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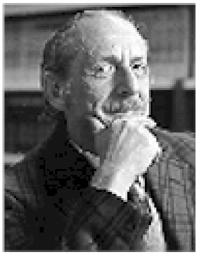

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EUGENE GARFIELD
INSTITUTE FOR SCIENTIFIC INFORMATION®
3501 MARKET ST., PHILADELPHIA, PA 19104

The Most-Cited Physical-Sciences Publications in the 1945-1954 *Science Citation Index*. Part 3. Forty-Two *Citation Classics* in Astronomy and the Earth Sciences

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Last week, Stephen G. Brush, Department of History and Institute for Physical Science and Technology, University of Maryland, College Park, commented on 20 mathematics articles that were most cited in the 1945-1954 cumulation of the *Science Citation Index*®.[1] This continued his discussion of the most-cited physical-sciences publications during this period, the first part of which appeared in *Current Contents*® *(CC*®*)* last May and presented 52 *Citation Classics*® in physics and chemistry.[2]

In the essay that follows, Brush concludes his analysis with a discussion of highly cited articles in astronomy (22 papers) and the earth sciences (20). As in Parts 1 and 2, he compares these high impact articles with other lists of publications deemed "influential" by historians of science. By doing so, he illustrates how historians and scientists interested in the contemporary development of their fields can use quantitative citation data to augment subjective impressions about major trends in contemporary research.

Among these trends in astronomy, Brush discusses the importance of quantum mechanics and research bearing on the origin of the universe as well as chemical elements in the crucial postwar decade. With respect to the earth sciences, under which he includes research on the upper atmosphere and solar-terrestrial interactions, Brush focuses on various topics: "Rossby waves" that influence global weather conditions, seeding clouds for artificial rainmaking, and plate tectonics and continental drift.

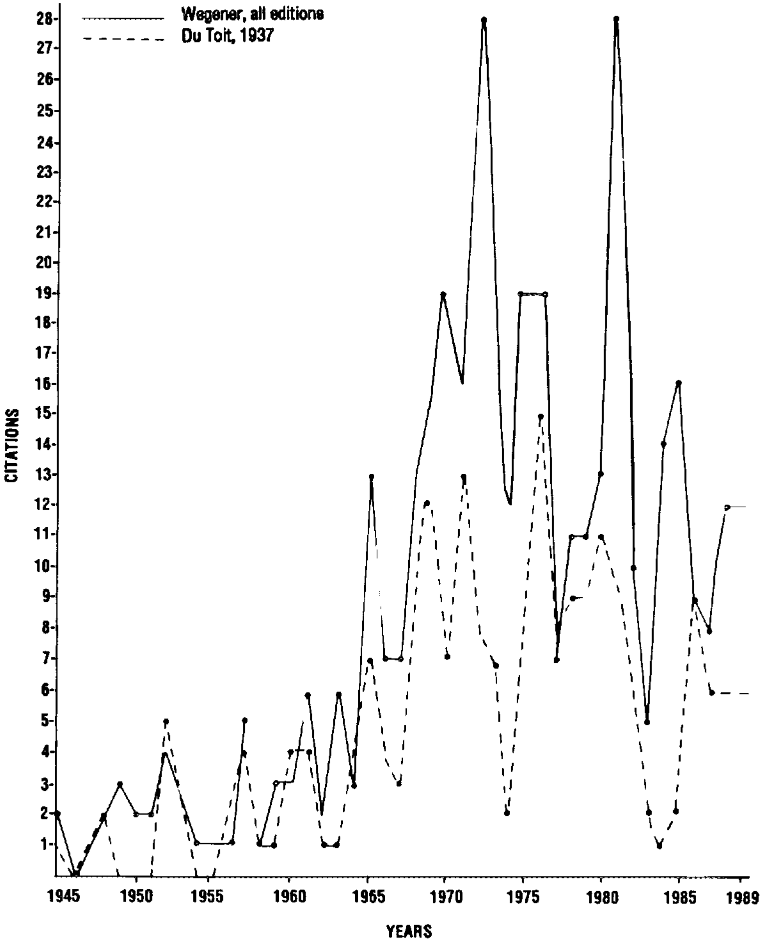
Plate tectonics and continental drift are an interesting example of a resisted or "premature" discovery.[3] In the early 1900s, a German meteorologist, Alfred L. Wegener, proposed that the continents once formed a single land mass, which he called "Pangaea." This land mass broke into continents millions of years ago of which some drifted thousands of miles apart under "pole-fleeing" and lunar-solar tidal forces.[4] In 1915 he described his theory in detail in a book, *Die Entstehung der Kontinente und Oceans* (*The Origin of Continents and Oceans*), which has been published in several languages and was reprinted in 1968.[5]

His theory contradicted the scientific dogma of his time that the continents were fixed. Most geologists resisted Wegener's concept. But the South African geologist Alexander L. Du Toit was one of the more prominent champions of the controversial theory.[6] He presented his own explication of the theory in a 1937 book, *Our Wandering Continents*.[7]

As Brush points out in the following essay, the theory of continental drift was not widely accepted until the 1960s, during the so-called "revolution in the earth sciences." Figure 1 presents a graph of the annual distribution of citations, 1945-1989, to the books by Wegener (387 to all editions) and Du Toit (213). While neither was cited more than six times per year through 1964, citations in 1965 and thereafter increased.

CC readers interested in the earth and geosciences should refer to our earlier citation studies of the most-cited articles and journals in these fields.[8-11] Brush's insights into astronomy and astrophysics can be augmented by previous *CC* essays discussing these fields.[12-14]

Figure 1: Annual distribution of citations, 1945-1989, to key books on continental drift by Alfred L. Wegener and Alexander L. Du Toit. (See references 5 and 7, respectively.)



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2. -------. The most-cited physical-sciences publications in the 1945-1954 *Science Citation Index.* Part 1. *Current Contents* (20):7-17, 14 May 1990.
3. **Garfield E.** Premature discovery or delayed recognition—why? *Essays of an information scientist.* Philadelphia: ISI Press, 1981. Vol. 4. p. 488-93.
4. **Bullen K E.** Wegener, Alfred Lothar. *Dictionary of scientific biography.* New York: Scribner's, 1980. Vol. 14. p. 214-7.
5. **Wegener A.** *The origin of continents and oceans.* London: Methuen, 1968. 248 p.
6. **Wilson J T.** Du Toit, Alexander Logie. *Dictionary of scientific biography.* New York: Scribner's, 1980. Vol. 4. p. 261-3.
7. **Du Toit A L.** *Our wandering continents: an hypothesis of continental drifting.* Edinburgh, UK: Oliver & Boyd, 1937. 366 p.

8. **Garfield E.** Journal citation studies. 10. Geology and geophysics. *Op. cit.*, 1977. Vol. 2. p. 102-6.
9. -------. Journal citation studies. 11. *Journal of Geophysical Research*. *Ibid.* p. 114-7.
10. -------. Journal citation studies. 38. Earth sciences journals: what they cite and what cites them. *Ibid.*, 1983. Vol. 5. p. 791-800.
11. -------. The 1981 geosciences articles most cited from 1981 through 1983. *Ibid.*, 1985. Vol. 7. p. 251-63.
12. -------. Journal citation studies. 12. *Astrophysical Journal* and its *Supplements*. *Ibid.*, 1977. Vol. 2. p. 120-4.
13. -------. Journal citation studies. 43. Astrosciences journals—what they cite and what cites them. *Ibid.*, 1985. Vol. 7. p. 152-63.
14. -------. Training our cites on the stars: Helmut Abt's observations on astrosociology. Parts 1 & 2. *Current Contents* (39):5-11, 24 September 1990; (40):5-11, 1 October 1990.

The Most-Cited Physical-Sciences Publications in the 1945-1954 *Science Citation Index*. Part 3. Astronomy and Earth Sciences

Back to Introduction

Stephen G. Brush
Department of History and
Institute for Physical Science and Technology
University of Maryland
College Park, MD 20742

This essay concludes an examination of the physical-sciences publications most cited in the 1945-1954 *Science Citation Index*® by presenting 42 highly cited papers in astronomy and the earth sciences. In Part 2, the 20 most-cited papers in mathematics were examined, and Part 1 presented 52 chemistry and physics publications.[1,2] These papers are compared with other publications (including some highly cited books) considered important by scientists and historians of science. The essay discusses some of the major trends, achievements, and researchers in these fields in the period including World War II.

Introduction

In Part 1 of this essay, the 52 most-cited physical-sciences publications in the 1945-1954 *Science Citation Index*® (*SCI*®) were presented and discussed.[1] The list of books and articles was composed almost entirely of publications in chemistry (25) and physics (25). There were only two in mathematics, and none in the earth sciences or astronomy.

Rather than omit these fields, ISI® has compiled lists of the articles in mathematics, astronomy, and the earth sciences most cited in the 1945-1954 *SCI*. This compilation allows us to take a look back at a historic period in science and see what papers were *Citation Classics*® during this time. Last week, the most-cited mathematics papers were examined.[2]

In this essay, I discuss highly cited articles in astronomy and the earth sciences. Of course, as noted previously in Parts 1 and 2, one should not simply rely on citation counts as a measure of the importance or quality of a publication. Thus, the lists of most-cited publications are compared with independent judgments of the scientific community (as indicated by prestigious awards, such as the Nobel Prize or Fields Medal, for example) or of historians of science.

Citation Data *vs.* Independent Expert Judgment

Unfortunately, it is not so easy to obtain such judgments for astronomy and the earth sciences as it is for physics, chemistry, and mathematics, since there were no major international prizes that covered these fields in the 1930s and 1940s. While there is no Nobel Prize specifically designated for astronomy, two scientists won the Nobel Prize for physics for astrophysical research done

Table 1: Major publications in astronomy (including astrophysics) during the period 1935-1949. Based on Lang K R & Gingerich O and Struve O & Zebergs V. (See references 3 and 4.) Only items reprinted or mentioned in these sources are included. An asterisk (*) indicates that the paper is included on the list of astronomy papers highly cited in the 1945-1954 *SCI*® (Table 3). A=1945-1954 citations.

A	Bibliographic Data
18	**Alpher R A, Bethe H & Gamow G.** The origin of chemical elements. *Phys. Rev.* 73:803-4, 1948.
2	**Ambartsumian V A.** Expanding stellar associations. *Astron. Zh. SSSR* 26:1-9, 1949.
41	***Baade W.** The resolution of Messier 32, NGC 205, and the central region of the Andromeda nebula. *Astrophys. J.* 100:137-50, 1944.
51	**Bethe H A.** Energy production in stars. *Phys. Rev.* 55:434-56, 1939.
15	**Bolton J G, Stanley G J & Slee O B.** Positions of three discrete sources of galactic radio-frequency radiation. *Nature* 164:101-2, 1949.
14	**Bondi H & Gold T.** The steady-state theory of the expanding universe. *Mon. Notic. Roy. Astron. Soc.* 108:252-70, 1948.
2	**Chandrasekhar S.** The highly collapsed configurations of a stellar mass. (Second paper.) *Mon. Notic. Roy. Astron. Soc.* 95:207-25, 1935.
1	**Chandrasekhar S.** Stellar configurations with degenerate cores. *Mon. Notic. Roy. Astron. Soc.* 95:226-60, 1935.
1	**Chandrasekhar S.** Stellar configurations with degenerate cores. (Second paper.) *Mon. Notic. Roy. Astron. Soc.* 95:676-93, 1935.
21	**Chandrasekhar S & Henrich L R.** An attempt to interpret the relative abundances of the elements and their isotopes. *Astrophys. J.* 95:288-98, 1942.
1	**Edlén B.** An attempt to identify the emission lines in the spectrum of the solar corona. *Ark. Mat. Astron. Fys.* 28B:1-4, 1941.
1	**Gamow G.** Nuclear reactions in stellar evolution. *Nature* 144:575-7, 1939.
16	**Hall J S.** Observations of the polarized light from stars. *Science* 109:166-7, 1949.
23	**Hey J S, Parson S J & Phillips J W.** Fluctuations in cosmic radiation at radio frequencies. *Nature* 158:234, 1946.
17	**Hiltner W A.** Polarization of light from distant stars by the interstellar medium. *Science* 109:165, 1949.
4	**Joy A H.** Rotation effects, interstellar absorption, and certain dynamical constants of the galaxy determined from Cepheid Variables. *Astrophys. J.* 89:356-76, 1939.
10	**Joy A H.** T Tauri variable stars. *Astrophys. J.* 102:168-95, 1945.
43	***Reber G.** Cosmic static. *Astrophys. J.* 100:279-87, 1944.
3	**Seyfert C.** Nuclear emission in spiral nebulae. *Astrophys. J.* 97:28-40, 1943.
6	**Spitzer L.** The dissipation of planetary filaments. *Astrophys. J.* 90:675-88, 1939.
28	***Strömgren B.** The physical state of interstellar hydrogen. *Astrophys. J.* 89:526-47, 1939.
29	***Unsöld A.** Quantitative Analyse des B0-Sternes τ Scorpii. II (The quantitative analysis of the B0-star τ Scorpii, part II). *Z. Astrophys.* 21:22-84, 1942.
3	**van de Hulst H C.** Radio waves from space: origin of radiowaves. *Ned. Tijdschr. Natuurkd.* 11:210-21, 1945.
16	**van de Hulst H C.** The solid particles of interstellar space. *Rech. Astron. Obs. Utrecht Pt. 2* 11:1-50, 1949.
18	**von Weizsäcker C F.** Über Elementumwandlungen im Innern der Sterne. II (Element transformation inside stars. II). *Phys. Z.* 39:633-46, 1938.
0	**von Weizsäcker C F.** Zur Entstehung des Planetensystems (The origin of the solar system). *Naturwissenschaften* 33:8-14, 1946.

before 1955: Hans A. Bethe, Cornell University, Ithaca, New York, and Subrahmanyan Chandrasekhar, University of Chicago, Illinois. William A. Fowler, California Institute of Technology (Caltech), Pasadena, who shared the prize with Chandrasekhar, published most of the work for which he was honored too late to be cited in the period 1945-1954. Martin Ryle and Antony Hewish, University of Cambridge, UK, are coauthors of a highly cited 1950 paper but won the prize primarily for work done later.

To get an idea of the most important publications in astronomy, I used *A Source Book in Astronomy and Astrophysics, 1900-1975*, compiled by Kenneth R. Lang, Tufts University, Boston, Massachusetts, and Owen Gingerich, Harvard University, Cambridge, Massachusetts, together with the book by Otto Struve and Velta Zebergs, National Radio Observatory, Green Bank,

Table 2: Chronologic distribution of publication dates for the astronomy and astrophysics papers most cited in the 1945-1954 *SCI* ® cumulation.

Publication Year	Number of Papers
1935-1939	3
1940-1944	10
1945-1949	7
1950-1954	2

West Virginia, *Astronomy in the 20th Century*.[3,4] Gingerich tells me that he and Lang reviewed a list of the 10 most-cited articles in the *Astrophysical Journal* and decided that most of them were not important enough to be reprinted.[5] On the other hand, they wanted to include some of Chandrasekhar's papers but were refused permission to do so.[6]

Table 1 lists 26 publications that originally appeared in the period 1935-1949, were reprinted or extracted by Lang and Gingerich or mentioned in their section introductions, and were also mentioned by Struve and Zebergs. The reason for selecting the period 1935-1949 is that most of the highly cited astronomy papers were published then, as can be seen in Table 2.

For the earth sciences, in which I include the study of the upper atmosphere and solar-terrestrial interactions, there are no general histories or source books that cover the entire field for the mid-twentieth century. So it is difficult to judge whether the most-cited publications are the most important ones. Only one scientist, Hannes Alfvén, University of California, San Diego, won the Nobel Prize for earth-science research done in the period 1935-1949. Most of his papers in that period appeared in Swedish journals not included in the *SCI* list of source publications. Moreover, the scientific community ignored or rejected most of his work even though many of his ideas were eventually confirmed and have become part of mainstream theories.[7] So it is not surprising that none of his publications were highly cited before 1955. Another Nobel laureate, Irving Langmuir, General Electric Company, Schenectady, New York, is the author of a highly cited paper in meteorology, but he had already received the prize before writing that paper.

Twenty-Two *Citation Classics* in Astronomy: Quantum Mechanics

In Part 1 of this essay, I pointed out the importance of quantum mechanics in several of the *Citation Classics* in chemistry.[1] Quantum mechanics also played an important role in the interpretation of astrophysical observations, as can be seen in the list of 22 astronomy papers most cited in the 1945-1954 *SCI*, which are shown in Table 3.

The spectrum of radiation coming from a star, planet, or interstellar matter can provide information about the physical and chemical state of the atoms emitting and absorbing that radiation—provided one has an adequate theory to explain the emission and absorption of radiation by atoms. Quantum mechanics, together with statistical mechanics, is that theory, as was shown in the 1920s by Cecilia H. Payne, Harvard University, and Henry Norris Russell, Princeton University, New Jersey.[8,9]

The highly cited papers in Table 3 by Walter S. Adams, Mount Wilson Observatory, Carnegie Institution of Washington, Pasadena (1949); Joel Stebbins, Mount Wilson Observatory, and colleagues (1940, 1945); and Gerard P. Kuiper, Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin (1938), provided data. The somewhat less frequently cited papers by Horace W. Babcock, Mount Wilson Observatory (1947); Chandrasekhar (1945); Chandrasekhar and Frances H. Breen, Yerkes Observatory (1946); Bengt Edlén, University of Uppsala, Sweden (1943); Donald H. Menzel, Harvard University, and Chaim L. Pekeris, Massachusetts Institute of Technology (MIT), Cambridge (1936); Simon Pasternack, Caltech (1940); Bengt Strömgren, Copenhagen Observatory, Denmark (1939); and Albrecht Unsöld, University of Kiel, Germany (1942, 1948), provided theoretical interpretations.

Missing from this list of highly cited astronomy papers, however, are the papers by Chandrasekhar identified as the ones for

Table 3: The 22 most-cited papers from astronomy and astrophysics journals covered in the 1945-1954 *SCI*® cumulation. Papers are listed in alphabetic order by first author. A=total number of 1945-1954 citations.

A	Bibliographic Data
26	**Adams W S.** Observations of interstellar H and K, molecular lines, and radial velocities in the spectra of 300 O and B stars. *Astrophys. J.* 109:354-79, 1949.
25	**Adel A.** The grating infrared solar spectrum. VI. The map from 14μ to 7μ . *Astrophys. J.* 94:451-67, 1941.
41	**Baade W.** The resolution of Messier 32, NGC 205, and the central region of the Andromeda nebula. *Astrophys. J.* 100:137-50, 1944.
33	**Babcock H W.** Zeeman effect in stellar spectra. *Astrophys. J.* 105:105-19, 1947.
29	**Chandrasekhar S.** On the continuous absorption coefficient of the negative hydrogen ion. *Astrophys. J.* 102:223-31, 1945.
27	**Chandrasekhar S & Breen F H.** On the continuous absorption coefficient of the negative hydrogen ion. III. *Astrophys. J.* 104:430-45, 1946.
35	**Edlén B.** Die Deutung der Emissionslinien im Spektrum der Sonnenkorona (The interpretation of emission lines in the spectrum of the sun's corona). *Z. Astrophys.* 22:30-64, 1943.
25	**Henyey L G & Keenan P C.** Interstellar radiation from free electrons and hydrogen atoms. *Astrophys. J.* 91:625-30, 1940.
25	**Herzberg G.** Laboratory production of the λ 4050 group occurring in cometary spectra; further evidence for the presence of CH_2 molecules in comets. *Astrophys. J.* 96:314-5, 1942.
26	**Johnson H L & Morgan W W.** Fundamental stellar photometry for standards of spectral type on the revised system of the Yerkes spectral *Atlas*. *Astrophys. J.* 117:313-55, 1953.
47	**Kuiper G P.** The magnitude of the sun, the stellar temperature scale, and bolometric corrections. *Astrophys. J.* 88:429-71, 1938.
32	**Menzel D H & Pekeris C L.** Absorption coefficients and hydrogen line intensities. *Mon. Notic. Roy. Astron. Soc.* 96:77-111, 1936.
26	**Pasternack S.** Transition probabilities of forbidden lines. *Astrophys. J.* 92:129-55, 1940.
43	**Reber G.** Cosmic static. *Astrophys. J.* 100:279-87, 1944.
30	**Ryle M & Hewish A.** The effects of the terrestrial ionosphere on the radio waves from discrete sources in the galaxy. *Mon. Notic. Roy. Astron. Soc.* 110:381-94, 1950.
49	**Stebbins J, Huffer C M & Whitford A E.** The colors of 1332 B stars. *Astrophys. J.* 91:20-50, 1940.
39	**Stebbins J & Whitford A E.** Six-color photometry of stars. III. The colors of 238 stars of different spectral types. *Astrophys. J.* 102:318-46, 1945.
43	**Strömgren B.** On the density distribution and chemical composition of the interstellar gas. *Astrophys. J.* 108:242-75, 1948.
28	**Strömgren B.** The physical state of interstellar hydrogen. *Astrophys. J.* 89:526-47, 1939.
29	**Unsöld A.** Quantitative Analyse des B0-Sternes τ Scorpii. II (The quantitative analysis of the B0-star τ Scorpii, part II). *Z. Astrophys.* 21:22-84, 1942.
28	**Unsöld A.** Quantitative Spektralanalyse der Sonnenatmosphäre (Quantitative spectral analysis of the sun's atmosphere). *Z. Astrophys.* 24:306-29, 1948.
29	**von Weizsäcker C F.** Über die Entstehung des Planetensystems (On the origin of the solar system). *Z. Astrophys.* 22:319-55, 1943.

which he received the Nobel Prize.[10] These papers presented perhaps the most brilliant application of quantum mechanics to astrophysics: the treatment of the degenerate electron gas taking account of relativistic effects, leading to a theory of the stability of white dwarf stars and the prediction of a limiting mass for such stars. The instability of stars more massive than Chandrasekhar's limit may lead to a supernova explosion.

Most of these papers appeared in the journals selected for the preparation of Table 3. But none received more than 24 citations during the 1945-1954 period. The importance of Chandrasekhar's work was not recognized until the 1970s, when it became fully integrated into the modern theory of stellar evolution and was found to provide an essential key to the processes leading to pulsars (neutron stars) and black holes.

The Origin of the Universe and Chemical Elements

Another major research area in astronomy is the origin of the universe and of the chemical elements, represented here by six papers listed in Table 1. Carl F. von Weizsäcker, Kaiser Wilhelm Institute, Berlin, Germany (1938), suggested how light elements might be formed from hydrogen in stars, and Bethe (1939) worked out the theory in more detail. George Gamow, George Washington University, Washington, DC (1939), also contributed to the theory.

The origin of the elements is related to the origin of the universe through the "Big Bang" concept in cosmology. The standard interpretation of the Hubble velocity-distance relation is that the universe is expanding as galaxies move away from each other, having originally been concentrated in a small region of space. According to Gamow and his colleagues, the expansion started with a state of extremely high density and temperature, in which all matter was in the form of protons, neutrons, and electrons. As it cools, the heavier elements are formed by fusion reactions, perhaps along the lines suggested by von Weizsäcker and Bethe.

The authors of the fundamental paper on the synthesis of chemical elements following the Big Bang were listed as Ralph A. Alpher, Johns Hopkins University, Baltimore, Maryland; Bethe; and Gamow (1948) so they could call it the "$\alpha \beta \gamma$" theory. Bethe agreed to be listed as coauthor *in absentia* for the sake of the pun.

The use of Hubble's relation led to a basic difficulty: the "age" of the universe (time elapsed since the Big Bang) came out to be only two billion years, less than the age of the earth as determined by radiometric dating. This difficulty gave an opportunity for Hermann Bondi and Thomas Gold, University of Cambridge (1948), to propose their alternative "steady-state" theory, in which new matter is continually created rather than being created all at once. But the difficulty was resolved in a less sensational way thanks to research by Walter Baade, Mount Wilson Observatory (1944), reported in the only one of these six papers that appears on the most-cited list in Table 3.

Baade's resolution of individual stars in the galaxy Messier 32 led eventually to a revision of the astronomical distance and time scales. By 1952 it appeared that the galaxies were at least twice as far away as had previously been believed, and the universe must therefore be twice as old. Subsequent revisions of the distance and time scales extended the age of the universe to more than 10 billion years, while estimates of the age of the earth stabilized at about 4.5 billion years after 1953.[4,11]

The Most-Cited *vs.* the Most-Influential Astronomy Publications

Comparing Tables 1 and 3 shows that only four of the items considered "influential" by Lang-Gingerich and Struve-Zebergs also appear on the list of most-cited publications in astronomy journals. Note, however, that the list of most-cited papers does not include general science journals such as *Nature*, *Science*, and *Naturwissenschaften*, or physics journals such as *Physical Review*. Thus, 10 of the 26 Table 1 papers could not have appeared in Table 3 because they were not published in "astronomy" journals. On the other hand, von Weizsäcker's paper in Table 3 was a longer version of the 1946 paper that appears in Table 1 and should therefore be counted as a most-cited paper judged to be important by Lang and Gingerich.

The result of this analysis is that 25 percent (4 out of 16) of the papers published in astronomy journals judged to be important both by Lang-Gingerich and Struve-Zebergs appear on the list of the 22 most-cited papers in those journals. Another seven papers are by authors who published other papers that are on the most-cited list. Conversely, of the 22 most-cited papers, 4 (18 percent) are on the Lang-Gingerich and Struve-Zebergs list, and another 7 are by authors of the papers on that list.

Even the most highly cited papers in astronomy average no more than five or six citations per year. The careful reader of Table 3 will notice that one paper—"Fundamental stellar photometry for standards of spectral type on the revised system of the Yerkes spectral *Atlas*" by Harold L. Johnson, Yerkes Observatory, and William W. Morgan, McDonald Observatory, University of Texas at Austin, Fort Davis—was cited at a much higher rate since it was published in 1953. This paper is the only astronomy publication included among the 250 most-cited *Citation Classics* for the following decade, 1955-1964, when it received 342 citations.[12]

Twenty *Citation Classics* in the Earth Sciences: Meteorology and Geology

Table 4 lists the 20 papers from earth-sciences journals that were most cited in the 1945-1954 *SCI*. The highest impact paper, with 49 citations, was an analysis of motions in the atmosphere by the Swedish meteorologist Carl-Gustaf A. Rossby (b. 1898–d. 1957) and his collaborators at MIT. This is one case in which the most frequently cited paper in a field is one of the most important original research contributions (in part a rediscovery and interpretation of work by S.S. Hough, University of Cambridge, in 1897) in that period.[13,14] According to meteorology historian Gisela Kutzbach, University of Wisconsin, Madison:

> Rossby was instrumental in bringing American meteorology to a position of world leadership.... In connection with a project on long-range forecasting started in 1935, he began to investigate the circumpolar system of long waves, now called Rossby waves, in the westerly winds of the middle and upper troposphere. These waves exert a controlling influence on weather conditions in the lower troposphere. Rossby developed a dynamic theory of these long waves...and derived a simple formula, now called the Rossby equation, for their propagation speed. This formula became perhaps the most celebrated analytic solution of a dynamic equation in meteorological literature. Rossby's theoretical analysis profoundly influenced both applied and theoretical meteorology and oceanography during subsequent decades.[15]

Rossby's theory has become a standard technique for studying global patterns of fluid motion, in the ocean as well as in the atmosphere.[16-19] It has also been applied to develop hypotheses about hydromagnetic oscillations in the earth's core in order to explain the westward drift of the geomagnetic field.[20,21]

The other highly cited meteorology paper in Table 4 has quite a different character. The American scientist Langmuir (b. 1881–d. 1957), winner of the 1932 Nobel Prize for his work in surface chemistry, had a lifelong interest in weather. During World War II he was involved in projects to generate smoke screens (for concealment from enemy aircraft) and to deice airplane wings.[22]

After the war his colleague at General Electric, Vincent Schaefer, discovered that the condensation of supercooled water vapor could be triggered by "dry ice" (solid carbon dioxide). One of Langmuir's assistants at General Electric, Bernard Vonnegut, subsequently found that crystals of silver iodide were more convenient for this purpose. Langmuir enthusiastically pursued the theoretical analysis and experimental testing of schemes for artificial rainmaking. His highly cited 1948 paper presents the results of this research with numerous suggestions for further work. Langmuir's research helped to transform weather modification from a dubious art to a progressive science, though not as yet a very exact one.[23-26]

Langmuir stressed the importance of what he called "divergent phenomena" in nature—very large effects can be triggered by very small causes.[20] For this reason he warned, at the end of his 1948 paper, that it may never be possible to forecast the weather with great accuracy. This is now known, thanks to "chaos theory," as the "Butterfly Effect"—"a butterfly stirring the air today in Peking can transform storm systems next month in New York."[27]

For some critics the hazards of divergent phenomena were illustrated by one of Langmuir's own experiments. On October 13, 1947, a hurricane moving northeastward in the Atlantic Ocean was seeded with dry ice. Shortly afterwards it changed course and headed west, striking the coast of South Carolina and Georgia, doing considerable damage to Savannah. It is not known for certain whether the seeding caused the change of course; a detailed analysis 10 years later concluded that the shift was the

Table 4: The 20 most-cited papers from earth-sciences journals covered in the 1945-1954 *SCI*® cumulation. Papers are listed in alphabetic order by first author. A=total number of 1945-1954 citations.

A	Bibliographic Data
28	**Barshad I.** Vermiculite and its relation to biotite as revealed by base exchange reactions, x-ray analyses, differential thermal curves, and water content. *Amer. Mineral.* 33:655-78, 1948.
31	**Bowen N L & Schairer J F.** The system, $FeO\text{-}SiO_2$. *Amer. J. Sci.* 24:177-213, 1932.
38	**Bowen N L & Schairer J F.** The system, $MgO\text{-}FeO\text{-}SiO_2$. *Amer. J. Sci.* 29:151-217, 1935.
29	**Bowen N L & Tuttle O F.** The system $MgO\text{-}SiO_2\text{-}H_2O$. *Geol. Soc. Amer. Bull.* 60:439-60, 1949.
32	**Bowen N L & Tuttle O F.** The system $NaAlSi_3O_8\text{-}KAlSi_3O_8\text{-}H_2O$. *J. Geol.* 58:489-511, 1950.
35	**Flint R F & Deevey E S.** Radiocarbon dating of late-Pleistocene events. *Amer. J. Sci.* 249:257-300, 1951.
37	**Greig J W.** Immiscibility in silicate melts. *Amer. J. Sci.* 13:1-44, 1927.
45	**Grim R E.** Modern concepts of clay materials. *J. Geol.* 50:225-75, 1942.
30	**Grim R E, Bray R H & Bradley W F.** The mica in argillaceous sediments. *Amer. Mineral.* 22:813-29, 1937.
44	**Grim R E & Rowland R A.** Differential thermal analysis of clay minerals and other hydrous materials. Part 1. *Amer. Mineral.* 27:746-61, 1942.
37	**Grim R E & Rowland R A.** Differential thermal analysis of clay minerals and other hydrous materials. Part 2. *Amer. Mineral.* 27:801-18, 1942.
28	**Hendricks S B & Jefferson M E.** Polymorphism of the micas with optical measurements. *Amer. Mineral.* 24:729-71, 1939.
28	**Kerr P F & Kulp J L.** Multiple differential thermal analysis. *Amer. Mineral.* 33:387-419, 1948.
34	**Langmuir I.** The production of rain by a chain reaction in cumulus clouds at temperatures above freezing. *J. Meteorol.* 5:175-92, 1948.
28	**Penndorf R.** The vertical distribution of atomic oxygen in the upper atmosphere. *J. Geophys. Res.* 54:7-38, 1949.
32	**Ramsdell L S.** Studies on silicon carbide. *Amer. Mineral.* 32:64-82, 1947.
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27	**Taber S.** Perennially frozen ground in Alaska: its origin and history. *Geol. Soc. Amer. Bull.* 54:1433-548, 1943.
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result of natural causes.[28] But the incident forced Langmuir to be much more cautious in carrying out his ambitious schemes for weather modification.

Geology Before the Revolution

If asked to identify the most important publications in geology and geophysics before 1950, earth scientists and historians of science would probably mention those that played an important role in the "revolution in the earth sciences" leading to the establishment of plate tectonics in the 1960s.[29,30] A list compiled from this postrevolutionary viewpoint might look something like Table 5. But none of those works appear on the list of publications in earth-sciences journals most frequently cited in the decade 1945-1954 in Table 4.

One could regard this as evidence that the latter were of no permanent value to science. But some are still cited in the geological literature of the 1980s, so this is not a fair judgment. Instead, we might suspect that, as a result of the revolution itself, scientists' judgments about what research findings are most significant have changed; they see the world in a different way.[31]

Judging the past in terms of present knowledge is a well-known feature of the way scientists look at history. Historians call it the "Whig interpretation" of the history of science. Here is where citation data can help the historian who wants to avoid whiggishness, by pointing to research that was highly cited in its own day but now likely to be overlooked because of changed paradigms.

Although a few geologists such as Arthur Holmes, University of Edinburgh, UK, and South African Alexander L. Du Toit ac-

Table 5: Major publications in earth science (geology/geophysics) during the period 1935-1949, according to writers on the "revolution in the earth sciences." Based on Glen W, LeGrand H E, and Marvin U. (See references 29, 30, and 33.) Only works prominently mentioned in two or more of these sources are included. A=1945-1954 citations.

A	Bibliographic Data
23	**Bullard E C.** The magnetic field within the earth. *Proc. Roy. Soc. London Ser. A* 197:433-53, 1949.
11	**Du Toit A L.** *Our wandering continents: an hypothesis of continental drifting.* Edinburgh, UK: Oliver & Boyd, 1937. 366 p.
22	**Elsasser W M.** Induction effects in terrestrial magnetism. I. Theory. *Phys. Rev.* 69:106-16, 1946.
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20	**Elsasser W M.** Induction effects in terrestrial magnetism. III. Electric modes. *Phys. Rev.* 72:821-33, 1947.
7	**Graham J W.** The stability and significance of magnetism in sedimentary rocks. *J. Geophys. Res.* 54:131-67, 1949.
0	**Gutenberg B.** Structure of the earth's crust and the spreading of the continents. *Geol. Soc. Amer. Bull.* 47:1587-610, 1936.
19	**Hess H H.** Drowned ancient islands of the Pacific basin. *Amer. J. Sci.* 244:772-91, 1946.
17	**Holmes A.** *Principles of physical geology.* London: Nelson, 1944. 532 p.
17	**Néel L E F.** Théorie du trainage magnétique des ferromagnétiques au grains fins avec applications aux terres cuites (Theory of the magnetic drag of fine grain ferromagnetism with applications to baked earth). *Ann. Geophys.* 5:99-136, 1949.
3	**Vening Meinesz F A.** *Gravity expeditions at sea. Volume 1.* Delft, The Netherlands: Waltman, 1932.
17	**Vening Meinesz F A, Umbgrove J H & Kuenen P H.** *Gravity expeditions at sea. Volume 2.* Delft, The Netherlands: Waltman, 1934.
2	**Vening Meinesz F A.** *Gravity expeditions at sea. Volume 3.* Delft, The Netherlands: Waltman, 1941.
4	**Vening Meinesz F A.** *Gravity expeditions at sea. Volume 4.* Delft, The Netherlands: Waltman, 1948.
2	**Willis B.** Continental drift: ein Märchen. *Amer. J. Sci.* 242:509-13, 1944.

cepted the German geophysicist Alfred L. Wegener's theory of continental drift, the majority view during the 1930s-1950s was that the continents are fixed in position, aside from relatively small up-and-down motions. The gravity measurements of Felix A. Vening Meinesz, University of Delft, The Netherlands, revealed anomalies that were eventually explained with the help of plate tectonics. Research in paleomagnetism suggested that the earth's magnetic field had completely reversed itself several times in the past several million years. This evidence was not taken seriously until Louis E.F. Néel, Faculty of Science, Grenoble, France, showed that it could not be interpreted as spontaneous self-reversal within the rock, and a possible mechanism for reversal was suggested by the dynamo model for terrestrial magnetism by Walter M. Elsasser, Columbia University, New York, and E.C. Bullard, Toronto University, Ontario, Canada.

The most-cited geology paper, "Modern concepts of clay materials" by Ralph Early Grim, then with the Illinois State Geological Survey, is also the only one reprinted in the source book by Kirtley F. Mather, Harvard University, a collection compiled before the importance of Wegener's theory of continental drift became obvious to everyone.[32] Grim (b. 1902) was later research professor of geology at the University of Illinois, Urbana. Mather says "his research has shed much light on many problems of sedimentation and stratigraphy."[32] (p. 327)

Five other highly cited papers in geology, by Norman L. Bowen and colleagues at the Carnegie Institution of Washington's Geophysical Laboratory, reported experimental studies of the behavior at high temperatures and pressures of substances present in the earth's crust and mantle. These studies demonstrated the value of using quantitative physicochemical techniques to study geological problems. For example, there was a long-standing controversy about the origin of granite. Is it formed by fractional crystallization from the molten basaltic magma in the earth's mantle and subsequently extruded through the crust to the surface? Or is granite a secondary rock formed on the surface by the melting of sediments? Bowen later argued that his experiments favored the first alternative.[33-35]

In retrospect one might suppose that by raising a new question—What is the process that brings granite from the mantle to the surface?—Bowen's work challenged the dominant "fixed continents" theory. Presumably, plate tectonics, with its postulates of mantle convection and upwelling of molten magma through mid-ocean ridges, could provide a better explanation for the upward transport of granitic material. But such an explanation has not yet been developed to the extent needed to satisfy experts in petrology, and in any case we cannot infer any causal connection between Bowen's papers and the revolution in the earth sciences. Instead, his papers were highly cited because they provided exceptionally clear and persuasive explanations of an important new method.[36]

Conclusions

In a recent study, Loet Leydesdorff and Olga Amsterdamska, University of Amsterdam, The Netherlands, selected four highly cited bioenergetics papers and sent a questionnaire to all the authors who cited those papers, asking why they gave the citations. From the responses, they concluded:

> Any interpretation of simple citation counts as indicators of impact, quality, or importance must be considered problematic.... The impact of a cited paper on the conduct of research or on the interpretation of results is often slight.... It differs from case to case.... Citations are not a valid indicator of the quality of cited papers at the moment they are published.[37]

It can hardly be disputed that the number of citations is not a direct measure of the quality or importance of a publication. I have mentioned a number of authors and publications that have been considered very important by the scientific community but were infrequently cited, even compared to other papers published in the same journals in the same time period.

Nevertheless, the fact that a publication is highly cited indicates something, and the historian of science should try to find out what that is. Some papers, such as those by Richard Feynman, Caltech; Julian Schwinger, Harvard University; Niels Bohr, Institute for Theoretical Physics, Copenhagen, and John Wheeler, Princeton University; and Robert Mulliken, University of Chicago, were original contributions of fundamental importance by any measure.[1] In physics and chemistry, a substantial number of the highly cited publications were authored or coauthored by Nobel laureates, even though they may have received the prize for other work. In mathematics, as also in physics and chemistry, some books and review articles become *Citation Classics* because they are convenient sources for techniques and data.

But to me, the real value of a list of highly cited publications is that it focuses attention on papers like those of Rossby and Nathan Jacobson, Yale University, New Haven, Connecticut, that are highly valued by specialists and clearly have played an important role in the development of smaller fields but have not been adequately recognized in general surveys.

* * * * *

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