looking up

the rise of astronomy in america

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How shall we study the development of science in America?

Fifteen years ago Hunter Dupree announced to the American Historical Association that the field of the History of American Science had "found itself." It had done so, he claimed, because historians, following the advice of Arthur Schlesinger, Sr., had recognized the central role of science in recent American history and had refused to let their ignorance of science prevent them from writing about it. Rejecting the demand of George Sarton (founder of the history of science discipline in the United States) that they should be "deeply familiar with at least one branch of today's science" and "should have a more superficial acquaintance with various other branches," Dupree and his colleagues decided that they could dispense with such scientific training and perhaps did not even need to have an interest in the subject matter of science at all; their subject was the scientists and their relation to society.[1]

One consequence of this attitude was Dupree's conclusion that historians of "American science" need not worry about whether the contributions of American scientists were of any importance to science itself, as judged by scientists in other countries; "since science has meant much to American civilization, the indebtedness would not change if a watertight proof were made that American civilization had been woefully inept or even a complete failure in its contributions to science."[2] Thus

American science is to be studied because of its role in American society; the European reputation of an American scientist does him no good at home (unless he can convert it into the cash and prestige that goes with a Nobel Prize).

The opposing view, presented just as forcefully at about the same time but still held by only a minority of historians, is that there is no such thing as American science.[3] Science is the search for knowledge, and if the knowledge is valid it must be independent of the nationality of the person who discovered it. Unless there is a distinctively American *method* for conducting scientific research, talking about "American science" is a rather artificial designation which makes no more sense than creating such categories as "young science" or "male science" or "right-handed science" to describe science engaged in by persons with these characteristics.

"The history of American science," from this viewpoint, could be considered a legitimate subfield, not of the history of science, but of American history—at least if it is studied without regard to science as an international activity. If the development of American society is the primary object of interest, one can certainly ask what role was played by persons who were considered scientists, even if no one outside the country had ever heard of them. One can study the population of American scientists—their institutions, journals, salaries, education, psychological characteristics, etc.—without worrying about whether their research had any recognized value in the world scientific community. All this is quite worthwhile, but it is not the history of *science* unless one can establish the place of those Americans in the international scientific community; if they had any ambitions *as scientists,* they had to look to that community for problems worth solving and for recognition when they had solved them.

Being myself a believer in pluralism, I would not want to discourage Professor Dupree and his fellow historians of American science from continuing what they have been doing so competently and enthusiastically for the last two or three decades although I lean toward the second viewpoint in my own research. But when I look at the way science is presented by American historians, in textbooks, articles and lectures, I am disturbed to see a considerable amount of distortion even by their own criteria. "Science" seems to mean only the atom bomb, social Darwinism and various inventions that have changed our daily lives. The historian seems to assume that the great majority of Americans, like the majority of historians, have no interest in knowledge about nature for its own sake, but think of science only as it affects their safety, religious beliefs or personal comfort.

i

major american contributions to astronomy, 1801-1950

To come to the subject of this paper, I think historians have greatly underestimated the interest of Americans in astronomy, and have neglected to consider the question of how the United States managed to rise to world leadership in a relatively "pure" branch of science (practical applications such as navigation were not enough to account for this phenomenon) well before the immigration of European scientists in the 1930s, which is usually credited with producing our postwar superiority in fundamental research.

A glance at some of the most popular U.S. history textbooks published during the past two decades shows that while science is generally accorded a few pages, astronomy is barely mentioned at all; the reader is led to believe that there is no significant difference between the contributions of John Winthrop and Maria Mitchell, on the one hand, and those of George Ellery Hale and E. P. Hubble, on the other. Worse than that is the complete neglect of American astronomy in the late nineteenth century, which, I hope to show, was the most remarkable period in its history. Even the *Encyclopedia of American History* (1976), which attempts to present a systematic list of major American contributions to astronomy, fails to mention the three most important American astronomers of that period (see below, Table 4) and ignores the most important discovery to which Americans contributed (Table 3). But the general American historian can hardly be blamed for such oversights when there is no comprehensive survey of the history of American science *in its relation to world science* to which he can turn. If he looks, for example, at George Daniels' *Science in American Society*—an excellent book, based firmly (a little too firmly, some would say) on recent scholarship—he will find only one page on astronomy out of about 200 on the period from 1800 to 1915.[4]

If we expect authors who lack any detailed knowledge of astronomy to include that subject in their surveys of U.S. history, and indeed if we want to discuss the rise of American astronomy at all, we must be explicit about what were the most important astronomical discoveries in America, and who were the American astronomers most highly regarded in Europe. For this purpose I have made a survey of the major events in astronomy and the major astronomers, during the period 1800-1950, together with an attempt to determine how many of them can be called American. Having an idea of where the Americans stood on the international scene will provide some of the necessary perspective to discuss what they were doing and will make it more meaningful to ask questions such as "why did American astronomy make such spectacular advances in the late nineteenth and early twentieth centuries?" It is quite possible that the *answer* involves certain special features of American society in this period; I am not trying to disparage the role of social factors in the history of science. My point is simply that one cannot even ask the *question* unless one has some reason to think that astronomy advanced more rapidly in the United States than in other countries at that time.

In Tables 1, 3 and 5, I have listed ten major events in astronomy for each 50-year period from 1800-1950, together with the people responsible for the events and their nationalities. These lists have been compiled by going through several books on the history of astronomy. To avoid bias *in favor* of Americans, I have used books by non-American-born authors.[5] Of course, I cannot prove that these are *the most important events* in those periods; all I am doing is presenting an *assumption* which is sufficiently explicit that anyone may criticize it. The rank ordering of events, like the selection of events, represents a value judgment, that is, my interpretation of the collective judgment of these authors.

One general criticism can be made of all these lists: the authors are mostly astronomers rather than historians, and they tend to judge the importance of earlier events in the light of present-day knowledge rather than historical context. This is what historians call the "Whig interpretation"—the past is seen through the eyes of the present.[6] Two examples are Fraunhofer's discovery of the dark lines in the solar spectrum (Table 1) and the first steps toward radio astronomy by Jansky and Reber (Table 5); only with the advantage of hindsight can we recognize that these discoveries were destined to open up major new areas of research. But I don't think this kind of bias has much effect on the national comparisons.

Notice that I use "event" in a broad sense, to include the gradual development of apparatus, techniques and theories as well as observational discoveries that occurred at a definite time. Also, I have sometimes grouped together events that seem closely related. When several people are involved in the same event, the assignment of fractional credit is somewhat arbitrary; generally the first name listed is the one usually given most of the credit, except where a slash (/) indicates equal shares. As will be seen, the main conclusions do not depend on the accuracy of these details.

A separate compilation has been made of ten major astronomers in each period (Tables 2, 4 and 6). These lists are subject to all the qualifications mentioned above for the lists of events, with the additional complication that some careers overlapped two periods. In such cases, I first assigned the person to one period on the basis of the completion of his major works, then gave him full credit for all his work regardless of date. It should be noted that two astronomers who were highly regarded at the beginning of the nineteenth century—Laplace and William Herschel—were completely eliminated by this process since their most important work was done in the late eighteenth century. Piazzi just barely escaped elimination by making his discovery of Ceres on January 1, 1801. In spite of such artificialities, I think it is useful to have separate lists of astronomers and events. Progress depends on those who devote their lives to persistent high-quality, but unspectacular work, as well as on those who are lucky enough to make glamorous discoveries. Olbers, Argelander, Encke, Barnard, Zöllner, Newcomb, Lyot, Baade, Oort and Kuiper all made a number of significant contributions but were overshadowed by the fame of others. Conversely, several of the major events, such as the introduction of spectrum analysis or the development of relativity theory, are credited to people who were not considered astronomers at all.

It is obvious from the tables that Germany enjoyed unquestioned leadership in astronomy during the first half of the nineteenth century, but suffered a precipitous decline thereafter, mitigated by the contributions of physicists (Kirchhoff, Hemholtz and Einstein). German physics, as is well known, was advancing rapidly after 1840. The British reached their astronomical peak in the 1860s and 1870s; their reputation was preserved in the twentieth century by Eddington and other theorists not named in Table 6. The French lost their high standing in physical science after the death of Laplace (1827) and never recovered it despite the isolated triumphs of LeVerrier and Poincaré in celestial mechanics. Among the smaller countries, Italy provided some important work in the nineteenth century, but was replaced by Holland in the twentieth.

One could argue, with some justification, that American contributions have been underrated by the non-American authors whose judgments are summarized here. The work of W. C. Bond and especially his son G. P. Bond in stellar photography deserves a place in Table 1, as does the solar research of C. A. Young and S. P. Langley in Table 3. The development of photoelectric photometry by J. Stebbins might well have been added to Table 5, along with the Chamberlin-Moulton "planetesimal hypothesis" for the origin of the solar system, in which I have a special interest.[7] But I prefer to leave the tables as they stand and use these omissions as evidence that the tables indicate the *minimum* level of American achievement in each period.

After completing this survey and preparing Tables 1-6, I received Dieter B. Herrmann's new book, *Geschichte der Astronomie von Herschel bis Hertzsprung* (Berlin, 1978). Since it is based on more extensive historical research than most of the other histories of astronomy I had consulted, rather than simply average it in with them I decided to use Herrmann's judgments as an independent check. This can be done "objectively" since he presents as an appendix a chronological list of ninety-two events in astronomy from 1801 to 1931. A national breakdown of his *Chronik* is given in Table 7. Making allowance for some pro-German bias, we see that his list confirms the general pattern of a

TABLE 1

Major Events in Astronomy, 1801-1850

1. Distances of stars by parallax measurements
   F. W. Bessel (**German**), F. G. W. Struve (**German/Russian**), Thomas Henderson (**British**)
2. Discovery of Neptune, resulting from theoretical calculation
   U. J. J. Le Verrier (**French**)
3. Dark lines in solar spectrum, beginning of astronomical spectroscopy
   Josef von Fraunhofer (**German**)
4. 11-year periodicity of sunspots
   Samuel Heinrich Schwabe (**German**)
5. First asteroid, Ceres: discovery, orbit calculation
   Giuseppe Piazzi (**Italian**), K. F. Gauss (**German**)
6. Improvements in telescope—glass, clock drive, etc.
   Josef von Fraunhofer (**German**)
7. Short-period comet, showing apparent effect of resisting medium
   J. F. Encke (**German**)
8. Powerful telescope showing spiral shape of nebulae, etc.
   William Parsons, Earl of Rosse (**British**)
9. Detailed map of moon
   Wilhelm Beer and Johann Madler (**German**)
10. Survey of stars in Southern Hemisphere
    John Herschel (**British**)

TABLE 2

Major Astronomers, 1801-1850

1. Friedrich Wilhelm BESSEL (1784-1846) **German**
2. John Frederick William HERSCHEL (1792-1871) **British**
3. Friedrich Georg Wilhelm STRUVE (1793-1864) **German/Russian**
4. William Parsons, Earl of ROSSE (1800-1867) **British**
5. Friedrich Wilhelm August ARGELANDER (1799-1875) **German**
6. Johann Franz ENCKE (1791-1865) **German**
7. Giuseppe PIAZZI (1746-1826) **Italian**
8. Josef von FRAUNHOFER (1787-1826) **German**
9. Heinrich Wilhelm Matthias OLBERS (1758-1840) **German**
10. Urbain Jean Joseph LE VERRIER (1811-1877) **French**

TABLE 3

Major Events in Astronomy, 1851-1900

1. Development of spectrum analysis
   G. R. Kirchoff (**German**), R. W. Bunsen (**German**)
2. Detailed spectra of stars; Doppler shift indicating speeds
   William Huggins (**British**)
3. Classification of stellar spectra
   Angelo Secchi (**Italian**), H. W. Vogel (**German**), E. C. Pickering (**American**), Antonia Maury (**American**), Williamina Fleming (**British/American**)
4. Surface features of Mars, especially "canals"
   Giovanni Schiaparelli (**Italian**)
5. Study of sun: prominences, spectra, helium
   P. J. C. Janssen (**French**)/Norman Lockyer (**British**)
6. Theory of contracting gaseous sphere (thermodynamics)
   Hermann von Helmholtz (**German**), William Thomson, Lord Kelvin (**British**), J. H. Lane (**American**), August Ritter (**German**)
7. Applications of photography
   L. M. Rutherfurd (**American**)/Henry Draper (**American**)/David Gill (**British**)/ Warren de la Rue (**British**)/ A. A. Common (**British**)/ Isaac Roberts (**British**)/ James Keeler (**American**)
8. Surveys of stellar magnitudes
   E. C. Pickering (**American**), Charles Pritchard (**British**), Gustav Mueller (**German**), Paul Kempf (**German**)
9. Constitution of Saturn's rings
   J. C. Maxwell (**British**), Edouard Roche (**French**), James Keeler (**American**)
10. Lunar theory
    P. A. Hansen (**German**), C. E. Delaunay (**French**), G. W. Hill (**American**), J. C. Adams (**British**), Simon Newcomb (**Canadian/American**)

TABLE 4

Major Astronomers, 1851-1900

1.	William HUGGINS (1824-1910) **British**
2.	Angelo SECCHI (1818-1878) **Italian**
3.	Joseph Norman LOCKYER (1836-1920) **British**
4.	Giovanni Virginio SCHIAPARELLI (1835-1910) **Italian**
5.	Edward Charles PICKERING (1867-1919) **American**
6.	Pierre Jules Cesar JANSSEN (1824-1907) **French**
7.	John Couch ADAMS (1819-1892) **British**
8.	Johann Karl Friedrich ZOLLNER (1834-1882) **German**
9.	Simon NEWCOMB (1835-1909) **Canadian/American**
10.	Edward Emerson BARNARD (1857-1923) **American**

TABLE 5

Major Events in Astronomy, 1901-1950

1.	Theory of stellar structure and energy transfer Arthur Eddington (**British**), Robert Emden (**Swiss/German**), Karl Schwarzschild (**German**), James Jeans (**British**), H. N. Russell (**American**), Arthur Schuster (**British**)
2.	Determination of distances, period-luminosity relation for Cepheid variables Henrietta Leavitt (**American**), Ejnar Hertsprung (**Danish**), Harlow Shapley (**American**)
3.	Recession of galaxies, distance-velocity law, expanding universe E. P. Hubble (**American**), V. M. Slipher (**American**), A. A. Friedmann (**Russian**), M. L. Humason (**American**)
4.	Classification of stars, dwarfs and giants, color-luminosity diagram as basis for theory of stellar evolution Ejnar Hertzsprung (**Danish**), H. N. Russell (**American**), Annie J. Cannon (**American**), Antonia Maury (**American**)
5.	Construction of large telescopes George Ellery Hale (**American**)
6.	Size, shape and differential rotation of Milky Way galaxy Harlow Shapley (**American**), Bertil Lindblad (**Swedish**), J. H. Oort (**Dutch**)
7.	Beginnings of radio astronomy K. G. Jansky (**American**)/Grote Reber (**American**)
8.	Relativity theory Albert Einstein (**German**)
9.	Grouping of stellar motions into two streams J. C. Kapteyn (**Dutch**)
10.	Theory of ionization equilibrium and its application to interpretation of stellar spectra M. N. Saha (**Indian**), Cecilia Payne[-Gaposchkin] (**British/American**)

TABLE 6

Major Astronomers, 1901-1950

1.	George Ellery HALE (1868-1938) **American**
2.	Arthur Stanley EDDINGTON (1882-1944) **British**
3.	Harlow SHAPLEY (1885-1972) **American**
4.	Henry Norris RUSSELL (1877-1957) **American**
5.	Edwin Powell HUBBLE (1889-1953) **American**
6.	Jacob Cornelius KAPTEYN (1851-1922) **Dutch**
7.	Walter BAADE (1893-1960) **German/American**
8.	Jan Hendrik OORT (b. 1900) **Dutch**
9.	Gerard Peter KUIPER (1905-1973) **Dutch/American**
10.	Bernard LYOT (1897-1952) **French**

sudden rise of American astronomy in the period 1851-1900. (The only American events he notes in the period 1801-1850 are the founding of Harvard College Observatory and the initiation of Gould's *Astronomical Journal,* both of which can be considered important only in retrospect.)

Probably no one will be surprised to hear that the United States had risen to world leadership in astronomy by the mid-twentieth century, but the rapidity of the ascent is remarkable. Starting from essentially zero at the beginning of the nineteenth century, the Americans had overtaken the Germans to jump into second place by the end of that century and were already challenging the British for the top spot. The discoveries announced by 1930 were sufficient to put the United States ahead of all other countries; the development of radio astronomy and the construction of the 200-inch telescope prepared the way for additional discoveries (not all of them American) after 1945.

The Europeans acknowledged American primacy, sometimes by remarks on the public record and significantly by coming to the United States to do their research. Even before the great "intellectual migration" of the 1930s, astronomers were visiting American observatories and staying as long as possible, or, when they returned home, complaining about the relatively inadequate facilities in their own countries, while admiring the way the Americans obtained and used their instruments.[8]

ii
the founding parents

The early phase of American astronomy, to about 1876, may be characterized as a period in which Americans brought themselves up to the level of European knowledge and began to show their aptitude in the use of new technology. I will describe this period by briefly mentioning six people. None of them can be called an astronomer of the first rank by world standards, but they show how things got started. The group consists of two Yankees—a glassmaker and a female librarian; a wealthy

TABLE 7

National Distribution of Events in Astronomy, 1801-1931 as listed in Herrmann's Geschichte der Astronomie

	Percentage of events in each period		
Country	**1801-1850**	**1851-1900**	**1901-1931**
Germany	61	30	31
Great Britain	11	7	4
United States	7	29	37
France	5	13	0
Italy	7	10	0
Russia	5	3	3
Austria	4	0	3
Greece	0	2	0
Switzerland	0	3	3
Netherlands	0	0	7
Denmark	0	0	4
South Africa	0	0	1
India	0	0	3
Estonia	0	0	1
Sweden	0	0	1
Canada	0	2	0

New Yorker; a chemist who immigrated from England; a white and a black from Maryland.

Benjamin Banneker (1731-1806), the black, attracted considerable attention because of the intellectual distance he had to travel from his own origins (though his father had already escaped the status of slavery and become a landholder) rather than his ultimate achievements. He made a clock in 1753 without, apparently, ever having seen one, and starting in 1792, he published an almanac which involved astronomical calculations on a fairly high level. His example showed that a black could reach a level of scientific and mathematical competence far above that of the average white.[9]

Alvan Clark (1804-1887) perfected the glassmaker's art of making optical instruments at his factory in Cambridgeport, Massachusetts; he became known as a maker of high-quality telescope lenses. His son, Alvan Graham Clark (1832-1897), worked with him and in 1862, while testing an eighteen-and-a-half-inch objective later installed at the Dearborn Observatory in Chicago, discovered the dark companion of Sirius predicted by Bessel; this was the first "white dwarf" to be discovered. Clark telescopes were responsible for much of the success of American astronomy in the latter part of the nineteenth century and after.[10] The British astronomer William Huggins bought a Clark object-glass in 1858 and used it for some of his discoveries.[11]

John William Draper (1811-1882), born in England, studied chemistry at University College London and became interested in the chemical effects of light. After emigrating to Virginia in 1832, he obtained a medical degree and in 1839 became professor of chemistry and natural philosophy at the college of New York University. He took up the new invention of photography, made one of the first photographic portraits of a person and took one of the first good pictures of the moon (1840). In 1844 he took the first photograph of a diffraction spectrum. In 1847 he showed that incandescent solids emit a continuous spectrum of radiation with rays of increasing refrangibility (that is, increasing frequency) as the temperature increases; it was by trying to determine the nature of this spectrum that Max Planck was led to the quantum theory in 1900. In 1874 Draper published a best-selling book, *History of the Conflict between Religion and Science,* largely a polemic against the efforts of theologians to obstruct research.[12]

John Draper's son, Henry Draper (1837-1882), was also known for work in astronomical photography; he married Mary Anna Palmer, daughter of Courtland Palmer, who had made a fortune in the hardware business and in New York real estate. After Henry Draper's death, Mrs. Draper used the family wealth to support astronomical work at the Harvard College Observatory, especially the survey of stellar spectra organized by E. C. Pickering (see below). Antonia Maury, one of the women whose work at Harvard will be discussed shortly, was a granddaughter of John William Draper; Henry was her uncle.[13]

Another pioneer of astronomical photography was Lewis Morris Rutherfurd (1816-1892), a wealthy New York amateur. In the 1860s he developed a practical method for photographing the spectra of the sun and stars so as to reveal a large number of Fraunhofer lines which are not visible with the ordinary spectroscope. He made diffraction gratings which he distributed to other astronomers; these were superseded in the 1880s by those made at Johns Hopkins University by Henry Rowland.[14]

The net effect of the introduction of photographic methods was to make it possible for astronomers to take large numbers of observations in a fairly routine way at night, then analyze the results during the day, often with the help of assistants who were not professional astronomers. This is one way astronomy became "Big Science," involving team research; it is also one reason why opportunities were opened up for women in astronomy, even if at first their jobs were fairly routine and tedious.[15]

The first woman in American astronomy was Maria Mitchell (1818-1889). She was librarian at the Atheneum in Nantucket, Massachusetts, when she discovered a comet with her telescope in 1847. For this she won a prize established in 1831 by the King of Denmark for the first comet to be discovered with a telescope. As a result of the publicity generated by this event, she gained some recognition from the scientific community; after being employed for several years by the Nautical Almanac Office to compute ephemerides of Venus, she became Professor of Astronomy and Director of the Observatory at the new Vassar College for women.[16]

Daniel Kirkwood (1814-1895) was the first American to make his reputation in theoretical astronomy. Born in Maryland, he held various positions as schoolteacher and administrator before being appointed professor of mathematics at Indiana University in 1856. In 1849, he proposed a formula relating the rotations and orbits of planets similar to Kepler's third ("harmonic") law for their revolution periods and distances; the apparent success of this formula in revealing a new regularity in the solar system earned him, for a brief time, the title of "the American Kepler."[17] Kirkwood was for several years a strong supporter of Laplace's nebular hypothesis for the origin of the solar system, and the "Kirkwood gap" in the asteroid belts, for which he is now best known, were originally thought to demonstrate yet another regularity in support of Laplace's theory.[18] Kirkwood is the unacknowledged originator of one of the modern explanations for the direction of planetary rotation.[19] But he later rejected the nebular hypothesis and provided two of the most convincing arguments against it.[20]

For the most part, these six pioneers were self-educated in astronomy, worked alone and had no institutional support until after they had established their reputations. It was still extremely difficult to become a professional astronomer in America, as Cleveland Abbe found when he tried in the 1860s.[21] Yet Americans were quick to learn the new techniques that were revolutionizing astronomy—spectroscopy and photography—and they were beginning to have excellent telescopes available.[22] As Simon Newcomb put it, "The born astronomer, when placed in command of a telescope, goes about using it as naturally and effectively as the babe avails itself of its mother's breast."[23] In one small subfield Americans had already taken the lead; by 1876 they had discovered more asteroids than any other country.[24]

Insofar as the early development of American astronomy can be attributed to social or cultural factors, the factors seem to be the ones often associated with this period of American history: a democratic *openness* to bright, energetic people without professional training or certification by the establishment and an emphasis on *practical skills and technology*. But the validity of these factors as general causes is undermined by the growing importance of Harvard and the "California-Wisconsin axis" in astronomical research and education[25] and the success of astronomers like Newcomb and Kirkwood in abstract theoretical investigations.

iii
the transition to big astronomy

The year 1877 marked a turning point in American astronomy. The opposition (close approach) of Mars provided the opportunity for two sensational discoveries. Asaph Hall (1829-1907) had recently been put in charge of a twenty-six inch Clark refracting telescope at the Naval Observatory in Washington, D.C. It was at that time the largest in the world. Hall discovered the two moons of Mars, confirming a "prediction" made by Jonathan Swift in *Gulliver's Travels* (1727).[26] One moon, Phobos, is so close to the planet that it revolves in less than eight hours, that is, less than the period of rotation of Mars. This fact did not agree with the accepted theory of the origin of planets and satellites, and thus Hall's discovery was part of the American assault on the nebular hypothesis (an assault which culminated in the work of Chamberlin and Moulton; see note 7).

The other discovery of 1877 was made in Italy but exploited in America: Schiaparelli's detailed examination of the surface of Mars revealed markings which he called "canali." The word really means "channels" in Italian, but the press seized on the idea that they were *canals* constructed by intelligent beings. Percival Lowell (1855-1916) pursued this idea and was responsible for creating much of the widespread fascination with "life on Mars" which continues to the present day.[27] Indeed if the most pragmatic criterion of whether a hypothesis is taken seriously is willingness to spend billions of dollars to test it, then surely the question "is there life on Mars?" ranks among the leading scientific problems of all time, and we have Percival Lowell to thank for making it so.

Lowell was a wealthy New Englander who could finance his own research and that of others. He was one of the first astronomers to act on the notion that observatories must be located someplace where atmospheric conditions are favorable for seeing, that is, away from urban centers. So he established the Lowell Observatory at Flagstaff, Arizona, in 1894. In addition to elaborating on Schiaparelli's "canali," Lowell described periodic darkenings of certain regions of Mars, which seemed to be correlated with the change in size of the polar "ice cap." He interpreted the darkening as a seasonal growth of vegetation, stimulated by water melting from the icecaps and flowing through the canals, which appeared to be more prominent at those times.

Lowell also believed that there must be another planet beyond Neptune, and organized a search for it at his observatory. Thanks to his persistence and his contagious enthusiasm for this project, another planet was in fact discovered after his death, by Clyde Tombaugh in 1930. Its name, *Pluto,* though of legitimate classical origin (Greek/Roman god of the underworld), was chosen to commemorate *P*ercival *L*owell by its first two letters.[28]

Lowell's real achievement, not always appreciated by other astronomers, was to arouse popular interest in astronomy and thus gain support for research whose results were not so easy to understand. He was an excellent writer and speaker, a master of literary style as well as a competent astronomer and mathematician.

The years after 1877 saw the beginnings of major collaborative research programs and the construction of huge new telescopes in the United States. These projects were successful because of the enthusiasm and organizing talents of a handful of astronomers and the availability of money. Massive support for astronomy came from several Americans who had made their fortunes by methods which they, or the public, considered somewhat unethical; philanthropy allowed them to acquire social respectability and even immortality by giving them the means to have their names associated with a famous educational or scientific institution. Astronomy in particular appealed to those who were curious about the mysteries of the universe.[29]

James Lick, a Pennsylvania piano and organ maker, went to California during the Gold Rush and made his money by land speculation. It is said that he first wanted to build a pyramid for himself, bigger than that of Cheops, but was eventually persuaded to endow the biggest telescope in the world so that it could be determined whether there are animals living on the moon. In any case, the money was available after 1876, and the trustees of the Lick estate decided to buy a thirty-six-inch

Clark refracting telescope and construct an observatory on Mount Hamilton near San Francisco.[30]

The Lick Observatory was built in 1888 and was immediately put to good use by its first resident astronomers, James Keeler (1857-1900) and Edward Emerson Barnard (1857-1973). Keeler measured speeds of nebulae using the Doppler effect and obtained detailed photographs showing the spiral structure of many nebulae.[31] Barnard discovered a fifth satellite of Jupiter in 1892, and began a major project to photograph the Milky Way.

George Ellery Hale (1868-1938) of Chicago was the one person mainly responsible for the construction of the observatories and telescopes which have dominated twentieth-century astronomy: the Yerkes Observatory at Williams Bay, Wisconsin (opened in 1897); the Mt. Wilson Observatory near Pasadena, California (1904), and the Palomar Observatory, also in Southern California, completed with its famous 200-inch telescope in 1948. He also helped to establish the California Institute of Technology as a major center of scientific research in the western United States.[32]

Hale's father manufactured hydraulic elevators and was able to purchase good enough telescopes to encourage his son's early interest in astronomy. George was largely self-educated in astronomy though he had a bachelor's degree from MIT. His own research was primarily concerned with the physical properties of the sun. In 1889 he invented a "spectroheliograph" to photograph solar prominences and measure the intensity of a single spectral line in various parts of the sun. His major discovery was the magnetic properties of sunspots; he found a twenty-three-year cycle in which the magnetic polarity is reversed.[33]

Hale promoted the idea that the goal of astronomy should now be to say *what* a heavenly body is, as well as *where* it is. Today this seems obvious, but it was not so in the mid-nineteenth century. August Comte, the French philosopher who founded "positivism," asserted in 1835 that reliable knowledge of the universe beyond our solar system would be forever unattainable, so it is futile even to speculate about the nature of the stars.[34] Here as in many other cases "positivism" turned out to be shortsighted "negativism"; astronomers were busily analyzing the chemistry of the stars only a few decades after Comte issued his dogmatic pronouncement. Not only could one identify the elements responsible for spectral lines, one could also learn something about the physical conditions of the stars (temperature, magnetic fields, for example) by examining the fine structure of those lines. Thus spectrum analysis became an important part of *astrophysics,* a new science in which Hale was one of the leaders.[35]

In 1892, Hale was appointed associate professor of astrophysics at the new University of Chicago. Shortly after this, Hale learned from Alvan Clark that the forty-inch blanks for lenses for a planned new telescope, ordered by the University of Southern California, were available for sale; the original order had been cancelled because the collapse of the land boom in Southern California had wiped out the value of the property which had been donated to pay for the telescope. Hale needed $300,000 to buy and mount the lenses and install them in a suitable building, and so he searched for a donor. He found Charles Tyson Yerkes, a streetcar tycoon who apparently wanted to improve the reputation he had acquired from shady dealings (he was known as "Yerkes the Boodler"), and persuaded him that cold cash would put his name on the best telescope in the world. Yerkes was convinced: "You shall have all you need if you'll only lick the Lick!" After some haggling, the Observatory was built; not only was the telescope lens four inches bigger than the one at Lick, but Hale made sure that it included a physical laboratory with facilities for developing photographs and doing spectroscopic experiments.[36]

In 1904, Hale obtained $150,000 from the institution founded by Andrew Carnegie, the Scottish-American industrialist who made his millions in steel. Carnegie had written a magazine article in 1889, expressing his ideas on philanthropy; impressed by the Lick Observatory, he wrote that "If any millionaire be interested in the ennobling study of astronomy . . . here is an example which could well be followed, for the progress made in astronomical instruments and appliances is so great and continuous that every few years a new telescope might be judiciously given to one of the observatories upon this continent, the last being always the largest and best, and certain to carry further and further the knowledge of the universe and of our relation to it here upon the earth."[37]

With the Carnegie money, Hale built the Mt. Wilson Observatory near Pasadena. His father had already given him a disk for a sixty-inch reflecting telescope in 1896, but no funds were available at Chicago to mount it; now he was able to use it, starting in 1908, and launched a program of studying stellar spectra. At Mt. Wilson he also did his work on the magnetic fields of sunspots.

Hale then persuaded John D. Hooker, a Los Angeles businessman, to give the money for a 100-inch telescope at Mt. Wilson. One of the early spectacular results was obtained by using A. A. Michelson's interferometer with this telescope to measure the diameter of the "red giant" star Betelgeuse; Francis Pease and J. A. Anderson found that it is 300 million miles. Though it does not appear on my list (Table 5), this feat was very impressive at the time; Eddington included it in his list of the six most important discoveries in astronomy during the 100 years up to 1922.[38]

Hale's last major project was the Palomar Observatory, started in 1928 with a grant of six million dollars from the Rockefeller Foundation. Hale did not live to see its completion (1948), but it undoubtedly contributed to his reputation as the most important astronomer in the first part of the twentieth century (Table 6).

Not all astronomers approved of the use of capitalist profits to finance their work. In 1906 Mary Bird resigned her position as Director of the Smith College Observatory because the College accepted money from Carnegie and Rockefeller.[39]

iv
the role of women

Another person who helped to convert astronomy to the "Big Science" style and the physical approach was Edward Charles Pickering (1846-1919). Like Hale, he is known not so much for his own discoveries as for his talent in organizing institutions in which other people could make discoveries (see note 13). He was a physicist at MIT (one of the first to organize a laboratory course for undergraduates in the United States) when he was appointed Director of the Harvard College Observatory, starting in 1877. His major goal was a comprehensive survey of the brightness (and later the spectra) of *all* stars. In 1887 his brother William Henry Pickering (1858-1938) joined the Observatory staff and became the first Director of the Harvard southern observatory, established in Peru in 1891. William developed the methods of photographing spectra and discovered the ninth moon of Saturn in 1899 (its retrograde motion was yet another blow against the nebular hypothesis).

Just as Humphry Davy is supposed to have said that his most important scientific discovery was Michael Faraday, one might say that Edward Pickering's most important scientific discovery was women. The Harvard Observatory had already initiated a policy of hiring women as computers in 1875, but they were not allowed to make photometric observations in the unheated telescope shelter during the first major survey (1879-1882) because "the fatigue and the exposure to the cold in winter are too great for a lady to undergo," as Pickering explained.[40] Later, the development of photographic methods, the improvement of physical facilities at the Observatory and a change in male attitudes allowed women to take a more prominent role in research there.

There is a story, not very plausible, that Pickering's initial use of women was a result of his violent temper: his male assistant got bored with the tedious work of classifying spectra and became too careless, so Pickering said, "Damn it, my cook can do a better job than that."[41] His cook was Williamina Paton Fleming (1857-1911), who emigrated with her husband from Scotland to Boston in 1878. She found employment as a domestic servant in Pickering's house, separated from her husband and gave birth to a son named Edward Pickering Fleming in 1879. Pickering, impressed by her intelligence, gave her an additional part-time job at the Observatory, and she started to work full time there in 1881. Although she began as a copyist and computer, she eventually classified 10,351 stars for the *Henry Draper Memorial Catalogue* (1890). She was put in charge of giving assignments to the corps of women computers and in 1899 was given an official Harvard appointment as Curator of Astronomical Photographs. Her classification system for stars, as revised by Annie Jump Cannon (see below), is the one now in use.[42]

Pickering, pleased with the work done by the first woman he hired, published in 1882 a pamphlet on variable stars which was expressly designed to interest women in astronomy. His might be called the first "affirmative action" program in science although it was motivated in part by the stereotyped belief that women are best suited for tedious routine work which requires great attention to detail.[43] In fact that is what astronomy needed at the time since in studying the stars, one has to deal with a large number of small pieces of information which must be classified before new theories can be established. In this respect, stellar astronomy around the end of the nineteenth century, like biology in the eighteenth century, conformed fairly well to the Baconian conception of science as systematic observation and classification, though (like nineteenth-century biology) it was soon to break out of that mold with grand evolutionary schemes and bold conjectures.[44]

In addition to Williamina Fleming, three other women made major contributions to stellar astronomy during the Pickering era at Harvard. The next, Antonia Caetana de Paiva Pereira Maury (1866-1952), was not very happy with the role of diligent computer and refused to fit herself into the regular routine schedule of the Observatory. She was the niece of Henry Draper (whose name was associated with the ongoing star-catalogue project through the financial support of his widow) and granddaughter of John William Draper (see above). She graduated from Vassar in 1887 and joined the staff in 1888. Edward Pickering had just found that the spectral lines from the star Mizar (in Ursa Major) are sometimes double and sometimes single. This could be attributed to orbital motion around another star, and thus it was the first discovery of a "spectroscopic binary." Antonia Maury confirmed this discovery and the next year discovered another spectroscopic binary, Beta Aurigae, by herself.

Maury's major work was the classification of 681 bright stars, published in 1897. Although she didn't classify as many stars as Fleming or Cannon, and her classification scheme was not as generally accepted by other astronomers as theirs was, she did recognize one kind of distinction that turned out to be quite significant. She proposed a subdivision, called the "c" division, for stars with very narrow, sharply defined hydrogen and "Orion" (helium) lines and with very intense calcium lines.[45]

The Danish astronomer Ejnar Hertzsprung (1873-1967), working at Potsdam, based his discovery of dwarf and giant stars on Maury's classification. According to his interpretation, the "c" division contained giant stars of very great luminosity. This type plays an important role in the "Hertzsprung-Russell diagram" and in theories of stellar evolution.[46]

Annie Jump Cannon (1863-1941) graduated from Wellesley College in 1884, but didn't take up astronomy until ten years later. She joined the Observatory staff in 1896 and stayed there the rest of her life, being appointed Curator of Astronomical Photographs in 1911. She classified more than 200,000 stars for the *Henry Draper Catalogue,* including virtually all stars brighter than the ninth magnitude. She was the first woman to receive an honorary degree from Oxford University, in 1925; not until 13 years after that did Harvard recognize her with a suitable title, "William Cranch Bond Astronomer." She revised the Fleming classification system, establishing the present order of spectral types designated by letters in the sequence: O B A F G K M. (Students now memorize this sequence by means of the mnemonic phrase, proposed by Henry Norris Russell, "Oh Be A Fine Girl, Kiss Me!") It was adopted by the International Solar Union in 1910 and is known as the "Harvard Spectral Classification."[47] (In 1922 the International Astronomical Union finally recognized Maury's "c" classification by adding this as a prefix to the letter for the spectral type.)

Henrietta Swan Leavitt (1868-1921) graduated from Radcliffe in 1892 and took a permanent position at the Observatory in 1902, later becoming chief of the photographic photometry department. She was in charge of the project to establish stellar magnitudes by photography and specialized in variable stars, of which she discovered about 2400. On the basis of detailed study of one particular group known as the Cepheid variables, photographed at the Harvard southern observatory in Peru, she proposed in 1908 the general rule that brighter variables have longer periods. Since in this particular group all of the stars were assumed to be at the same distance, this meant that the intrinsic brightness (luminosity) was directly correlated with the period of variation.[48]

Hertzsprung was the first to recognize that this period-luminosity relation could be used to measure stellar distances; it is only necessary to have a good direct measurement of the distance of the Cepheid variables, and the Leavitt formula can then be used to find distances of other variables. By this method Hertzsprung was able to make the first reasonable estimate of the distance of the Small Magellanic Cloud. (John Herschel had studied the Magellanic Clouds from the observatory at the Cape of Good Hope in 1834-38 and thought they were outside our galaxy, but other astronomers did not accept this suggestion.) Hertzsprung estimated a value of 30,000 light years in 1913. In 1922, Harlow Shapley (1885-1972) and Donald Menzel at Harvard used a similar method to estimate the distance to the Large Magellanic Cloud and found the result 110,000 light years (later reduced to 85,000). Shapley then used the Cepheid variables and the period-luminosity relation to construct a theory of the size and shape of our galaxy and the distance scale for other galaxies.[49]

Meanwhile, Vesto Melvin Slipher (1875-1969) was studying the spectra of spiral nebulae at the Lowell Observatory, using the Doppler effect to estimate their speeds. He found that, of fifteen nebulae studied in the years 1912-1917, thirteen are receding from us and only two are approaching. The accumulating evidence that these nebulae are really separate galaxies far outside the Milky Way was capped by the discovery of Cepheid variables in the Andromeda nebula in 1923-25. This feat was accomplished by Edwin Powell Hubble (1889-1953) using the 100-inch telescope at Mt. Wilson. With the help of the Leavitt-Hertzsprung-Shapley method he estimated its distance as 900,000 light years.[50]

With this and other evidence on speeds and distances of galactic nebulae, Hubble was able to establish in 1929 one of the most startling correlations of twentieth-century science: the galaxies are, on the average, fleeing from us at a speed proportional to their distance. This simple relation is the basis of the "expanding universe" concept and of theories such as the "big bang" cosmogony.[51]

There is no need to go further into the twentieth century. By 1930, American astronomy had risen as far as it could: to the top.

I suggest a result of this achievement which I cannot prove in a brief article: American research in other areas of science was stimulated by the success of astronomy. This effect has been described in one very important case by Robert Seidel; he shows how astronomers established a "research spirit" at the University of California and helped to promote faculty research in physics and chemistry in the early decades of the twentieth century.[52] Scientists elsewhere in the United States must have been encouraged by the feats of astronomers to believe that Americans could do first-rate work and overtake the Europeans if they tried hard enough. As pioneers of "big science," the astronomers also laid the foundations for future financial support of other sciences: they propagated the idea that basic research often requires very expensive equipment and the organization of large teams of people and convinced the public as well as wealthy donors that such research is worthwhile. In this way, the rise of American science in general can be partly credited to astronomy.

In this paper I have not attempted to answer the questions that historians of "American science" or readers of this journal are likely to ask. For example:

(1) Is the concept of "professionalization" valid here, or—as Nathan Reingold has recently suggested[53]—should one classify astronomers instead as "researchers," "practitioners" and "cultivators"? Surely one wants to distinguish between amateurs like Lewis M. Rutherfurd and Percival Lowell, who became researchers able to compete with the pro-

fessionals on more than equal terms, and those who remained cultivators, discovering an occasional comet or reporting on variable stars. Similarly, one wants to note that a professional like Annie Jump Cannon could evolve from a practitioner into a researcher when the scientific community wasn't looking.

(2) What role did the organization of scientific societies play in promoting the growth of American astronomy? Or did they retard that growth by enforcing methodological conformity and discouraging mavericks?[54]

(3) Did the removal of astronomy from school curricula around 1900[55] have any effect on recruitment into or support for the discipline in the twentieth century?

(4) Did the international reputations of American astronomers give them any special power to influence the policies of their institutions or the attitudes of their society?

(5) Was astronomy one of the few routes to achievement and intellectual gratification open to scientifically talented women in the late nineteenth century? (Did the rise of American physics come too late to take advantage of this situation?)

(6) Were the socioeconomic conditions that favored support for astronomy in late nineteenth-century America duplicated in other countries at other times with comparable results? How do these conditions differ from those favorable to sciences with more direct practical application?

Unless one has some way to tell who were the successful researchers and when the discipline was making most rapid progress, there is no point in even asking these questions. Moreover, they are questions that should also be asked about other countries; in view of the results presented in section I, it appears that comparative studies should focus on Germany, whose precipitous decline in the late nineteenth century provides such a striking contrast not only with the rise of American astronomy, but also with the rapid advances in German physics and chemistry during the same period.

V

postscript: the last quarter-century

In view of the widespread belief that American science and technology have begun to decline during the past decade, partly because of cutbacks in government support and partly because of public hostility and indifference, it would be interesting to compile another table for the period 1951-1975. Unfortunately, sources of the kind used in preparing Tables 1-6—histories of astronomy written by non-Americans, from which judgments as to the most important discoveries and astronomers can be derived—are difficult to find for this period. The best source for this purpose is a survey conducted by the National Science Foundation, in response to a Congressional recommendation in 1976 that the National Science Board should "study the support of innovative research" by the Foundation. A panel of twenty-eight astronomers was asked to list "the most significant innovations since about 1955" including "theoretical developments, empirical findings and discoveries, developments in instrumentation, developments in analytical method." On the basis of replies from sixteen of those queried, a list of twenty-two innovations was compiled.[56] An unpublished document gives a compilation of the number of times each innovation was mentioned together with other details.[57]

The following list of the four most important events in astronomy during the period 1955-1974 is based on the National Science Foundation survey; as will be seen, it should be considered to give an *upper limit* on the American contributions for the period 1951-1975. Names are listed in alphabetical order. When a second nationality is given, it usually indicates only the place where the work was done.
Quasars and pulsars each received twelve votes; X-ray sources and background radiation were each mentioned eleven times.

There are two major reasons why this list is not quite comparable with the ones given for earlier periods. First, the panelists who made the judgments are probably mostly American though they are not identified in the report of the survey. Second, the gap between 1950 and 1955, though it might seem relatively small in time, hides a development that some astronomers would consider one of the five most important innovations during the period 1951-1975: radio astronomy.[58] We must not let this fall through the crack, having included "beginnings of radio astronomy" as one of the ten major events in the period 1901-1950. Our sources for that period emphasized the work of the Americans Jansky and Reber, but all assessments of postwar astronomy give great weight to the *British* work (A. C. B. Lovell, J. S. Hey, Martin Ryle, F. Graham Smith) with some mention of Australians such as J. L. Pawsey and B. Y. Mills.

TABLE 8

tie for 1st	1.5	Quasars
		Jesse L. Greenstein (**American**), Thomas A. Matthews (**Canadian/American**), Allan R. Sandage (**American**), Maarten Schmidt (**Dutch/American**)
	1.5	Pulsars
		S. Jocelyn Bell (**British**), Thomas Gold (**Austrian/American**), Anthony Hewish (**British**), Franco Pacini (**Italian/American**)
tie for 3rd	3.5	X-Ray Sources: Extrasolar, Galactic & Extragalactic
		Herbert Friedman (**American**), Riccardo Giacconi (**Italian/American**), Herbert Gursky (**American**), Francis R. Paolini (**American**), Bruno R. Rossi (**Italian/American**)
	3.5	Microwave Background Radiation (3°K)
		Arno A. Penzias (**German/American**), Robert W. Wilson (**American**)

Even allowing for some nationalistic bias, we must still conclude that American astronomy was responsible for about half of the major events during the past quarter century. If the British are given most of the credit for the development of radio astronomy in the period 1946-1955, this together with the discovery of pulsars puts them in second place, but a substantial distance behind the Americans.

It is not possible to compile a meaningful listing of major astronomers from the data in the NSF survey; almost all of the twenty-two innovations involved more than one person, and only three astronomers (Sandage, Schwarzschild, Hoyle) participated in more than one of them. If each innovation is weighted by the number of times mentioned, and credit is assigned by dividing that weight by the number of astronomers involved, Penzias and Wilson come out with the highest score.

In its report to Congress, the National Science Board stated that NSF had supported, wholly or in part, 29 percent of the twenty-two innovations in astronomy. Two of the *major* advances discussed above involved NSF support, but that was for only one of the four astronomers involved in the discovery of pulsars (Pacini), and partial support for one of the five who studied X-ray sources (Friedman). Support for the most important discovery in which Americans or American facilities were involved, quasars, can be considered part of the financial as well as scientific legacy of George Ellery Hale since the work was done at the Hale Observatories in California. The rocket research on X-ray sources was sponsored primarily by the United States Air Force while the discovery of background radiation was supported entirely by the Bell Telephone Laboratories as part of a research program related to satellite systems.

That American astronomers have not had to rely entirely on government support of their research is fortunate. A wide variety of reasons for doing and financing astronomy has guaranteed that the enterprise continues after attaining a certain level of success. Americans do not have a unique method for doing astronomy, but in the last hundred years they seem to have been able to stimulate and combine better than other cultures the essential factors for success: creative thinking, hard work, money and organizations that could utilize all available talent, female as well as male.

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notes

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1. A. Hunter Dupree, "The History of American Science—A Field Finds Itself," *American Historical Review* 71 (1966), 863-874; Arthur M. Schlesinger, "An American Historian Looks at Science and Technology," *Isis* 36 (1946), 162-166; George Sarton, "Is it Possible to Teach the History of Science?" *A Guide to the History of Science* (Waltham, Mass., 1952), 60 (quoted by Dupree, *op. cit.*, 865).

2. Dupree, *op. cit.*, 863.

3. ". . . there is no such thing as American history alone. Who believes, for example, in a separate intellectual entity known as 'American science'? Certainly not my colleague who teaches a history course so labelled at a nearby university . . . ," Walter [now Susan] F. Cannon, "History at the Smithsonian," *Smithsonian Journal of History* 1 (1966), 65-72.

4. Richard B. Morris, ed., *Encyclopedia of American History,* Bicentennial Edition (New York, 1976), 783-787. The list of 500 Notable Americans includes thirty-three scientists but none of them are astronomers, with the possible exception of Benjamin Banneker who is identified as a "mathematician and astronomer" though not credited with any original contributions to either field. (*Ibid.*, 969, 979.) The "popular U.S. History textbooks" examined were: S. E. Morison and H. S. Commager, *The Growth of the American Republic,* Vol. 2 (New York, 1962); N. M. Blake, *A History of American Life and Thought* (New York, 1963); S. E. Morison, *The Oxford History of the American People* (New York, 1965); Richard Hofstadter, William Miller and Daniel Aaron, *The Structure of American History,* second edition (Englewood Cliffs, N.J., 1973); John M. Blum, Edmund S. Morgan, Willie Lee Rose, Arthur M. Schlesinger, Jr., Kenneth M. Stampp and C. Vann Woodward, *The National Experience: A History of the United States,* third edition (New York, 1973); Richard N. Current, T. Harry Williams and Frank Freidel, *American History: A Survey,* fourth edition (New York, 1975); Robert Kelley, *The Shaping of the American Past* (Englewood Cliffs, N.J., 1975).

George H. Daniels, *Science in American Society: A Social History* (New York, 1971); "Acknowledgment," *Science* 175 (1972), 124-125.

5. The procedure used was:

(1) Search for *all* available books on history of astronomy which covered the fifty-year period.

(2) Eliminate those by American authors. Two partial exceptions were made: Otto Struve and Gerard de Vaucouleurs were born in Russia and France, respectively, and came to the United States as adults; both make a serious effort to give proper credit to scientists from all countries in their works on the history of astronomy cited below.

(3) In reading each book, compile a preliminary list of up to ten discoveries which the author seems to consider most important for each period. After a preliminary list of about fifteen discoveries is prepared by combining these lists, it is necessary in some cases to go back to check whether an author mentioned at all some discovery that the others considered significant. Then, for each author, the most important discovery in the period is counted fifteen points, next ten, then nine, eight, etc. down to two points for tenth (if he mentions that many); all others mentioned are given one point. The reason for this particular assignment of points is that most authors give the impression that one discovery in a period is significantly more important than any others. "Importance" is estimated by order of appearance, space devoted to topic and use of qualitative adjectives.

(4) A separate list is maintained for names of all astronomers mentioned regardless of what discoveries they made; the same procedure as above is used to compute the rank order of importance, but somewhat greater weight is given to the amount of space devoted to the person.

Other aspects of the methodology are presented in the text. It is obviously desirable to secure an independent replication of the results before they are taken seriously.

Table 1 is based on the following sources: Agnes Clerke, *A Popular History of Astronomy during the Nineteenth Century,* 4th ed. (London, 1902); A. S. Eddington, "A Century of Astronomy, *Nature* 105 (1922), 815-817; H. C. King, *Exploration of the Universe: The Story of Astronomy* (London, 1964); Patrick Moore, *The Development of Astronomical Thought*

(Edinburgh, 1969); A. Pannekoek, *A History of Astronomy* (New York, 1961) [translated from *De Groei van ons Werelbeeld* (Amsterdam, 1951)]; Charles-Albert Reichen, *A History of Astronomy* (Geneva, 1963); Rudolf Thiel, *And There was Light: The Discovery of the Universe* (New York, 1957) [translated from *Und es ward Licht* (Hamburg, 1956)]; Gerard de Vaucouleurs, *Discovery of the Universe* (New York, 1957). Table 2 is based on the Clerke and Vaucouleurs books, and also Giorgio Abetti, *The History of Astronomy* (New York, 1952) [translated from Italian]; Angus Armitage, *A Century of Astronomy* (London, 1950); and H. MacPherson, *Makers of Astronomy* (Oxford, 1933).

Table 3 is based on the works of Armitage, Clerke, Eddington, King, Moore, Pannekoek, Reichen, Thiel and Vaucouleurs, and also Reginald L. Waterfield, *A Hundred Years of Astronomy* (New York, 1938); and Ernst Zinner, *Astronomie: Geschichte ihrer Probleme* (Munchen, 1961). Table 4 is based on the books of Abetti, Armitage, Clerke, MacPherson, and Vaucouleurs, and also W. Alfred Parr, "A Short History of Astronomy," in T. E. R. Phillips and W. H. Steavenson, eds., *Hutchinson's Splendour of the Heavens,* Vol. II (London, 1923), 972-976.

Table 5 is based on the books of Abetti, Armitage, King, Moore, Pannekoek, Reichen, and Vaucouleurs *(op cit.),* on Otto Struve and Velta Zebergs, *Astronomy of the 20th Century* (New York, 1962) and on H. Spencer Jones, "Astronomy," in A. E. Heath, ed., *Scientific Thought in the Twentieth Century* (London, 1951), 57-78. Table 6 is based on the works of Abetti, Armitage, Struve and Vaucouleurs.

Attention should be called to the list of important twentieth-century discoveries published by the native-born American astronomer Harlow Shapley, but his list is not very much different from Table 5; he gives more weight to relativity, the theory of evolution of chemical elements, the discovery of Pluto and the discovery of magnetic fields in sunspots (the last two being American contributions). See his articles, "Astronomical Highlights of the Half-Century," *Review of Popular Astronomy* 56 (Jan.-Feb., 1962), 28-30, and (with similar titles) *Irish Astronomical Journal* 5 (1959), 190-194; *Science Newsletter* (Nov. 25, 1961), 350. Shapley's list was originally prepared, with advice from his colleagues, for the purpose of compiling his *Source Book in Astronomy 1900-1950* (Cambridge, Mass., 1960) and therefore should be taken as a serious attempt to evaluate the major astronomical events in this period.

6. The phrase was originally used by Herbert Butterfield in his critique of the writing of British constitutional history, to describe the tendency of historians to judge events on the basis of whether they represented progress toward liberal democracy; see *The Whig Interpretation of History* (London, 1931). In recent years historians of science have used "whiggism" as a label for the tendency of scientists to judge historical events and earlier scientists on the basis of present-day theories. See, for example, H. F. Kearney, *Science and Change 1500-1700* (New York, 1971), 17-22; his book illustrates the dangers of the opposite extreme, philosophising about science without understanding its technical aspects.

Another way in which whiggism might distort these lists is suggested by the following comment of a referee: "The lists of major astronomers could be characterized more as lists of the discoveries of major phenomena than as lists necessarily of the most eminent professional astronomers of their time, especially for the early periods. Airy in England is an example of a prominent professional left out. Probably there was some general tendency for professional astronomers to be engaged in routine star surveys, leaving it to amateurs and to less fully engaged professionals to make more often the startling new discoveries, especially when amateurs led in the development of new instruments up to the twentieth century."

7. Stephen G. Brush, "A Geologist among Astronomers: The Rise and Fall of the Chamberlin-Moulton Cosmogony," *Journal for the History of Astronomy* 9 (1978), 1-41, 77-104.

8. A. Fowler, "Spectroscopic Astronomy," *Nature* 104 (1919), 234-235. F. W. Dyson, "Advances in Astronomy" (lecture in 1921), *Royal Institution Library of Science,* Vol. 2 (New York, 1970), 239-242. Thiel (*op. cit.*, note 5), 318-321. Remarks about the superiority of foreign facilities are sometimes motivated by a desire to obtain more support for enterprises at home, rather than by objective judgment; what is significant is that the British and Germans began to point to Americans rather than each other for this purpose.

9. Silvio A. Bedini, *The Life of Benjamin Banneker* (New York, 1972). I have deliberately omitted all of the earlier history of American astronomy. For a general survey, see *Astronomy* 4 (July 1976). A concise but comprehensive account of developments in the early nineteenth century has recently been published by Deborah Jean Warner, "Astronomy in Antebellum America," in N. Reingold, ed., *The Sciences in the American Context: New Perspectives* (Washington, D.C., 1979), 55-75. She argues that the 1834 publication of John Herschel's *Treatise on Astronomy* was an important stimulus to astronomical activity in the United States.

10. Deborah Jean Warner, *Alvan Clark & Sons: Artists in Optics* (Washington, D.C., 1968).

11. William Huggins, "The New Astronomy: A Personal Retrospect," *The Nineteenth Century* 41 (1897), 907-929.

12. Donald Fleming, *John William Draper and the Religion of Science* (Philadelphia, 1950). On Draper's role in the history of the radiation law see S. G. Brush, *The Kind of*

Motion We Call Heat (Amsterdam, 1976), 480-481, 514. See also Daniel Norman, "John William Draper's Contribution to Astronomy," *The Telescope* 5 (1938), 11-16.

13. Charles A. Whitney, "Draper, Henry," *Dictionary of Scientific Biography* 4 (1971), 178-181. Bessie Zaban Jones and Lyle Gifford Boyd, *The Harvard College Observatory: The First Four Directorships 1838-1919* (Cambridge, Mass., 1971). Howard Plotkin, "Edward C. Pickering, the Henry Draper Memorial, and the Beginnings of Astrophysics in America," *Annals of Science* 35 (1978), 365-377.

14. Deborah Jean Warner, "Lewis M. Rutherfurd: Pioneer Astronomical Photographer and Spectroscopist," *Technology and Culture* 12 (1971), 190-216.

15. Jones and Boyd, *op. cit.*, Chapter XI. Mrs. M. Fleming, "A Field for Woman's Work in Astronomy," *Astronomy and Astro-Physics* 12 (1893), 683-689.

16. Phebe Mitchell Kendall, *Maria Mitchell: Life, Letters, Journals* (Freeport, N.Y., 1971 [reprint of 1896 ed.]). Helen Wright, *Sweeper in the Sky* (New York, 1949).

17. Ronald L. Numbers, "The American Kepler: Daniel Kirkwood and his Analogy," *Journal for the History of Astronomy* 4 (1973), 13-21.

18. Daniel Kirkwood, "On the Nebular Hypothesis, and the Approximate Commensurability of the Planetary Periods," *Monthly Notices of the Royal Astronomical Society* 29 (1869), 96-102. Brian G. Marsden, "Kirkwood, Daniel," *Dictionary of Scientific Biography* 7 (1973), 384-387.

19. Daniel Kirkwood, "On Certain Harmonies of the Solar System," *American Journal of Science*, ser. 2, 38 (1864), 1-18. Kirkwood suggested that the tidal force of the sun acting on a fluid proto-planet, whatever might be its original direction of rotation, would force it into synchronous rotation and revolution (like that of the moon); this would amount to a slow rotation in the forward direction (i.e. the same as the direction of orbital motion) which would be accelerated on further cooling and contraction of the planet. Cf. G. P. Kuiper, "On the Origin of the Solar System," in J. A. Hynek, ed., *Astrophysics* (New York, 1951), 403.

20. Another theorist was Jonathan Homer Lane (1819-1880). While working at the Office of Weights and Measures (later the National Bureau of Standards), he studied the thermodynamics of a hot gaseous sphere contracting under the action of its own gravity. He showed that as the sphere radiates heat into space it contracts, but the heat generated by the contraction exceeds that lost by radiaion so it gets hotter. This result was an important step in the developmnt of the theory of stars, but Lane never followed it up after publishing his one paper on the subject in 1870. N. Reingold, "Lane, Jonathan Homer," *Dictionary of Scientific Biography* 8 (1973), 1-3; T. J. J. See, "Historical Sketch of J. Homer Lane," *Popular Astronomy* 14 (1906), 193-206; A. J. Meadows, *Early Solar Physics* (Oxford, 1970), 81, 257-276 [reprint of Lane's paper in *American Journal of Science*].

21. Norriss S. Hetherington, "Cleveland Abbe and a View of Science in Mid-Nineteenth-Century America," *Annals of Science* 33 (1976), 31-49. As late as 1896, G. W. Hill complained that American libraries still lacked the most important European books and memoirs in his special field; see "Remarks on the progress of celestial mechanics since the middle of the century," *Bulletin of the American Mathematical Society, Series* 2, ? (1896), 125-136. Abbe's failure may be contrasted with the success of another American who managed to overcome similar difficulties in the same period; see Arthur Norberg, "Simon Newcomb's Early Astronomical Career," *Isis* 69 (1978), 209-225.

Further information on this subject may be found in Marc Rothenberg's Ph.D. Dissertation, *The Educational and Intellectual Background of American Astronomers*, Bryn Mawr College, 1974. There are interesting remarks on the popularization of astronomy in the article by Jeanne E. Bishop, "United States Astronomy Education: Past, Present, and Future," *Science Education* 61 (1977), 295-305.

22. Deborah Jean Warner, "The American Photographical Society and the Early History of Astronomical Photography in America," *Photographic Science and Engineering* 11 (1967), 342-347. Daniel Norman, "The Development of Astronomical Photography," *Osiris* 5 (1938), 560-594. David F. Musto, "A Survey of the American Observatory Movement, 1800-1850," *Vistas in Astronomy* 9 (1967), 87-92. Elias Loomis, *The Recent Progress of Astronomy; Especially in the United States* (New York, 1850), Chapter IV; "Astronomical Observatories in the United States," *Harper's New Monthly Magazine* 13 (1856), 25-52. Robert P. Multhauf, "Holcomb, Fitz, and Peate: Three 19th-Century American Telescope Makers," *U.S. National Museum Bulletin* 228 (1962), 155-184. W. C. Rufus, "Astronomical Observatories in the United States Prior to 1848," *Scientific Monthly* 19 (1924), 120-139. D. B. Hermann, "Zur Statistik von Sternwartengruendungen im 19. Jahrhundert," *Die Sterne* 49 (1973), 48-52. Trudy E. Bell, "History of Astrophotography," *Astronomy* 4 (July 1976), 66-79.

23. Simon Newcomb, "Some Aspects of American Astronomy," in R. M. La Follete, ed., *The Making of America*, Vol. 7 (Chicago, 1906), 80. A similar metaphor for the scientist's motivation can be found in Bishop Sprat's *History of the Royal Society* (London, 1667; reprinted, St. Louis, Missouri, 1958), 344.

24. Of 166 asteroids known, forty-nine were discovered in the United States. Charles A.

Young, "Address of the Vice President, Section A," *Proceedings of the American Association for the Advancement of Science* 25 (1876), 35-48.

25. Donald E. Osterbrock, "The California-Wisconsin Axis in American Astronomy," *Sky and Telescope* 51 (1976), 9-14, 91-97. On the relations between professionals and amateurs see Marc Rothenberg, "Reorganizing American astronomy, 1897-1911," presented at the XV International Congress of History of Science, Edinburgh, 1977 (in press). As late as 1891 an amateur associated with a major observatory could make an important discovery. S. C. Chandler, an actuary employed by a life insurance company who was a "volunteer observer" at Harvard, established the 14-month period of the free nutation of the Earth's axis ("Chandler wobble"). See Solin I. Bailey, *The History and Work of Harvard Observatory 1839 to 1927* (New York, 1931), 266-267. E. C. Pickering also encouraged systematic observation of variable stars by amateurs (*ibid.*, 189).

26. Hall, the son of a Connecticut clock manufacturer, attended Central College in McGrawville, New York, where "he met Chloe Angeline Stickney, a frail but determined suffragist, who taught mathematics while completing her senior year. Hall was among her pupils, and she soon became his fiancee." After their marriage he studied astronomy and in 1862 found a job at the Naval Observatory. "A year after his arrival, a professorship in mathematics opened at the Naval Observatory. Hall, believing the office should seek the man, simply waited, but unknown to him, his wife proposed his name by letter to the superintendent of the observatory, and Hall was given the position."—Owen Gingerich, "Hall, Asaph," *Dictionary of Scientific Biography* 6 (1972), 48-50. According to Angelo Hall, Chloe sacrificed her own plans for a scientific career in order to promote her husband's; see *An Astronomer's Wife* (Baltimore, 1908).

Owen Gingerich, "The Satellites of Mars: Prediction and Discovery," *Journal of the History of Astronomy* 1 (1970), 109-115.

27. Norriss S. Hetherington, "Lowell's Theory of Life on Mars," *Leaflets of the Astronomical Society of the Pacific* No. 501 (March 1971). A. Lawrence Lowell, *Biography of Percival Lowell* (New York, 1935). Brian G. Marsden, "Lowell, Percival," *Dictionary of Scientific Biography* 8 (1973), 520-523. William Graves Hoyt, *Lowell and Mars* (Tucson, 1976). According to a recent psychoanalytic interpretation, Lowell's observation of the Mars canals was the result of sublimated voyeuristic impulses and unresolved oedipal conflicts. See Charles K. Hofling, *British Journal of Medical Psychology* 37 (1964), 33-42.

28. Marsden, *op. cit.* Clyde W. Tombaugh, "Reminiscences of the Discovery of Pluto," *Sky and Telescope* 19 (1960), 264-270. William Stuckey, "The Man who Discovered Planet X," *Science Digest* 78 (2) (August 1975), 54-61. Morton Grosser, "The Search for a Planet Beyond Neptune," *Isis* 55 (1964), 163-183.

29. Howard S. Miller, *Dollars for Research: Science and its Patrons in Nineteenth-Century America* (Seattle, 1970), Chapter 5.

30. E. G. Gudde, "A Century of Astronomy and Geodesy in California," in *A Century of Progress in the Natural Sciences 1853-1953* (San Francisco, 1955), 65-74. Owen Gingerich, "James Lick's Observatory," *Pacific Discovery* 31 (February 1978), 1-10.

31. His spectrographic proof that Saturn's rings are composed of small particles (Table 3) was accomplished during a seven-year absence from Lick as Director of the Allegheny Observatory. For further information on Keeler see Sally H. Dieke, "Keeler, James Edward," *Dictionary of Scientific Biography* 7 (1973), 270-271; Donald E. Osterbrock, "James E. Keeler, pioneer astrophysicist," *Physics Today* 32 (1979), 40-47.

32. Helen Wright, *Explorer of the Universe: A Biography of George Ellery Hale* (New York, 1966). Helen Wright, Joan N. Warnow and Charles Weiner, eds., *The Legacy of George Ellery Hale* (Cambridge, 1972). R. H. Kargon, "Temple to Science: Cooperative Research and the Birth of the California Institute of Technology," *Historical Studies in the Physical Sciences* 8 (1977), 3-31.

33. C. F. Bartholomew has announced a doctoral dissertation at London University on "A Critical Assessment of the Contribution of G. E. Hale (1868-1938) to the Progress of Research in Solar Physics During the Period 1890-1930." See also Robert Howard, "Research on Solar Magnetic Fields from Hale to the Present," in *The Legacy of George Ellery Hale*, 257-265.

34. Auguste Comte, *Cours de Philosophie Positive*, Vol. 2 (Paris, 1968), 280-281 [originally published in 1835]. Harriet Martineau's English edition of 1853 renders Comte's pronouncement as follows: "The field of positive philosophy lies wholly within the limits of our solar system, the study of the universe being inaccessible in any positive sense." This is immediately followed by a note, by J. P. N[ichol]: "As before remarked, M. Comte speaks much too absolutely here, in oversight of what modern astronomical researchers have really accomplished." —*The Positive Philosophy of Auguste Comte* (New York, 1855), 189.

35. On the rise of astrophysics in America see D. B. Herrmann, "Zur Fruehentwicklung der Astrophysik in Deutschland und in den USA," *NTM, Zeitschrift fuer Geschichte der Naturwissenschaften, Technik und Medizin* 10 (1973), 38-44; Michael Mendillo, David DeVorkin, and Richard Berendzen, "Astrophysics is born: 1840-1900," *Astronomy* 4 (7) (July 1976), 50-63.

36. Helen Wright, *Explorer of the Universe*, 98.

37. Andrew Carnegie, "The Best Fields for Philanthropy," *North American Review* 149 (1889), 682-698, 687; reprinted in E. C. Kirkland, ed., *The Gospel of Wealth and other Timely Essays* (Cambridge, Mass., 1962).

38. A. S. Eddington, *op. cit.* (Note 5). The others were #1 and #2 in my Table 1, #2 and #7 in Table 3, and #9 in Table 5. See D. H. DeVorkin, "Michelson and the problem of stellar diameters," *Journal for the History of Astronomy* 6 (1975), 1-18.

39. "Miss Mary Bird's Resignation," *Popular Astronomy* 14 (1906), 447-448.

40. Jones and Boyd, *op. cit.* (note 13), 188.

41. Mitchell Wilson, *American Science and Invention: A Pictorial History* (New York, 1954), 276.

42. Owen Gingerich, "Fleming, Williamina Paton," *Dictionary of Scientific Biography* 5 (1972), 33-34. In the course of examining photographs, she also discovered ten of the twenty-eight novae recorded by the time of her death.

43. In 1916, the Maria Mitchell Association raised money to establish the "Edward C. Pickering Astronomical Fellowship for Women," and this has encouraged continued entry of women into astronomy. (Jones and Boyd, *op. cit.*, 412-413.) Fleming argued: "While we cannot maintain that in everything woman is man's equal, yet in many things her patience, perseverance and method makes her his superior," (*op. cit.*, note 15, 688).

44. For a critique of the Baconian model of science, see S. G. Brush, "Can Science come out of the Laboratory Now?," *Bulletin of the Atomic Scientists* 32 (April 1976), 40-43.

45. Owen Gingerich, "Maury, Antonia Cateana de Paiva Pereira," *Dictionary of Scientific Biography* 9 (1974), 194-195.

46. Hertzsprung pointed out the importance of Maury's "c" division to E. C. Pickering, and chided him for its omission from the latest Harvard catalog, in a letter dated 22 July 1908 (at Harvard University Archives, quoted in part by Gingerich, *op. cit.*).

47. According to current theory, the sequence is one of decreasing temperature, from greater than 25,000°K for class O to less than 3,500°K for class M. On Cannon, see Owen Gingerich, "Cannon, Annie Jump," *Dictionary of Scientific Biography* 3 (1971), 49-50. In 1919, the British astronomer, H. H. Turner, noting that the classification of stars "has been largely the work" of Annie Jump Cannon, remarked: "I am told that there is a man who can deftly straighten rifle barrels—he gives a glance along the barrel, a tap with a hammer, and lo! it is straight. His value is recognised at some £15 a week. Miss Cannon has the same deftness with the spectra—but I fear that (to judge from the report of the Board of Visitors of Harvard Observatory) her great skill is not so appropriately rewarded." Quoted in "Giant Suns" in *The Royal Institution Library of Science, Astronomy* II (New York, 1970), 232.

48. Helen Buss Mitchell, "Henrietta Swan Leavitt and Cepheid Variables," *The Physics Teacher* 14 (1976), 162-167. Owen Gingerich, "Leavitt, Henrietta Swan," *Dictionary of Scientific Biography* 8 (1973), 105-106.

49. Owen Gingerich, "Shapley, Harlow," *Dictionary of Scientific Biography* 12 (1975), 345-352, and references cited therein; Struve and Zebergs, *op. cit.* (note 5), Chap. XIX. Richard Berendzen, Richard Hart and D. Seeley, *Man Discovers the Galaxies* (New York, 1976).

50. J. D. Fernie, "The Historical Quest for the Nature of the Spiral Nebulae," *Publications of the Astronomical Society of the Pacific* 82 (1970), 1189-1230. Berendzen, Hart and Seeley (*op. cit.*, note 49).

51. G. J. Whitrow, "Hubble, Edwin Powell," *Dictionary of Scientific Biography* 6 (1972), 528-533. J. D. North, *The Measure of the Universe: A History of Modern Cosmology* (Oxford, 1965). Norriss S. Hetherington, *The Development and early Application of the Velocity-Distance Relation*, Ph.D. Dissertation, Indiana University, 1970.

52. Robert W. Seidel, "The Origins of Academic Physics Research in California," *Journal of College Science Teaching* 6 (1976), 10-23.

53. Nathan Reingold, "Definitions and Speculations: The Professionalization of Science in America in the Nineteenth Century," in Alexandra Oleson and Sanborn C. Brown, eds., *The Pursuit of Knowledge in the Early American Republic: American Scientific and Learned Societies from Colonial Times to the Civil War* (Baltimore, 1976), 33-69. Reingold proposes the following definitions on page 38:

"1. *Researchers* are individuals characterized by a single-minded devotion to research, resulting in an expertise yielding an appreciable accomplishment by past standards certainly and in retrospect in some instances. Most, but not all, are in scientific occupations.

"2. *Practitioners* are individuals wholly or largely employed in scientific or science-related occupations. Those who publish are less prolific and less significant in terms of accomplishment than researchers.

"3. *Cultivators* are best described at this point rather than defined . . . ." Lewis M. Rutherfurd is identified as a person who appears at first to be a "cultivator" but must ultimately be classified as a "researcher" (p. 45).

54. Cf. Rachel Laudan, "Ideas and Organizations in British Geology: A Case Study in

Institutional History," *Isis* 68 (1977), 527-538; C. Truesdell, *Essays in the History of Mechanics* (New York, 1968), 300-303.

55. Jeanne E. Bishop, *op. cit.* (note 21) and "The Committee of 10," *Sky and Telescope* 57 (March 1979), 212-214.

56. *Report of the National Science Board to the Subcommittee on Science, Research and Technology of the Committee on Science and Technology, U.S. House of Representatives, regarding Peer Review Procedures at the National Science Foundation.* Report NSB 77-468 (Washington, D.C., November 1977). Carlos E. Kruytbosch (with the assistance of Susan Papenfuss), "Some Social and Organizational Characteristics of Breakthrough Science: An Analysis of Major Innovations in Four Fields of Science, 1950-1976," paper presented at the IX World Congress of Sociology, Uppsala, Sweden, Aug. 17, 1978.

57. Carlos E. Kruytbosch (private communication).

58. John Gribbin, *Our Changing Universe—The New Astronomy* (New York, 1976). Gribbin, a British astronomer who created a popular sensation a few years ago by predicting that Los Angeles would be hit by an earthquake in 1982 [J. R. Gribbin and S. H. Plagemann, *The Jupiter Effect* (New York, 1974)], gives a survey from which I infer the following evaluation of astronomical advances in the period 1951-1975: (1) development of radio astronomy; (2) quasars; (3) pulsars; (4) interstellar molecules; (5) solar neutrinos; (6) X-ray sources; (7) background radiation. These events are, according to the NSF survey: not mentioned; (1.5); (1.5); (5); (7); (3.5); (3.5).