

THE INDUSTRIALIZATION OF AMERICAN ASTRONOMY, 1880–1940

Big science took root in America long before World War II, as machines, money, personnel and leadership made astronomy the biggest of the sciences in the age of little science.

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The rise of big science is often linked to World War II and the cold war. However, such an interpretation ignores the historical roots of big science in the six decades preceding the war. Here we discuss one aspect of the development of big science in America: the industrialization of astronomy and astronomy's emergence as the biggest of the sciences in an age of little science.

The history of the growth of big science rests on machines, money, personnel and leadership. After the Civil War, powerful new research technologies became available to astronomers in the form of large refracting telescopes and then reflecting telescopes, as well as expensive auxiliary equipment. The dramatic growth of the economy created individuals of great wealth, some of whom became generous patrons of astronomy. Further, the emerging American system of graduate education began producing trained astronomers. In this context the astronomical community expanded under the leadership of entrepreneurs, who adapted the business community's methods and models to the task of organizing large-scale scientific research.

Key to understanding the emergence of big science is not the size of a scientific community, but rather its structure. By the 1880s American astronomy was investing heavily in expensive new instrumentation and seeking institutional forms and organizational structures that would ensure the cost-effective production of scientific knowledge. Astronomy was the first of the sciences to employ factory methods, including mechanized data collection and the use of unskilled or semiskilled workers to facilitate the mass production of knowledge. Further, American astronomers demonstrated entrepreneurial skills earlier than many other scientists and, as a consequence, the astronomical community rapidly developed new institutions and practices that linked it to other sectors of American culture and society.

By the 1910s the production of astronomical knowledge had become centralized in a few large hierarchically organized institutions. This article traces

that process by looking at six astronomers whose activities exemplify the entrepreneurial spirit.

The first entrepreneurial astronomers

In the mid-1870s new directors were appointed at three leading astronomical facilities in the US. These three astronomers—Simon Newcomb, superintendent of the Nautical Almanac Office, Lewis Boss, director of the Dudley Observatory in Albany, New York, and Edward C. Pickering, director of the Harvard College Observatory—were pioneers who developed new ways of producing astronomical knowledge. Newcomb and Boss were experts in celestial mechanics and astrometry. Pickering, called to Harvard from a professorship of physics at the Massachusetts Institute of Technology, devoted his energies to the new field of astrophysics.

Newcomb, Boss and Pickering all engaged in large-scale research. Newcomb reorganized the Nautical Almanac Office, the US Navy bureau responsible for producing the *Nautical Almanac*, so that he could develop new mathematical models for the orbits of the moon and planets. Boss set out to revitalize the Dudley Observatory. The institution possessed the 8-inch Olcott meridian circle, but previous directors had not made effective use of this world-class instrument. Boss became part of an international project sponsored by the *Astronomische Gesellschaft*, the 19th-century equivalent of the International Astronomical Union. The project divided the sky into zones and measured with great accuracy the positions (right ascension and declination) of stars to the ninth magnitude. The resulting precision catalogs provided a solid foundation for the study of stellar proper motions and other problems in astrometry and stellar statistics. Pickering committed the Harvard College Observatory to research programs in stellar photometry and spectroscopy, and developed powerful new photographic methods for the wholesale acquisition of photometric and spectroscopic data.

These three astronomers had come of age when America was poised on the brink of industrialization. They had grown up in the

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ANDREW CARNEGIE (LEFT) AND GEORGE ELLERY HALE walking arm in arm in Pasadena, California, March 1910. Hale was part of the second generation of industrial astronomers. During Carnegie's visit to Mount Wilson and the observatory offices in Pasadena, he and Hale discussed problems connected with casting and figuring the 100-inch telescope mirror. They also discussed the need for increased support from the Carnegie Institution of Washington to mount and house the instrument and pay for new staff members who would be assigned to the telescope. Technical and funding problems delayed completion of the instrument until 1917.

1840s and 1850s, a period marked by the rise of such entrepreneurial heroes as Cyrus Hall McCormick, inventor of the reaper; sewing machine magnate Isaac M. Singer; Samuel F. B. Morse of telegraph fame; and Charles Goodyear, who developed vulcanized rubber products.

Along with Indian fighters, explorers and Civil War generals, these and other business leaders became national heroes. Their activities were widely reported in the daily press, magazines and popular biographies, and they became role models for the young. For those destined to become leading American astronomers, perhaps the most important activity of these business leaders was the creation of large-scale, hierarchical organizations devoted to the production and distribution of goods and services. Factories, carefully organized around machine production (that is, mass production) and a well-defined division of labor, became units in complex, large-scale and vertically structured organizations that extended downward to control raw materials and upward to oversee the distribution and sale of finished products. In time, a few industrial giants came to control key sectors of the economy. These were the great trusts and oligopolies of the late 19th and early 20th centuries. Observatories developed along similar lines and frequently came to dominate the production of various lines of astronomical knowledge.

Simon Newcomb arrived at the Naval Observatory, in Washington, DC, in the early 1860s to find a scientific institution dominated by independent craftsmen. There

was no coordinated plan of work. Each astronomer observed what and when he pleased. The result was low productivity and discordant data. Newcomb convinced the observatory superintendent to institute a division of labor among the scientific staff. The result was an improvement in the quantity and quality of astrometric data.

As director of the Nautical Almanac Office, starting in 1877, Newcomb was able to implement plans for the efficient production of scientific knowledge. By 1880 he had a large staff of assistants at work developing new mathematical models of the orbits of the moon and planets. As a by-product, Newcomb and his team reexamined the fundamental astronomical constants, including the speed of light, the solar parallax, precession, nutation, refraction and aberration.

Unlike organizations created by other astronomical entrepreneurs, Newcomb's labor force was an all-male affair. He also liked to employ human calculating machines, mathematical prodigies whose amazing powers were of inestimable value to large-scale research in celestial mechanics before the advent of machine computing. Further, Newcomb was able to secure the services of the eccentric recluse George Washington Hill, perhaps the greatest celestial mechanician America ever produced. In retirement, Newcomb continued doing research, with support from the Carnegie Institution of Washington.

Lewis Boss, when he became director of the Dudley Observatory, already had a reputation as a scientist with

an insatiable appetite for hard work, a reputation earned as an astronomer with the commission that had determined the US-Canadian boundary. At the Dudley, Boss and his staff observed, reduced and prepared for publication an *Astronomische Gesellschaft* zone catalog in the record time of just four years. Even though the young American had been the last to sign on, he was the first to present a manuscript for publication. The Dudley catalog rested on 20 000 observations of 8241 stars. In the 1880s Boss gained additional organizational and administrative experience as chief of one of the federally sponsored transit-of-Venus expeditions. In the 1890s he raised funds to move the Dudley Observatory to a more suitable location and modernized the Olcott transit instrument. Boss also developed a large-scale research program in astrometry involving the observation of 26 000 stars from celestial pole to pole. This resulted in a 1909-11 expedition to Argentina, where the Olcott transit was set up and Dudley staff observed southern stars.

In 1906 the Dudley Observatory became a department of the Carnegie Institution of Washington. Carnegie patronage ensured continuous support for the great catalog. So arduous and time consuming were the observations and their reduction and analysis that only in the 1930s were the massive volumes published. Boss also found time to edit the *Astronomical Journal* and participate in the affairs of the National Academy of Sciences. As an administrator, he oversaw a staff of astronomers and a large corps of female high school graduates, who labored with five-place log tables over printed forms as they applied various corrections, reduced the observations and prepared the results for publication. Boss made no significant contributions to instrumentation, however; the work of the Dudley Observatory was accomplished using

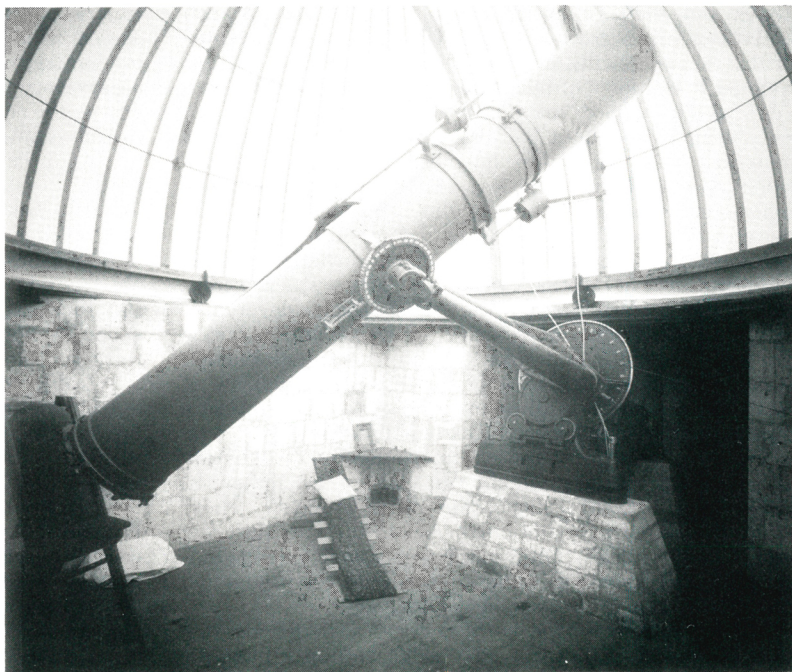
the traditional visual transit circle.

Edward Pickering was also a master organizer and administrator, cut from the same cloth as Boss and Newcomb, but the Harvard College Observatory director went further. Central to Pickering's success was the wholesale acquisition of data by photography. He developed new instruments that mechanized the collection of data and made large-scale research programs more efficient and cost effective. He also expanded the observatory staff with the addition of a large number of unskilled and semiskilled workers.

Pickering started from the conviction that astrophysics needed reliable data on the brightness of the stars and their spectra. Photometric and spectroscopic catalogs would permit astronomers to study the distribution of stars in space by magnitude as well as by spectral type. Spectroscopic data would lead, in time, to knowledge of stellar composition, temperature, mass, rotation and motion in the line of sight (radial velocity), and above all would throw light on the vexing problem of stellar evolution. And there was an unexpected by-product: the discovery of variable stars and novae in such numbers that scientists came to realize stellar variability was far more widespread than had been assumed.

Pickering's introduction of photographic methods not only changed the scale of astronomical research but resulted in standardization as well. In both visual and photographic photometry, it was necessary to make a careful study of errors and to devise a system for their correction. More important, the very concept of stellar magnitude had to be made uniform. Pickering and other Harvard astronomers played a central role in this process. Further, there were competing systems for the classification of stellar spectra. Here too, Pickering and other

THE BRUCE PHOTOGRAPHIC TELESCOPE constructed by Alvan Clark & Sons for the Boyden station of the Harvard College Observatory at Arequipa, Peru, in the early 1890s. The 24-inch instrument is an early example of a high-speed photographic refractor, with aperture $f/5.5$. Using plates that measured 14×17 inches, the telescope's camera recorded 5 square degrees of sky in a single exposure. The instrument is named for business and real estate heiress Catherine Wolfe Bruce, who provided \$50 000 for its construction.



HARVARD COLLEGE OBSERVATORY

OBJECTIVE-PRISM SPECTROGRAM of the region around Eta Carinae in the Southern Milky Way, 13 May 1893. This 140-minute exposure was made on a blue-sensitive emulsion with the 8-inch Bache photographic doublet at the Boyden station of the Harvard College Observatory in Arequipa, Peru. Note the absorption lines in many of the spectra.

Using a hand lens, skilled assistants in Cambridge examined the original glass negative and determined the spectral type of each star. The Bache instrument was constructed with a grant from the National Academy of Sciences.

astronomers at the Harvard College Observatory were key in developing a standard system of classification and securing its acceptance by the American and international astronomical communities.

Standardization is an important aspect of big science. In the American industrial economy, mass production meant that equivalent machines produced equivalent products. Gone were the days of individual craftsman for whom each product was unique. The mass production of astronomical data reflected practices of the industrial economy, with standardized methods resulting in standardized products.

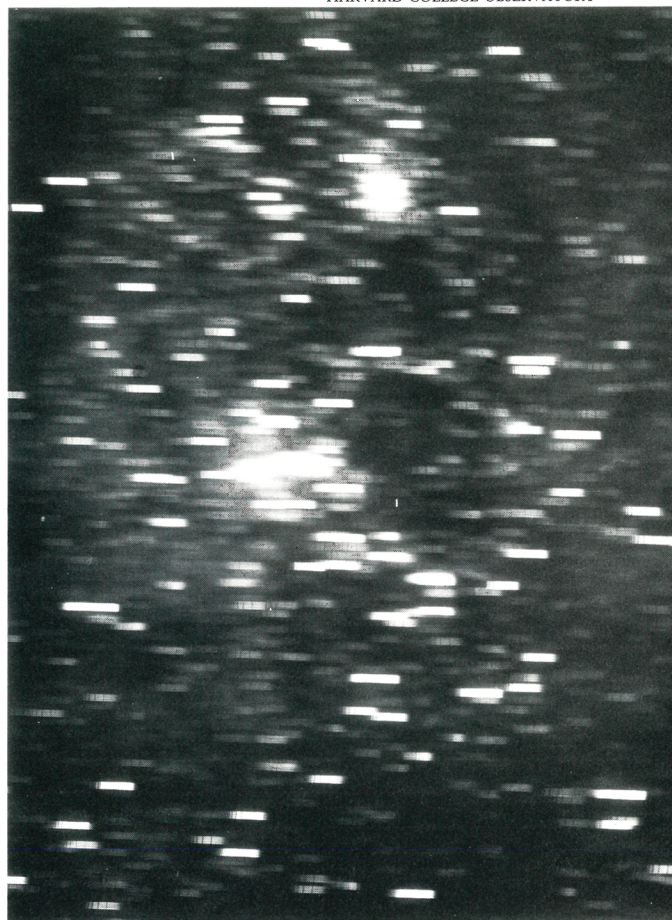
Pickering sought to mechanize the production of astronomical knowledge. From motors that rocked the trays in which photographic plates were developed to automated telescopes, the Harvard College Observatory led the way in mechanizing research. Pickering designed a variety of photographic instruments, including the powerful 24-inch Bruce photographic refractor for the Harvard station in Peru.

At the Harvard College Observatory, data were collected wholesale. Small-aperture, wide-angle lenses recorded sizable portions of the sky on a single plate, and large prisms in front of the objectives of photographic refractors captured the spectra of many stars at once. Oxford astronomer Herbert Hall Turner commended Pickering on his skill as an organizer and administrator of large-scale research, noting that in 1890 Harvard telescopes produced 9000 plates containing photometric or spectroscopic data. Another British astronomer, David Gill, characterized Pickering as a scientist who knew how to command patronage and use resources effectively.

Second-generation entrepreneurs

A second generation of entrepreneurial astronomers was represented by William Wallace Campbell, George Ellery Hale and Frank Schlesinger. They were the children of industrial America, whose economy was dominated by such captains of industry as steel baron Andrew Carnegie; John D. Rockefeller, who made his millions in oil; and Thomas Edison, whose fertile brain and well-equipped laboratory produced inventions that transformed urban America.

Campbell, Hale and Schlesinger continued the organizational and administrative structures and strategies developed earlier. It was, however, the younger generation that redefined the role of the observatory director so that it closely resembled that of a chief executive officer of the great corporations of industrial America. For Newcomb, Boss and Pickering, the observatory was the basic ecological unit of science. They were individualists whose primary loyalties were to their own institutions. Campbell, Hale and Schlesinger held that same view, but they also valued cooperation and often acted to enhance resources available to the whole astronomical community. Further, they were keenly aware of the need to link astronomy



with powerful new institutions in American society, especially graduate schools and philanthropic foundations.

William Campbell assumed the directorship of the Lick Observatory, in northern California, in 1901. His primary scientific goal was an authoritative catalog of stellar radial velocities, finally published in 1927. Like Boss and Pickering, and later Schlesinger, Campbell established an observing station south of the equator. Under his administration, the Lick Observatory also flourished as a center for double-star research and work on nebulae, especially their distributions and spectra. To ensure public support for the observatory, Campbell nurtured the Astronomical Society of the Pacific, established earlier as a support group for the observatory. Campbell was a master of university politics and skilled at dealing with the state legislature. In 1923 he became president of the University of California and in 1932 president of the National Academy of Sciences.

Although the Lick Observatory had been a branch of the university since being founded in 1888, its role in graduate education was not clearly defined until the beginning of the new century. The presence of graduate students at the observatory augmented the scientific work force. Campbell also secured funds to pay for assistants to analyze spectrograms, double-star observations and material collected on solar eclipse expeditions. It was Campbell who, in cooperation with the Berkeley astronomy department, made California the leading producer of astronomy PhDs in the decades leading up to World War

**AUTOMATED PATROL
CAMERAS** at the Harvard
College Observatory's Agassiz
station in Harvard,
Massachusetts, around 1935.

These photographic
instruments recorded a large
area of the sky, capturing
variable stars, novae and the
trails of asteroids. Edward C.
Pickering developed the earliest
form of these instruments
before the end of the 19th
century.



II. This achievement gave Campbell considerable power in the American astronomical community.

George Hale best represents the observatory director as a powerful and visionary CEO. While an undergraduate at MIT, he invented the spectroheliograph, an instrument that made possible solar observations in monochromatic light. With help from his father, a Chicago businessman, Hale established the Kenwood Astrophysical Observatory in Chicago. His primary interest was solar physics, and he developed new research strategies based on photography. The high point of Hale's scientific career was the discovery of the Zeeman effect in sunspot spectra and related work on the solar magnetic field.

In the early 1890s Hale moved to the just-opened University of Chicago and soon convinced millionaire Charles T. Yerkes to finance the observatory that was to carry his name. At the Yerkes Observatory, located in southern Wisconsin on the shores of Lake Geneva, Hale headed a complex organization that included scientists, graduate students, a corps of assistants, optical and mechanical engineers responsible for the construction and maintenance of instruments, and a service and clerical staff. Despite the success of the Yerkes Observatory and its 40-inch refractor, Hale longed for a better site, with skies free of dust and haze, where he could exploit the capabilities of new instruments.

Competition for patronage sometimes led to conflict between entrepreneurial astronomers. When Andrew Carnegie created the Carnegie Institution of Washington in 1902, Hale was quick to submit a request for funds to construct a 60-inch reflector and locate the instrument where it could be most effective. He was also at work designing a new generation of solar telescopes that would join the large reflector on Mount Wilson, in southern California. However, Carnegie funding for the Mount Wilson Observatory involved a struggle between Hale and Boss, with Campbell at the Lick Observatory as odd man out. In brief, Hale and Boss both sought major funding from Carnegie for very large projects. Hale desired funding for his 60-inch reflector and solar telescopes. Boss wanted to construct a southern observatory dedicated to astrometry, as well as to expand the

Dudley Observatory and guarantee its future. While Hale and Boss both encouraged Campbell to apply for Carnegie Institution funds to build a new telescope at Lick, Boss made it clear that he would support Campbell only if the younger astronomer joined in blocking Hale's Mount Wilson request. In the end, though, Hale was able to mobilize the political resources needed to achieve his goal. In 1904 the Carnegie Institution of Washington funded the Mount Wilson Observatory.

(Carnegie also provided long-term support for the Dudley Observatory, but did not finance a permanent observatory south of the equator. Campbell was the loser in the struggle. He had to develop the Lick station in Chile without Carnegie assistance.)

In addition to building institutions (the Kenwood, Yerkes and Mount Wilson observatories) and fathering the largest telescopes in the world (the 40-inch refractor at Yerkes and the 60- and 100-inch reflectors at Mount Wilson), Hale was influential in developing new resources for the American and international astronomical communities. In 1895 he inaugurated the *Astrophysical Journal*, and in 1899 he played a leading role in establishing the American Astronomical and Astrophysical Society. He also was the guiding spirit behind the creation in 1904 of the International Union for Cooperation in Solar Research, out of which grew the International Astronomical Union following World War I. Each of these institutions made it possible for astronomers to agree on standards for the mass production of scientific knowledge and, in the case of the American Astronomical and Astrophysical Society, define the astronomical profession in America. Beyond these activities, Hale was instrumental in modernizing the National Academy of Sciences and creating the National Research Council, which became the primary source of postdoctoral fellowships in the US. Failing health forced Hale to retire from Mount Wilson in 1923, but he poured his restless energy and unquenched ambition into the creation of the California Institute of Technology and the plan for a 200-inch reflecting telescope on Mount Palomar, in southern California.

Arguably, Hale was the most important American

Harvard College Observatory

	1880	1890	1900	1910	1920	1930
Astronomers	8	13	12	14	9	9
Semiskilled or unskilled staff members	8	24	33	30	21	25
Total	16	37	45	44	30	34

Dudley Observatory

	1880	1890	1900	1910	1920	1930	1940
Astronomers	2	4	4	11	12	14	5
Semiskilled or unskilled staff members	1	1	0	21	20	41	28
Total	3	5	4	32	32	55	33

STAFFS OF THE HARVARD AND DUDLEY OBSERVATORIES, showing two patterns of growth. Harvard grew first, followed by Dudley, which grew after 1906, when it became the Department of Meridian Astronomy of the Carnegie Institution of Washington. Dudley published its great five-volume astrometric catalog in 1936–37, after which the Carnegie Institution withdrew support. (Harvard data from S. I. Bailey, *The History and Work of the Harvard Observatory, 1839–1927*, McGraw-Hill, New York, 1931, p. 274. Dudley data from B. Boss, *History of the Dudley Observatory, 1852–1956*, Dudley Observatory, Albany, New York, 1968, appendices I–III.)

astronomer in the first half of the 20th century. His legacy remains visible today in the institutions he created and the standards he helped develop.

Frank Schlesinger, born in 1871 and the youngest of the six entrepreneurs, was the only one to earn a PhD (the doctorate became normative in American astronomy only after 1900). He was the father of photographic astrometry in the United States. He developed new instruments and methods that permitted the wholesale acquisition of astrometric data by photography. In comparison to the visual methods used by Boss at the Dudley, Schlesinger's innovations resulted in an increase of several orders of magnitude in the rates of data acquisition, reduction and analysis. These methods made astrometry more cost effective.

Schlesinger early displayed a remarkable combination of talents that made him one of the most creative scientific entrepreneurs. Part applied mathematician, part engineer, part organizer and administrator, he produced astrometric data of the highest order, efficiently and with a minimum investment of resources.

A skilled and imaginative mathematician, Schlesinger developed algorithms that reduced the time needed to analyze astrometric plates. His methods routinized photographic astrometry and standardized the product. At the Yale University Observatory, which he directed from 1920 to 1941, he analyzed data using punch-card readers, becoming the first American astronomer to employ this new method of mechanical computing.

As an engineer, Schlesinger made wide-ranging contributions to photographic astrometry. While director of the Allegheny Observatory, in Pittsburgh (in the years before he went to Yale), he designed and supervised construction of the 30-inch Thaw photographic refractor, used to measure stellar parallax, as well as wide-field astrometric cameras. Schlesinger also developed new technologies for the measurement of plates, including an efficient measuring engine that would accept 17 × 17-inch plates, covering a field of eleven square degrees with minimum distortion. At Yale, Schlesinger designed a 26-inch photographic refractor for a South African station. The instrument was used to measure the parallax of southern stars.

Schlesinger organized both the Allegheny and Yale observatories on the model of mechanized assembly line production that, by the beginning of the 20th century, had

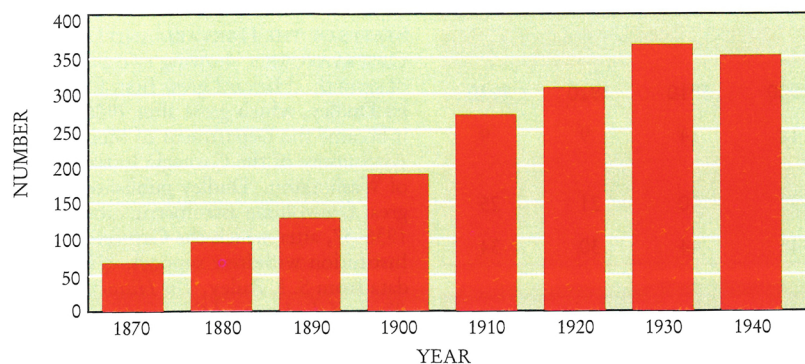
come to dominate several sectors of the American economy. Astronomers at Allegheny and later Yale had to meet production quotas. The Thaw refractor, for example, averaged 200 stellar parallax plates per month. The superintendent of the South African station was required to agree to minimum monthly production levels as part of his contract. Schlesinger assembled a corps of assistants (all women) who measured plates and analyzed astrometric data and then prepared the material for publication.

These six entrepreneurial astronomers represent two generations of aggressive leaders who pioneered in the industrialization of American astronomy. They modernized the plant and nurtured the reputation of American astronomy until both reached world-class status. Their organizational, administrative and fundraising skills were at least as important as their scientific talents. These individuals played leading roles in defining the course of American astronomy from the 1880s through the 1930s.

The industrialization of American astronomy vastly increased the quality and quantity of astronomical data and generally ensured that new information became available in a timely fashion. There was, however, a socioeconomic down side to this shift. The work was labor intensive, and by 1910 the factory observatory was organized around a large and stratified labor force. Female assistants, many with undergraduate science degrees from women's colleges such as Vassar and Mount Holyoke in

CARNEGIE PATRONAGE

The Carnegie Institution of Washington was central to the expansion of American astronomy. Without its patronage, astronomy could never have become the biggest of the sciences in the age of little science. During its first 21 months of operation, January 1902–October 1903, the institution received applications totalling \$2.2 million. Requests from scientists accounted for 65 percent of the total. Astronomers led the way with proposals for almost \$600 000, or 40 percent of funds requested by all the sciences. Behind astronomy came the biological (33 percent) and earth sciences (16 percent). Requests from the American physics community amounted to a mere \$37 000 (2.5 percent). All six entrepreneurial astronomers discussed in this article received Carnegie patronage.



SIZE OF THE AMERICAN ASTRONOMICAL COMMUNITY, 1870–1940.

the eastern US, found there was no upward mobility for them and only low salaries. Men with no more than a high school education entered the astronomy work force at a higher level and were able to move up. These conditions obtained until after World War II. Only in the 1950s did women in the American astronomical community begin to achieve upward mobility commensurate with their training and productivity.

The limits of growth

The progress of astronomy toward the status of big science was not linear. After World War I, American astronomy reached a plateau. With a few notable exceptions, neither private donors nor foundations were interested in funding the construction of large new instruments, and recruitment slowed. To be sure, the Rockefeller Foundation supported the 200-inch telescope on Mount Palomar, but the project was long delayed and the Hale reflector did not come on line until 1948. In the 1920s astronomers expected to benefit from the National Research Fund, yet another brainchild of Hale's. That organization was designed to secure corporate funding for American science, but fell victim to the Wall Street crash of 1929. During the 1930s, money, machines and personnel were not available on a scale sufficient to fuel the growth of astronomy. Entrepreneurial leadership also was in short supply.

But there were other factors that may help explain why American astronomy stalled out. The innovative large-scale research programs devised by the first- and second-generation entrepreneurs had, by the 1920s, become ends in themselves. Product lines seemed to be frozen and many astronomers appeared willing to continue along well-worn paths. At the Nautical Almanac Office, Newcomb's successors were concerned only with the routine production of ephemerides. The energies of the Dudley staff were absorbed by the great catalog as defined by Boss in the 1890s; no serious efforts were made to adopt the more-cost-effective methods of photographic astrometry developed by Schlesinger. The Harvard College Observatory continued Pickering's programs and added large-scale data collecting projects in galactic astronomy and variable stars. All too often these activities became so tightly focused that little attention was given to questions of interpretation. Even more than at the Harvard College Observatory, astronomers at Lick were caught up in routine data collection. Much the same can be said of Mount Wilson after Hale's retirement. To be sure, the work of Edwin P. Hubble on the expanding universe provides an important exception. Schlesinger continued to develop new methods and instrumentation for astrometric research, but Yale became a highly organized factory

for the production of multivolume data catalogs.

By the 1920s once-innovative research programs had been reduced to routine and custom. Younger leaders often seemed to be caretakers rather than risk takers. A few astronomers sought to apply the new physics (relativity and quantum mechanics) to astrophysical problems, but on balance the interwar years were not as productive as the period from the 1890s to about 1920. For example, physicists, not astronomers, solved the stellar energy problem in the 1930s, even though it was astronomers who alerted physicists to the topic. Only after World War II would American astronomers break the bonds of custom and move again in creative directions. Well grounded in the new physics, using new instruments (often developed for military purposes) and funded by new federal patrons (including both the military and the National Science Foundation), a new generation of innovative young leaders would usher in an epoch of renewed growth, and American astronomy would take its place with the other big sciences.

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