fashion. (See DeVor-kin, “Electronics in Astronomy.”)



**FIG. 1** Edwin Dennison, head of the Astro-Electronics Laboratory operated by the Mount Wilson and Palomar observatories, on the April 1967 cover of *Engineering and Science*. He is shown with the new data-acquisition system the lab had built for the 200-inch telescope on Palomar Mountain. (Source: Image courtesy of the Archives of the California Institute of Technology, Pasadena.)

Caltech described it as “one of the first major telescopes to operate with a computer” so as to collect data in a digital format<sup>37</sup> (fig. 2).

Astronomers using the older telescopes that Caltech and Carnegie operated also began to record their data in digital form (as opposed to standard analog means, such as strip charts, photographs, and punch cards). In 1968, for instance, almost a third of scientists’ observing runs at the 200-inch tel-

37. “60-inch Telescope Dedicated at Palomar.”

OCTOBER  
2014  
VOL. 55

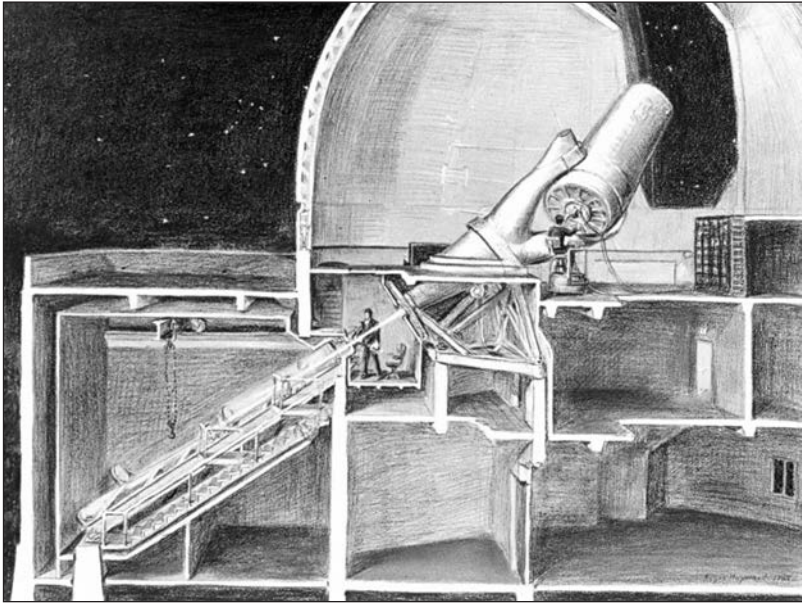


FIG. 2 Architect's cutaway sketch of the sixty-inch telescope on Palomar Mountain that was dedicated in 1970. Note the direct link between the telescope and the computer in the observatory dome. (Source: Photo ID 10.18-9, image courtesy of the Archives of the California Institute of Technology, Pasadena.)

escape on Palomar used some type of digital data recording. At the more venerable 100-inch telescope on Mount Wilson, researchers used a digital data system on 68 percent of nights.<sup>38</sup> Other major observatories in the United States could report similar patterns, as digital computers and the electronic instrumentation that fed data to them became more commonplace.

The switch to digital data collection did not come smoothly because it often entailed new ways of thinking about how one did the science. Dennison predicted that future astronomers would soon work in a "special electronics observing room." Instead of spending nights in the cold, dark observatory dome, often riding on the telescope itself in a cramped space that was actually called a "cage," they would comfortably watch the data-acquisition process via "closed circuit TV."<sup>39</sup> Not all scientists agreed with predictions like this. Dennison's boss, Babcock, objected, saying it would be "at least 30 years before the astronomer is out of the telescope."<sup>40</sup> Dennison persisted, articulating a general "philosophy and practice" of doing

38. "Instrumentation," in *Annual Report of the Director, Mount Wilson and Palomar Observatories, 1967-1968*, 56, in HWBP-HL, box 14, folder 247.

39. Edwin W. Dennison, "Data Systems."

40. *Ibid.*, 156.

astronomy; he believed, for example, that the “observer must never be a link in the data-collection chain.” This would reduce systemic data-collection errors and minimize observer “fatigue and discomfort,” as well as any sense “he is being manipulated by . . . the equipment.”<sup>41</sup> Controversial as it might have seemed at the time, Dennison’s philosophy was an attempt to help lubricate a particular data-friction point—namely, the ways in which data were collected in the first place.

Spanning the analog/digital divide also did not come cheaply. The AEL grew from two people and a budget of \$50,000 in 1963 to twenty-one and an annual budget of \$500,000 a decade later. The rapid pace of technological change in the computing industry, as well as the increased costs of instrumentation, alarmed administrators. In April 1969 Carl Anderson, the Nobel Prize-winning physicist who chaired Caltech’s Division of Physics, Mathematics, and Astronomy, wrote a “Statement of Needs in Astronomy” for his school. His estimate of about \$2 million accounted only for hardware, not the salaries of the experts needed to build the “new large data room with small computer and disk memory” and a system to allow photographic plates to be “completely digitized.”<sup>42</sup>

The increasing proliferation and cost of digital instrumentation circa 1970 suggested the telescope’s decentering as astronomers’ primary research tool. Consider an illustration that Dennison showed at a 1971 conference on telescope design: instead of situating the telescope front and center with various peripherals arrayed around it, he moved it to the margins. More centrally positioned were the “16K core memory,” “universal I/O controller,” “magnetic tape,” and “future large computer.”<sup>43</sup> After seeing this diagram, a German telescope designer remarked that the traditional observatory might eventually just become a “big computer with a large optical analog-input [that is, the telescope] at its periphery.”<sup>44</sup> One should not over-interpret this one schematic diagram, but it does symbolize something new about how astronomers pictured the relationships between their primary research tools (fig. 3).

Despite some successes, Dennison found himself and the AEL pulled between the “laboratory development of new devices and techniques” and more quotidian tasks, such as maintaining existing equipment. For his part, Dennison believed that he was doing bona fide “astronomical re-

41. Edwin W. Dennison, “Electronic Optical Astronomy”; Dennison, “Instrumentation,” in *Annual Report of the Director, Mount Wilson and Palomar Observatories, 1965–1966*, in HWBP-HL, box 9, folder 160.

42. Memorandum and report from Carl Anderson to Horace W. Babcock, 21 April 1969, folder 445, box 25, in HWBP-HL. Caltech operated with a combination of both private and federal money. Anderson estimated that Caltech’s astronomy program alone would need about 30 percent more in private funds of what it was currently receiving—about \$1.7 million—in federal grants.

43. Edwin W. Dennison, “Computer Control of Large Telescopes.”

44. *Ibid.*, 371.

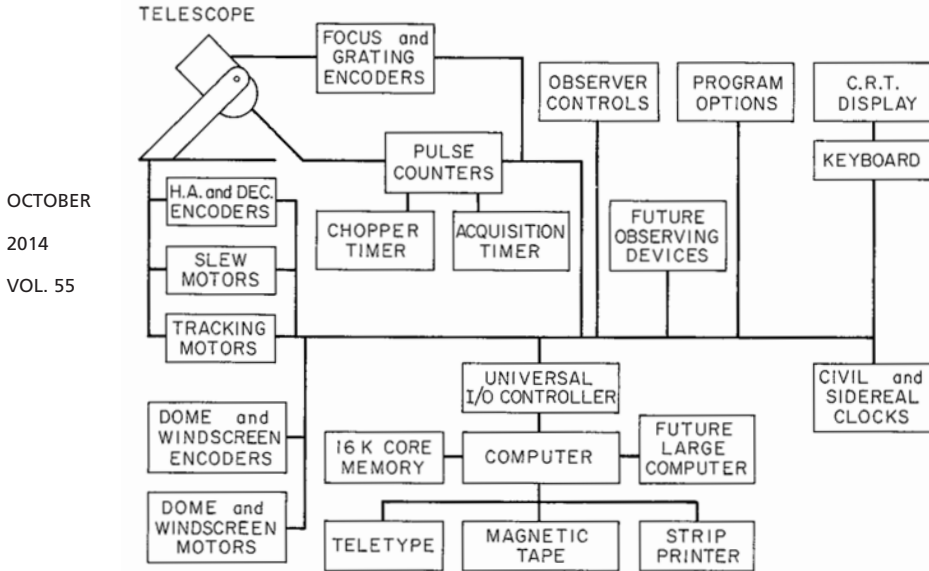


FIG. 3 Schematic of the typical Mount Wilson and Palomar observatories computer system. (Source: From a 1971 paper by Edwin Dennison, image courtesy of the Astronomical Society of the Pacific, San Francisco.)

search” (albeit “in the area of electronic instrumentation”), which meant that it was “subject to the same uncertainties as all research efforts.”<sup>45</sup> In June 1974, however, Babcock terminated Dennison’s leadership of the AEL. Among other things, he cited Dennison’s “philosophy of instrument development” that led to “large, open-ended systems [that] too frequently failed to work properly.”<sup>46</sup> Babcock also charged that Dennison had not run the lab with a “true engineering approach” that adapted with “sufficient rapidity to the changing technological advances.”<sup>47</sup>

Robert Kohler describes how the “fly people” working with *Drosophila* “experienced . . . the moral economy in different ways.”<sup>48</sup> Years after his

45. Memorandum, Edwin W. Dennison to Horace W. Babcock, 27 March 1969, in HWBP-HL, box 25, folder 461.

46. Memorandum, Horace W. Babcock to Edwin W. Dennison, 19 June 1975, folder 19, box 42, in Robert F. Bacher papers, Archives of the California Institute of Technology, Pasadena (hereafter RFBP-CIT).

47. A review of the AEL after Dennison’s removal, for example, revealed that software for observatory equipment was programmed in assembly language, rather than a more accessible language like FORTRAN. Moreover, the AEL’s lead computing specialist, who was not trained in programming per se, designed systems that, because they only had “about one line of comment for every 150 lines of source text,” were “chaotic.” See report, J. Frederick Bartlett to James A. Westphal, “Astro-Electronics Laboratory, Programming, Staff—Study Conclusions and Recommendations,” 11 September 1974, folder 894, box 50, in HWBP-HL.

48. Kohler, *Lords of the Fly*, 105.

termination, Dennison recalled how he felt excluded from the traditional researchers who met weekly for lunch at Caltech's faculty club. "Being an instrumentation astronomer," he recalled, "was about third class in the minds of some people. There was very little conversation there about instruments."<sup>49</sup> Dennison's perception of the moral economy also differed. Some Caltech scientists preferred a "cut and try" approach to building the tools essential to their personal research programs; Dennison, on the other hand, wanted to build instruments that could be easily understood and employed by a wider community of users.

When he was terminated, Dennison acknowledged that the pace of change had outstripped his original training as an astronomer and self-taught "gadgeteer." "I am unable," he told Babcock, "to do detailed circuit design or code computer programs"; instead, his "broad and comprehensive" expertise was "on the concepts of current technology." Dennison, in his defense, also reminded Babcock that he was hired as an astronomer and had "never considered [himself] an engineer."<sup>50</sup> Although some scientists wondered whether it "might be desirable to include electrical engineering in the training for astronomy," increasingly sophisticated electronic instrumentation and digital data systems demanded engineering skills more specialized than those possessed by most astronomers.<sup>51</sup>

Looking beyond the local environment of the AEL, one sees differing views among scientists about how computers should be integrated into astronomical research in general. Most still saw them largely as machines for model-building in which "physical laws are utilized to compute the behavior of a complex system" (like a star's interior) and less as tools to manage, reduce, and analyze data.<sup>52</sup> Given astronomers' prevailing view that *computer* typically referred to a large mainframe machine devoted to batch processing, some proposed a national center for astronomical computing.<sup>53</sup> Astronomers also pondered the trade-offs between adopting a "large general purpose machine" and the "small computer used on line for data reduction."<sup>54</sup> Issues about data sharing also arose; for example, one radio astronomer complained that too much data "is not used effectively in optical astronomy." This, in turn, prompted questions about whether scien-

49. Edwin W. Dennison, oral-history interview with the author, 18 January 2012.

50. Letter, Edwin W. Dennison to Horace W. Babcock, 14 January 1976 (emphasis in original), folder 19, box 42, in RFBP-CIT.

51. "Transcript of the Draft Minutes of the Third Meeting of the Astronomy Survey Committee, 2-3 February 1970," folder 2, box 100, in JLGP-CIT.

52. Jesse L. Greenstein, ed., *Astronomy and Astrophysics for the 1970s*, vol. 2, 202-3.

53. Letter, Dmitri Mihalas to Geoffrey Burbidge, 18 January 1971, folder 4, box 96; letter and report, A. G. W. Cameron to Astronomy Survey Committee, 23 March 1971, folder 2, box 100—both in JLGP-CIT. In the late 1950s and the '60s, biomedical researchers had similar discussions about the virtues of large centralized computers versus mini-computers; see November, *Biomedical Computing*.

54. "Minutes of the Eighth Meeting of the Astronomy Survey Committee, 11-12 February 1971," folder 9, box 100, in JLGP-CIT.

tists' data should be made available as a "public record." Caltech's Greenstein—an optical astronomer at an elite institution with ample access to observing time—disagreed, saying that "the problem is less one of poring over data achieved in the past than of opening up new frontiers."<sup>55</sup>

OCTOBER  
2014  
VOL. 55

In 1970 astronomers had no clear consensus about what the future would look like if digital data became the norm, resulting in a somewhat ad hoc approach to computing. Unlike the National Institutes of Health and its promotion of biomedical computing, no central government agency nor research institution articulated a clear vision for the future of how digital computers and digital data would be used. Nonetheless, scientists had managed to broach the issue of the growing amount of digital data and the possibility, indeed the imperative, of easily sharing it.

### Making Data "Born-Digital"

By the early 1970s astronomers worked with an emerging ensemble of digital techniques. These coexisted with older practices rooted in the analog world. Perhaps reflecting the views of astronomers who had spent much of their careers using photographic methods to record data, Greenstein confessed that the complexity of the new devices, as efficient as they might be, still sometimes caused him to "return from observing in a state of personal rage."<sup>56</sup> One of the machines that both enraged and enchanted him was not built in Pasadena, but was instead an import from the United Kingdom.

In the mid-1960s Alexander Boksenberg held a lecturer position at University College London (UCL), where he had recently completed his doctoral work. Like many young scientists entering astronomy, his formal training was in physics. For his thesis he built specialized instrumentation that measured electron-atom collisions, and he had not given astronomy "a second thought" as a graduate student. But when the only vacancy at UCL after finishing his degree was in a research group doing ultraviolet astronomy, Boksenberg began to design instruments that rockets and balloons would launch high into the earth's atmosphere.<sup>57</sup>

In 1968 British astronomers were considering which instruments would best complement the Anglo-Australian Telescope, a new facility under construction in Siding Spring, Australia. The ideal device, senior scientists told Boksenberg, would somehow combine a photoelectric image tube with the means to record what it collected "electronographically." It

55. "Transcript of the Draft Minutes of the Third Meeting of the Astronomy Survey Committee," in JLGPCIT. W. Patrick McCray's "The Contentious Role of a National Observatory" provides a sense of the divide between scientists at private institutions and those at public ones.

56. Jesse L. Greenstein, "Large Telescope Astronomy," 19.

57. Alexander Boksenberg, personal communication with the author.





FIG. 4 Alexander Boksenberg, circa 1980, shown with an image-intensifier tube from the Image Photon Counting System. (Source: Image courtesy of the Emilio Segrè Visual Archives at the American Institute of Physics, College Park, Maryland.)

would produce something like a photograph, but with the image's density at any point directly proportional to the light intensity so as to facilitate photometric measurements.<sup>58</sup> A key challenge, however, was to transform the image's brightness on a phosphor screen into an electrical signal that could be digitally stored for later analysis (fig. 4).

Boksenberg realized that he could build such a “perfect device” by the “judicious use of existing commercial devices.”<sup>59</sup> The machine ultimately

58. Image tubes were an extension of earlier photomultiplier tubes. In its basic form, an image tube is an evacuated tube with a photocathode at one end and a phosphor screen at the other. Incoming photons strike the photocathode and release electrons; after being accelerated and focused, these hit the phosphor screen and produce a flash of light in the same relative position as where the initial photons hit the photocathode. An electronographic image can be contrasted with a photographic image in which the chemical emulsion's response to incident light is nonlinear, thus complicating attempts to convert an exposure's image density to the observed object's actual brightness. See Dennis McMullan and Ralph Powell, “The Electronographic Camera.”

59. Boksenberg, personal communication.

OCTOBER  
2014  
VOL. 55

came together as an international assembly of components. Boksenberg, imagining the digital equivalent of a person's retina/brain combination, began with a four-stage image tube made by EMI, a British firm. A lens focused the image onto a Dutch high-quality television camera tube.<sup>60</sup> Electronics cleaned up the intermediate output, subtracted the sky background, and fed the data to a signal processor. A mini-computer made by a U.S. firm rejected readings due to noise and digitally tagged the central position of genuine photon events to create a sharper image. The final product was a digital picture that an observer could monitor in real time as it was generated. Boksenberg called this ensemble of equipment the Image Photon Counting System (IPCS).<sup>61</sup>

Funding from Britain's Science Research Council helped Boksenberg produce a lab prototype. An improved version followed, built more ruggedly so that it could be transported to a mountaintop observatory for field tests. Boksenberg wanted to quickly build credibility for his innovative instrument, so he sought evaluations from top optical astronomers rather than "leading up from minor facilities."<sup>62</sup> This presented a sticking point: the Anglo-Australian Telescope was not operating yet and British astronomers lacked easy access to first-class optical telescopes. To remedy this deficiency, Boksenberg successfully applied for guest observing time on the Palomar 200-inch telescope.

He arrived in Pasadena during autumn 1973 with the IPCS packed into huge wooden crates that contained electronics, power supplies, a computer, and the detector's cooling system. A digital electronics expert and a software specialist also came along. In short order, the whole operation was nicknamed "Boksenberg's Flying Circus" (BBC was still airing the British comedy series *Monty Python's Flying Circus*). The traveling version of the IPCS had a loudspeaker and a small light on the side of the equipment. When a photon was recorded, the light would flash and the speaker would chirp, letting an observer know that the instrument had collected data. As one astronomer noted: "You could actually hear the photons coming in—*bip, bip, bip*—and watch the image build up. You could know you had observed the right length of time to get what you wanted. The ICPS was very exciting to use."<sup>63</sup>

Boksenberg and his colleagues tested the IPCS at Palomar by collecting spectral data on very faint objects like quasars, which were harder to observe with traditional instrumentation. He eventually loaned the IPCS to astronomers at Caltech so that they could use it at Palomar for an extended period of time and further explore its capabilities. Boksenberg's "gift" was

60. Alexander Boksenberg and D. E. Burgess, "An Image Photon Counting System for Optical Astronomy."

61. Boksenberg, personal communication.

62. Ibid.

63. Mike G. Edmunds, oral-history interview with the author, 20 June 2000.

consistent with a moral economy in which scientists exchange and swap resources.<sup>64</sup> He had a valuable yet temperamental new instrument, while Caltech astronomers had access to the world's biggest optical telescope. Over the next decade, Boksenberg authored several papers with Caltech scientists and made the full transition from physics into astronomy.

Over the next few years, Boksenberg and his flying circus built other versions of the IPCS. One of these featured upgraded hardware and a simpler user interface; it became standard equipment at the Anglo-Australian Telescope. Another version went to a facility the United Kingdom operated in the Canary Islands, where it became part of that observatory's standard equipment. The European Space Agency selected a third variation of the IPCS as the detector in the Faint Object Camera, which went into space with the Hubble Space Telescope in 1990.

Although somewhat unusual in the degree to which it traveled and was replicated, the IPCS was just one species in a veritable zoo of new electronic tools. Often plugged directly to digital computers, these instruments offered astronomers a diverse array of options for intensifying, recording, and storing images. Boksenberg summarized the various techniques that scientists had at their disposal to collect data in a figure he showed at a conference in 1975 (fig. 5). At the top was a "photon," shown arriving at the telescope after traveling thousands or billions of light years. In the past, these photons were simply captured on a photographic plate (shown on the far right of the image). But light from stars and galaxies now faced a maze of options before it was recorded and converted into astronomical data.

Soon after Boksenberg's talk, however, astronomers placed their bets on one of the options shown on his diagram. As early as 1977, astronomers predicted that charge-coupled devices (CCDs) would become the "detector of choice for the entire observational community," even though at the time the CCDs had a small community of users.<sup>65</sup> The CCD quickly became their preferred digital-recording medium. But during this relatively short period of acceptance and adoption, as Boksenberg's graphic makes clear, astronomers relied upon all sorts of devices and, in fact, had a wide range to choose from. Some of these devices produced data that was born-digital, some were hybrid instruments, and others were anchored to astronomy's analog/photographic tradition.

New tools like the IPCS and CCD detectors had the potential to reduce data friction by transforming incoming light directly into digital data. These tools accelerated the overall trend toward the digitization of astronomers'

64. Kohler, *Lords of the Fly*, chap. 5, notes how "swapping stocks" was common among *Drosophila* biologists, as well as maize geneticists and other molecular biologists.

65. The lengthy process of innovation, resistance, and acceptance is recounted in Robert W. Smith and Joseph N. Tatarewicz's "Replacing a Technology" and "Counting on Invention." The CCD, which resulted in the Nobel Prize in Physics in 2009, was first reported in W. S. Boyle and G. E. Smith, "Charge Coupled Semiconductor Devices."

OCTOBER  
2014  
VOL. 55

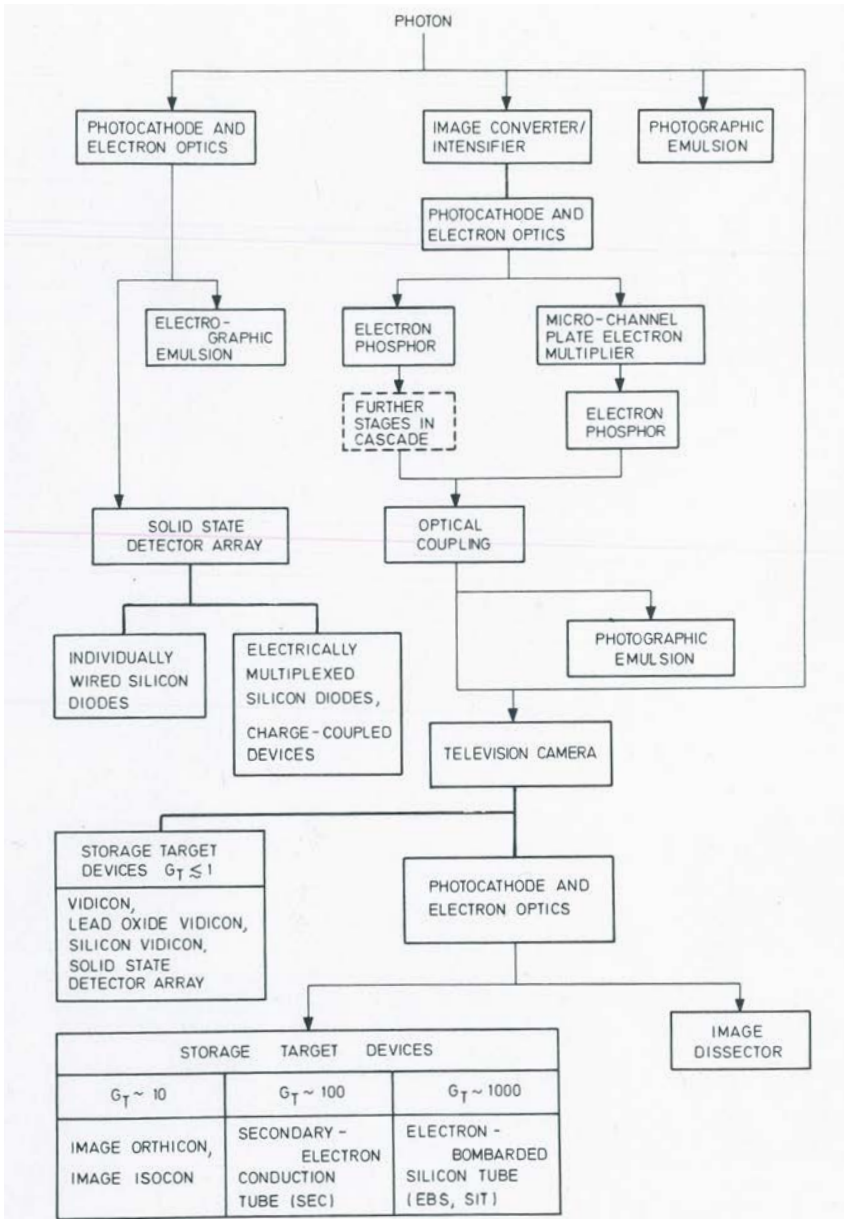


FIG. 5 Illustration from a 1975 talk by astronomer Alexander Boksenberg showing the myriad "image intensification and storage methods" available to astronomers in the mid-1970s before charge-coupled devices became the preferred medium. (Source: C. de Jager and H. Nieuwenhuijzen, eds., *Image Processing Techniques in Astronomy*, 60. Attempts to locate the copyright-holder of this image were unsuccessful.)

data. But to convert data originally collected on an analog medium to a digital format required overcoming some data friction. For example, astronomers had built automated “measuring engines” since the 1950s.<sup>66</sup> These electronically recorded information captured on photographic plates, such as coordinates of stars and galaxies.<sup>67</sup> A decade later, firms like PerkinElmer made automatic “microdensitometers” that allowed researchers to measure the optical density of a star or galaxy recorded on a photographic plate and hence its actual brightness. By scanning and analyzing astronomical photographs, these machines converted the analog information they contained to a digital format that a computer could process and store.<sup>68</sup>

By the end of the 1970s astronomers’ basic research materials were increasingly born-digital or otherwise converted into digital form. This compelled astronomers, electrical engineers, and software writers to collaborate with one another more often. Not surprisingly, friction resulted because these communities sometimes had different motivations and goals. For example, the astronomer wanted results “now, no matter how inefficient, *ad hoc*, and inelegant the method,” while the computer scientist was as much “concerned with methods as with a particular astronomer’s results.”<sup>69</sup> A cartoon circulated at a 1979 workshop asked “Who should wear the pants in astronomical I[mage] P[rocessing]?” as it depicted a delicate balance between “competition” and “team spirit”<sup>70</sup> (fig. 6). Perhaps dealing with digital data would become its own “discipline within astronomy” that called for a “new type of animal” with skills in computer hardware, image processing, and systems development.<sup>71</sup> Besides fostering the increased need for collaboration and an expanded professional skill set, the ever-more-frequent digital nature of astronomical data raised an issue that challenged community traditions and norms in more profound ways. As astronomers’ data were routinely digitized, critical questions of sharing, ownership, and access came to the fore.

66. Manual versions of these instruments have a much longer history. For example, before World War I, the Gaertner Scientific Corporation made a single-screw measuring engine; see McCormick Museum, “Gaertner Single Screw Measuring Engine.”

67. John Lentz and Richard Bennet, “Automatic Measurement of Star Positions”; S. Vasilevskis, “Automatic Measurement of Astrographic Plates.”

68. Examples include the “General Automatic Luminosity and X-Y” (GALAXY) measuring engine built at the Royal Observatory, Edinburgh, and the Advanced Plate Measuring (APM) system built at Cambridge University. See G. S. Walker, “The Design and Development of the GALAXY Machine”; and Edward J. Kibblewhite, “The Cambridge Automatic Plate-Measuring Project.”

69. Mike Disney, “Concluding Remarks.”

70. The cartoon comes from E. B. Newell, “Who Should Wear the Pants in Astronomical Image Processing?”

71. Disney, “Concluding Remarks.”

OCTOBER  
2014  
VOL. 55



FIG. 6 Cartoon from a 1979 conference proceedings illustrating the creative tensions between scientists and computer engineers. (Source: Attempts to locate the copyright-holder of this image were unsuccessful.)

### A Shared Sky

Imagine that it is 1976 and you are an observational astronomer. Regardless of what kind of telescope you use—optical or radio, public or private, orbiting in space or sitting on a mountaintop—if you wanted to share data you collected, could you? In the older analog tradition, astronomers loaned photographic plates to colleagues, while observatories maintained physical libraries of the same. But as more data was born-digital or converted to a digital format by plate-scanning machines, the ease of sharing it increasingly posed a problem.

Several factors contributed to astronomers' sense of crisis around these questions. The prime driver was the "swelling flood of data" that astronomers' nightly observing runs produced.<sup>72</sup> Scientists also lacked appropriate

72. Mike Disney and P. T. Wallace, "STARLINK." In the 1970s radio astronomers,

tools to tackle the “daunting task” of turning data into an “astrophysically useful form.”<sup>73</sup> So despite the growing capabilities of new digital detectors and instruments, astronomers’ ability to “extract and study the relevant bits from this mass of data” lagged.<sup>74</sup> Even greater challenges waited over the horizon. In the late 1970s scientists in the United States, United Kingdom, and Europe anticipated the launch of what became the Hubble Space Telescope. The “immense amount of data” that Hubble and other space-based facilities would generate meant that the existing “bottleneck” would be “greatly aggravated [and a] lot of valuable science could be lost” because of poor data-handling capabilities.<sup>75</sup>

At the same time, astronomers’ research practices were changing. More scientists, for example, wanted to combine data collected from different parts of the electromagnetic spectrum. However, digital data recorded by scientists using a radio telescope in Australia were rarely compatible with those collected, for instance, by optical astronomers in California. “The data transport problem,” a scientist at the Netherlands Foundation for Radio Astronomy noted, “is getting larger each year as more people seek to combine data from different instruments.”<sup>76</sup> Moreover, each institution typically produced its own in-house software packages to read the often-unique data formats that its instruments produced. Taking a data tape made at one site and trying to read it elsewhere required that it be “deblocked, decoded, and converted to the second machine’s internal number formats. . . . This is both time consuming and a bother.”<sup>77</sup> In other words, significant data friction inhibited astronomers’ ability to share research with colleagues or combine data collected at different telescopes. One tool that could help smooth this friction was a common format for astronomical data.

Starting in late 1976 a small group of astronomers, each possessing some computer-programming experience and employed at national observatories, began to address the problem. At Kitt Peak National Observatory, for example, Donald Wells took the lead role. Like Dennison, Wells started his career as a research astronomer. He also taught himself how to pro-

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long used to working with data generated in electrical form, also expressed concerns about data handling similar to those by their optical counterparts; see Jesse L. Greenstein, ed., “Introduction,” in *Astronomy and Astrophysics for the 1970s*, vol. 1.

73. Michael J. Disney, “Centre for Optical Data Analysis,” unpublished report, n.d. (ca.1978), in RSEP.

74. Letter, Stephen E. Strom to Peter Boyce, 6 July 1977, in DCWP.

75. “Minutes of the First Meeting, Panel on Astronomical Image and Data Processing,” October 1978, in RSEP. The overall situation closely resembles a “presumptive anomaly,” as described by Constant, *The Origins of the Turbojet Revolution*.

76. Letter, Ronald H. Harten to Colleagues, 9 June 1978, in DCWP.

77. For example, if astronomers at X institutions wanted to share data, they needed to write X(X-1) programs to translate data between various formats; see report, Ronald H. Harten, “A Proposal for a Data Transport Tape Format,” June 1978, in DCWP.

OCTOBER  
2014  
VOL. 55

gram in FORTRAN and ALGOL.<sup>78</sup> After he moved to Kitt Peak's Tucson headquarters in 1972, Wells's interests shifted from traditional astronomical research to information management and data handling. Because the national observatory's telescopes were open to all astronomers who successfully submitted a peer-reviewed proposal, Wells wanted to likewise design data tools that the entire community could use.

In December 1976 Wells was visited by Ronald Harten, an American-born radio astronomer working in the Netherlands, who wanted to learn about the image-processing work being done at Kitt Peak. Harten disliked not being able to easily move data among the radio telescopes in the Netherlands where it was collected and the offices where scientists later analyzed it. He told Wells about his experiments with a "magic record size" that might be the first step toward a solution.<sup>79</sup> At this point, different computer systems read data files in basic units of information interchange called "record lengths," which varied in size. If the chunk of data was a common multiple of the various record lengths that commercially available computer systems read, then this "universal commensurability" would enable the "packing and unpacking" of files on "a wide variety of computers."<sup>80</sup>

Throughout 1977 Wells and Harten worked separately to devise a provisional data-format system. Interactions with John Dickel, a radio astronomer from the University of Illinois, helped test their formats. Wells recalled that Dickel, who wanted to look at supernova remnants using both radio data collected in the Netherlands and optical data from Kitt Peak, "would bring radio data to me and I would transform his optical pictures so they would align."<sup>81</sup> Wells and Harten also devoted considerable time to engineering the "header" of the data record. Akin to what today is called "metadata," the header gives crucial information—where the picture was taken and with what instrument, the celestial coordinates of the image, observing conditions, and so forth—that precedes the data of the actual astronomical image. Because Wells and Harten represented the optical and radio astronomy communities respectively, they needed to create headers general enough to apply to data collected in either waveband; they also wanted to create a header system that would be "flexible and self-defining" yet open to "indefinite expansion" in the future.<sup>82</sup>

78. Donald C. Wells, oral-history interview with the author, 16–17 July 2002.

79. Donald C. Wells, "Happy Birthday, FITS!" 29 March 1992, available at <http://www.cv.nrao.edu/fits/documents/overviews/history.news> (accessed 15 October 2012).

80. D. C. Wells, E. W. Griesen, and R. H. Harten, "FITS." The number ultimately chosen for the record length was 23,040 bits. This was equivalent to 2,880 8-bit bytes, or 3,840 6-bit bytes. Moreover, it was also divisible by the byte lengths of computers in the market back then—that is, divisible by 6, 8, 12, 16, 18, and so on.

81. Wells, oral-history interview. An example of this work is found in John R. Dickel, Stephen S. Murray, Jeffrey Morris, and Donald C. Wells, "A Multiwavelength Comparison of Cassiopeia A and Tycho's Supernova Remnant."

82. Wells, Griesen, and Harten, "FITS."



As they developed their respective data-interchange formats, neither was especially committed to the form they had personally designed. As Wells wrote Harten: “I believe that any well defined and widely accepted format is infinitely preferable to none.” Harten agreed, noting that his “general purpose scheme” was designed to attract the interest of as many scientists as possible. Through their respective efforts, Wells wrote that “the community is being exposed to our ideas,” but the time was quickly coming for an “attempt to meld the opinions of a number of people to try to reach a compromise that can be accepted by all.” Securing support from researchers at the major national observatories was critical. “If NRAO [the National Radio Astronomy Observatory in the United States], KPNO [Kitt Peak], and Westerbork [a Dutch national radio astronomy facility] have the same system,” Harten predicted, “then most of the battle is won.”<sup>83</sup>

It is important to recognize the role of *national* observatories in this process. Throughout the 1960s and much of the '70s, the National Science Foundation (NSF) generously funded the building and operation of several new radio and optical telescopes. Unlike privately run facilities where use was restricted to a small group of astronomers, telescopes that the NSF supported were open to the entire science community. While astronomers working at MWPO would informally share research data among themselves, the NSF understandably had a vested interest in ensuring that data collected at its facilities, which served a much larger community, could circulate as easily as possible.<sup>84</sup> If enlisting the participation of observatories outside the United States made this data circulation transnational, so much the better.

In January 1979 Peter Boyce, a program director for astronomy at the NSF, arranged for representatives from the major national observatories in the United States to meet to discuss digital-image analysis. In particular, Boyce wanted to smooth the data exchange between optical and radio astronomers so that their observations might be combined.<sup>85</sup> Given the general agreement that a “tape interchange standard is important,” a small committee representing Kitt Peak, NRAO, and NASA’s Space Telescope project was set up to “facilitate the communication of digital data.”<sup>86</sup> Three months later, Wells met with people working on data formats at the Very Large Array (VLA), the flagship U.S. radio astronomy facility then under construction.<sup>87</sup> In less than two days, Wells and his NRAO counterpart, Eric Greisen, drafted an informal agreement derived, in part from the

83. The quotes are from letters between Donald C. Wells and Ronald H. Harten, 17 May and 5 June 1978, in DCWP (emphasis in original).

84. Letter, Peter B. Boyce to Donald C. Wells, 15 January 1979, in DCWP.

85. Peter B. Boyce, personal communication with the author.

86. The founding of the Space Telescope Science Institute (STScI), which manages the Hubble Space Telescope, was not formally announced until January 1981.

87. “Notes from January 26, 1979 NSF Image Analysis Meeting”; letter, Donald C. Wells to Stephen Strom and Geoffrey Burbidge, 8 March 1979—both in DCWP.

OCTOBER  
2014  
VOL. 55

data-format engineering done earlier by Harten. The agreement for what they called the Flexible Image Transport System (FITS) would “implement the transfer of images between observatories [in a] general format [that was] flexible and contains virtually unlimited room for growth.”<sup>88</sup> Their mutual acceptance of a particular record length (2880 8-bit bytes) meant that data standardized into the FITS format could be read “on all computers commercially available in the U.S. today [1979].”

Wells and Greisen tested their system with a trial exchange of data. One magnetic tape contained radio data collected at NRAO and processed using an IBM 360 system. The other had optical data from Kitt Peak executed by a CDC-6400 machine. The notorious incompatibility of these two 1960s-era machines offered a robust check of how “flexible” the data-interchange system actually was.<sup>89</sup> FITS passed these first tests and Wells presented the results at an international meeting in June 1979.<sup>90</sup>

As a tool for data sharing, FITS offered astronomers a “syntax” for communicating data with one another or among their respective institutions. As such, it embodied an inherently transnational aspect. Greisen, Wells, and Harten also considered the value of FITS as an archival format. As Wells and others refined the data standard, they kept in mind that information preserved with FITS should be able to be read by *all* computer systems, no matter how outdated, in the future. For Wells, an aficionado of U.S. history, this was analogous to James Madison’s goal of protecting minority interests in the drafting of the Constitution.<sup>91</sup> Therefore, a policy of “once FITS, always FITS” was eventually adopted to ensure a certain type of “backward compatibility” when it came to data. Moreover, knowing the potential value of astronomical data collected decades earlier in older formats like photographic plates, they came to regard FITS “not only as a way to talk to remote astronomers in the here and now,” but also as a tool “to talk to future astronomers.” The FITS format, in other words, was designed, in part, to enable computers (and astronomers) to read digital data years after it was first collected.<sup>92</sup>

Producing a common data-exchange format, however, would be fairly

88. “Draft of Flexible Image Transport System,” 29 March 1979, in DCWP.

89. Eric W. Greisen, “FITS.”

90. Donald C. Wells, “FITS.”

91. Donald C. Wells, personal communication (email) with the author. Wells sometimes included a quote from Benjamin Franklin to John Hancock—“We must indeed all hang together or, most assuredly, we shall all hang separately”—in his talks and papers to highlight the need for the astronomy community to unite behind FITS or another suitable standard.

92. Donald C. Wells, “Speculations of the Future of FITS.” More recently, Harvard University launched a project to digitize the 500,000 photographic plates in the university’s collection and put them online; see Yudhijit Bhattacharjee, “Stars in Dusty Filing Cabinets.” Lorraine Daston’s “The Sciences of the Archive” also places astronomy among the historical sciences with a “Janus-faced perspective . . . reaching back into the past and forward into the future.”

worthless if other institutions did not adopt it. This made FITS as much a political goal as a technical standard. Wells recalled “playing politics with FITS” as he tried to “mobilize an opinion in the community of sharing data, of always using the same formats. . . . I was trying to stamp out the heretics, people with alternative data formats.”<sup>93</sup> Astronomers quickly recognized the value of data standardization; by the end of 1980, national observatories in Sweden and Australia, in addition to those in the Netherlands and the United States, had adopted FITS as their basic data format.<sup>94</sup>

Of course, FITS advocates could not compel astronomers to share their data. But for scientists inclined to do so, the process had become more frictionless. FITS presented astronomers working across the electromagnetic spectrum with a lingua franca for recording, archiving, and sharing digital data. And, of course, as more scientists and institutions adopted FITS, the more essential it became for other scientists to enlist it as well.<sup>95</sup> In 1982 the International Astronomical Union officially encouraged this by recommending that “all astronomical computer facilities recognize and support” FITS as the standard global-interchange format for digital data.<sup>96</sup> The standardization that FITS brought was only one step, albeit a necessary one, in the eventual evolution of astronomers’ perception of the telescope as a “data factory” where greater efficiency and productivity became goals that observatory directors sought.<sup>97</sup>

Developed more than three decades ago, FITS has proven remarkably long-lived as a data standard for astronomy.<sup>98</sup> In time, researchers from disciplines far afield from astronomy recognized the usefulness of FITS. In December 2011 the Vatican Library announced that it had begun transforming tens of thousands of paper documents and manuscripts, some older than 1,800 years, into digital images using the FITS format.<sup>99</sup> FITS became, in other words, a potent oil that could reduce the friction inherent in the inter-institutional and transnational circulation of all kinds of information.

93. Wells, oral-history interview.

94. See, for example, letter, Denis Warne (of the Mount Stromlo and Siding Spring Observatories in Australia) to Donald C. Wells, in DCWP.

95. The process of getting other scientists to adopt FITS resembles, of course, the enlistment process described in Michel Callon and John Law, “On Interests and Their Transformation.”

96. “Resolution C1,” in Richard M. West, ed., *Proceedings of the Eighteenth General Assembly, Patras 1982*, 46–47.

97. McCray, *Giant Telescopes*, 265–99.

98. The latest major update for it was in July 2008. See, for example, <http://tdc-www.harvard.edu/astro.image.html> and [http://fits.gsfc.nasa.gov/fits\\_standard.html](http://fits.gsfc.nasa.gov/fits_standard.html) (both accessed 1 November 2012).

99. For examples of the journalistic coverage of FITS and the Vatican, see [http://www.vaticanlibrary.va/home.php?pag=newsletter\\_art\\_00149&BC=21](http://www.vaticanlibrary.va/home.php?pag=newsletter_art_00149&BC=21) and [http://www.vaticanlibrary.va/home.php?pag=in\\_evidenza\\_art\\_00115&ling=eng&BC=11](http://www.vaticanlibrary.va/home.php?pag=in_evidenza_art_00115&ling=eng&BC=11) (accessed 4 August 2012).

## Astronomers after the Flood

OCTOBER  
2014  
VOL. 55

No single event, instrument, or individual catalyzed the digitization of astronomy. The transition unfolded at institutions and observatories around the world and in concert with the overall maturation of the computer and electronics industries. Yet, for astronomers in the 1980s, changes in the tools used to collect data at the telescopes and to reduce, analyze, and share them appeared to happen swiftly. This was noted as early as 1978 when the National Academy of Sciences assembled a blue-ribbon committee, chaired by Harvard astronomer George Field, to prepare a new decadal survey for astronomy.<sup>100</sup> Members, many with long careers that overlapped the photographic and digital-data eras, perceived that the interaction between astronomers and digital tools had already changed markedly since the last such committee had concluded its work just six years earlier.

Unlike previous surveys, the Field committee included a panel especially devoted to “Data Processing and Computational Facilities.” Princeton astronomer Edward Groth, who had contributed to the development of FITS, chaired this. Two of the topics that his panel addressed—observational data processing and data archiving—had not even been issues significant enough to warrant examination just a few years prior.<sup>101</sup> In contrast, astronomers in the United States and abroad were already applying metaphors like *flood* and *deluge* to describe the new data regime their field was entering.

When interviewing observational astronomers active during the 1970s, one sometimes encounters anecdotal evidence about colleagues who used to have file cabinets stuffed with stacks of photographic plates that remained unanalyzed and unpublished. Perhaps apocryphal, such tales remain instructive, in that they critique contemporary research practices. While almost impossible to verify, the commonality of such stories points to underlying beliefs and expectations in the larger astronomy community about the ownership of data. For instance, Richard Ellis, a rising star among British observational astronomers in the late 1970s, used Boksenberg’s IPCS as often as he could, returning from observing runs at the Anglo-Australian Telescope with his data captured on magnetic tapes. As far as ownership went, Ellis saw it as “my data. Especially with the big telescopes. I went there. I came home with my data tapes.”<sup>102</sup> Such recollections are typical among astronomers active at the time.

100. These reports set national research and facility priorities for the next decade, and this was the third such survey. The first, chaired by Lick Observatory director Albert E. Whitford, concluded in 1964; the second, led by Caltech astronomer Jesse Greenstein, was completed in 1973.

101. Astronomy Survey Committee, *Astronomy and Astrophysics for the 1980s*, 302–3.

102. Richard S. Ellis, oral-history interview with the author, 28 November 2011. Other interviews with astronomers from this period confirm the sentiment.

The expectation or obligation to share data was also related to where one collected it. A researcher at a private institution or observatory like Palomar circa 1980 might feel no especial compulsion to circulate data beyond immediate colleagues or collaborators. However, the expectation to share had greater purchase if one did research at a public observatory or used one of NASA's space-based telescopes. Years before the Hubble Space Telescope was launched, scientists agreed that digital data collected via researchers' peer-reviewed proposals would be available only to the original investigator for just one year. After that, the data would "be made available to the community at large as well as the general public." The development of policies and practices for archiving astronomical data raises a host of issues, too far-ranging to be discussed here, about open access, data ownership, and data sharing. The situation in ground-based astronomy is especially peculiar, given that a substantial amount of research is *still* carried out in the United States at privately owned and operated facilities.<sup>103</sup>

New technologies—whether they produced digital data or were community-accepted formats for sharing this data—did not themselves change the moral economy of astronomy. However, astronomers' development of them produced a new space in which different ideas, practices, and behaviors about data and their ownership could emerge. The recording of astronomical phenomena as digital data, their storage in a format that could be easily shared and circulated, and the building of tools for processing, managing, and preserving this data helped reshape long-accepted research practices. These processes were fundamentally tied to the astronomy community's changing beliefs, expectations, and values about how resources for research—scientific data in this case—could and should be shared among its members. And although they do not speak of "moral economies" per se, astronomers promoting database-driven science claimed that so-called virtual observatories would lead to a "democratization of science." Riffing on journalist Thomas Friedman's bestselling 2005 book *The World Is Flat*, a few scientists argued that publicly accessible astronomical databases had the potential to increase access to data resources and "make the sky flat."<sup>104</sup>

Looking across astronomers' three overlapping data eras—photographic, electronic, and digital—we can make a few broader observations about data friction and moral economies. In the traditional photographic era data friction was high, as it was difficult (and expensive) to trade, share, move, and reproduce raw data. Yet the moral economy was relatively simple: "raw" data generally belonged to the individual or institution collecting them. What commonly circulated were processed data and findings included in publications. In the transitional and adjoining electronic era,

103. Riccardo Giacconi, "Science Operations with Space Telescope (NASA CP-2244)," 11.

104. S. George Djorgovski, "Data-Intensive Astronomy."

OCTOBER  
2014  
VOL. 55

data friction was somewhat reduced. But collecting data on punched computer cards or converting a photograph into digital format did not substantially reduce data friction, and what circulated was still mostly processed data. Once astronomers entered the born-digital era, standards like FITS substantially reduced data friction and made it easier to move and share raw information. But at this point, the moral economy became harder for a period as astronomers developed and accepted new practices and behaviors. In short, when data friction was high the moral economy was relatively simple. The reduction of data friction contributed to a more complex moral economy as issues of sharing, ownership, and access became more challenging.<sup>105</sup>

The transformation of astronomers' view of the sky from analog to digital also helped to catalyze significant changes in scientific practice. Although this conversion largely happened outside the time period that this article addresses, these processes started in the 1970s. Today's astronomers, like many scientists, query, search, and mine massive databases and routinely speak of *data pipelines*.<sup>106</sup> This term serves partly as a metaphor and partly as a reflection of the underlying physical reality as data flows from, say, an orbiting space telescope to a digital repository. Some contemporary researchers even call astronomy a branch of information science—namely, *astro-informatics*.<sup>107</sup> Bruno Strasser has described how collecting information about protein and gene sequences merged with experimental practices in the late twentieth century to create a “hybrid culture” in the life sciences.<sup>108</sup> Similar patterns occurred in contemporary astronomy as researchers started to merge the observational data they collected with that placed in digital archives by colleagues.

Besides spreading the expertise required to do astronomy over a wider array of fields, such as solid-state physics, software design, and electrical engineering, digitization challenged astronomers' sense of professional identity.<sup>109</sup> As late as the 1970s observational astronomers “made their rep-

105. My thanks to David Brock for valuable suggestions on this point.

106. An investigation of the online SAO/NASA Astrophysics Data System (ADS) indicates that the term *data pipeline* appears to have entered into common usage in the early 1990s.

107. See, for example, <http://www.astro.caltech.edu/ai12/> (accessed 18 October 2012). Another view is that of Thomas J. Loredo et al., “The Astronomical Information Sciences: A Keystone for 21st-Century Astronomy,” Position Paper no. 34, 2009, “Astro-2010: The Astronomy and Astrophysics Decadal Survey: State of the Profession Position Papers,” available at [http://sites.nationalacademies.org/BPA/BPA\\_049492](http://sites.nationalacademies.org/BPA/BPA_049492) (accessed 10 October 2012). See also Timothy Lenoir, “Shaping Biomedicine as an Information Science”; and David Baltimore, “How Biology Became an Information Science.”

108. Strasser, “The Experimenter’s Museum.”

109. Peter Galison, “Bubbles, Sparks, and the Postwar Laboratory”; David Mindell, *Digital Apollo*, chaps. 2–4; and November, *Biomedical Computing* describe similar transformations in other scientific areas, as well as in cinematography. See the 2012 documentary film *Side by Side*, directed by Christopher Kenneally.

utations based on how they performed at the telescope.”<sup>110</sup> But by the mid-1990s, being an astronomer no longer meant “that you go to the telescope and push the buttons yourself”; instead, after the changes described in this article had become standard practice, “it means that you deal with the data.”<sup>111</sup> Just as Dennison’s 1971 schematic decentered the telescope in favor of a “future large computer,” the digital database packed with terabytes of astronomical information became a new site for knowledge production. In 1995 24 percent of refereed papers published using the Hubble Space Telescope were based on archived data, typically collected by other researchers and accessed via the World Wide Web; by 2011 this number had climbed to 44 percent.<sup>112</sup>

Finally, it is important not to overlook the special role that national observatories played in helping reduce data friction and reshape astronomy’s moral economy. Scientists working at government-supported observatories in the United States and the Netherlands developed FITS, while national or international space-based facilities enacted policies that challenged the norms of data ownership and pioneered publicly accessible data archives. After astronomers adopted FITS as the community data standard, optical and radio astronomers at several national observatories went on to develop software packages to do interactive digital data processing.<sup>113</sup> These tools, rightly seen as public goods, became available for all astronomers to use and helped open up another chapter in astronomy’s evolving moral economy.<sup>114</sup>

After 1965 the telescope gradually merged with the computer, the software program, and the database into a hybrid instrument. But computer chips and digital data alone did not remake astronomy; astronomers pursued these new tools to fulfill their desires for increased research efficiency and the ability to share data more easily. Like all technological choices the

110. Alan M. Dressler, oral-history interview with the author, 15 November 1999.

111. From “Discussion Session,” in Todd Boroson, John Davies, and Ian Robson, eds., *New Observing Modes for the Next Century*, 249.

112. This is based on statistics at <http://archive.stsci.edu/hst/bibliography/pubstat.html> (accessed 10 March 2013). I am using the Hubble Space Telescope as an example because, among major public observatories, it maintains the most accessible records of this sort, although similar patterns would be found at other observatories. Moreover, this pattern becomes even more striking if one considers the number of publications that combined both observer and archived data. In 2011 it was 18 percent, meaning that 62 percent of Hubble publications drew on archived data in some manner.

113. For example, in the 1980s astronomers at the U.S. Optical Astronomy Observatory built the Interactive Data Reduction and Analysis Facility (IRAF) while their radio counterparts developed the Astronomical Image Processing System (AIPS). Both took advantage of the FITS data format. Other European observatories developed similar software tools that were shared to varying degrees. In the United Kingdom, another project, STARLINK, aimed to create a linked computer network over which scientists could share not only data, but also software programs to process and analyze it.

114. This bears some resemblance to the processes and goals described in Christopher M. Kelty’s *Two Bits*.

OCTOBER  
2014  
VOL. 55

digital turn came with trade-offs, as older ways of doing science changed. In 1966 *Time* magazine called Caltech astronomer Maarten Schmidt the “man on the mountain [who] checks his instruments, loads a camera and settles down to his lonely vigil” for the night.<sup>115</sup> Jump ahead three decades and astronomers’ daily routine looks strikingly familiar to mine (and probably yours): they come to the office in the morning, turn on their computers, and get to work.

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OCTOBER  
2014  
VOL. 55

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OCTOBER  
2014  
VOL. 55

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OCTOBER  
2014  
VOL. 55

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