AN ABSTRACT OF THE THESIS OF

William A. Harburg for the degree of Master of Arts in Interdisciplinary Studies in the co-departments of General Science, History, and History presented on October 28, 1985 .

Title: The Development of Astronomy in the United States Prior to 1900

Redacted for Privacy

Abstract Approved: ______________________
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From the earliest English colonization to the present day, there has been interest in astronomy in this country. The purpose of this thesis is to show how the science of astronomy developed in America from the earliest observations by educated colonists using imported instruments and publishing in European journals, to the end of the nineteenth century, when advances in technology and education had brought American astronomers to a position of equality with European astronomers in technique, instrumentation, publications, and facilities.

The information presented in this paper is derived from a survey of the literature on the subject, including European and American books and articles, and unpublished dissertations and theses. Both modern European and American writers agree that the momentum gained by the American astronomers by the late nineteenth century was directly responsible for the unquestioned leadership in the science enjoyed here through the first half of the twentieth century.

The Development of
Astronomy in the United States Prior to 1900

by

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A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Arts in
Interdisciplinary Studies

Completed October 28, 1985

Commencement June 1986

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Redacted for Privacy

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Professor of History in charge of co-field

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Date thesis is presented October 28, 1985

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THE DEVELOPMENT OF ASTRONOMY IN THE UNITED STATES PRIOR TO 1900

I. INTRODUCTION

American astronomy owes its fundamental existence entirely to the European astronomy that preceded it. Although there was undoubtedly a great deal of astronomical activity throughout the native American population, it went unrecognized up to very recent times.[1] The English colonists, dependent on the mother country for culture and education, naturally looked to her for guidance in scientific matters.

In Europe, much of the foundation for present-day astronomy was laid long before the American Revolution. Aristotle and Ptolemy had been superseded by Copernicus and Kepler, Brahe and Galileo. The earliest New England colonists might have heard little of these men since the first English-language text in the American colonies that exposed the ideas of Copernicus was Vincent Wing's *Astronomia Instaurata* of 1656. It was immediately adopted at Harvard, where essays on the subject were published in 1659.[2] These were dangerous times for new ideas in Europe; Reformation and Counter-Reformation encouraged conformity. Scholars whose ideas appeared to contradict Scripture might be suspected of heresy. Those who too openly espoused the "New Astronomy" of Copernicus and Kepler could find themselves in serious trouble, as had Giordano Bruno and Galileo Galilei.

In the American colonies, things were different. When the Reverend John Davenport, Congregationalist founder of New Haven Colony and notable bigot, was shown a Harvard essay in 1659 that quoted Wing, Kepler, Gassendi, Galileo, and other authorities on the Copernican system, he merely responded that the student who wrote it should "enjoy his opinion, and I shall rest in what I have learned."[3] Davenport did not demand the student's expulsion from school nor that he should be kept from the pulpit for these possibly heretical ideas. He merely disagreed. In Europe, many promoters of the New Astronomy had to fight the Church and clergy; in America, the clergy propagated it. Even the famous witch hunters, Increase and Cotton Mather, had no trouble digesting it.[4]

This does not mean that the American colonists all knew of or approved the New Astronomy. It does show that ideas of this sort could find a congenial home on this continent. There was no mountain of official disapproval to be avoided or overcome, for if the ideas were not accepted everywhere in the New England colonies, they were at least never banned. True, there were probably few people interested in astronomy in the colonies. To most of those early colonists trying to make their way on a hostile continent, the concerns of philosophers must have seemed distant, indeed. There was also no optical industry to produce instruments in the new land; everything of this nature was imported. The first telescope of any size in America was probably one belonging to John Winthrop, Junior, Governor of Connecticut, purchased in London in 1662.[5]

In this paper, I intend to show that although there was little interest or activity in astronomy through the colonial period and into the early federal times of the United States, the congenial intellectual atmosphere of the early days, the amazing economic and industrial growth of the new nation, and the widespread interest in science in the nineteenth century combined to help the efforts of American astronomers and instrument makers to come to the forefront in astronomy and laid the groundwork for their virtual dominance of this science in the middle of the twentieth century.

This thesis is the result of study of both primary and secondary sources in the field, and was prompted by the absence of any broad history of American astronomy. Many of the primary sources are taken from modern reprints. The secondary sources are, for the most part, journal articles by specialists in the field of historical astronomy, physics, and physical science. Other secondary sources include books by well-known present-day astronomers, science historians, and science popularizers.

NOTES

[1]Von Del Chamberlin, "Prehistoric American Astronomy (c. 1054 A.D.)," *Astronomy*, July 1976, p. 10.

[2]Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: The Harvard University Press, 1971), p. 1.

[3]Samuel Eliot Morison, *Puritan Pronaos* (New York: New York University Press, 1936), pp. 239-240.

[4]Cotton Mather, "Of Comets" and "Of Gravity" from *The Christian Philosopher* (1721) in Gilman M. Ostrander, *The American Enlightenment: A Source Book in American Intellectual History* (University City, Mo.: Marston Press, 1970), p. 6.

[5]John W. Streeter, "John Winthrop, Junior, and the Fifth Satellite of Jupiter," *Isis* 39 (1948):159.

II. ASTRONOMICAL ACTIVITY IN COLONIAL AND EARLY FEDERAL AMERICA

The Schools

Astronomical activity developed very slowly in colonial America. As in most young nations, there was neither a great deal of time nor a surplus of money to expend on pure science. Colleges had begun to appear in New England during the seventeenth century, but their emphasis was on religious studies; there were no observatories and little in the way of instruction in astronomy. What interest Americans had in astronomy until about 1800 had to be satisfied by the latest developments of that science in Europe.

Many of the early immigrants to New England were educated men who desired good educations for their offspring.[1] Harvard College, founded in 1636 (a mere sixteen years after the arrival of the Mayflower) was the first colonial school to which they could be sent. The early colonists were deeply religious Puritans, so it is little wonder that the college was established as a religious studies institution, particularly since Puritans, as non-conformists, were barred from Oxford and Cambridge.[2] Originally a three-year course of study, the Harvard curriculum of 1643 offered arithmetic, geometry, and astronomy for senior students.[3]

In 1652, the college became a four-year institution, and offered "junior and senior sophisters" special texts for study and "disputations once a week on philosophical and astronomical questions."[4] There was little in the way of instrumentation for the earliest students of astronomy; Harvard's first telescope, a 42-inch focal-length refractor, was a gift in 1671 from Governor John Winthrop, Jr.[5]

In 1731, Harvard advanced in science education when a wealthy English merchant, Thomas Hollis, endowed the school with a fund to establish a professorship in mathematics. He set certain criteria for the instructor, including the stipulation, "He should teach the doctrine of the sphere, the use of the [astronomical] globes, the motions of the heavenly bodies according to the different hypotheses of Ptolemy, Brahe, and Copernicus."[6]

Hollis did not limit his largess to the founding of the mathematics chair. He also sent the college a great deal of equipment. Little of an early inventory of this equipment is concerned with astronomy, but covers all that Hollis apparently thought necessary for the teaching of science. The headings of the inventory are "Mechanicks," "Opticks," "Hydrostaticks," and "Pneumaticks". The only device that might possibly be useful to the teaching of astronomy in this inventory is "a small telescope with a concave eye-glass" whose value was reckoned at one shilling, sixpence. In a letter to the school in 1732, Hollis, besides listing more equipment sent on the ship bearing his letter, states that he hopes "Professor [Isaac] Greenwood will make good use of each, for the promoting of useful knowledge and to the advancement of natural and revealed religion." Among the scientific instruments in this shipment was "A new invented engine or macheen called an orrery, showing the daily and annual motion of the sun, earth, and moon."[7]

Harvard had not totally lacked for mathematics instruction previous to Hollis's donation, for in 1713, retired professor Thomas Brattle, a mathematician and amateur astronomer, had left 200 pounds sterling for "the maintenance of some master of arts . . . one best skilled in mathematics."[8] Other contributions increased the inventory of astronomy apparatus so that in his inventory of 1738, Greenwood lists "a 24 feet telescope" and an "eight feet telescope," as well as surveying instruments and "an Astronomical quadrant of more than two feet radius."[9]

Other schools were not far behind Harvard in their establishment of mathematics and science chairs, but their records are not so complete. It is known that William and Mary (founded 1693) had a chair of mathematics in 1724, which was filled by Master Hugh Jones. Unfortunately, William and Mary was occupied by both British and French troops during the Am+rican Revolutionary War, and little record remains of the earliest science teaching there.[10]

Yale, founded in 1701, has left good records of the instructors and texts in use there in the eighteenth century. Astronomy was taught as a part of the philosophy curriculum; the texts used until 1722 were Abraham Pierson's college notes on John Magirus's *Physiologicae Peripateticae Libri Sex* (Cambridge, 1642) and the "Notes of Physicks" in *The Logician's Schoolmaster* of 1660 by Alexander Richardson. The work by Magirus has been described as "an Aristotelian text presenting little but a compilation of medieval lore."[11] Between 1716 and 1722, instructors Samuel Johnson and Daniel Brown introduced the Copernican system into their astronomy teaching.[12]

As bases for the presentation of the "New Astronomy," their texts were Whiston's *Astronomical Lectures, read in the Public Schools at Cambridge* (London, 1715), and William Derham's *Astro-Theology: Or a Demonstration of the Being and Attributes of God, from a Survey of the Heavens* (London, 1715).[13] In this, Yale was considerably behind Harvard, where the Copernican system was being taught at least as early as 1659. The textbook at Harvard was Vincent Wing's *Astronomia Instaurata* (London, 1659) which brought to American readers the discoveries of Copernicus, Galileo, and Kepler.[14]

Perhaps the most important work in use in the American colleges in the late seventeenth and early eighteenth centuries was *Institutio Astronomica* (1653) by Pierre Gassendi. The *Astronomica* was ostensibly an impartial exposition of the Ptolemaic, Tychonian, and Copernican systems, but leaned heavily toward the last. At Yale, the *Astronomica* was required reading for seniors in 1720. A Cartesian text used at Yale was Jacob Rohault's *Phisica* (Paris, 1671), amplified and adorned by Yale instructor Samuel Clark, who added footnotes "correcting" and "refuting" Descartes.[15]

Astronomy in colonial America and the early federal United States was not a separate study but was taught as part of a classical curriculum to exercise the mathematical skills of the young theological scholars. It was not preparation for a career as either an astronomer or as a teacher of astronomy. The rewards for such study were strictly personal. Since there were few philosophical societies in America before the nineteenth century, th+re could be little local recognition of any work done in science. Any recognition that did result was from England at first, then from France and Germany in the nineteenth century.

There was, of course, a use for mathematics and astronomy in the science of land survey, and as early as 1730, New Englander Joseph Thompson donated a complete set of survey instruments to Yale College.[16] Many of the famous men of the colonial and early federal eras were skilled surveyors, including George Washington and Thomas Jefferson. The importance of land survey increased as the continent was opened up for settlement. Since accurate orientation on the earth depends on astronomical observation, it was necessary for these surveyors to have some knowledge of astronomy. Sea navigators used astronomy similarly to reckon their position, but the eighteenth century was nearly ended before improved instruments and techniques made such navigation accurate.

The Astronomers

The lack of recognition at home did not prevent a few astronomers from taking part in international scientific projects. John Winthrop, Junior, a charter member of the Royal Society, believed he had found a fifth moon of Jupiter in 1664.[17] He was cautious about his discovery and delayed announcing it officially to the British scientific community, but the discovery appears in several letters to his friends.[18]

Winthrop presented his telescope to Harvard College in 1671, where it was used by mathematician Thomas Brattle (1658-1713) of Boston to observe the comet of 1680. Brattle fixed the comet's position relative to catalogued stars on each of his observations, then sent his work to the Royal Observatory, where it was received by John Flamsteed.[19] Flamsteed passed the observations along to Isaac Newton who used them, along with other observations collected from Europe and America, in the preparation of his famous *Philosophia Naturalis Principia Mathematica*. Newton praised the accuracy of Brattle's observations as well as those of another American, Robert Storer of Maryland. Newton, together with Halley, calculated the comet's orbit and found that its period was 575 years. They believed it to be a return of the same comet that "inflamed the firmament" in 44 b.c., shortly after the death of Julius Caesar.[20]

At Harvard College another American astronomer came to the attention of the European scientific community early in the eighteenth century. This was the Reverend Thomas Robie (1689-1729), who observed the aurora borealis in December, 1719, and published an eight-page pamphlet about it. He interpreted the occurrence not as a divine display (a likely explanation in the New England of his time), but as a scientifically explicable phenomenon, and expressed abhorrence for any prognostications based on it. "I don't mean that the sight was not surprising to me," he explained, "but I only mean that no man should fright himself by supposing that dreadful things will follow."[21]

During his tenure as a professor of mathematics and astronomy at Harvard, Robie further distinguished himself by publishing a dozen almanacs, an article on his observation of a solar eclipse of 1723, and other articles on the aurora borealis, Jupiter's satellites, lunar eclipses, and the zodiacal light. By 1725 he had become a Fellow of the Royal Society and "the most famous New Englander in science in his day."[22]

Another New Englander whose work was recognized outside America was John Winthrop IV (1714-1779), the second Hollis Professor of Mathematics and Natural Philosophy at Harvard. He published papers on sunspots in 1739, on the transit of Venus and a lunar eclipse in 1740, on Halley's Comet in 1759, and in 1767, a paper on the density of comets.[23] Winthrop's interest in astronomy led him to convince the Province of Massachusetts to sponsor an expedition in 1761 to St. Johns, Newfoundland, to observe a transit of Venus. He was invited by the Corporation of Harvard to take along some of the school's equipment, including "a pendulum clock, a Hadley's octant with 'Nonius' divisions, a refracting telescope with cross-hairs, and a curious reflecting telescope, adjusted with spirit levels at right angles to each other."[24]

Winthrop's Newfoundland trip was the result of Edmund Halley's earlier interest in a transit of Venus across the face of the sun as a tool with which to measure the parallax of the sun and thereby find its precise distance from the earth.[25] Winthrop was able to mark five positions on the solar disk, thus getting a fairly precise line of the apparent path of Venus. His greatest difficulty was in determining his exact longitude on the earth, but he finally did so by careful observation of the occultation of a star by the moon.[26]

The observational results of Winthrop's trip were read into the *Philosophical Transactions of the Royal Society* on November 15, 1764. Winthrop described his preparations and equipment and gave his table of observations.[27] He had had a great deal of difficulty in determining exactly when the disk of Venus actually touched the limb of the sun because of an illusion of a link or "ligament" that seemed to form between the two bodies.[28] Winthrop partially overcame this problem by reporting both the time when the ligament formed and the time when he thought the two edges of the bodies were actually in contact.[29] The *Philosophical Transactions* go on to report that Mr. Winthrop's figures were used by Mr. James Short, FRS, along with observational figures collected by other astronomers at the Cape of Good Hope to calculate a parallax of 8.25 seconds of arc.[30] This gives a distance to the sun of 100 million miles which, considering the equipment used, is quite accurate.

In January of 1769, the newly-formed American Philosophical

Society of Philadelphia appointed a committee of thirteen of its members to observe another transit of Venus. These observers were divided into three groups to observe from different Pennsylvania locations: Philadelphia, Norriton (a village seventeen miles north of Philadelphia), and from the lighthouse at Cape Henlopen on Delaware Bay. In charge of the Norriton group was a surveyor and clock maker, David Rittenhouse (1732-1796), a leading member of the Society.[31]

Rittenhouse built a log cabin observatory near his home in Norriton for the purpose of the transit project. The cabin is considered to have been the first observatory in the American colonies, although it was a temporary structure and no trace of it remains. According to one witness, it had only one window, so it is hard to see how several observers could use it at one time.[32] The observatory was equipped with Rittenhouse's own telescope and "a reflecting telescope with a Dolland[33] micrometer" that had been purchased in London by Benjamin Franklin, another member of the Society. Money from the project came from both the Society and from the Pennsylvania Assembly, who saw to it that "instruments were supplied in sufficient number."[34]

Unfortunately, as the moment arived for which all the observers had been waiting, when the disk of Venus began to intrude on the edge of the sun's disk, Rittenhouse became so exited that he fainted! He quickly recovered his poise, but in the meantime his inexperienced assistants had failed to keep accurate track of the time. The time variation in their observations amounted to nearly one minute when they should have been accurate to one second.[35] As it turned out, none of the other American observers had made their observations perfectly which reduced the value of their contribution to the Royal Society's 1769 project.

A few years after Rittenhouse's fiasco with the Venus transit, John Winthrop's successor as Hollis Professor at Harvard, Doctor Samuel Williams, made an astronomical expedition under even more rigorous conditions than his predecessor. A total eclipse of the sun was expected to take place in 1780, but would not be observable in totality in Boston. The eclipse would be visible from what is now the state of Maine, but it was wartime, and Maine was in British hands. Williams convinced the American authorities that he should be allowed to make the observations, nevertheless. He was allowed to enter Maine and set up his equipment, but whether from miscalculation or from some restriction on the part of the British garrison, he was not in the path of totality. All was not lost, however, for he was the first to report an obervation of "Bailey's Beads," an optical illusion produced by the light shining between the lunar peaks This was fifty-six years before the effect was described by the English astronomer, Francis Bailey, for whom the effect is named.[36]

Williams described his observation: "The sun's limit became so small as to appear like a circular thread or rather like a fine horn. Both the ends lost their acuteness and seemed to break off in the form of small drops or stars, some of which were round, and others of an oblong figure."[37]

A change came in the work of American astronomers with the advent of the Revolutionary War. In colonial American colleges, the emphasis had been on classical philosophical considerations insofar as astronomy was concerned. American astronomers considered themselves a part of the international community of scholars. With independence, the practical side of such things as science became more important. The three main concerns of the struggling republic were agriculture, manufacturing, and commerce. Anything that did not appear to advance one of these received no support from government, business, or individuals. Basic research and philosophical concerns became secondary. "Promotion of Useful Knowledge" became the chief concern of the American Philosophical Society of Philadelphia (founded 1769) and the new Academy of Arts and Sciences of Boston (founded in 1785).[38] Three practical areas to which the astronomy of the late eighteenth and early nineteenth centuries could be applied were surveying, preparation of almanacs, and navigation. In these applications, two Americans stand out clearly: Benjamin Banneker and Nathaniel Bowditch.

Born in 1731, a self-educated tobacco farmer and son of a freed slave, Banneker was not introduced to astronomy until the advanced age of 58. His neighbor in Tidewater, Virginia, George Ellicott, lent him some works to read, including James Ferguson's *An Easy Introduction to Astronomy* (1769), *Mayer's Tables* (1770) by the Reverend Nevil Maskelyne, and Charles Leadbetter's *Compleat System of Astronomy*[39] (1770). The books were loaned in 1789; by 1790 Banneker had produced a complete almanac for 1791. The almanac included sun and moonrise tables, moon phases, eclipses, church feasts and fasts, tide tables, mathematical puzzles, medical advice, and news highlights of the previous year.

Banneker was unable to publish his first almanac, but it brought him to the attention of George Ellicott's cousin, Major Andrew Ellicott, who had been selected by Secretary of State, Thomas Jefferson, to survey the boundaries of the District of Columbia. Major Ellicott had been unable to find anyone to act as his "scientific assistant," that is, some one to look after the equipment, regulate the clock on a daily basis with solar fixes, and do necessary mathematic calculations associated with surveying. He wrote his cousin asking about Banneker, whose almanac he had seen, and upon receiving an enthusiastic reply, employed Banneker as his assistant.[40]

After satisfactorily executing his duties with the surveying team, Banneker resumed farming and almanac writing. He published his work annually in Baltimore and other cities from 1792 to 1797. Banneker's work helped bring the science of astronomy to the attention of the public, for his efforts were widely publicized by abolitionist groups and were noticed by Thomas Jefferson, who wrote Banneker a congratulatory letter concerning his almanacs.[41]

Nathaniel Bowditch (1773-1838), another self-educated American, turned his interest in astronomy to practical account better than any other American of his time. From a seafaring family, Bowditch had a talent for navigation, which is dependent on mathematics and astronomy. He went to sea early in 1795 as a company clerk and second officer of a small Salem merchant ship. While on the voyage, he used his self-taught knowledge of navigation. At this time, many ship captains had only a vague idea of their positions after several weeks at sea, so a man who understood celestial navigation was always welcome. Bowditch not only accurately navigated the ship, but developed an improved method for making lunar observations. In his journal entry for Christmas, 1795, he wrote: "Thursday thought of a method of making a lunar observation which to me is new & in some respects I think is preferable to any method hitherto published."[42] As it turned out, Bowditch's method was indeed new, and being simpler than earlier methods, it was quickly adopted by other navigators.[43]

The Practical Navigator (1772), an English work by John Hamilton Moore, was the best book on ship navigation in use at the turn of the century, but Bowditch found many errors in its tables during his voyages. A Newburyport printer, Edmund M. Blunt, wished to bring out an American edition of the book, and since Bowditch had become locally famous for his navigational skill, went to see him about any necessary revisions.[44] Bowditch not only supplied corrections for many of Moore's tables, but added new tables he felt were necessary. Included in Blunt's *New Practical Navigator* (1799) was Bowditch's improved method of working out lunar observations.[45]

Bowditch went on examining Moore's book after *The New Practical Navigator* was published. He had found thousands of errors in its tables, but continued to find more. He examined every figure in the book, keeping track of his corrections, and eventually found 8,000 errors, 2,000 of which he traced to Sir Nevil Maskelyne's Requisite Tables for the *Nautical Almanac.*[46]

When the new book was published in 1802 under the title *The New American Practical Navigator*, it was no longer Moore's, but now had

Bowditch's name on the cover. It was a very complete revision, with a great amount of useful information added to make it easier for mariners to use. The book led the reader through a brief chapter of instruction in geometry and trigonometry, displayed scales and showed how they were used, took him through logarithms, and the handling of navigation instruments in a very simplified way, so that the book became the chief method of instruction in the art. The English publishing firm of John and James Hardy and Steele of London recognized the improvement and bought the rights to the book from Blunt. They published it in England simultaneously with Blunt's American printing.[47]

In the final quarter of the eighteenth century, astronomy had been changing in Europe. This new astronomy can be described as "gravitational," that is, the application of mathematic techniques to celestial motions, based on the work of Kepler and Newton.[48] This development of the science was practically unknown in the United States until Bowditch undertook the translation of Pierre Simon Laplace's summary of mathematical astronomy, *Mécanique Céleste* of 1799. The translation was published in four volumes between 1824 and 1839; a fifth volume was not completed before Bowditch's death.[49]

The translation had at least one surprising consequence, for the mathematical methods of astronomy developed in Europe were nearly as unknown in England as they were in America. As British shipmasters had become dependent on Bowditch's *New American Practical Navigator*, so did English astronomers have Bowditch's translation of Laplace as their best guide.[50]

The efforts of these early American astronomers have one thing in common: they were all examples of "positional" or "observational" astronomy. In each case, the astronomer was trying to reckon the position and motion of heavenly bodies, usually for down-to-earth, practical concerns such as timekeeping or surveying. Considering the equipment they were using, their results were good. In the cases of the various Venus transit observations, the astronomers were often developing their techniques on the spot, during the observation, as did Winthrop when the "ligament" suddenly appeared between the sun and Venus.

The Am+rican astronomers proved that they could follow the lead of the Europeans. They could take part in international projects, work up calculations based on techniques developed in Europe, and make reasonably accurate measurements to European specifications. Poor as they were by later standards, Rittenhouse's figures were as good as most of those collected by the Royal Society for the transit of 1769, and Bowditch proved that at least one astronomical science could be improved on by an American.

What Americans had not yet done was advance the science of astronomy. The ability to grasp the fundamentals of the science and to make simple observations were what Americans had thus far displayed; all the theoretical groundwork had been laid in Europe. Astronomy in America, immediately after the Revolution, had to have a practical application. As a result, there were few theoretical astronomers in the country, and no observatories. Until 1830, there was no telescope in the country with an aperture of five inches, yet

William Herschel in England had built a reflector with a four-foot wide mirror in the eighteenth century!

As the nineteenth century progessed, however, the accumulated expertise of the mathematicians and astronomers working in comparatively primitive circumstances began to bear fruit. No advances had been or would be made for some years, but the groundwork had been laid. Observatories would now begin to spring up thoughout the country, and many of the new colleges would offer courses in at least basic astronomy.

NOTES

[1]Historian S.E. Morison calculated that as of 1646, 130 alumni of Oxford, Cambridge, and Dublin Universities had emigrated to the American colonies. See Samuel Eliot Morison, *The Oxford History of the American People* (New York: The Oxford University Press, 1965), p. 71.

[2]Ibid., p. 72.

[3]Samuel Eliot Morison, *Three Centuries of Harvard* (Cambridge: Harvard University Press, 1946), pp. 344-345.

[4]Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: The Harvard University Press, 1971), p. 1.

[5]John W. Streeter, "John Winthrop, Junior, and the Fifth Satellite of Jupiter," *Isis* 39 (1948):159.

[6]Colyer Meriwether, *Our Colonial Curriculum* (Washington D.C.: Capitol Publishing Co., 1907), p. 170.

[7]T. Hollis to G. Hutchinson (1732) quoted in Morison, *Three Centuries*, (n. 3) p. 346.

[8]Meriwether, *Curriculum* (n. 6) p. 169.

[9]Ibid., p. 204.

[10]Ibid., p. 172.

[11]Richard Warch, *School of the Prophets* (New Haven: Yale University Press, 1973), pp. 208-209.

[12]Ibid., p. 210.

[13]Ibid., p. 211

[14]Jones and Boyd, *Harvard* (n. 4) p. 2.

[15]Warch, *School* (n. 11) pp. 210-212.

[16]Meriwether, *Curriculum* (n. 6) p. 72.

[17]Winthrop was in error in his observation. The fifth moon of Jupiter, Amalthea, was not discovered until astronomer E.E. Barnard at Lick Observatory found it with the 36-inch refractor. It is 13th magnitude--far too faint to be seen in a small telescope.

[18]Streeter, "Winthrop" (n. 5) pp. 159-163.

[19] Samuel Eliot Morison, *Puritan Pronaos* (New York: New York University Press, 1936), pp. 245-246.

[20] Isaac Newton, *Mathematical Principals of Philosophy and System of the World* trans. Andrew Motte (1729) and Florian Cajori (1934) (Berkeley: University of California Press, 1934), pp. 516-517.

[21] Frederick K. Kilgour, "Thomas Robie, Colonial Scientist and Physician," *Isis* 30 (1939):479.

[22] Jones and Boyd, *Harvard* (n. 4) pp. 5-6.

[23] Harry Woolf, *The Transits of Venus* (Princeton, New Jersey: The Princeton University Press, 1959), p. 93.

[24] John A. Winthrop, *A Relation of a Voyage From Boston to Newfoundland For the Observation of a Transit of Venus, June 6, 1761* (Boston: Eddes and Gill, 1761), pp. 4-22.

[25] Halley's method was to determine the distance between the paths made by Venus across the face of the sun as seen by widely separated observers on earth. The observer notes the time taken by Venus to travel across the sun's disk. The difference in time gave a means of determining the parallaxes of Venus and the sun.

[26] Woolf, *Transits* (n. 23) p. 133.

[27] John A. Winthrop, "Observation of the Transit of Venus, June 6, 1761, at St. John's, Newfoundland: By John Winthrop, Professor of Mathematicks and Philosophy at Cambridge, New England," *Philosophical Transactions of the Royal Society* 54 (November 1764):279-283.

[28] Winthrop believed this was an illusion caused by the atmosphere of Venus or the sun, but it was probably due to the small, poor quality lenses of his instrument. See Simon Newcomb, *Popular Astronomy* 92 (1882):193

[29] Winthrop, "Observation", *Phil. Trans.* (n. 27) p. 281.

[30] Ibid., p. 283.

[31] John C. Greene, "Some Aspects of American Astronomy, 1750-1815," *Isis* 44 (1954):339-358

[32] Ibid., p. 354.

[33] John Dolland was the foremost English manufacturer of optical instruments in the eighteenth and early nineteenth centuries.

[34] Elias Loomis, "Astronomical Observatories in the United States,"

Harper's New Monthly Magazine, June, 1856, p. 26.

[35]Simon Newcomb, "On Hell's Alleged Falsification of His Observation of the Transit of Venus in 1769," *Monthly Notices of the Royal Astronomical Society* 13 (1883):371-372.

[36]Jones and Boyd, *Harvard* (n. 4) p. 23.

[37]Samuel Williams, "An Account of a Voyage to Penobscot for the Observation of the Eclipse of October 27, 1780," *Memoirs of the American Academy* 1 (1785):86-102.

[38]Michael Mendillo, David DeVorkin, and Richard Berendzen, "History of American Astronomy," *Astronomy*, July 1976, p. 41.

[39]Silvio A. Bedini, *Banneker* (New York: Scribner's, 1972), pp. 79-80.

[40]Ibid., p. 108.

[41]Ibid., pp. 112-114.

[42]Lunar observations were necessary to navigators of Bowditch's time because accurate timepeices were extremely expensive and were only carried on naval vessels and large merchant ships. With a chronometer set to Greenich time, a navigator need only compare it to local time from the sun's position to get his longitude.

[43]Arthur Berry, *A Short History of Astronomy From Earliest Times Through the Nineteenth Century* (New York: Dover Publishing Co., 1961), p. 63.

[44]Ibid., p. 81.

[45]Ibid., p. 94.

[46]Ibid., pp. 106-107.

[47]Ibid., pp. 111-115.

[48]Mendillo, DeVorkin, Berendzen, "American Astronomy" (n. 38) p. 34.

[49]Ibid., p. 42.

[50]Ibid., p. 43.

III. THE OBSERVATORIES

Pre-Civil War

George Biddle Airy reported in 1832 to the British Association for the Advancement of Science, "I am not aware that there is any public observatory in America, though there are some able observers."[1] The Astronomer Royal was absolutley correct; there were none. It can be argued that there was really no reason to build an observatory; there were no highly trained observers nor were there any instruments of a size that would require permanent housing. Neither were there facilities at which to train professional astronomers.

Regardless of the actual necessity for an observatory, there had been interest in building one on the model of the Greenwich observatory from the earliest years of the new republic. It was an article of national pride as well as "necessary to the progress of science" in the country to build a permanent structure and equip it with the latest and largest instruments available. Both Philadelphia, led by the American Philosophical Society, and Boston, guided by Harvard College, vied for the prestige of erecting the first public American observatory in the late eighteenth century, but their efforts came to nothing.[2]

One of the earliest attempts to procure a government observatory was that of Ferdinand Hassler (1770-1843), a Swiss surveyor. Hassler left his post as mathematics instructor at West Point in 1807 to organize a proper coast survey. In the same year, he presented a plan for a Department of Coastal Survey to Congressman Albert Gallatin of Vermont. Included in his proposal was a recommendation for a permanent observatory. Congress approved of his plan generally, but deleted the portion concerning the observatory. There were no instruments available in the country; Hassler went to Europe to purchase these. The War of 1812 further interfered with the plan, so no official survey was begun until 1816.[3]

Congress continued in its hostility to the idea of building a permanent observatory using public funds. On December 6, 1825, in his first annual message to Congress, President John Quincy Adams requested money for "the erection of an astronomical observatory, with provision for the support of the astronomer, to be in constant attendance of observation upon the phenomena of the heavens, and for periodical publication of his observations." Congress reacted in the by-then familiar manner and refused to fund any such project.[4]

Even earlier, in 1810, a congressman from Connecticut, Timothy Pitkin, Jr. asked that an observatory be built in Washington, D.C. to "establish a first meridian."[5]

The establishment of a national first meridian was considered of great importance early in the history of the new republic, not just for navigational and survey needs, but as a status symbol and an expression of independence. This was important to many people because the meridian at Greenwich, England had been in use for some years as a starting point for sea navigation, and England was considered an enemy country. Secretary of State James Monroe made it clear in 1812, in a rather belated answer to Pitkin's Congressional Memorial of 1810, that the administration was favorably disposed toward the establishment of a first meridian, and that "The establishment of a first meridian for themselves has become, by the usage of nations, an appendage, if not an attribute, of sovereignty." The Secretary went on, "It is sufficient to remark that every nation which has established a first meridian has also established an Observatory."[6]

The arguments in favor of a national observatory continued through the 1820's. As noted, such powerful advocates as President Adams could not move Congress to vote money for the purpose and in 1830, when Congress did vote to establish a Depot for the Bureau of Charts and Maps under the auspices of the Navy, it stipulated that the money appropriated to that end would go for a storage area for the equipment of the bureau, not for the construction of an observatory. In 1833, the director of the Depot, Lt. Charles Wilkes, built an observatory near the capitol, at his own expense, in which he mounted a transit instrument loaned by the Coast Survey.[7]

John Quincy Adams's interest in astronomy did not end when he left the office of president. He continued while a Representative from Massachusetts to sponsor bills for a national observatory. He became interested in the Smithson bequest, and was not only involved in planning the museum, but had visions of building an observatory.[8] Adams did the groundwork for the project, writing to Sir George Airy with a request for information in 1839. He wished to know the proper building size, the types of equipment, and the cost to erect an observatory comparable to those in Europe.[9] Nothing happened immediately, but Congress voted funds in 1842 for a National

Observatory in Washington, D.C. The facility began operating in 1844 as the Naval Observatory.[10]

While the government agencies wrangled over a national observatory, there were successful efforts being made by schools and private individuals toward the establishment of observatories. David Rittenhouse built a small brick observatory in Philadelphia for his own use which was noted by the French mathematician J.J. Lalande in the preface to the 1792 edition of his *Astronomie* as the only observatory known to him in America.[11] A makeshift observatory at Yale College was used for thirty years to house what was in 1830 the largest telescope in the United States, a five-inch diameter Dolland refractor with a ten-foot focal length. Unfortunately, the Athenaeum tower in which it was placed was decorative in nature and not built to house a telescope, so the instrument was mounted on casters and rolled from window to window to make observations. The windows were so low, the telescope was limited to observations of no more than thirty degrees above the horizon. Two Yale professors, Elias Loomis (1811-1889) and Denison Olmsted (1791-1859) were, nevertheless, able to use the instrument to observe the 1835 return of Halley's Comet.[12]

There is much doubt as to where the first permanent observatory was built in the United States. There is some evidence that there was one at William and Mary College before the Revolutionary War, but successive waves of British and French troops quartered there destroyed much of the College. No trace of the observatory remains, but a letter to the American Philosophical Society from David Rittenhouse mentions an observation made there by the president of the college, Dr. James Madison.[13]

One of the earliest American observatories was erected at Chapel Hill by the president of the University of North Carolina in 1830. President Joseph Caldwell (1773-1835) had received $6,000 from the trustees to buy books and other necessary items for the young school. Caldwell went to Europe and spent about half of the money on astronomical equipment, the rest on books. He installed the instruments in his own home from 1824 until the "observatory" was completed. The poorly-built building quickly began to leak and even before Caldwell's death in 1835, the instruments were moved to the attic of the chemical and metallurgical building, where they fell into disuse.[14]

The oldest American observatory still standing is that erected in 1836 by Professor Albert Hopkins (1807-1872) at Williams College, in Williamstown, Massachusetts. It is a small building, forty-eight by twenty feet with a thirteen-foot dome. The college did not actually have the funds necessary to build an observatory; much of the work of stone quarrying and erecting was done by Professor Hopkins and his students. Hopkins also donated about one fourth of the money necessary for the instruments.[15] The equipment for the observatory included a "Herschelian" reflector telescope of ten-foot focus. It had American-made setting circles that read to one minute of arc, considered only fair by 1836. The observatory also featured an English-made transit instrument and astronomical clock. The Herschelian reflector was replaced with an American-made seven-inch diameter refractor in 1852.[16]

In the years following the establishment of the observatory, Professor Hopkins made observations of the moon for longitude, Polaris for latitude, and several occultations of stars by the moon to locate the observatory on the earth with great precision, for the land surveys done up to that time were relatively crude. In 1849 he made observations in synchronization with the Philadelphia High School observatory that was built in 1838. They were linked by telegraph, so there was no chance of time differential. With these observations he was able to determine the longitude of both places within a fraction of a second of arc, thus providing a standard of reference for the survey of a large surrounding territory.[17]

With the completion of the Williams College site, observatory-building began in earnest all over the new nation. In Hudson, Ohio, Elias Loomis was called from his teaching post at Yale University to build, equip, and staff an observatory for Western Reserve College. He went to Europe in 1836 to purchase instruments, returning in 1837 with a four-inch diameter, sixty-six inch focal length equatorial refractor with setting circles accurate to one second of arc, an eighteen-inch transit circle with a three-inch objective, and "a clock with a mercury pendulum, which loses no time in winding." By 1838 Loomis had the observatory functioning but could not observe as much as he would have liked because he was the only astronomer and carried a full teaching schedule as well.[18] It seems strange that a state freshly cut from the wilderness as was Ohio in the 1830's would be one of the first to offer astronomy as a regular course and also have, for its time, the best facilities and, perhaps, the best astronomer in the nation.

Two other observatories, both for instructional purposes, were built before 1840. One, by the city of Philadelphia at the Philadelphia High School in 1838, the other, for training Army officers in surveying, at West Point, New York in 1839. The West Point facility was not actually staffed or fully equipped until 1843. The main instrument at the Military Academy was a six-inch diameter Lerebours equatorial refractor made in Paris.[19]

In the 1840's, observatories were being built at a very rapid rate in the United States, nearly a dozen in the decade. The country had definitely gone observatory-mad; every college had to have one or face a loss of status. In the Washington area, an observatory was built at Georgetown University, and commenced operations in 1844. Again an instructional observatory for the use of students, it was equipped with a five-inch equatorial mount refractor, a transit instrument, and a forty-five inch meridian circle. The instruments were all English-made, but by the middle of the century, they were considered inferior to those built in Germany and France.[20]

The most important of the early college observatories was certainly Harvard's. Like some of the others, the gestation process was long; the "Harvard Corporation" attempted from 1815 to get an observatory for the school. A board was selected to study the problem and make recommendations. One member was Nathaniel Bowditch, already famous for his books on navigation. The driving force behind the endeavor to build an observatory was the Perkins Professor of Mathematics and Astronomy, Benjamin Peirce. It was 1839 before

Harvard was able to have an observatory; a two-story house on campus was converted by adding a circular cupola to the roof. William Cranch Bond (1789-1859), a chronometer and watch maker, was enticed by Harvard's president, Josiah Quincy, to become their first astronomer, even though he had had no formal training. It is likely that Quincy chose Bond because of his connection with the college as an instrument maker, and because he had several fine astronomical instruments of his own. Bond served for the first seven years of his twenty-year tenure without pay.[21]

Through public subscription, the College raised the enormous sum of $25,000 for the purpose of building a proper observatory and equipping it with "an instrument fully equal to the best . . . and even superior, if that is possible."[22] The instrument selected was indeed superior to the rest; a fifteen-inch diameter refractor built by Merz and Mahler in Munich. It was slightly larger than one the Bavarian firm had recently completed for the Imperial Russian Observatory in Pulkova, and so was the largest refractor in the world. The installation of the new refractor in 1847 gave the Observatory great impetus toward leadership in the field of positional astronomy throughout the nineteenth century.[23]

Perhaps the most famous American observatory of its time was in Cincinnati. It was built with funds raised by Ormsby MacKnight Mitchel (1809-1862), who lectured to vast audiences on the subject of astronomy, and sold shares in the "Cincinnati Astronomical Society." He raised enough money to build a large observatory building (completed in 1843) and to furnish it with a Merz and Mahler twelve-inch refractor telescope. Until Harvard received its fifteen-inch, this was the largest telescope in America.[24] John Quincy Adams, by then 77 years old, but with his enthusiasm for observatories undiminished, journeyed all the way from Dedham, Massachusetts, to lay the cornerstone and deliver a long oration.[25]

The Cincinnati Observatory was a curiosity. It was owned by the Society's members; there was no school connection, except that Mitchel was a professor of mathematics and philosophy at Cincinnati College. The shareholders "bought in" to the society at twenty-five dollars per share, which entitled them to use the telescope practically on demand. Mitchel volunteered to serve as director of the observatory with no salary for the period of ten years. He actually did so for sixteen years until he was offered a paid position as director of the Dudley Observatory in Albany, New York.[26]

Most of the other observatories built in the 1840's were not distinguished by size, instrumentation, or by the work done there. These include Sharon Observatory in Darby, Pennsylvania, Tuscaloosa Observatory in Alabama, Friends Observatory in Philadelphia, Amherst College Observatory in Massachusetts, and Dartmouth College. One private observatory, that of Lewis Morris Rutherfurd (1816-1892) built in New York City in 1848, was equipped with a "remarkably good" six-inch refractor built by Henry Fitz of New York.[27]

The observatory building boom continued on through the 1850's; six more college facilities were either built or under construction by 1856, and several outstanding private observatories as well. The greatest problem facing the pre-Civil War observatories was financing.

Most were built on minimum budgets, often with no money set aside for maintenance, replacement of obsolete equipment, or even to pay the staff. Even large, well equipped operations like the Harvard and Cincinnati observatories could not have continued to operate without the selfless dedication of directors W.C. Bond and O.M. Mitchell, both of whom served for years without pay.

Some observatories were able to keep operating by selling time service. The Allegheny Observatory, built in 1860, contracted with the Pennsylvania Central Railroad to provide accurate time for $1000 per year. The Director of the observatory, Samuel Pierpont Langley, also sold the same service to the city of Pittsburg for $500. Harvard sold time service, not only to railroads and cities, but to jewelers and hotels as well. In 1875, Harvard's annual income from this source was $2400.[28]

So far, we have looked at the earliest American observatories, most of which were built and operated with a minimum of funds. Excepting the Naval Observatory and that of West Point, the facilities discussed were built by public subscription or money set aside by the colleges. For the most part, they were built for instructional purposes. Little research could be done because of the inferior size and quality of their instruments. The observatories were sited in convenient places or where free land was obtainable, while little consideration was given to air quality, subsequent construction, or to population growth in the surrounding area. There was little in the way of support funding for the early observatories--they were apparently expected to support themselves.

In the next section, I will describe the three most important observatories built between the Civil War and the end of the century. Two of these were built and supported with funds obtained directly from wealthy individuals or foundations; the third was built as a private observatory, but staffed by professional astronomers.

Post Civil War

Three of the most important observatories in the United States were built after the Civil War. These are the Lick Observatory of the University of California, the Lowell Observatory in Flagstaff, Arizona, and the Yerkes Observatory of the University of Chicago.

The Lick Observatory was the result of a San Francisco land speculator's desire to leave a permanent memorial to himself. James Lick's first impulse is said to have been to have a pyramid erected to his memory on Market Street in downtown San Francisco. He was urged, however, by George Davidson, of the California Academy of Sciences, and Joseph Henry, of the Smithsonian Institution, to build an observatory.[29]

As a result of this urging, Lick, in 1875, deeded $700,000 to a trust fund for land, buildings, and for a "powerful telescope, superior to, and more powerful than, any telescope yet made." The observatory was to be built on Mount Hamilton, near San Francisco, and the federal land at the mountain was deeded by the government to the University of California for the project.[30]

Lick had unconsciously chosen the best site for several hundred miles around. Tests conducted there by Chicago astronomer S.W. Burnham with a 6-inch Clark refractor over a period of two months in 1879 resulted in 41 "first-class" nights, 7 "medium" nights, and only 11 cloudy or foggy nights in which observations could not be made. The "seeing" was so excellent, Burnham discovered and catalogued 42 "new" double stars, and 5 "third companions" to stars formerly thought to be doubles.[31] Most of the stars Burnham examined were in the southern hemisphere, out of reach of his 18.5-inch refractor in Chicago, but he reported that "Mount Hamilton offers advantages superior to those found at any . . . permanent observatory."[32]

By the 1890's, it had become obvious that observatories could no longer be sited in or near large cities. Population growth, industrial smoke and fog, and the spread of electric lighting all combined to make the "seeing" very poor. From this time, observatory sites were thoroughly tested before the buildings went up.[33]

One of the first observatory sites selected on the basis of low population, good weather, and excellent "seeing," was the Lowell Observatory of Flagstaff, Arizona. Transparency and steadiness of the atmosphere was very important to its founder, Percival Lowell, because his main interest was to study the planet Mars.[34] To observe or photograph details on planetary disks, greater air stability is necessary than for stellar observations.[35]

In 1877, G.V. Schiaparelli, director of the Royal Observatory in Milan, announced that he had found dark streaks on the planet, which he called "canali," meaning "channels." When his work was translated into English, the word became "canals," which led to a great deal of misunderstanding and confusion. Schiaparelli did not mean to imply that artificial waterways existed on Mars, but several American astronomers, including Lowell, thought he did.[36]

To study Mars, Lowell, a wealthy Bostonian, built a fine facility for astronomical work in one of the best locations in the country. The site was selected by Harvard astronomer Andrew C. Douglass, who spent the months of March and April, 1894, in traveling and observing at several locations mapped out by Lowell. Flagstaff had not only the best "seeing," but the local residents offered to provide land and to build a road from the town to the site. The idea was not so much to find a site with a more or less clear atmosphere, but one where the air was "steady."[37] Little time was allowed Douglass to find a site, because the most favorable time for viewing Mars would occur in October, 1894, when it would be closest to the earth.

To get his observatory operating quickly, Lowell borrowed a 12-inch refractor from Harvard Observatory and an 18-inch refractor from manufacturer John Brashear. The Alvan Clark firm built a dual mount for the two instruments that were housed in a building that was prefabricated and shipped while Douglass was still testing for the best site. The road was completed on the third of May, by which time the local workmen had finished the foundation for the dome. The building was completed and telescopes installed by the time Lowell arrived on the 28th of May, surely a triumph of planning and foresight.[38]

Besides being a center for planetary study, the observatory's location made it an excellent place for photographic and spectroscopic work. The excellent "seeing" greatly assisted astronomer Clyde Tombaugh in his discovery of the planet Pluto,[39] and was a key factor in observatory director V.M. Slipher's spectroscopic work on the radial velocities of spiral nebulae.[40]

The last major astronomical facility built in the United States before the turn of the twentieth century was the Yerkes Observatory of the University of Chicago. The story of the Yerkes Observatory actually began in California in 1887 when the University of Southern California decided to build an observatory featuring the largest telescope in the world. The University of California had just received the 36-inch Alvan Clark telescope for the Lick Observatory, and sectional jealousy forbade the southern Californians from being outdone. They accordingly ordered a 40-inch refractor from the Clark firm, who in turn, ordered two blank glass disks from M. Mantois in Paris. By the time the disks were cast and delivered to Cambridgeport, the school could no longer afford an observatory, and the Alvan Clark firm found itself with $20,000 tied up in unsaleable glass.[41]

In 1892, the existence of the lens blanks came to the attention of George Ellery Hale (1868-1938), a young professor at the new University of Chicago. Hale discussed them with President Harper of the University, and they went together to talk to Chicago tramway baron, Charles T. Yerkes. Yerkes agreed to pay for the lenses, provided someone else paid for the mounting and buildings. As it turned out, he was unable to resist Hale's salesmanship, and eventually paid the entire cost for the establishment of the observatory, over $349,000![42]

The Warner and Swazey Company contracted to build the mounting, which was finished and exhibited at the Columbian Exposition in Chicago in the summer of 1893. Hale chose a site on the shores of

Lake Geneva, 80 miles north-west of Chicago, because he had had a bad experience with high altitude when testing a prospective site at Pike's Peak--a severe electrical storm drove him off the mountain.[43]

The objective glass was finished in October, 1895 and installed in its 20-ton tube on May 21, 1897. Two days later, observations began. The observations ceased suddenly a few days after they began, for the elevating floor surrounding the telescope mount crashed forty-five feet to the ground. No permanent damage was done, but the opening ceremonies had to be postponed for two weeks.[44]

The five-day opening ceremony included tours of the new observatory and speeches from public figures and scientists. In attendance were many of the best-known astronomers, including the new director, George Ellery Hale. Others were Simon Newcomb, James Keeler, Edward C. Pickering, A.A. Michelson, E.E. Barnard, S.W. Burnham, and a host of others representing all the major observatories in the United States and several in Europe.[45]

The Yerkes Observatory was the last and greatest of those built in the United States in the nineteenth century. It was also the last one built around a large refracting telescope, for in the new century, different priorities would rule. The advent of astrophysics and photography determined that larger apertures would be required, because both spectroscopes and photographic emulsions produce results proportional to the amount of light falling on them. This could only come from the enormous light-gathering power of reflecting telescopes, for technical reasons ruled out making refractors much larger than the Yerkes 40-inch.

Dozens of small observatories had been built between 1830 and 1900; many would succumb to fiscal problems or community indifference, but those that remained would continue to train astronomers who would staff the great research centers that then existed or would be built in the twentieth century.

NOTES

[1]Sir George Biddle Airy, "Report for the Annual Meeting," *British Association for the Advancement of Science* 1 (1831-1833):125-189.

[2]Nathan Reingold, "The Rise of Astronomy," *Science in Nineteenth Century America* (New York: Hilt and Wang, 1964), pp. 134-143.

[3]Florian Cajori, "A Century of American Geodesy," *Isis* 14 (1930):411-416.

[4]U.S. Congress, Senate, Message from the President, *On the Erection of an Astronomical Observatory* 19th Cong., 1st Sess., 1825, *Journal*, 6 December, 1825, p. 357.

[5]U.S. Congress, House, *Report of Representative Pitkin*, H.R. 277, 11th Cong., 2nd Sess., 1810, p. 53.

[6]U.S. Congress, House, *Secretary of State James Monroe's Reply to Congressman Pitkin's Request for a First Meridian* 12th Cong., 1st Sess., 1812, *Journal*, February, 1812, p. 194.

[7]U.S. Congress, Senate, *Report of Lieutenant James M. Gillis on the Depot of Charts*, S. Doc. 114, 28th Cong., 2nd Sess., 1845, p. 64.

[8]Robert L. Black, *The Cincinnati Telescope* (Cincinnati: The Historical and Philosophical Society of Ohio and the University of Cincinnati, 1944), p. 27.

[9]Sir George Biddle Airy, *Autobiography* (Cambridge: The Cambridge University Press, 1896), p. 39.

[10]U.S. Congress, *Gillis Report* (n. 7), p. 66.

[11]Joseph Jerome Le Francais de Lalande, *Astronomie* (Paris: Veuve Desaint, 1792. Reprinted in New York by Johnson Reprint Co., 1966), p. li.

[12]Elias Loomis, *The Recent Progress of Astronomy, Especially in the United States* (New York: Harper Bros., 1851. Reprinted by Arno Press Reprints, 1980), pp. 160-162.

[13]David Rittenhouse, "Observations at William and Mary College by Doctor James Madison," *Transactions of the American Philosophical Society* (Philadelphia: 1789), v.3, p. 150.

[14]Willis J. Milham, *Early American Observatories* (Williamstown, Mass.: Williams College Press, 1938), pp. 32-33.

[15]Ibid., p. 38.

[16]Truman Henry Safford, *A Discourse to Commemorate the Fiftieth Anniversary of the Dedication of the Hopkins Observatory at Williams College* (Williamstown, Mass.: Williams College Press, 1888), pp. 16-17.

[17]Elias Loomis, "Astronomical Observatories in the United States," *Harper's New Monthly Magazine,* June 1856, pp. 25-52.

[18]Elias Loomis, "On the Longitude of the Hudson (Ohio) Observatory." *The Astronomical Journal* 8 (1850):61-64.

[19]Loomis, *Recent Progress* (n. 12), pp. 69-70.

[20]Ibid., pp. 165-170.

[21]Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: Harvard University Press, 1971), pp. 40-45.

[22]Josiah Quincy, quoted in Jones and Boyd, *Harvard* (n. 21), p. 51.

[23]Ibid., pp. 52-68.

[24]Ibid., p. 38.

[25]John Quincy Adams, *An oration delivered before the Cincinnati Astronomical Society on the Occasion of Laying the Cornerstone of an Astronomical Observatory on the 10th of November, 1843* (Cincinnati: Shepard and Company, 1843).

[26]Black, *Cincinnati* (n. 8), pp. 31-42.

[27]Loomis, *Recent Progress* (n. 12), pp. 94-100.

[28]Jones and Boyd, *Harvard* (n. 21), pp. 159-161.

[29]Michael Mendillo, David DeVorkin, and Richard Berendzen, "History of American Astronomy," *Astronomy*, July 1976, p. 41.

[30]*Publications of the Lick Observatory* 1 (1887):9-12.

[31]Ibid., pp. 13-17.

[32]Ibid., p. 20.

[33]Norman J. Lockyer, "The Development of Astronomy in America," *Publication of the Astronomical Society of the Pacific* 12 (1900):113.

[34]Reginald Waterfield, *A Hundred Years of Astronomy* (New York: The Macmillan Company, 1938), pp. 50-51.

[35]The Earth's atmosphere contains many currents of air at different temperatures. At the boundaries of these currents, where they tend to mix, they produce refraction of the light from celestial objects. The constant motion of the currents is reflected in the image of any object being studied through a telescope, so planetary details are obscured. Some areas like the Rocky Mountains have very transparent air, but because of the violence of the air currents, the "seeing" is rarely good.

[36]Percival Lowell, *Mars and Its Canals* (New York: The Macmillan Com any, 1911), p. 193.

[37]William Graves Hoyt, *Lowell and Mars* (Tucson: The University of Arizona Press, 1970), pp. 31-34.

[38]Ibid., p. 35.

[39]Ibid., pp. 278-281.

[40]Ibid., p. 117.

[41]Jones and Boyd, *Harvard* (n. 21), p. 267.

[42]George Ellery Hale, *Signals From the Stars* (New York: Scribner's Sons, 1931), pp. 15-16.

[43]George Ellery Hale, *Ten Years Work of a Mountain Observatory* (Washington, D.C.: The Carnegie Institute, 1915), pp. 6-7.

[44]Henry C. King, *The History of the Telescope* (Cambridge: Sky Publishing Co., 1955), pp. 314-316.

[45]Walter S. Adams, "Some Reminiscences of the Yerkes Observatory 1898-1904," *Science* 106 (1947):197.

IV. THE TELESCOPE BUILDERS

Background and Early Constructors

Telescope building, as might be expected, paralleled the rise of the observatories. There was little call for instruments in America through the seventeenth and eighteenth centuries, and there were few optical firms who could have undertaken even a small telescope lens. As the observatories began to develop in the 1830's and 1840's, they usually looked to Europe for their optical needs. The finest instruments came from Germany, with lens systems and mountings developed by in the early nineteenth century by Joseph Fraunhofer (1787-1826). His remarkable instruments became the standard of the world when the German astronomer Friederich Wilhelm Bessel (1784-1846) used one in 1837 to measure the parallax and thus the distance of the star 61 Cygni, while at the same time proving the motion of the earth around the sun.[1]

Fraunhofer built refractor telescopes which focus light much like a magnifying glass, with an objective lens mounted in one end of a tube and an eyepiece in the other. Early versions of the refractor did not produce clear images of stars because they were subject to chromatic aberration.[2] This problem was partially overcome in the seventeenth century by constructing extremely long instruments--one was 210 feet from objective to eyepiece. They were hung from tall poles and were not enclosed in tubes, but were mounted on a board and left completely open from objective to eyepiece to save weight.[3]

In 1733, English optician John Dolland patented an improvement to the refractor. A concave lens of flint glass was mounted directly behind the crown glass objective. This cancelled most of the aberration and allowed the instruments to be made much shorter. The telescopes no longer had to be hung from tall poles, but could be housed permanently.[4]

Reflecting telescopes were also available, but were not completely satisfactory because their metal mirrors oxidized rapidly and required disassembly and polishing after only a few month's use. After the European discovery of silvering glass in 1856, the reflecting telescope became more popular.[5]

While metal mirrors could be made larger than lenses and so gather more light, the astronomers of the early part of the nineteenth century were mainly interested in the measurement of the positions and motions of the brighter heavenly bodies, and did not require great light-gathering power. Once the problem of chromatic aberration had been overcome, refractors were preferred over the metal-mirrored reflectors.[6] In 1847, when Harvard president Josiah Quincy specified "an instrument fully equal to the best"[7] for his new observatory, he was thinking of a refractor; moreover, of one constructed in Europe, for American technology had not yet caught up.

The greatest problem facing American telescope makers was not the technology or the techniques of lens grinding, but in finding optical grade glass. An optician, Amasa Holcomb, of Southwick, Massachusetts, first attempted grinding and polishing telescope lenses in 1826.

Discouraged by the difficulty of obtaining suitable glass in the United States, he turned his attention to reflectors. He succeeded remarkably well; by the 1850's, his telescopes were found in several observatories in the United States, and some had been exported to Europe. Holcomb provided his instruments in four sizes, from a ten-inch diameter mirror with a fourteen-foot focal length to a four-inch mirror having a focus of five feet.[8]

In the middle of the 1850's, Henry Fitz of New York City began manufacturing large refracting telescopes. He offered six models, from an eight-inch diameter, fourteen-foot focus model, down to one of three-inches aperture. One six-inch model was ordered by the government for an expedition to Chile. Tests against a similar lens made by Fraunhofer were performed; the lenses were found to be identical in optical resolving power.[9] The price list for these instruments has survived; we find that the eight-inch diameter model sold for $800.00, while the three-inch was a mere fifty dollars. Of course, this was the bare telescope; the mounting and accessories were extra. A five-inch diameter, seven-foot focal length Fitz instrument was installed at Erskine College at a total cost of $1050, including a "German type" mount, clockwork drive, and a micrometer eyepiece. At the time, this was considerably less than the cost of a European telescope of the same dimensions.[10] In 1830, Yale College paid $1200 for a Dollond five-inch telescope with no accessories whatever.[11]

As the nineteenth century progressed, there was more and more call for telescopes and other astronomical instruments in the United States. The new observatories being built created this demand, and several American firms began to supply it. The two most important of these were Alvan Clark and Sons and John Brashear.

Alvan Clark

The most successful American builder of telescopes in the nineteenth century was Alvan Clark (1804-1887). In 1843, Clark, a portrait painter, assisted his eldest son to construct a bell-metal telescope mirror. He found that it tarnished almost as fast as they worked but his interest in telescopes had been aroused, and he turned to grinding lenses.[12] Clark experimented with lens grinding and figuring[13] for several years, but could never get completely error-free results. He eventually was allowed to examine the fifteen-inch Fraunhofer at Harvard and found that even this masterpiece of the lens-grinder's art had some errors of figure. Heartened, Clark offered his lenses for sale, but they aroused little interest in the United States.[14]

In 1851, Clark corresponded with the Reverend W.R. Dawes (1799-1868), a well-known amateur astronomer in England, telling him of his success in separating double stars with a five-inch refractor he had recently built. Dawes was impressed enough to send Clark the locations of several "difficult" double stars against which to test his lens. The test was so successful that Dawes bought a Clark telescope, then later bought four others! With a Clark seven-inch, Dawes discovered two hitherto unknown double stars, 8 Sextans and 51 Cygni. Dawes told other English astronomers about his new instruments. English physicist William Huggins purchased one of Dawes's 8-inch Clark refractors and used it in making the first photograph of a spectrum in 1863. He again used it in 1864 to prove spectroscopically the gaseous nature of nebulae.[15]

Much the same problem with glass that confronted Holcomb and turned him to manufacturing reflector telescopes was found by Clark in his manufacture of lenses. In the middle 1840's Clark completed two 5-inch telescopes; one of East Cambridge, Massachusetts glass, the other of glass purchased from Guinand, the famous French glass maker. Although the instruments were otherwise identical, the one of American glass could separate double stars to within one second of arc, while the French glass model was able to separate a close pair of stars in Gamma Andromedae whose distance is only one-third of a second, making it a far superior instrument for use in positional astronomy. Clark vowed never again to use American glass, at least until a better quality could be found.[16]

Clark did not immediately give up on telescope mirrors. Through 1848, he built several with diameters up to 8 inches.[17] William Cranch Bond, director of the Harvard Observatory mentions one of these in a diary entry of April 24, 1846.

> Recd a note from Mr. Alvan Clark inviting George [Bond's son and successor as director] and myself to try his new Reflecting Telescope made by himself he says he has now done his utmost to perfect it. I have been there three times already when it was said to be in good order, but its performance was quite inferior--giving nothing but a round disc to a star. It is the same old story , I think; dozens of these small things have been made heretofore and the same story told about them--thus far there is no proof of his having accomplished any thing uncommon, and yet one is blamed and thought hardly of, for not extolling it as a wonderful affair.[18]

This was apparently the swan song for the Clark mirrors; no more were built by the firm until the twentieth century.

By 1860, with his reputation firmly established, Clark was ready to begin advancing the standards of telescope-making set by Fraunhofer and others. He purchased two blank disks nearly nineteen inches in diameter from England, and with an order in 1860 from F.A.P. Barnard, president of the University of Mississippi, proceded to grind and figure the largest lens made to that time.[19] The Civil War intervened; the lens could not be delivered when it was completed. In testing the new lens in 1862, Clark's son, Alvan G. Clark (1832-1897), became the first person ever to see the tiny companion of Sirius, whose existence had been predicted by Bessel in 1844, based on a "wobble" in Sirius's proper motion.[20]

Clark immediately wrote to George P. Bond, director of the Harvard Observatory, telling him about the lens and the remarkable discovery he had made on its first test. Bond came to Cambridgeport to see for himself. The lens was all Clark had claimed. Unfortunately, the Clark firm had over eleven thousand dollars tied up in the project, and Harvard was unable to buy it. Bond feared the new telescope would be bought by some observatory that could not properly use it, and he was proven correct. It was sold to the new Dearborn Observatory in 1863, where it had limited use. Eventually, it went to Northwestern University.[21]

After the Civil War, the firm of Alvan Clark and Son was preeminent in the field of American telescope building. The firm provided telescopes and lenses for most of the new observatories that were springing up all over the country (see Appendix III). In 1872 the U.S. Naval Observatory in Washington ordered a lens of unheard-of size, twenty-six inches! It was to be installed for $46,000, truly a princely sum at that time. The great refractor, delivered by Clark's in 1873, was used in 1877 by naval astronomer Asaph Hall to discover the two tiny moons of Mars.[22]

This set off a race among the telescope constructors in which sheer size was the determining criteria of excellence. In 1879, the Leander J. McCormick Observatory of the University of Virginia ordered a Clark instrument identical to that constructed for the Navy. In 1880, the London firm of Sir Howard Grubb ground a twenty-seven-inch objective for the Vienna Observatory, to which Clark's replied in 1883 with a thirty-inch glass for the Pulkova Observatory in Russia.[23]

In 1884, Messrs. Henry and Gautier in Paris ground an objective of over thirty-one inches for the Nice Observatory, and followed this with a lens nearly thirty-three inches in diameter for the Paris-Meudon Observatory. Clark's then produced the 36-inch telescope for the Lick observatory of the University of California, completed in 1886, and finally, the world's largest objective glass, the 40-inch refractor for the Yerkes Observatory at the University of Chicago.[24]

The story of this 40-inch telescope is a monument to George Ellery Hale's ability to extract large sums of money from wealthy people. Hale describes how he financed not only the great 40-inch telescope, but the entire dome, mounting, and accessories.

> Learning in August, 1892, that two disks of optical glass large enough for a 40-inch telescope were available through Alvan Clark, I informed President Harper of the University of Chicago, and we jointly presented the opportunity to Mr. Charles T. Yerkes. He said he had dreamed since boyhood of the possibility of surpassing all existing telescopes, and at once authorized us to telegraph Clark to come and sign a contract for the lens.[25]

The "Great Refractor Race" was by no means the only employment of the Alvan Clark and Sons optical firm in the years following the Civil War. Astronomical photography was beginning to make an impact on the science, but ordinary telescope lenses were poorly adapted for focussing images on film. They were ground to bring the yellow-green portion of the light to best focus, for this is the part the eye most readily accepts. The photographic emulsions of the time were most sensitive in the blue portion of the spectrum, making truly sharp images difficult to achieve. Astronomer Lewis Morris Rutherfurd (1816-1892) of New York City solved the problem for himself by grinding an auxiliary lens for his eleven-inch Clark refractor. When placed between the objective and the photographic plate, it corrected the color and gave sharper images.[26] Clark's made auxiliary photographic lenses for many telescopes, and also found that reversing the objective lens made it better adapted for photography. The telescope they built for the University of Denver in 1894 has a twenty-inch objective that is specially fitted to be reversed for either photographic or visual work.[27]

Other major telescopes made by Clark's, most of which are still in use, were a fifteen-inch refractor for Washburn Observatory in 1878, and a 24-inch refractor for the Lowell Observatory in Flagstaff, Arizona. Completed in 1894, the Lowell refractor was followed by the only large reflector ever made by Clark's, a 42-inch mirror. Lowell also was equipped with a thirteen-inch Clark photographic refractor, which was used by Clyde Tombaugh in 1930 for his discovery of Pluto.[28]

John Brashear

One other builder of major telescopes came on the scene a little later than the Clarks. This was John A. Brashear (1840-1920). Brashear started out as a gang foreman in a Pittsburg steel mill, but he had an interest in astronomy and so taught himself the art of lens-grinding. By 1875, he had a passable 5-inch objective lens for which he built a telescope. It served fairly well for entertaining Brashear's neighbors, but he wanted to improve his lens, so he took it to Samuel Pierpont Langley (1834-1906), then director of the Allegheny Observatory in Pittsburg. Langley was impressed with Brashear's work, but believed that a reflector telescope would be more within the skill of the beginner, and advised him to try to grind a large mirror. Brashear borrowed a book on mirror making from Langley and produced an excellent 12-inch mirror. By the time he was finished with it in 1877, he had devised a simpler, yet more accurate method of silvering glass, a method that was still in use as late as 1917. Astronomer and telescope constructor George Willis Ritchey (1864-1945) used Brashear's process to silver the mirror of the 100-inch Hooker telescope at Mount Wilson.[29]

In 1877, Brashear began working in his spare time at the Allegheny Observatory, building and repairing equipment. By 1880, he had enough confidence in his own work to advertise offering "silvered glass specula, diagonals and eyepieces" for sale. On Christmas eve of that year, he shipped the first orders, mirrors to three amateur astronomers, for a total of $118.00. His small shop had been swamped with orders from that single advertisement, but he kept his job at the mill because he could not work rapidly enough to make a living at optical work.[30]

In 1881, Professor Langley introduced him to William Thaw, a wealthy Pittsburg businessman, who offered to set Brashear up in the telescope manufacturing business. Thaw agreed not only to loan him the money for tooling and quarters, but to pick up the difference between the price Brashear's work would bring and the cost of producing it, if Brashear would send no work from his shop until it was as perfect as it could be made. It was not long until Brashear was so well-known that his shop became self-supporting. Brashear hired a machinist, George Klages, and also brought his son-in-law, John McDowell, into the firm to assist in filling the backlog of orders that had accumulated while the shop was being set up.[31]

No account of John Brashear is complete without a discussion of his relationship with Professor Henry Augustus Rowland (1848-1901), organizer and first chairman of the Department of Physics at Johns Hopkins University. Rowland, who was interested in wave-length analysis of the solar spectrum, had worked out a theory for concave gratings, optically curved metal plates with many parallel lines inscribed on them, that acted as a prism in dispersing light.[32] Rowland started with three samples of flat gratings that had been produced by Professor Rutherfurd in New York. The largest of these was 1.75 inches square and was ruled with 17,396 lines to the inch, apparently the best Rutherfurd could do without introducing sizeable errors in line spacing.[33]

Rowland, believing that he could improve on Rutherfurd's gratings, designed a machine in 1882 that could produce gratings up to 6.25 by 4.25 inches, and rule any required number of lines to the inch, the number being limited only by the wear of the cutting diamond.[34]

By 1883, Rowland was producing curved gratings which advantageously focussed the complete spectrum in a circle. The light had neither to pass through a prism and be partially absorbed, nor strike a mirror and be only partially reflected.[35] The excellence of the Rowland gratings immediately created a great demand for them. Rowland became heavily burdened, since the gratings had not only to be ruled, but the surfaces had to be accurate to 0.00002 of an inch, approximately one-fifth the wave length of visible light. After Brashear's had polished some prisms for him, Rowland sent some speculum metal plates to be corrected and polished. The finished plates were so nearly perfect that Rowland contracted with Brashear's to supply the plates, and to distribute them after they had been engraved.[36]

The Brashear firm continued to turn out objective glasses and telescope mirrors into the twentieth century. Brashear's made numerous thirty-inch and larger telescopes,[37] and capped them all with a seventy-two-inch reflecting telescope for the Dominion Observatory in Victoria, British Columbia, in 1913. At the time of its completion, it was the largest telescope in the world.[38]

It is evident that the art of building telescopes had progressed in America with excellent speed. In 1800, if one wished to buy any sort of telescope, it was necessary to turn to Europe, but by 1900, Europe was already turning to the United States for the finest instruments. Americans had still not learned the art of optical glassmaking, at least to the standard demanded for the great refractors, but this was offset by the lessened demand for refractors after the discovery of a method of silvering glass for telescope mirrors. The groundwork had been laid for the development of the big reflector telescopes that would appear in the twentieth century, built with the expertise and technology accumulated both in Europe and in the United States during the nineteenth century. The increased wealth of the country added not a little, and the amazing salesmanship of George Ellery Hale and others would make this wealth available to build telescopes far larger than anyone could have conceived fifty years earlier.

NOTES

[1] *The Cambridge Encyclopedia of Astronomy*, 1977 ed., s.v. "Major Trends in the History of Astronomy."

[2] Chromatic aberration is produced by differences in refraction of the various colors of light passing through a lens. The different colors come to focus in different planes. The effect produced in the eyepiece is an image with a colorful ring around it. Spherical aberration is due to the spherical form of the lens or mirror giving different foci for central and marginal rays.

[3] W.J.S. Lockyear, "The Growth of the Telescope," *Nature* 62 (1923):109-117.

[4] Fred Hoyle, *Astronomy* (London: Rathbone Books, Ltd., 1962), p. 60.

[5] Reginald Waterfield, *A Hundred Years of Astronomy* (New York: The Macmillan Company, 1938), pp. 66-67.

[6] Ibid., p. 77.

[7] Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: The Harvard University Press, 1971), p. 51.

[8] Elias Loomis, *Recent Progress of Astronomy, Especially in the United States* (New York: Harper Bros., 1851), p. 243.

[9] Ibid., p. 246.

[10] Ibid., p. 257.

[11] Jones and Boyd, *Harvard* (n. 7), p. 37.

[12] Ralph S. Bates, "Alvan Clark and Sons," *The Telescope*, July-August 1940, p. 62.

[13] "Figuring" is the process of grinding and polishing a lens or mirror to a precise, mathematically computed curve.

[14] Deborah Jean Warner, *Alvan Clark and Sons, Artists in Optics* (Washington, D.C.: Smithsonian Institution Press, 1968), p. 16.

[15] George E. Pendray, *Men, Mirrors, and Stars* (New York: Harper's, 1946), pp. 242-245.

[16] Loomis, *Recent Progress* (n. 8), pp. 245-252.

[17] Warner, *Clark and Sons* (n. 14), p. 15.

[18] *Harvard Library Bulletin* 15 (October 1867):372-373.

[19] Simon Newcomb, *Astronomy for Everybody* (Garden City, N.J.: Garden City Publishing Co., 19?2), pp. 58-59.

[20] Jones and Boyd, *Harvard* (n. 7), pp. 122-123.

[21] Ibid., pp. 123-125.

[22] Newcomb, *Astronomy for Everybody* (n. 19) p. 158.

[23] Bates, *Alvan Clark* (n. 12), p. 52.

[24] Waterfield, *A Hundred Years* (n. 5), p. 76.

[25] George Ellery Hale, *Signals from the Stars* (New York: Scribner's Sons, 1931), pp. 15-16.

[26] Pendray, *Men, Mirrors* (n. 15), p. 251.

[27] H.T. Kirby-Smith, *United States Observatories: Directory and Travel Guide* (New York: Van Nostrand Reinhold Co., 1976), p. 101.

[28] Pendray, *Men, Mirrors* (n. 15), pp. 249-250.

[29] John A. Brashear, *An Autobiography of a Man Who Loved the Stars* (New York: The American Society of Mechanical Engineers, 1924), pp. 35-53.

[30] Ibid., pp. 65-72.

[31] Ibid., pp. 69-74.

[32] Ibid., p. 74.

[33] John David Miller, "Henry A. Rowland and His Electromagnetic Researches" (Ph.D. dissertation, Oregon State University, 1970), p. 301.

[34] Ibid., pp. 302-304.

[35] Daniel J. Kevles, *The Physicists* (New York: Alfred A. Knopf, 1978), p. 27.

[36] Brashear, *Autobiography* (n. 29), pp. 75-76.

[37] See Appendix IV for a listing of Brashear's major instruments.

[38] Marian Card Donnelly, *A Short History of Observatories* (Eugene: University of Oregon Books, 1973), p. 133.

V. EDUCATION, JOURNALS, AND ORGANIZATIONS OF NINETEENTH CENTURY AMERICAN ASTRONOMERS

Education

As was seen in an earlier chapter, several American colleges were teaching basic astronomy early in the 19th century. They were teaching positional astronomy, that is, the measurement of the positions of the stars relative to coordinates that described their positions. Emphasis was placed on the motions of the planets and their satellites, the earth and its satellite, and of comets.[1] Positional astronomy provides the basis for the down-to-earth sciences of surveying, navigation, and the calculation of almanacs. Unfortunately, the results of the observations made in this country before the 1840's were not dependable because of the crudity of the early instruments and because the data recorded was uncertain in accuracy. The data reflected only the apparent position of any observed body at the time of observation. As early as the mid-eighteenth century, Astronomer Royal James Bradley (1693-1762) had realized that aberration, atmospheric refraction, nutation, and precession had all to be calculated for each observation to get truly accurate results, but he did not have the necessary mathematics.[2]

By 1818, European mathematicians had devised the necessary tools for the reduction of observational data. In that year, Friederich Wilhelm Bessel (1784-1846) republished Bradley's 1798 catalogue of 3000 stars. Bessel's edition was the first celestial catalogue in which the stellar positions were corrected for aberration, nutation, and precession.[3] American schools were not teaching this so-called "German Method" until well into the century.

Through the middle of the nineteenth century, only three American institutions were regularly turning out men who could legitimately claim to be astronomers. These schools were West Point, Yale, and Harvard. Naturally, the United States Military Academy was mostly interested in its graduates being able to locate themselves accurately in the wilderness for the purpose of map-making. In 1812, Jared Mansfield was appointed Professor of Experimental and Natural Philosophy. He got rid of the astronomy text then in use, William Enfield's *Institutes of Natural Philosophy*, published in 1750, and substituted Olinthus Gregory's 1815 *Treatise on Mechanics*. He expanded the course to include: "Physical causes of the planets, satellites, and comets, and the determination of their orbits;" and the theory and practice of correcting astronomical observations for the various sources of error, such as parallax, aberration, and nutation.[4]

Another change came in 1817 when Superintendent Sylvanus Thayer returned from a study trip to Europe. He transplanted a number of the ideas of the Ecole Polytechnic to West Point. His new curriculum for cadets emphasized mathematics, engineering, natural philosophy, and, of course, French. The philosophy courses contained a great deal of astronomy; six of the eight West Point graduates who would become professional astronomers during the nineteenth century were students during Thayer's administration. In 1833, Andrew Jackson became

President of the United States, and did not approve of the direction of the Academy. Thayer was forced to resign; the school then put more emphasis on purely military subjects, particularly engineering.[5]

In 1834, a new Professor of Philosophy and Astronomy, William Bartlett, began teaching at West Point. His philosophy was Jacksonian; he stuck to training engineers rather than astronomers. Bartlett published a four-volume work entitled *Elements of Natural Philosophy* in 1855. The fourth volume, *Spherical Astronomy*, was a compendium of earlier French and English works, but reflected none of the "German Method" that was beginning to have a strong influence on astronomy.[6]

At Yale University, Denison Olmsted (1791-1859) joined the faculty as a lecturer in Natural Philosophy and Mathematics in 1825. He introduced his own text, *An Introduction to Astronomy*, in 1844, which was revised and used as a basic text through the 1860's.[7] After 1836, when a reorganization of the Mathematics Department left Olmsted with only the Natural Philosophy courses to lecture, he spent more time writing textbooks. These were very popular and would eventually sell over 200,000 copies. A tutor under Olmsted, Elias Loomis, was an even more successful author. His writing brought him wealth. When he died, his bequest to Yale University for the building of an observatory amounted to over $300,000.[8]

In 1847, Olmsted was established in a separate Department of Philosophy and Arts, out of which grew the Graduate School and the Sheffield Science School.[9] All through his tenure, Olmsted pressed for an observatory to be built for teaching astronomy, but in 1859 when he died, there was still no better place for the school's astronomical equipment than the tower of the Athenaeum.[10] (See page 27.)

Olmsted has been described as neither a good astronomer nor a good mathematician, but he did have the knack of inspiring his students.[11] Besides Loomis, who graduated and became a Yale instructor in 1830 and Director of the Hudson, Ohio observatory in 1836, there was Hubert Anson Newton, Yale 1850. Newton tutored mathematics until 1855, then went to Paris to study "higher geometry" at the Sorbonne. He returned to take over Olmsted's professorship and to continue a study of meteor swarms that Olmsted had begun. Olmsted realized that meteor swarms returned on predictable schedules in the same manner as comets and he believed there was a connection between them. With the advantage of his European mathematical studies, Newton was able to calculate the orbital period of the November meteor showers which are in a long, comet-like orbit and are apparently cometary debris.[12]

Harvard University had, almost from its earliest days, a considerable reputation for teaching astronomy. From the inception of the Hollis professorship in 1727, there was always a resident professor, if not of astronomy, at least one who could teach the necessary mathematics for astronomy; and often, it was one of considerable professional standing. From Isaac Greenwood, the first Hollis professor, through John Winthrop (IV) who succeeded Greenwood in 1738 and remained at his post for forty years, on into the nineteenth century, Harvard set a high standard for its professors of mathematics and astronomy. Winthrop's lectures embraced subjects directly related to mathematics and physics. These included Newton's laws of motion, gravity, magnetism, fluids, optics, and of astronomy: the "Motions and Phaenomina [sic] of the Planets and Planetary System." Winthrop illustrated his lectures with an orrery, which served the same purpose as the later planetarium. He apparently set difficult problems for his students; a bibliography of the *Mathematical Theses of Junior and Senior Classes, 1782-1839* contains 406 titles, some of them with the kind of lunar and solar projections and related astronomical calculations that Winthrop expected his students to master.[13]

Of the 112 persons employed as astronomers in the United States between 1825 and 1875, twenty-one had been either Harvard associates or students. Considering that many of the remaining ninety-one were German or French-trained immigrants, it speaks well for the programs of instruction at Harvard. There were actually three ways one could get astronomical training at Harvard during the nineteenth century; through the College of Liberal Arts, the Lawrence Scientific School (between the years 1848 and 1855), and through the Observatory, as a graduate student.[14]

The Lawrence Scientific School was the creation of President Edward Everett and Professor Benjamin Peirce, both of whom wished to strengthen the scientific program at Harvard. From 1848 through 1855, the Observatory formed part of this school. The Observatory's course, "Practical Astronomy and the Use of Astronomical Instruments" was priced by the Director, William Cranch Bond, at $50.00 per term, but it offered neither lectures, classes, nor credit. Students were expected to "consult appropriate texts on their own."[15] Bond, like his successors, really did not want students. In a letter to President Sparks in 1853, he wrote that the Observatory lacked space, that it was unsafe to entrust the expensive instruments to novices, and that both day and night observations would suffer from teaching and demonstrations.[16]

Harvard continued to offer theoretical astronomy courses such as "Application of Spherical Trigonometry to Astronomy and Navigation" throughout the nineteenth century, but there were no formal laboratory courses. This situation changed when Robert W. Willson joined the University staff in 1891. He first offered "Practical Astronomy Intended Primarily for the Use of Students of Engineering." In 1894, he followed this with a course in descriptive astronomy. By 1897, his courses broke away from the Engineering Department and became a section under the Physics Department.[17] At the turn of the century, Willson converted an old zoology hall into an astronomical laboratory and classroom, where his astronomy and practical navigation courses became great favorites.[18]

Before the advent of Willson's laboratory, the astronomical students followed a path of instruction in the mathematics department under Benjamin Peirce who lectured on celestial mechanics and Joseph Lovering, who lectured on "Celestial Mechanics and the Undulatory Theory of Light.[19] After completing his undergraduate studies, the budding astronomer would either finish his studies in Europe, or try to catch on at an operating observatory as an assistant. Several Harvard graduates such as G.P. Bond, Truman Safford, E.C. Pickering, and G.E. Hale were able to become assistants at the Harvard Observatory and learn on-the-job.[20]

By the end of the century, there were many American universities teaching astronomy. Truman Safford (1836-1901), child genius and long-time astronomer at Harvard, wrote in 1889 that the United States had acquired a "school" of astronomers; that is, there were many observatories at which astronomy could be studied beyond the theoretical level. In an article in *The Siderial Messenger,* Safford wrote, "Any young man who . . . felt himself impelled to study astronomy, could find instructors, and . . . could usually get remunerative employment."[21] This was true in 1889, but earlier it was necessary for a budding astronomer to study in Europe, and particularly in Germany, if he intended to become employed in an observatory because the American colleges did not begin teaching the European methods of attaining great precision until the middle of the century.[22]

The change in the teaching of astronomy in the United States between 1844 and 1863 can easily be seen by a comparison between the textbook written and used by Denison Olmsted at Yale from 1844 into the 1860's, and a text written by Astronomer William Chauvenet (1820-1876) of Washington College in St. Louis, in 1863. In his introduction, Olmsted wrote that he is trying to "unite the various types of treatises on astronomy, between those that disregard demonstrative evidence and rely on popular illustration or have exhibited the science in naked mathematical formulae."[23] The book, which is very basic, is mainly definitions and illustrations. It has a minimum of mathematics, and does not even mention the spherical triangle or the mathematical reduction of observations.

Chauvenet, who did his graduate work in Germany, wrote:

> The methods of investigation . . . are in accordance with what might be called the modern school of astronomy, or more distinctly, th+ German school, at the head of which stands the unrivalled BESSEL. In this school, the investigations both of the general problems of Spherical Astronomy and of the theory of astronomical instruments are distinguished by the generality of their form and their mathematical rigor. When approximative methods are employed for convenience in practice, their degree of accuracy is carefully determined by means of exact formulae previously investigated; the latter being developed in converging series, and only such terms of these series being neglected as can be shown to be insensible in the cases to which the formulae are to be applied. And it is an essential condition of all the methods of computation from data furnished by observation, that the errors of the computation shall always be practically insensible in relation to the errors of observation; so that our results shall be purely the legitimate deductions from the observations, and free from all avoidable error.[24]

Chauvenet devotes the last hundred pages of his second volume to an exhaustive treatise on the method of "least squares," a way of determining one or more unknown quantities in a number of observations. He writes, "The most probable values [in reducing data collection] are those which make the sum of the squares of the residual errors a minimum." Chauvenet divides the types of errors in observations into two main types: consistant or regular, and irregular or accidental. The regular errors are further divided into theoretical errors such as refraction or aberration, instrumental (due to constructional errors in objectives or mountings), and to errors of the observer (Bessel's "personal equation"). The irregular errors he attributes to tremors or to anomalous changes in air density, or expansion or contraction of the instrument because of temperature changes.[25]

In contrast to Chauvenet's systematic method is Elias Loomis's more liberal approach. Loomis had read Bessel and Bruennow not so much to learn a new methodology, but to improve his teaching. In his introductory remarks to his *Introduction to Practical Astronomy*, Loomis writes that he aims his book at:

> 1. Amateur observers who have in their possession astronomical instruments which they wanted to employ to the best advantage.
> 2. Every person who has occasion to engage in astronomical calculation.
> 3. The entire corps of young men who are engaged in a course of liberal education.[26]

Loomis was writing for amateurs, engineers, and liberal arts students, while Chauvenet wrote for the young, would-be astronomer preparing for a career in the field.

One early proponent of the German method was Theodore Dwight Woolsey, President of Yale University from 1846 to 1871. Woolsey spent several years studying at Goettingen in the early 1840's, and returned filled with those ideals of exact scholarship that had pushed the German universities far ahead of ours. Goettingen was founded some 36 years after Yale, but had "surged ahead" in library, faculty, equipment, and "tone of scholarship."[27] Others who went to Germany to study, then came back to the United States to fill important chairs of astronomy were Chauvenet and H. A. Newton.

One of the most famous American graduates of Goettingen was Benjamin Apthorp Gould, who received a Ph.D. there in 1846. He was director of the Dudley Observatory from 1855 to 1859, then began publication of the *Astronomical Journal*, modeled after the German

Astronomische Nachrichten. Gould intended to "Germanize" American astronomy to the fullest extent; he even applied for the position of Superintendent of the *National Almanac*, with plans to make it similar to the *Berliner Jahrbuch*, but was not chosen for the job. Gould, believing that he had been rejected for political reasons, lashed out in a letter to German astronomical editor, H. C. Schumacher in 1849, "Our science is very full of charlatanism, so that the one with the loudest mouth is valued as the best head; also the truly distinguished minds . . . lack morale [sic] courage."[28] In a later letter to Friederich H. A. von Humboldt, Gould claimed that all his effort was to "serve to the utmost the science of my country."[29]

Although Gould was not entirely successful in a campaign to have all American students of astronomy trained in the German methods, it happened, nevertheless, by way of immigration. Between 1848 and 1854, several very well-known German astronomers came to the United States. C. H. F. Peter went to Hamilton College, Franz Francis Bruennow to the University of Michigan, Charles A. Schott to the Coast Survey, and the National Almanac job for which Gould contested was taken by Ernst Schubert. The impressive credentials of these men and their excellent performance probably had a more positive effect on the young astronomers than Gould's articles in the *Astronomical Journal*, and it became common for American astronomy students of the mid-century to finish their educations on the continent.[30]

It would appear, then, that German methodology reached the American astronomical scene through three paths: the publication of journals and textbooks, the migration of German-educated astronomers to the United States, and by the movement of young American students to the German universities in the 1840's and 1850's. Those who studied there brought back not only ideas and techniques, but they transplanted the research spirit and doctrine of fanatical precision prevalent there back to their home country. After the Civil War, the numerous observatories opening up throughout the country could be staffed by thorough professionals. Science historian Dieter Hermann has calculated that between 1790 and 1850, 65% of the internationally known astronomers were trained in Germany, while America contributed practically none. Between 1850 and 1910, however, German-trained astronomers amounted to 29% of the total, while America contributed 20%.[31]

Societies

Astronomers did not apparently feel the need for a separate national society in the early days of the republic, for none was organized until late in the nineteenth century. There were several local societies formed; the Cincinnati Astronomical Society in 1842 that built the Cincinnati Observatory, the Allegheny Astronomical Society of 1859 in Pittsburg that was responsible for bringing large telescopes to that city, and "The Cambridge Branch of the American Astronomical Society" that appeared at Harvard in 1854. The last group, formed in the hopes of becoming a truly national astronomical society, lasted only three years but was the forerunner of the Astronomical and Astrophysical Society that was established at Harvard at the end of the century.[32]

Lacking their own organization, many of the astronomers became members of the more general scientific societies. These ranged from Benjamin Franklin's "Junto" of Philadelphia, formed in 1727, to the American Association for the Advancement of Science (AAAS) and the National Institute for the Promotion of Science (NIPS). In the 1840's these two scientific societies were the only ones that could be considered national in character, rather than local. The NIPS, founded after the demise of the earlier Columbian Institute, was organized in 1840 by the famous amateur botanist, Joel Poinsett and others, and worked in a blaze of publicity, claiming support from "other scientific societies and of the scientific community in general."[33] Members included ex-President John Quincy Adams and a number of other high government officials, but few professional scientists of the day supported it. The largely amateur membership and the political tone of the Institute (several Congressmen and government employees were officers of the Society) apparently kept the serious scientists away. The NIPS sponsored the first national scientific conference held in the United States, which met in Washington in April, 1844. The opening speech was made by the President of the United States, John Tyler, but the conference was ignored by the scientific establishment. Soon after the conference, the Institute began to disintegrate, and although several attempts were made to revive it, it perished upon the expiration of its charter in 1862.[34]

The second national society founded in 1840 was in complete contrast to the Institute. The American Association of Geologists was founded by men from several state geological surveys. From their second meeting, they began to accept other professional scientists as members, and by 1844, they were acknowledged in the scientific community as the only national society designed for the promotion, rather than the diffusion, of science. The Association kept a very low profile and shunned publicity, but as the membership grew, this was no longer possible. By 1847, there were so many non-geologists in the society, the name was changed. The society then reincorporated as the American Association for the Advancement of Science.[35]

Among the members of the AAAS were astronomers William Chauvenet, Benjamin Gould, Daniel Kirkwood, and Simon Newcomb, all well-known in the field. Benjamin Gould was also a member of an unofficial club called the "Scientific Lazzaroni," a Harvard-centered group of intellectuals who were not totally satisfied with the AAAS. They believed there was too much amateur participation and control, particularly of publications.[36]

From 1851, the Lazzaroni worked to organize a more select society, one to include only the leaders in American science. In 1863, during the Civil War, Senator Henry Wilson of Massachusetts pushed a bill through Congress on the final day of the winter session that established the National Academy of Science (NAS). The Academy was organized on the French model with the members placed in different sections: mathematics, physics, astronomy, geography, and so on. Selection of the membership was in the hands of the organizers, that is, the Lazzaroni. The new officers moved rapidly. The law was signed on March 3, 1863. By March 5, letters were in the hands of the "chosen." Even Joseph Henry, Secretary of the Smithsonian Institute, knew nothing of the new Academy until he received his invitation.[37]

Strangely, three American astronomers of world-wide reputation were left out of the original membership. These were George P. Bond, Director of the Harvard Observatory; Elias Loomis, former astronomer at Yale and Director of the Dudley Observatory; and John W. Draper, chemist and amateur astronomer, who led the world in applying photography to astronomy. Unfortunately for the reputation of the NAS, there was a great deal of evidence that some of these omissions were due to personal differences between the officers of the Academy and those left out. In a letter from Dalles Bache, Chief of the Coastal Survey and leading member of the Lazzaroni, to John Fries

Frazer, professor of chemistry and physics at the University of Pennsylvania, Bache wrote that, "There are some men too mean to bring into our Academy thus slightly intimating that I so class Geo. P. Bond."[38]

Bond had another strike against him. Harvard mathematician Benjamin Peirce, one of the Lazzaroni, was pretty certain that he would be chosen Director of the Harvard Observatory on the death of George Bond's father and first Harvard Observatory director, William Cranch Bond. From the time of the announcement of George Bond's appointment, Peirce, who had been on good terms with the father and son, had nothing good to say about George, and often made derogatory comments about his work. Loomis was probably left out because he, like Bond, was American-educated and not a "mathematical" astronomer. Draper, as an amateur, was probably considered "a dabbler" and not qualified as a member. As a result of the high-handed tactics of the organizers, there was much internal dissension, both from those who felt the organization was insufficiently "democratic," and from those whose friends were excluded. These internal problems, along with competition from the AAAS, were probably responsible for the Academy's failure to seize a position of leadership in nineteenth century American science similar to that enjoyed by the British Association for the Advancement of Science in England.[39]

It was not until 1889 that astronomer and Director of the Lick Observatory, Edward S. Holden established the Astronomical Society of the Pacific. If not truly national in scope, it could boast membership of many of the active professional astronomers of the time.

Astronomers did not have a national organization until the formation of the Astronomical and Astrophysical Society of America at Harvard in September, 1899. The stated purpose of the Society was "The advancement of astronomy, astrophysics, and related branches of physics." Among those prominent in bringing about the new organization were George Ellery Hale and Simon Newcomb, who was chosen the first president.[40]

Publications

One of the ways the professional level of American science was raised was through journals that published the results of serious research. Unfortunately, the principal journals available in the United States up to the middle of the nineteenth century were forced, by economic considerations, to publish all sorts of quasi-scientific articles. James Dwight Dana, editor of the once-prestigious *American Journal of Science*, had to include articles in his journal that would appeal to "general, rather than scientific intelligence," because the journal depended on the subscriptions of non-scientists.[41]

For lack of their own journal, American astronomers published their articles in general science publications or in foreign journals up to 1846. The first articles in the first issue of the *Transactions of the American Philosophical Society* of 1771 were accounts of the transit of Venus in 1769,[42] and the Society continued to publish astronomy papers through the nineteenth century. The *American Journal for Science and Arts* published original papers from astronomers and theoreticians as early as 1823, but it was a mass-audience publication largely devoted to apocrypha, and not suitable for serious papers.

From its inception in 1848, the *Proceedings* of the American Association for the Advancement of Science welcomed articles by astronomers. Benjamin Peirce and William Chauvenet contributed mathematical astronomy articles, while others announced discoveries or described new techniques or equipment.[43]

Two American journals were published strictly for astronomy in the mid-nineteenth century; the *Siderial Messenger*, and Benjamin Gould's *Astronomical Journal*. The *Siderial Messenger* had two separate lives as a journal. The first was under Ormsby McKnight Mitchel, who started it as a way to raise money for his starving Cincinnati Observatory. It was published more or less regularly from 1846 to 1861, when Mitchel, who had become Director of the Dudley Observatory, left to join the Union Army. Mitchel printed articles from both American and European astronomers; he was so impressed with an article by Johann Maedler at the Dorpat Observatory in Russia, that he reprinted it in three successive issues! The article offered Maedler's theory that the fixed stars actually revolved around Alcyone in the Pleiades. The *Siderial Messenger* never had the professional stature of Gould's *Astronomical Journal*, for as a money-making proposition, it had to have a wide appeal.[44]

Gould was not as interested in having a financially successful journal as he was in raising the intellectual level and status of American astronomers. He published only articles that seemed to him professional in nature, and he leaned heavily toward "mathematical" astronomy. The *Journal*, which Gould had begun in 1849, also ceased publication during the Civil War years and was not revived until 1886.[45] There was no professional astronomical journal printed in the United States for over twenty years.

Earlier, in 1882, William W. Payne (1837-1911), Director of the Goodsell Observatory of Carleton College, began publishing his own *Siderial Messenger*, which provided an outlet for astronomical news and reports. In 1892, George E. Hale joined with Payne to add astrophysics to the columns of the *Messenger*. The marriage, under the name of *Astronomy and Astrophysics* lasted three years, then in 1895 split into two new journals, *Popular Astronomy* edited by Payne, and *The Astrophysical Journal: An International Review of Spectroscopy and Astronomical Physics*, edited by Hale with the assistance of James E. Keeler of the Allegheny Observatory. The first issue of the Journal in 1895 contained articles by A.A. Michelson on the "spectro-photography" of the sun, Henry A. Rowland and R.T. Tatnall on the arc spectra of boron and beryllium, and by Edward C. Pickering on detecting variable stars from their spectra. There were no articles on positional astronomy.[46]

By 1900, the education available to American astronomers was on a par with that offered in Europe. No longer need an aspiring student travel to France or Germany to learn the most advanced mathematics or observational techniques. Good instruction in all phases of astronomy was readily obtainable in colleges throughout the country, many of which had an observatory. (See Appendix II) This was a far cry from the situation at the beginning of the nineteenth century, when there was not one observatory in the nation, and only a few schools teaching rudimentary astronomy.

The increase in educational facilities for studying astronomy reflected the general increase in interest displayed by the public, and of the far-sighted planning of such great college administrators as Sylvanus Thayer of West Point, Theodore Dwight Woolsey, of Yale, and a number of Harvard presidents, from Josiah Quincy in the eighteenth century through Edward Everett and Charles Eliot in the nineteenth. Professors of the quality of Denison Olmsted and Benjamin Peirce were able to transmit their enthusiasm, and particularly in Peirce's case, their insistence on excellence.

By the end of the nineteenth century, American astronomers were well represented by professional journals. It was no longer necessary to publish in European journals or in general science magazines, although many have continued to do so up to the present. Throughout the second half of the century, the figure of Benjamin Gould rises higher and higher in stature as many of his ideas became incorporated in the thinking of the astronomical community. He set high standards for the articles he published, and he wanted the United States to assume a position of leadership in the field. This could only happen through higher standards being set by the schools, and by a strong swing toward the "mathematical" astronomy as it was being practiced on the continent by 1838. The professional organizations also tended to raise the general level of excellence, both by example and by holding high standards for admission into their societies.

NOTES

[1]Arthur Berry, *A Short History of Astronomy From Earliest Times Through the Nineteenth Century* (New York: Scribner's, 1972), p. 354.

[2]Fred Hoyle, *Astronomy* (London: Rathbone Books, Ltd., 1962), pp. 145-162.

[3]*The Cambridge Encyclopedia of Astronomy,* 1977 ed., s.v. "Major Trends in the History of Astronomy."

[4]S.E. Tillman, "The Academic History of the Military Academy, 1802-1902," *The Centennial of the United States Military Academy at West Point, New York* (Washington, D.C.: the Government Printing Office, 1904), pp. 263-264.

[5]Mark Rothenberg, "The Educational and Intellectual Background of American Astronomers" (Ph.D dissertation, Bryn Mawr College, 1975), pp. 10-25.

[6]Colonel Charles W. Larned, "The Genius of West Point," *The Centennial of the United States Military Academy at West Point, New York* (Washington, D.C.: The Government Printing Office, 1904), p. 484.

[7]Dennison Olmsted, *An Introduction to Astronomy* (New York: Collins and Brother, 1866), pp.iii-iv.

[8]Brooks Mather Kelley, *Yale, A History* (New Haven: Yale University Press, 1974), pp. 166-247.

[9]Ibid., p. 82.

[10]Ibid., pp. 205-206.

[11]Rothenberg, "Educational Background" (n. 5), p. 36.

[12]Hubert Anson Newton, "The Original Accounts of the Displays in Former Times of the November Star Showers Together With a Description of the Length of its Cycle, its Annual Period, and the Probable Orbit of the Group of Bodies Around the Sun," *American Journal of Science* 37 (1864):53-61,371-389.

[13]Bessie Zaban Jones and Lyle Gifford Boyd, *Harvard Observatory* (Cambridge: Harvard University Press, 1971), pp. 6-10.

[14]Ibid., p. 11.

[15]Rothenberg, "Educational Background" (n. 5), p. 78.

[16]Harvard generally had three or four "assistants," i.e., low-paid trainees, working under the supervision of the astronomers, but rarely had undergraduates taking the course. The assistants often went on to become well-known astronomers. The school administraton tried (unsuccessfully) to change this from the directorship of W.C. Bond on through the end of the century.

[17]Jones and Boyd, *Harvard* (n. 14), pp. 92-93.

[18]Solon I. Bailey, "Harvard Astronomy," *The Development of Harvard University Since the Inauguratipn of President Eliot, 1869-1929* (Cambridge: The Harvard University Press, 1930), p. 304.

[19]Samuel Eliot Morison, *Three Centuries of Harvard* (Cambridge: The Harvard University Press, 1946), 382.

[20]Jones and Boyd, *Harvard* (n. 13), p. 93.

[21]Ibid., p. 179.

[22]Truman Henry Safford, "A School of Astronomers," *Siderial Messenger* 8 (1889):199.

[23]Rothenberg, "Educational Background" (n. 5), pp. 61-62.

[24]Denison Olmsted, *An Introduction to Astronomy* (New York: Collins and Brother, 1866), p. iii.

[25]William Chauvenet, *A Manual of Spherical Astronomy: Embracing the General Problems of Spherical Astronomy, the Special Applications to Nautical Astronomy, and the Theory and Use of Fixed and Portable Instruments* (Philadelphia: J.B. Lippincott and Co., 1863), v.1, p. 3.

[26]Ibid., v.2, p. 470.

[27]Elias Loomis, *Introduction to Practical Astronomy* (Harper Brothers, 1865), pp. iv-v.

[28]John C. Schwab, "The Yale Curriculum, 1701-1901," *Educational Review* 22 (1901):8.

[29]Benjamin Gould to Hermann Schumacher quoted in Dieter Hermann, "Gould," *Journal for the History of Astronomy* 2 (1971):101.

[30]Benjamin Gould to Friederich von Humboldt, quoted in Seth Carlo Chandler, "Benjamin Apthorp Gould," *Monthly Notices of the Royal Astronomical Society* 57 (1896-7):22.

[31]Rothenberg, "Educational Background" (n. 5), pp. 129-130.

[32]Hermann, "Gould," (n. 29), pp. 98-108.

[33] Ralph S. Bates, *Scientific Societies in the United States* (Cambridge: The Massachusetts Institute of Technology Press, 1945), p. 52.

[34] George H. Daniels, "The Process of Professionalization in American Science," *Isis* 47 (Summer 1967):69.

[35] Sally G. Kohlstedt, "A Step Toward Scientific Self-Identity in the United States: The Failure of the National Institute," *Isis* 51 (September 1971):81-103.

[36] Bates, *Scientific* (n. 29), p. 77.

[37] Nathan Reingold, *Science in Nineteenth Century America: A Documentary History* (New York: Hill and Wang, 1964), pp. 200-202.

[38] Bache to Fraser quoted in Reingold, *Science* (n. 37), p. 205.

[39] Ibid., p. 207.

[40] Bates, *Scientific* (n. 33), p. 98.

[41] Daniel J. Kevles, *The Physicists* (New York: Alfred A. Knopf, 1978), p. 6.

[42] *Transactions of the American Philosophical Society 1* (1769-1771):1-37.

[43] Bates, *Scientific* (n. 33), p. 77.

[44] Hermann, "Gould" (n. 29), pp. 98-102.

[45] Ibid., pp. 102-108.

[46] Jones and Boyd, *Harvard* (n.13), p. 363.

VI. NINETEENTH CENTURY DEVELOPMENTS IN AMERICAN ASTRONOMY

Positional Astronomy

As the number and size of the observatories and telescopes began to increase in the United States, so did the numbers of astronomers whose work was specifically oriented toward astronomical research. The desire to make discoveries was strong in the nation in the middle of the nineteenth century. Unfortunately, there was not enough money available for most observatories to do research, so the instruments in many of the colleges were designed from the start as demonstration equipment for undergraduates. The telescopes were generally too small or too poorly sited to be really useful.[1]

This was not true in the case of Harvard Observatory. As part of the campaign by Harvard personnel to build an observatory and purchase fine equipment for it, mathematics professor Joseph Lovering wrote to President Josiah Quincy in 1845 that the University needed new equipment because they "did not posess a single instrument which was adapted to making an astronomical observation which would have any scientific value." He went on further, "The University possesses no instrument of much value for determining either time or position, the two great elements which the theoretical astronomer wants, and which the observatory is expected to furnish."[2]

It is evident that Lovering had a research facility in mind for the school, rather than one purely for instruction. The research mission of the Observatory is further reflected in the "Statutes of the Observatory" written in 1839:

> The objects of the observatory are, to furnish accurate and systematic observations of the heavenly bodies for the advancement of Astronomical Science, to co-operate in Geodetical and Nautical Surveys, in Meteorological and Magnetical Investigations, to contribute to the Tables useful in Navigation, and , in general, to promote the progress of knowledge in Astronomy and the kindred sciences.[3]

The first director of the Observatory, William Cranch Bond (1789-1859), certainly saw the observatory in that light. He had few students in the time of his directorship because he felt instruction would interfere with observation. Bond, with his son, who was an assistant astronomer and successor as Director, George Phillips Bond (1825-1865), turned the observatory's main efforts into photometry; that is, cataloging the positions and relative brightness of the stars. That is not to say they did nothing else. George Bond is credited along with William Lassell in England with the discovery of the eighth moon of Saturn on September 16, 1848, and in that same year, the Bonds communicated studies they had done on the nebulae in Orion and Andromeda to the American Association for the Advancement of Science.[4]

The science of photometry was nothing new in the 1840's. The earliest document on the subject that we know today is the *Almagest* of Claudius Ptolemy (ca. A.D. 100-178), written in about A.D. 137. In it Ptolemy catalogued 1022 stars by their positions in the sky relative to signs of the zodiac. He assigned each star a number based on a scale of one to six to describe its relative brightness or magnitude.[5] In 1856, an English astronomer, Norman Robert Pogson, pointed out that the first magnitude stars were 100 times as bright as those of the sixth magnitude, so each step in magnitude results in a difference of about two and one half times. By assigning a number to a star whose light seemed steady, other stars could be compared to it and their relative brightness recorded.[6]

The Bonds made a number of innovations to the study of astronomy during their tenures. One of these was the adaptation of a clockwork-driven cylinder upon which a paper was mounted. The cylinder rotated in precisely one minute while a pen drew a line around the cylinder. An electromagnet caused the pen to vibrate and record each second. The observer held a switch. When operated, a place would be marked on the rotating paper, thus marking the time of an observation with far greater precision than any method previously used. This machine, which Bond called a "chronograph," was received in England with great enthusiasm, and won a medal at the Great Exhibition at the Crystal Palace in 1851.[7]

In 1855, Bond published the results of his photometric observations made in the years 1852 and 1853. These compose a "Zone Catalogue" of 5500 stars between the celestial equator and 20 minutes north. All the stars in this zone up through the eleventh magnitude are recorded, along with many of the twelfth magnitude. William Bond wrote, "The plan of observation for the Zones . . . includes the determination of right ascension and declination of all stars from the equator to [zero degrees, twenty minutes] of north declination." Bond went on to say that the stars had each been measured twice, on two successive nights, to assure precision. The catalogue also contains a complete explanation of the "method of observation, reduction, and the instrumental means employed." The explanatory portion of the Catalogue runs to some ninety-two pages, the observational data another three hundred pages. It was an amazing amount of work, when one considers the mathematical reductions that had to be applied to each star's observational data.[8]

In the early 1850's, much of the working time of the two Bonds was devoted to observations of occultations of stars by the moon, comet searching and orbit computation, and their pioneer work in the "application of electro-telegraphic communication to the purpose of astronomical observation."[9] The "electro-telegraphic" observations required two or more observatories to be linked by wire to the same recording device. When an agreed-upon star would pass the meridian, each would signal. This gave very accurate longitudinal information.[10]

Another contribution to the science of astronomy by the Bonds probably outweighed all their others in importance. This was in the application of photography to astronomy when George P. Bond along with "daguerreotypist" J.A. Whipple succeeded in photographing the star Vega on July 16, 1850. Bond immediately forsaw the great advantage the photographic process would give to photometry, because brighter stars made a larger image on the photograph than dimmer ones. A measurement of the image size should easily determine the star's apparent magnitude, a much quicker process than visual comparisons against "standard" stars.[11]

By 1857, they had dropped the daguerreotype for the new collodion process, with which Whipple photographed the star Mizar in Ursa Major through the 15-inch refractor. Exposed for 80 seconds, it showed not only Mizar, but its faint companion Alcor, as well. This was the first successful photograph of a double star, and demonstrated not only that brighter and dimmer stars made different size circles on a photograph, but also that the distance between two very close objects could be measured at leisure on the photograph rather than by meticulous micrometer measurements through the telescope.[12] For an observatory that would specialize in photometry throughout the nineteenth century as would Harvard, this was a great advantage.

The Bonds were not the only ones in America experimenting with photography as a tool for astronomy. As early as 1840, the English-American chemist, John William Draper (1811-1882) used the Daguerre process to photograph the moon. In a memoir of 1840 Draper wrote,

> There was no difficulty in procuring impressions of the moon by the daguerreotype. By the aid of a lens and a heliostat, I caused the moonbeams to converge on a plate, the lens being three inches in diameter. In half an hour a very strong impression was obtained. With another arrangement of lenses I obtained a stain nearly an inch in diameter, and of the general figure of the moon, in which the places of the dark spots might be distinctly traced.[13]

Really excellent photographs of celestial objects were not attained until the early 1860's when New Yorker Lewis Morris Rutherfurd (1816-1892) made the first successful photograph of the Pleiades star cluster. He used an additional lens in his Clark telescope to bring to focus the blue rays of the spectrum to which the early photographic plates were most sensitive. His plates are accurate enough to provide a useful comparison with present-day star plates, so that motion within the cluster can be studied with a time base of over 100 years.[14]

Rutherfurd also solved another problem of astronomical photography. He found that when the plates were exposed long enough to record very faint stars, bright stars were overexposed and made large disks on the plate. This made their actual location indeterminate and prevented accurate measurement. Rutherfurd's solution was to expose the brighter stars for a shorter time than the dimmer ones. The images were thus kept to very small disks whose distance and angles from each other could be measured.[15]

Edward Pickering (1845-1919), the fourth director of the Harvard Observatory, continued the *Harvard Photometry* begun by William Cranch Bond in the middle of the century. Director from 1876 until his death, Pickering had invented his own photometer to be used at the telescope that measured the apparent brightness of a star to within one tenth of a magnitude.[16] Between 1879 and 1882 he determined the brightness of 4260 stars with this instrument. His photometer had a mirror device that would reflect a "standard" star (usually Polaris) so that it would be in the same field of view as the star being examined. A calibrated polarizer was used to dim the brighter star, a correction for the star's altitude would be applied, and the result was a magnitude figure based on Pogson's Ratio. The project was published in 1884 as the *Harvard Photometry,* and included the area from the North Celestial Pole to 30 degrees south of the equator. The collection included stars of magnitude 0 to 6.5. Later studies by Pickering at Harvard and Solon I. Bailey (1854-1920) at Harvard's

Arequipa, Peru facility, produced a listing published in 1902 that included 45,792 stars whose brightness was calculated to one hundredth of a magnitude.[17]

Photometry is historical in nature. It provides a base for star study, particularly for variable stars, and is indispensible for the study of novae. Any suspected change in a star's characteristics can be checked against the *Harvard Photometry* series back to the middle of the nineteenth century with great confidence in the accuracy of the information. Used in conjunction with spectrographic studies, determination can be made of brightness, distance, position, velocity, and even the physical composition of the stars. In the second half of the nineteenth century, the main effort of many of the research-oriented observatories was directed toward photometry.

Between 1898 and 1900, James Edward Keeler (1857-1900) began to photograph hundreds of faint nebulae through a large reflector at the Lick Observatory in California. The great light-gathering power of the reflector and the excellent "seeing" from this mountain site enabled him to secure photographs of objects far dimmer than had previously been found, thus helping to assure that the great telescopes built in the twentieth century would be reflectors. Keeler's photographs showed that nebulae were considerably more common than had been thought. His plates revealed at least 100,000 of these distant objects, and also showed that most of them had a spiral structure.[18]

There were many other contributions to positional astronomy in nineteenth century America. Two astronomers at the Naval Observatory, Asaph Hall (1829-1907), and Simon Newcomb (1835-1909), used the 26-inch Clark refractor to great advantage. Hall used it in discovering both moons of Mars in August, 1877. The Clark telescope had such excellent definition that other astronomers using lesser instruments had trouble finding the tiny satellites and doubted their existence.[19]

Simon Newcomb's work as an observer ended in 1877 when he became superintendent of the American Ephemeris and National Almanac office. He undertook a 20-year-long revision of the tables of celestial objects, eclipses, and other matters pertaining to navigation. This involved recalculation of all the tables of celestial motion, and he re-evaluated the motions of the moon, the four inner planets, and the orbit of Hyperion around Saturn. Newcomb made a contribution to the fundamental constants of astronomy when he pointed out the famous 43 second disagreement between the actual secular motion of Mercury's perihelion and its calculated motion. This set off the search for "Vulcan," a hypothetical planet between Mercury and the Sun. No such planet was found, but when Einstein's equations concerning energy and mass were applied in the twentieth century, the 43 second difference was finally explained.[20]

One other astronomer claims a place in any history of American astronomy: Edward Emerson Barnard (1857-1923). Offered a post as an assistant astronomer at Lick Observatory in 1888, he immediately proved himself one of the best of observers. In 1889, Barnard succeeded in making many photographs of the Milky Way which showed a number of lanes or holes in the near-solid wall of light.[21] He pointed out that they could hardly all be lanes or tunnels pointing directly at us. They must, therefore, be obscurations--"dark celestial clouds blotting out the vistas beyond," which indeed they are.[22]

Barnard's work at the eyepiece was rewarded in 1892 with the discovery of Amalthea, the fifth moon of Jupiter. It is the closest to Jupiter of all its moons, and, at 67 miles in diameter, the smallest found before the twentieth century. This was the last major object in the solar system to be discovered by eye. Since Amalthea, all astronomical discoveries in the solar system have been made on photographs.[23] In 1897, with the appointment as Professor of Astronomy at the University of Chicago, Barnard went to Yerkes Observatory from where he discovered "Barnard's Star," a tiny, swift-moving star in Ophiuchus that is one of the sun's nearest neighbors. Barnard did not live to see it, but a 1963 study of his name-star showed it had a tiny "wobble" in its motion, indicating that it had one or more Jupiter-like planets circling it. It was the first star to be so distinguished.[24] In the twentieth century, Barnard continued his study of nebulae and later published a catalogue of 182 of them.[25] Barnard's catalogue was extensively used in the 1940's by Bart J. Bok, of the Harvard Observatory, in his study of protostars.[26]

Astrophysics

In the early 1860's, Lewis Morris Rutherfurd (1816-1892) made a major contribution to astronomy when he attempted to arrange the stars into an orderly sequence according to differences seen in their spectra. Since stars of the same color seemed to produce spectra of the same general kind, his idea was to group them by color: red, white, and yellow. His efforts to classify stars by their spectra were overshadowed by those of Father Pietro Secchi in Rome and H.C. Vogel in Potsdam, but they still mark the beginnings of stellar spectroscopy, a science which was dominated by Americans by the turn of the century.[27]

The study of spectra of celestial objects began around 1815 when the Bavarian designer and builder of precision instruments, Joseph Fraunhofer (1787-1826), found that dark lines appeared across the colored spectrum when sunlight was viewed through a slit-prism-lens device called a spectroscope. These lines, which had been previously noted by English astronomer W.H. Wollaston in 1802, were spaced at irregular intervals from the furthest Fraunhofer could see in the red zone of the spectrum, clear across it, and apparently beyond the visible violet. Fraunhofer found hundreds of lines that he believed were part of the light from the sun itself and not due to aberration or to the earth's atmosphere.[28]

Fraunhofer was aware of bright-line spectra produced by burning gases, and although he was able to match up some of his dark lines with similar bright lines produced in the laboratory, he missed the implication that the same substances existed in the sun as in the laboratory. It was not until 1859 that German physicist Gustav Kirchoff (1824-1887) noted that the bright line spectrum of sodium became a dark line spectrum when cool sodium vapor was placed between the light source and his spectroscope. Kirchoff believed the sodium vapor was absorbing the bright lines from the light source, and since the lines matched precisely some of those from the sun, he concluded that the sun included sodium in its composition.[29]

In 1842, both Alexandre Bequerel in France, and John Draper's son, Henry, in the United States, managed to record the solar spectrum on daguerreotype plates, but only a few of the denser lines appeared. It was nearly twenty years before Rutherfurd attempted his stellar classification by spectrum, and even more years until 1869, when English astronomer Sir William Huggins (1824-1910) not only photographed many spectral lines from the stars, but concluded from a "shift" in the lines toward the red end of the spectrum that some of the stars were moving away from the earth. This aroused great interest in spectral photography all over the world, and marked the beginning of a new type of astronomy: astrophysics.[30]

The famous American amateur astronomer, Henry Draper (1837-1882), attempted to photograph an eclipse of the sun through a spectroscope in 1878. One of the questions of the time in the astronomical community was whether the sun's corona shone by its own or by reflected light. Draper's photographs showed only a continuous spectrum, from which he inferred (correctly) that the corona was not self-luminous. In a letter to Harvard Observatory director, Edward S.

Pickering, Draper wrote, "You have doubtless heard that I have been very fortunate in my results having photographed the spectrum of the corona and domonstrated its continuous or rather non-incandescent-gas character. The spectrum is really that of reflected solar light."[31]

In 1877, Draper announced that he had discovered oxygen in the sun by bright spectral lines, rather than dark ones. This immediately aroused a controversy in Europe, particularly with Norman Lockyer, who claimed to have preceded Draper by ten years in the discovery. Draper did not get a sympathetic hearing from the Royal Astronomical Society, even though he produced excellent, high-dispersion photographs to reinforce his claim in 1879. The Society may have felt that, as an amateur, Draper's studies were incomplete or invalid; that his claim was not proven theoretically; and some members including spectroscopist Sir William Huggins felt it was not even proven instrumentally.[32] Although Draper's theory was not widely accepted by spectroscopists, and made no turning point in the development of spectral analysis, it did arouse much debate. It also suggested that spectrum photography might be an excellent means of studying celestial bodies.[33]

Draper died in 1882, but his widow, Mary Anna Palmer Draper, was determined to leave some sort of astrophysical memorial to her husband. She at first thought of continuing his work at his private observatory through an assistant, but Edward Pickering eventually convinced her to give the money to Harvard Observatory to fund an enormous spectroscopic study of the entire sky. It was to be entitled the Henry Draper Memorial; in the first summer Harvard was able to obtain stellar spectra of 3000 stars. Mrs. Draper was so pleased she dedicated more money for instruments and personnel to continue the cataloguing on dimmer stars.[34]

The method used in the earliest photographs of stellar spectra was to focus the image of a star on the slit of a spectroscope, then spread it by prism or grating into a spectrum that could be photographed. This method gave large, bright images, but could only record one star at a time. Pickering's idea was to place a prism in front of the telescope's objective lens so that all stars in its field would be shown in spectral form. By moving the telescope at right angles to the line of the spectra, they were drawn out into bands on which the dark lines were quite evident.[35] This method greatly speeded the process of obtaining spectra. The photographic plates exposed for about five minutes recorded the spectra of stars brighter than the sixth magnitude. Longer exposures provided spectra of stars down to the eighth magnitude. Most plates made by Pickering contained about 200 stars. Compare this with Potsdam astronomer H.C. Vogel's first catalogue of stellar spectra published in 1883 that listed 4000 stars and required twenty years of observation to collect! Vogel did all his work right at the eyepiece of his telescope, each star requiring hours of fatiguing work, while the photographs took minutes of telescope time and could be examined whenever it was convenient.[36]

By 1889, Pickering had finished the spectral photographs of the northern hemisphere, and had established an observatory at Arequipa, Peru, to gather spectra from stars south of 30 degrees below the celestial equator. By the time the first *Henry Draper Catalogue* was ready in 1890, it contained the spectra of 10,351 stars. Eventually, some 225,000 appeared in the last *Henry Draper Catalogue* produced in 1924 by Pickering's successor, Harlow Shapely.[37] The enormous amount of work necessary to read each star's spectral characteristics under high magnification, then to determine a classification for each star fell to Pickering's three female assistants, Williamina Fleming, Antonia C. Maury, and Annie Jump Cannon. Mrs. Fleming had been in charge of the "computers," young mathematicians who reduced the data from observations. When she was given the task of classifying the first portions of the Henry Draper Catalogue, she found that the classification system then in use, that of Father Pietro Secchi which used four categories of stars, was inadequate. The new system of photography showed far more detail than could be read directly from the spectroscope, and would require more categories. Mrs. Fleming settled on fifteen groups, lettered A through O (skipping J) differentiated largely by the intensity of the spectral lines of hydrogen.[38]

A second study was begun of the brightest stars of the northern hemisphere, but its object was quality, not quantity. Pickering wanted to study carefully a small number of stellar spectra photographed with the widest possible dispersion of the spectrum. For this he employed Henry Draper's own telescope, the gift of Mrs. Draper. Each star was photographed separately through one to four prisms, giving spectra up to six inches long. When enlarged and examined under a microscope, they showed great complexity of structure. Where Draper's 1872 photograph of Vega showed four lines in a small area, the 1888 spectra now had over 100 lines. Detailed to study and catalogue the spectra was Antonia C. Maury. She did not believe that Mrs. Fleming's letter system of classification was adequate to describe the new spectra, so she devised a new one of twenty-two main catagories, each divided into three sub-catagories. The catalogue was nine years in compiling. Miss Maury examined some 4800 photographs and produced detailed analyses of 681 stars. *The Spectra of Bright Stars* was published in 1897.[39]

After the turn of the century, Miss Maury's catalogue was used by Danish physicist Ejnar Hertsprung in the development of his absolute magnitude sequence. Hertsprung believed that he could calculate the real luminosities of stars from their apparent luminosity if their distance was known. From their proper motions, he was able to calculate the distances and, therefore, the absolute magnitude of stars with statistical accuracy. He found that most red stars were either very bright (giants) or very dim (dwarfs). He also noted a collateral system in which some stars, regardless of color, were very bright, perhaps all giants. Using a division of spectra in Miss Maury's classification called the "c" division, which were spectra with narrow, sharply defined lines, he found the distinction beween the red giants and dwarfs that he sought; none of the "c" stars had any appreciable proper motion. They must, therefore, be very distant and all must be giants.[40]

While studying the spectral photographs, Miss Maury noticed that the lines were doubled on the star *Zeta Ursa Majoris*. Pickering believed that this might indicate a double star, and ordered a number of photographs taken. The lines separated, then contracted into single lines on successive photographs, confirming Pickering's first opinion. He explained the observation by assuming that the lines were separating because of blue-shifting from the star approaching earth, and red-shifting from the one retreating. This was the first example of its kind, but several more "spectroscopic doubles" were identified during the examination of the spectra for the bright star catalogue.[41]

The Henry Draper Catalogues were continued on into the twentieth century under the supervision of Miss Annie J. Cannon, who returned to Mrs. Fleming's systen of letter classification. It was necessary to revise the order of the spectra, however, due to better equipment giving better photographs, and a better understanding of the spectral lines. This letter method was accepted internationally, and is still in use. In the *New Draper Catalogue* (1918), Miss Cannon examined and classified over 200,000 spectra from photographs taken both at Harvard and at Arequipa, Peru.[42]

One leader in spectography in the nineteenth century is better remembered today for his leadership in building observatories. George Ellery Hale, Professor of Astrophysics at the University of Chicago, came there by way of M.I.T., Harvard Observatory, and a stint at the University of Berlin. He was one of the first of a new breed, more physicist than astronomer. When he returned from his studies in Berlin in 1892, Hale set up his own observatory at Kenwood, near Chicago.[43] Since his primary interest was in the sun, Hale devised an instrument he called a "spectroheliograph" with which he could take monochromatic photographs by the light of a single line of the spectrum. He put the instrument to work at Kenwood first, where he photographed solar eruptions and recorded intense magnetic fields associated with them.[44]

He later employed his instrument at Yerkes, where he had been named director. He found the magnification of the 40-inch lens of the refractor insufficient. To get the great magnfication he needed, Hale conceived a great reflector, with the main mirror sitting on the ground, the sun being reflected into it by a heliostat. The Wisconsin air was too misty; Hale moved his apparatus to Mount Wilson, in southern California, where, after trials, he eventually built a tall tower from which the sun was reflected to a focus deep underground. This gave him the extremely long focal length required for great magnification, yet kept the temperature constant. This was important because fluctuations in temperature caused the mirror to distort and lose its parabolic curve.[45] A further reason for the telescope to be fixed was that the size and weight of the spectograph was not limited by what could be easily carried by an ordinary telescope's mount and drive.[46]

While Hale was still Director at Yerkes, the Observatory made numerous spectrographic studies. One was an attempt carried out between 1898 and 1902 to determine if Class G stars evolved into Class M and N. They found that M and N stars are parallel sequences, and both can be traced back to G type stars like the sun.[47] Also in 1898 a new multi-prism spectograph built by Brashear was employed by Yerkes astronomer Edwin Frost to study the radial velocities of the so-called "helium stars." The result of this study was evidence that the sun, in its path around the galaxy, is receding from the stars behind it more rapidly than it is catching up to those ahead. The stars must, therefore, have a systematic motion that Frost described as "expansion in all directions."[48]

Hale, along with Yerkes astronomer George W. Richey, finally solved the old problem of taking photographs through the large refractors which still did not take thoroughly satisfactory pictures, even with reversed or supplementary lenses. They devised a yellow collodion filter to place in front of the photographic plate that cut off only blue light. Using a suitable photographic emulsion, they were able to take photographs of very dim objects that previously could not be obtained. Another modification to the 40-inch allowed the observer to look directly through the main telescope to guide it during long photographic exposures. This prevented the flexure of the long tube from affecting the photographs as it sometimes did when they used an attached supplementary telescope for tracking during long exposures.[49]

Hale achieved his greatest fame during the twentieth century by planning, financing, and building first the Mount Wilson Observatory, then the Palomar. His success in interesting the wealthy in investing in scientific projects, from Chicago tramway baron Yerkes to the Carnegie and Rockefeller foundations, or, as he put it, "giving them the opportunity" has never been equalled. American astronomy owes much to this scientist.

From a complete absence of astronomical research work in the

United States at the start of the century, the country had become a leader in the field by 1900. Several large, well-equipped observatories employed astronomers to no other purpose. Positional astronomy had become largely the science of photometry. The use of tools such as photography made changes in brightness or position of stars immediately apparent on photographic plates, many of which were of such quality that they are still useful as a record of the skys of the mid-nineteenth century. The catalogues produced by Harvard during the century were of an accuracy comparable with the best published in Europe at the time. Advances in techniques and equipment enabled astronomers to make new discoveries within the solar system, such as the two moons of Mars, and Barnard's discovery of the vast dust clouds of space.

In the new science of astrophysics, the Americans did not have so much ground to make up, and so were able to produce good results from the earliest days of the science. The stellar classification developed at Harvard which differentiated stars largely by the intensity of their spectral hydrogen lines was quickly accepted throughout the world and is still in use. The "mass production" techniques employing photography for the examination and classification of hundreds of thousands of spectra were also developed at Harvard during in the nineteenth century.

Perhaps the most important of the late nineteenth century astronomers was George Ellery Hale. The important discoveries he made in spectroscopy, particularly concerning the magnetic fields of the, sun are over overshadowed by his unparalled ability to interest wealthy people in giving large sums of money for astronomical purposes. The leadership enjoyed by the United States in this field in the twentieth century is due in large part to Hale's talent and personal leadership. He financed, planned, and supervised the construction of three of the largest, best equipped observatories in the world; Yerkes, Mount Wilson, and, in the 1930's, Mount Palomar in southern California. These provided the physical plant for the discoveries of such brilliant observers as E.E. Barnard, George W. Richey, Harlow Shapely, A.A. Michelson, and many others.

NOTES

[1]Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: Harvard University Press, 1971), p. 177.

[2]Ibid., pp. 44-45.

[3]William Cranch Bond, *History and Description of the Astronomical Observatory of Harvard College* (Cambridge: Metcalf and Company, 1856), p. lix.

[4]W. C. Bond, "Description of the Star Theta Orioni," *Memoirs of the American Academy of Arts and Sciences* 3 (1848):87-96.

[5]Claudius Ptolemy, *The Almagest* tr. R. Catesby Taliaferro (Chicago: Great Books of the Western World, 1952), p. 233.

[6]Isaac Asimov, *Eyes on the Universe* (Boston: Houghton Mifflin Co., 1975), p. 112.

[7]Bond, *History of the Observatory* (n. 3), p. xxix.

[8]W. C. Bond, *Annals of the Astronomical Observatory of Harvard College* v.1, (Cambridge: Metcalf and Co., 1855), p. iii.

[9]Bond, *History of the Observatory* (n. 3), p. cxlix.

[10]Edward S. Holden, *Memorials of William Cranch Bond and his son, George Phillips Bond* (San Francisco: C.A. Murdoch and Co., 1897), p. 242.

[11] George Bond to William Mitchell 7/6/1857, quoted in Holden, *Memorials* (n. 10), pp. 154-159.

[12]Ibid., p. 159.

[13]John William Draper, *Scientific Memoirs* (New York: Harper and Brothers Publishers, 1878), p. 123.

[14]Michael Mendillo, David DeVorkin, and Richard Berendzen, "History of American Astronomy," *Astronomy*, July, 1976, p. 50.

[15]Sir David Gill, "Applications of Photography in Astronomy," *The Royal Institution Library of Science v.1, Astronomy* ed. Sir Bernard Lovell. (Barking, Essex: Elsevier Publishing Co. Ltd., 1970), p. 314.

[16]Modern electronic methods determine brightness to one thousandth of a magnitude.

[17]Reginald Waterfield, *A Hundred Years of Astronomy* (New York:

The Macmillan Company, 1938), pp. 91-94.

[18]George Ellery Hale, "James Edward Keeler," *Astronomical Journal* 12 (1900): 102.

[19]Asaph Hall, "Discovery of the Satellites of Mars," *A Source Book in Astronomy, 1500-1900*, eds. Harlow Shapely and Helen Howarth, (New York: McGraw-Hill, 1929), p. 321.

[20]Giorgio Abetti, *The History of Astronomy*, tr. Betty Burr Abetti (New York: Henry Schuman, 1952), pp. 218-219.

[21]A century before, Sir William Herschel had viewed these same areas and thought them to be "holes" through which he could see out of the universe.

[22]Otto Struve and Velta Zebergs, *Astronomy in the Twentieth Century* (New York: Macmillan and Company, 1962), p. 54.

[23]Asimov, *Eyes on the Universe* (n. 6), pp. 131-132.

[24]Lou Williams Page, *Astronomy: How Man Learned About the Stars* (Menlo Park, California: Addison Wesley Pub. Co., 1969), p. 176.

[25]Hector Copeland Macpherson, *Makers of Astronomy* (Oxford: The Clarendon Press, 1933), pp. 177-179.

[26]Bart J. Bok, "Concerning Protostars," *A Source Book in Astronomy* ed. Harlow Shapely (Cambridge: Harvard University Press, 1960), pp. 300-306.

[27]Jones and Boyd, *Harvard* (n. 1), p. 232.

[28]Helen Wright, "Telescope, Spectroscope, and Camera," *Astronomy* eds. Samuel Rappaport and Helen Wright (New York: The New York University Press, 1964), pp. 80-81.

[29]William Francis Magie, *A Source Book in Physics* (New York: McGraw-Hill Book Co. Inc., 1935), pp. 354-360.

[30]Sir William Huggins, "Motion in the Line of Sight," *The Nineteenth Century Review*, June, 1897, pp. 294-296.

[31]Draper to Pickering, 8/3/1878, quoted in Jones and Boyd, *Harvard* (n. 1), p. 216.

[32]The experts were right. Later studies showed that Draper's bright lines only appeared to coincide with those of oxygen.

[33]Howard Plotkin, "Henry Draper, The Discovery of Oxygen in the Sun, and the Dilemma of Interpreting the Solar Spectrum," *Journal for*

the History of Astronomy 8 (1977):44-51.

[34]Jones and Boyd, *Harvard* (n. 1), pp. 226-231.

[35]Waterfield, *Hundred Years* (n. 17), pp. 65-66.

[36]Jones and Boyd, *Harvard* (n. 1), p. 234.

[37]Macpherson, *Makers of Astronomy* (n. 26), p. 178.

[38]Jones and Boyd, *Harvard* (n. 1), p. 235.

[39]Ibid., pp. 236-238.

[40]Ejnar Hertsprung, "Giants and Dwarfs," *A Source Book in Astronomy* ed. Harlow Shapley (Cambridge: Harvard University Press, 1960), pp. 248-252.

[41]Annie Jump Cannon, "Pioneering in the Classification of Stellar Spectra," *Source Book in Astronomy, 1900-1950* ed. Harlow Shapley (Cambridge: Harvard University Press, 1960), p. 153.

[42]Ibid., p. 159.

[43]Macpherson, *Makers of Astronomy* (n. 26), pp. 179-182.

[44]George Ellery Hale, "The Earth and Sun as Magnets," *Smithsonian Report for 1913* (Washington: U.S. Government Printing Office, 1913), pp. 145-158.

[45]Rudolph Thiel, *And Then There Was Light* tr. Richard and Clara Winston (New York: The New American Library, 1957), pp. 298-299.

[46]Walter S. Adams, "Some Reminiscences of the Yerkes Observatory 1898-1904," *Science* 106 (1947):175-204.

[47]Otto Struve, "Stellar Spectroscopy," *Science* 106 (1947):204-212.

[48]Adams, *Reminiscences* (n. 45), p. 196.

[49]George Ellery Hale, "Astronomical Photography with a Visual Telescope," *Science* 13 (1901):346-347.

VII. SUMMARY AND CONCLUSIONS

Astronomy has always been a preoccupation of at least a few Americans from the earliest colonial times to the present. The Puritan colonists were far from ignorant of the science and readily accepted both the heliocentric universe of Copernicus and the gravitational astronomy of Newton. Barred from Oxford and Cambridge as non-conformists, they were also not subject to restrictions concerned with "official belief." They may have been witch hunters but they accepted the New Astronomy.

The background of American astronomy was European and the textbooks were nearly all imported until the nineteenth century. In the fashion of the medieval *quadrivium*, colonial American colleges taught astronomy as part of the philosophy curriculum. Those who learned the methods of Newtonian astronomy were able to take part in international projects such as observations of the transits of Venus for the purpose of calculating the planetary distances. By the early nineteenth century, several Americans had made international reputations as observers, and one, Nathaniel Bowditch, had become known for his translation of the *Méchanique Céleste*, and for his *New American Practical Navigator*, a book used by seamen throughout the world. Internationally, the effect of his work cast a light of legitimacy on American scientific efforts.

The struggle to build and equip a national observatory went on for many years. It was thought by a number of people in early post-revolutionary America that a national observatory might be neccessary as a symbol of sovereignity, but it was hard to justify the expenditure of money for this end. Early in the nineteenth century, the mood of the country was utilitarian; the study of heavenly bodies probably seemed of far less importance than roads, bridges, canals, public buldings, and other governmental interests. It was left to the colleges to build the first observatories in the nation. The earliest of these were too small, ill-sited, and poorly equipped to produce discoveries or to institute any long-term studies, but from 1847, when the 15-inch refractor at the Harvard Observatory became active, this was no longer true.

There was one other telescope in the country in the 1840's that might have produced discoveries, had it been used for research, rather than to satisfy the curiosity of its subscribing owners. That was the "Cincinnati telescope" of Ormsby McKnight Mitchel, who raised the money to build the observatory and was its entire staff from 1843 to 1859. The observing time of the telescope was often interrupted by one of the subscribers wanting to look through the tube. This, and the lack of funds to hire even one other observer, prevented any useful work being done with the telescope. The Harvard telescope, on the other hand, was also purchased with funds raised through public subscription, but it was under the control of the college and was properly used as a research tool.

The great "observatory boom" of the 1840's produced a number of small college observatories, but they suffered from lack of funding to maintain astronomers or do much more than act as demonstration labs for students. An exception was the National Observatory which was completed in 1844. It was staffed by knowledgeable scientists who produced accurate observations for the calculation of ephemerides for celestial navigation. Later, with improved equipment, the observatory also produced several discoveries, such as the moons of Mars found by Asaph Hall in 1877.

Later in the century, the great observatories that were built for the University of California and for Chicago University had the finest equipment in the world, and were staffed by scientists dedicated to research. The reputations of many of the famous American astronomers of the late nineteenth and early twentieth centuries, including Edward E. Barnard, George E. Hale, James E. Keeler, and George W. Richey were made at these sites.

The equipment in these observatories was entirely American in origin, for the instruments of the Alvan Clark and John Brashear firms had surpassed those of the European manufacturers in size, power, and accuracy. This was certainly not the case in the early nineteenth century when the only high-quality astronomical instruments available were imported from Europe. In the 1830's, extremely high standards had been set for high-resolution optics, accurate mountings, and clockwork drives by Joseph Fraunhofer in Bavaria. No observatory that intended serious work would contemplate buying from any other maker, although the French firm of Lerebours probably produced as good optics. At the middle of the century, the English equipment was considered marginal, and the American-made instruments were distinctly inferior. By the 1870's, the situation had changed. American firms were beginning to supply European observatories, and had entirely supplanted the European products in the American market.

The technological situation in American astronomy during the nineteenth century can be contrasted with the situation that existed in England in the same time period. English inventors were responsible for both the first practical reflecting telescope and the achromatic refractor in the seventeenth and eighteenth centuries. Unfortunately, neither system was developed further in that country. The refractors were patented by Dolland, who apparently had little interest in improving on them. Other English manufacturers who tried to build telescopes using the Dolland system were either sued or threatened, so the English optical industry lost interest in producing improved refractors. Before Fraunhofer began building his fine refractors, he studied one built by Dolland. Patents were apparently not international in the early nineteenth century, so he used the Dolland system in his own manufacturing.

No great advances had been made on Sir Isaac Newton's reflecting telescopes in England or anywhere else because of the problems associated with using metal specula. By the time the process of silvering glass for mirrors was invented on the Continent, English commercial telescope building was moribund.

The lack of good instruments and the generally poor seeing conditions caused many English astronomers to turn to the study of the sun. For this, small instruments were adequate. The enormous lead in astronomy the English had in the late eighteenth century had entirely evaporated early in the nineteenth century, and by 1850, when France, Germany, and even the United States were moving rapidly ahead in the science, the English had fallen far behind.

Education of American astronomers kept pace with the flourishing of observatories. West Point, Yale, and Harvard in particular produced many of the astronomers that staffed the American observatories. They taught the mathematical methods of data reduction that were introduced from Germany in the late 1840's, and brought the accuracy of American observations up to European standards. Mathematicians such as Benjamin Peirce of Harvard and Hubert A. Newton of Yale, and the astronomer and publisher, Benjamin Gould, who studied mathematics in Germany, taught the German methodology and promoted the idea of fanatical precision in celestial observations.

While the standard of astronomical education was being raised in the 1840's, new societies were formed to promote a more professional environment in which American scientists might work. The most important of these, the American Association for the Advancement of Science, was formed by professional scientists who felt a need to have their own organization which would be free from politics and amateur domination. They were familiar with the drawbacks of another society of the time, the National Institute for the Promotion of Science whose president was an amateur botanist and whose membership was largely Congressmen and government employees. Leading members of the AAAS organized the National Academy of Science, theoretically an elite organization of leading American scientists. Astronomers had no separate national organization of their own until the end of the century, when the American Astronomical and Astrophysical Society was formed by George Hale and several other astronomers. In 1889, the director of the Lick Observatory, E.S. Holden, organized the Astronomical Society of the Pacific, but although it had many distinguished astronomers in its membership, it was not really national in scope.

Besides education and organization, a third factor in the rise of professionalism of the American astronomers of the nineteenth century were the professional journals. Communication of discoveries, theories, and techniques was a great problem before the middle of the century. The astronomers had to publish in foreign journals or general science magazines until O.M. Mitchel began the *Siderial Messenger* in 1846. It was not the complete answer, for Mitchel designed it as a money-making proposition, and he had to include quasi-scientific articles in it to broaden its appeal. This was not true of Benjamin Gould's *Astronomical Journal* which commenced publication in 1849. From the start, the German-trained Gould aimed to raise the level of American astronomy by publishing only papers reflecting serious research, and he leaned heavily toward mathematical astronomy. Gould's journal has continued to keep its highly professional content and standards to the present day.

Late in the century, George E. Hale joined with William W. Payne to form a new journal, *Astronomy and Astrophysics*, which later split into *Popular Astronomy*, edited by Payne, and *The Astrophysical Journal* edited by Hale. Both journals contributed their part; Payne's in providing a vehicle for articles of general astronomy that might not meet the restricted requirements of Gould's *Astronomical*

Journal, Hale's in providing a vehicle for purely astrophysical articles.

After 1865, the stage was set for rapid progress in American astronomy. The Bonds at Harvard, the Drapers and Lewis Rutherfurd in their private observatories were already producing excellent photographs of celestial objects. With the advantage of the Clark telescopes and associated equipment, discoveries began to be made that were a result of the superior resolving power of the telescopes. Examples are the discovery of the dwarf companion of Vega, and of the two tiny moons of Mars. Americans were no longer far behind Europe in astronomy, but were superior in some areas. At Harvard, from 1876 on, Edward Pickering displayed great expertise in both photometry and spectroscopy, using photography to enhance and accelerate both studies. It has been said that his greatest discovery was women, for he not only employed them as "computers" for reducing observations for the photometric data, but gave them key tasks in the production of the *Henry Draper Catalogues*, a long term spectroscopic study.

The *Harvard Photometry* gave accurate positions and apparent magnitudes for thousands of stars and provided a firm base for the study of stellar motion and absolute magnitude. The spectroscopic catalogues with the classification of stars provided by Pickering's female assistants were the basis for statistical studies of stellar spectra both in the United States and abroad. The result of these studies was our present-day knowledge of the relative size of stars, particularly those of the giant class.

At the end of the nineteenth century, the United States had good observatories, fine equipment, and many well-trained astronomers. As the new century progressed, there would be even greater telescopes built, sited scientifically, and able to detect radiation that has been millions, even billions of years enroute. The American version of the science was built on a European model, but it was one science at which Americans could, and did, excel.

It can not be said that any one thing was the primary cause of this rise to eminence. It has been attributed to the increased availability of money after the California gold rush, the influx of German scientists after the European unrest of 1848, a major change in the public idea of science brought about by newspapers and periodicals, the availability of year-around good-weather sites or just the urge to compete against the entrenched scientific superiority of the Europeans. It is likely that all these things played their parts. In my opinion, it was the world-wide growth of industrial technology that made possible the great telescopes, the vision of men like William Cranch Bond and George Ellery Hale who understood what was needed, and a great deal of surplus capital that could be invested in science with no hope of return. The colleges played their part in awakening young people to the possibilities and opportunities of this particular science, and the importation from Europe of the mathematics and a disciplined, rigorous approach produced fine astronomers. Nowhere else did the money, technology, expertise, and desire to excel come together so fortunately.

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APPENDICES

APPENDIX I

CHRONOLOGY OF AMERICAN ASTRONOMY TO 1900

Astronomers and Discoveries

1664. John Winthrop Jr. named first colonial Fellow of the Royal Society.

1680. Observation of a comet from Boston by Thos. Brattle and from Maryland by Arthur Storer mentioned by Newton in *Principia*.

1761. John Winthrop (IV) to St. Johns to observe a transit of Venus.

1769. Rittenhouse observes a transit of Venus from Philadelphia.

1780. Samuel Williams to Maine to observe a solar eclipse.

1822. Isaac Orr develops a "nebular hypothesis."

1833. Denison Olmsted makes his calculations on meteors from the constellation Leo.

1840. John Draper photographs the moon.

1842. J.W. Draper photographs the sun's spectrum.

1847. Maria Mitchell becomes first woman to be credited with the discovery of a comet.

1848. W.C. Bond independently discovers Hyperion, 8th satellite of Saturn.

Instruments and Observatories

1825. Congress votes $25,000 for the Depot of Charts and Maps.

1830. Yale gets a 5" telescope.

1831. Chapel Hill N.C. Observatory established.

1836. Williams College Observatory established.

1839. Harvard Observatory established, W.C. Bond named Director.

1844. National (Naval) Observatory begins operations.

1845. Cincinnati Observatory opens.

1847. Harvard gets 15" refractor.

1848. Benjamin Gould begins his *Astronomical Journal.*

1849. David Alter finds differing spectral characteristics for each metal.

1849. J.A. Whipple photographs the moon through a telescope.

1850. Whipple photographs the star Vega.

1850 W.C. Bond discovers the "crepe ring" of Saturn.

1857. Whipple photographs Mizar/ Alcor double star.

1862. A.G. Clark discovers Sirius B, whose existance was deduced by Bessel in 1835.

1869. Chas. A. Young discovers solar corona line and "flash spectrum."

1872. Henry Draper photographs the spectrum of Alpha Lyrae.

1877. Asaph Hall discovers both moons of Mars.

1877. H. Draper detects oxygen in the solar spectrum.

1880. E.C. Pickering calculates the diameter of Algol.

1886. Michelson-Morley aether experiment.

1889. E.C. Pickering deduces a close double star from a spectral photograph.

1889. E.E. Barnard deduces dark areas in Milky Way obscuration, rather than holes in the sky.

1847. Amherst College Observatory opens.

1851. Alvan Clark sells his first telescope.

1856. Lewis M. Rutherfurd corrects his refractor for photography.

1860. Allegheny Observatory opens.

1863. Clark completes 18½" "Mississippi" lens. Dearborn Observ.

1869. Henry Draper completes his 28" reflector telescope.

1873. Clark delivers 26" lens to the Naval Observatory.

1877. John A. Brashear builds his first reflector.

1881. Henry Rowland develops the parabolic diffraction grating.

1884. Clark completes the 30" lens for the Pulkova Observatory.

1885. Clark completes the 36" Lick refractor telescope.

1886. Rutherfurd develops a photographic method of stellar magnitude determination.

1886. E.C. Pickering introduces the objective prism for photographing stellar spectra.

1891. George Ellery Hale builds the "Rumford" spectroheliograph.

1891. Percival Lowell establishes an observatory to search for life on Mars.

1890. James Keeler photographs a spiral nebula.

1890. Pickering publishes first *Henry Draper Catalogue* with the spectra of 10,351 stars.

1890. Michelson develops the interferometric star measurement process.

1892. Keeler postulates Saturn's rings to be "brickbats."

1892. Barnard discovers Jupiter V (Amalthea).

1895. J.W. Schaeberle detects Procyon B.

1895. Hale resolves the double line of helium in the sun.

1895. Rowland completes his 40' map of the solar spectrum with the precise location of 20,000 Fraunhofer lines.

1897. Barnard receives the gold medal of the Royal Astronomical Society for his nebular photos.

1898. Barnard discovers "Barnard's Star," the second closest star to the solar system.

1898. W.H. Pickering discovers Saturn 9 (Phoebe).

1900. Annie Jump Cannon revises the stellar spectral classes to O,B,A,F,G,K,M.

1893. Clark's completes the 24" "Bruce" photographic telescope.

1893. J.W. Schaeberle builds the 40-foot "astrographic" camera.

1894. Lowell Observatory opens, has 18" Brashear refractor.

1894. Clark's develop a 24" reversible lens for both visual and photographic observation.

1896. Clark's install a 24" refractor at Lowell Observatory.

1897. Clark's completes the 40" Yerkes refractor--still the largest in the world.

1898. G.E. Hale builds a spectrograph for stellar radial velocity investigations.

APPENDIX II

A LISTING OF OBSERVATORIES BUILT IN THE UNITED STATES PRIOR TO 1900

This information is taken from Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard Observatory* (Cambridge: Harvard University Press, 1971); Elias Loomis, "Astronomical Observatories in the United States," *Harper's* 13 (1856): 25-52; and by the same author, *The Recent Progress in Astronomy, Especially in the United States* (New York: Harper Bros., 1851); and from Deborah Jean Warner, *Alvan Clark and Sons: Artists in Optics* (Washington D.C.: Smithsonian Institution Press, 1968).

1769. David Rittenhouse's log cabin observatory, Norriton, Pennsylvania.

1792. David Rittenhouse's private observatory, Philadelphia, Pennsylvania.

1830. Yale University, Athenaeum Tower.
University of North Carolina, Chapel Hill.
U.S. Depot of Charts and Maps, Washington, D.C.

1833. Lt. Charles Wilkes's Observatory, Washington, D.C.

1836. Williams College, Williamstown, Massachusetts.

1838. Western Reserve College, Hudson, Ohio.
Philadelphia High School, Pennsylvania.

1839. U.S.M.A., West Point, New York.
Harvard University, Cambridge, Mass.

1842. National Observatory, Washington, D.C.

1844. Georgetown University, Washington, D.C.

1845. Cincinnati, Ohio Community Observatory.

1846. Sharon College, Darby, Pennsylvania.
Friends Observatory, Philadelphia.

1847. Amherst College, Amherst, Massachusetts.

1848. Lewis Morris Rutherfurd's private observatory, New York City.
Charleston, North Carolina.

1849. Tuscaloosa, Alabama.
Dartmouth College, Hanover, New Hampshire.

1850. Shelby College, Shelbyville, Kentucky.

1851. Buffalo, New York.

1854. Michigan University, Ann Arbor, Michigan.

1855. Dudley Observatory, Albany, New York.

1856. Hamilton College, Clinton, New York.

1859. Hebron Academy, Maine.*
Jefferson College, Pennsylvania.*

1860. Allegheny Observatory, Pittsburg, Pennsylvania.

1866. Dearborn Observatory, University of Chicago, Illinois.*

1868. University of Mississippi.*
Vassar College, Poughkeepsie, New York.*
Weslyan University, Connecticut.*
1869. Lehigh University, Pennsylvania.*

1871. Mary Mead Abbey, New York.*

1872. Columbia University, New York.*

1873. Abbot Academy, Andover, Massachusetts.*

1874. Pritchett Institute, Missouri.*

1875. Henry Draper's private observatory, Hastings, New York.*

1876. Morrison Observatory, Glasgow, Missouri.*
University of Rochester, New York.*

1877. Bates College, Lewiston, Maine.*

1878. Carleton College, Northfield, Minnesota.*
Wisconsin State University, Superior, Wisconsin.
Antioch College, Ohio.

1880. Haverford College, Pennsylvania.*
Michigan State College, East Lansing, Michigan.
Mount Holyoke, Massachusetts.*

1882. Beloit College, Wisconsin.*
Princeton College, New Jersey.*

1883. Virginia State College, Ettrick, Virginia.

1884. Hartford (Connecticut) Public High School.*

1885. McKim Observatory, DePauw, Indiana.*

1886. Franklin and Marshall College, Lancaster, Pennsylvania.*
Smith College, Massachusetts.
Swarthmore College, Pennsylvania.*
Lick Obs+rvatory, California.

1887. Bucknell College, Pennsylvania.*

1888. Cornell University, New York.*
Durfee High School, Fall River, Massachusetts.*
Grinnel College, Iowa.*

1890. Wellesley College, 1890.*
Ladd Observatory, Brown University, Providence, Rhode Island.
Smithsonian Astrophysical Observatory, Washington D.C.

1891. Joliet (Illinois) High School.*
Harvard South, Arequipa, Peru.
Lowell Observatory, Flagstaff, Arizona.

1892. Minnesota State University.
Lawrence University, Wisconsin.

1894. Chamberlin Observatory, Denver University, Colorado.

1895. Boston University.*
Yerkes Observatory, University of Chicago.

1896. Pennsylvania State University.
Illinois State University.

1900. Indiana State University.

* Indicates date taken from first delivery by Alvan Clark and Sons.

APPENDIX III

ALVAN CLARK AND SONS INSTRUMENTS BUILT IN THE NINETEENTH CENTURY

The information in this appendix is quoted from Deborah Jean Warner, *Alvan Clark and Sons: Artists in Optics* (Washington, D.C.: Smithsonian Institution Press, 1968).

1848: 5-inch refractor--William Harvey Wells, Newburyport, Mass.

1852: 7.125-inch objective, installed in a Phelps mount, Williams College Observatory, Williamstown, Mass.

1853: 7.5-inch refractor, William R. Dawes, London.

1854: 4.25-inch refractor, probably the first complete instrument made by Clark. Amherst College, Mass., cost: $1800.

1855: 8-inch refractor, W.R. Dawes, London.
6.25-inch refractor, Kingston Observatory, Canada. Price: $850.

1857: 7-inch refractor, W.R. Dawes, London.
7.75-inch refractor complete with all accessories, U.S.N.A., Annapolis.

1858: 5-inch refractor complete, Maria Mitchell, Nantuckett.

1859: 8-inch short focal length refractor with mount and clock, W.R. Dawes, London.
8.25-inch short focal-length refractor with mount, W.R. Dawes, London.
6.1-inch refractor with equatorial mount, Hebron Acadamy, Maine.
7.5-inch objective, Phelps mount. Jefferson College, Pa.
5.5-inch refractor. T.W. Webb, England.

1864: 8-inch refractor. Bonner's Hill Observatory, Quebec, Canada.

1866: 7-inch refractor without drive or setting circles.
18.5-inch refractor complete with all accessories. Originally made for the University of Mississippi, sold to Dearborn Observatory, University of Chicago.
5-inch refractor with setting circles and clock. John R. Hooper, Baltimore.
9-inch equatorial refractor complete with many accessories. Sheffield School of Science, Yale University.

1867: 12-inch Fitz objective refigured by Clark's. Jacob Campbell, New York City.

1868: 9-inch Clark objective. W.S. Gilman, Palisades, New York.
5-inch refractor complete. T.H. Marvin, Palisades, New York.
5-inch Merz objective reground and refigured by Clark's. University of Mississippi.
12.5-inch Fitz objective reground and refigured by Clark's. Vassar College.
12-inch refractor complete with all accessories. Price: $6000. Weslyan University, Connecticut.

1869: 5.25-inch equatorial refractor complete with setting circles, drive clock, and spectroscope. Harvard College Observatory.
6-inch equatorial refractor with all accessories. Lehigh University, ra.

1870: 6-inch refractor. S.W. Burnham, Dearborn Observatory, Chicago.
Equatorial mounting for an 11-inch Rutherfurd lens, also a
5-inch equatorial with setting circles, no clockwork. Cordoba Observatory, Argentina.
8.25-inch objective for a Troughton and Simms meridian circle. Harvard College Observatory.

1871: 5-inch refractor. Mary Mead Abbey.
8-inch refractor. Elma Loines, Lake George, New York.

1872: 13-inch Fitz lens, refigured. Allegheny Observatory, University of Pittsburg.
6-inch equatorial refractor. Columbia University, New York.
7.33-inch refractor. B.M. Fish, Hamburgh, New York.

1873: 7.5-inch refractor with drive clock and setting circles. Price: $2150. Abbot Academy, Andover, Mass.
26-inch refractor. U.S. Naval Observatory, Washington.

1874: 9.4-inch equatorial refractor. D.W. Edgecomb, Newington, Conn.
a fixed solar telescope of 40-foot focus. Harvard Observatory.
8-inch equatorial refractor. Pritchett Institute, Mo.
Eight 5-inch equatorial refractors and eight chronographs for the 1874 Venus transit Expedition. U.S. Naval Observatory.

1875: 12-inch equatorial refractor. Henry Draper, Hastings, New York.
8-inch equatorial refractor. S.E. Seagrave, Providence, R.I.
9.75-inch Merz objective, reground and refigured by Clark's. U.S.M.A., West Point, New York.

1876: 11-inch Merz objective refigured by Clark's. Cincinnati Observatory.
12.25-inch equatorial refractor with accessories. Price:

$6000. Morrison Observatory, Glasgow, Mo.
6-inch equatorial. University of Rochester, New York.
12-inch objective glass. Vienna Imperial Observatory.

1877: 6.25-inch refractor. Bates College, Lewiston, Me.
13-inch Fitz objective refigured . Dudley Observatory, Albany, New York.
9.5-inch refractor with adjustable lens components for visual, photographic, or spectroscopic work.

1878: 4.94-inch refractor, equatorial mount. Antioch College, Ohio.
8.25-inch equatorial refractor. Price: $3000. Carleton College, Minn.
6.5-inch equatorial refractor. O.C. Wendell, Lowell, Mass.
15.56-inch refractor complete with all accessories. Washburn Observatory, University of Wisconsin.

1879: 6.5-inch Clark objective. George Davison, San Francisco, Ca.
Mirrors and lenses for measuring the speed of light. A.A. Michelson.

1880: 8.25-inch refractor. Cincinnati Astronomical Society.
9.4-inch equatorial refractor. Dartmouth College.
11-inch photographic triplet objective. Henry Draper, Hastings, New York.
8.25-inch objective by Fitz refigured, installed Clark clock drive and micrometer. Haverford College, Pa.
6-inch equatorial refractor with all accessories. E.L. Larkin, New Windsor, Ill.
5-inch equatorial refractor. R.W. McFarland, Columbus, Ohio.
6-inch refractor. University of Michigan.
8-inch equatorial refractor, many accessories. Mount Holyoke Observatory, Mass.
5.5-inch objective, mount by Fauth. U.S. Army Brigade of Engineers.

1881: 8-inch Clark equatorial. F.W.R. Englemann, Leipzig, Germany.
5-inch refractor. R. Patterson, Dansville, New York.

1882: 9.5-inch Clark objective, Warner and Swazey mount. Beloit College, Wis.
5-inch equatorial refractor. Columbia College, New York City.
23-inch equatorial refractor. Princeton University.
6.25-inch refractor. C.H. Rockwell, Tarrytown, New York.
16-inch equatorial refractor with all accessories. Lewis Swift, Rochester, New York.
5-inch refractor. Price: $500. C.W. Tallman, Batavia, New York.

1883: 8-inch refractor with setting circles, many other accessories. Anthony Chabot, Oakland, Ca.

6-inch refractor. F.J. del Corral, Saratoga Springs, New York.
8-inch Clark objective. Doane College, Crete, Nebraska.
6-inch equatorial refractor. Robert McKim, Madison, Indiana.
30-inch Clark objective, Repsold mount. Imperial Observatory, Pulkova, Russia.

1884: 11-inch refractor. Columbia College, New York City.
9.5-inch Clark objective. Hartford (Conn.) Public High School.
10-inch Equatorial Refractor complete with all accessories. Haverford College, Pa.
12-inch equatorial refractor. Price: $6280. U.S.M.A., West Point, New York.
26-inch equatorial refractor with all accessories. McCormick Observatory, University of Virginia.

1885: 8.25-inch corrector lens, a 5-inch guide telescope, and a
4.8-inch objective for a meridian circle. Carleton College, Minn.
9.53-inch Clark objective. McKim Observatory, De Pauw University, Indiana.
10.5-inch Clark objective, Repsold Mount. Leiden, The Netherlands.
6-inch equatorial refractor with all accessories. University of the Pacific.

1886: 6.25-inch refractor complete. Marshall Davis Ewell, Chicago, Ill.
11-inch Clark objective, Repsold mount. Franklin and Marshall College, Pennsylvania.
11-inch Clark objective lens, Warner and Swazey mount. Smith College, Mass.
6-inch Clark objective, Warner and Swazey mount, Brashear accessories. Swarthmore College, Pa.

1887: 6.5-inch equatorial refractor. R.R. Beard, Pella, Iowa.
10-inch equatorial with clock and setting circles. Bucknell College, Pa.
13-inch convertible visual-photographic refractor Harvard Observatory.
36-inch refractor with 33-inch photographic corrector lens, Warner and Swazey mount. Three 6-inch lenses for various portable instruments owned by the observatory. Lick Observatory, California.
8-inch Clark equatorial refractor. Holden Observatory, Syracuse, New York.

1888: 8-inch equatorial refractor complete with drive clock, setting circles, and filar micrometer.
5-inch equatorial with setting cicles and slow-motion controls. F.G. Blinn, Oakland, California.
4.5-inch Clark equatorial refractor complete. Cornell Univer-

sity, Ithaca, New York.
4.5-inch Clark objective, Brashear mount. Francis G. DuPont, Wilmington, Del.
8-inch Clark refractor. Durfee High School, Fall River, Mass.
5-inch equatorial refractor. Charles Goodall, San Francisco, California.
8-inch Clark objective. Grinnel College, Iowa.

1889: 5-inch photographic refractor with reversible objective lens. Richard S. Floyd, Clear Lake, Ca.
12-inch visual refractor and a 10-inch photographic refractor, also numerous spectroscopes and photometers, as well as modifications and repairs to practically all the instruments of the observatory through the end of the 19th century. Harvard.

1890: 6-inch Clark refractor. Wellsley College, Mass.

1891: 4.5-inch equatorial refractor. Joliet (Ill.) High School.
5-inch Clark equatorial refractor. E.S. Martin, Wilmington, North Carolina.

1892: 10-inch equatorial refractor. Lawrence University, Wis.
6-inch equatorial refractor complete. McCormick Observatory, University of Virginia.

1893: 24-inch short focal-length refractor with an objective prism for spectrosopy. Harvard College Observatory.

1894: 20-inch refractor, objective reversible for visual or photographic use. University of Denver.
12-inch refractor. Lowell Observatory, Ariz.

1895: 5-inch refractor, tripod mount. Boston University.
24-inch equatorial refractor. Lowell Observatory, Ariz.
40-inch objective lens, largest ever made. Yerkes Observatory, University of Chicago.

1898: 8-inch Clark objective, Repsold mount. Koenigliche Universitats-Sternwarte, Breslau, Germany.

1899: 5-inch equatorial refractor. Mare Island Naval Observatory.

Only one remarkable Clark product was delivered in the twentieth century, a 42-inch reflector telescope mirror delivered to Lowell Observatory in 1909. None of the Clark family was involved in the mirror, which was made by Carl Axel Lundin (1850-1915), a Clark employee from 1873.

The Clark firm also built literally hundreds of 4-inch and smaller complete telescopes and objectives for various astronomical instruments that are not listed here.

APPENDIX IV

MAJOR BRASHEAR INSTRUMENTS DELIVERED AFTER 1880

The information in this appendix is taken from John Brashear, *An Autobiography of a Man Who Loved the Stars* (New York: The American Society of Mechanical Engineers, 1924).

12-inch objective. Syrian Protestant College, Beirut, Lebanon.

12-inch objective. University of Illinois, Champaign, Illinois.

12-inch objective. Ohio State University, Columbus, Ohio.

Two 12-inch objectives. Kenwood Observatory, Chicago.

12-inch objective. Dudley Observatory, Albany, New York.

12-inch objective. 150-foot focal length, Mount Wilson Tower Telescope.

12-inch objective. Ladd Observatory, Providence, Rhode Island.

15-inch objective. Yale University.

14-inch objective. Philadelphia (Pa.) High School.

16-inch objective. Carleton College Observatory, Northfield, Minn.

15-inch objective. S.N. Smith, Newport News, Va.

15-inch objective. Dominion Astronomical Observatory, Ottawa, Canada.

18-inch objective. Flower Observatory, University of Pennsylvania.

15-inch objective. Philadelphia (Pa.) High School.

12-inch objective. University of Indiana, Bloomington.

30-inch reflector. Keeler Memorial-Allegheny Observatory, Pittsburg.

30-inch plane mirror. Yale University.

37-inch Cassegrain telescope. Lick Observatory Chilean expedition.

37-inch parabolic mirror. University of Michigan, Ann Arbor.

19.5-inch parabolic and plane mirrors. Dominion Observatory, Victoria, B.C.

20-inch objective. Chabot Observatory, Oakland, Ca.

24-inch objective. Swarthmore College, Pa.

30-inch objective. Thaw Memorial-Allegheny Observatory, Pittsburg, Pa.

16-inch "doublet" objective. Dr. Max Wolf, University of Heidelberg.

72-inch parabolic mirror with all optical accessories. Dominion Observatory, Victoria, B.C.