EOS®
EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

VOLUME 93 NUMBER 21
22 MAY 2012
PAGES 201–208

The Scientific Legacy of Hannes Alfvén

PAGES 201–202

This year marks 70 years since the publication of a paper with far-reaching consequences for space and plasma physics: the 1942 letter to *Nature* by Hannes Alfvén, “Existence of electromagnetic-hydrodynamic waves.” The letter, which was only half a page long, described a new type of low-frequency oscillation of a magnetized plasma.

The paper was long disregarded or openly rejected, as the new waves that it described could not be demonstrated experimentally at that time. But as experimental techniques improved in the laboratory and experiments in space became possible, it became evident that what are now called Alfvén waves are of fundamental importance in plasma physics in general and space plasma physics in particular. In fact, they constitute a cornerstone of a new field of physics: magnetohydrodynamics. Alfvén waves are found in just about every space plasma, such as the Sun, the solar corona, and the solar wind, as well as in magnetospheres of the Earth and other magnetized planets.

The discovery of an entirely new kind of wave is only one part of a rich scientific legacy that keeps the name of Alfvén very much alive in space science today. Only samples of the most important results of his work can be described in this article. Alfvén’s work was rewarded with many honors, including the 1970 Nobel Prize in Physics for “fundamental work and discoveries in magnetohydrodynamics with fruitful applications in different parts of plasma physics” (Figure 1).

Formative Years and Career

Alfvén was born on 30 May 1908 in Norrköping, Sweden. Two childhood experiences had a significant influence on his intellectual development and scientific career. One was a book on popular astronomy by French astronomer and author Camille Flammarion, kindling a lifelong fascination with astronomy and astrophysics. The other was his school’s radio club, where he was an active member and built radio receivers. This instilled in him a profound interest in electronics and explains his tendency later in life to approach astrophysical problems from an electromagnetic point of view—a tendency that served him well.

After high school, Alfvén studied physics at Uppsala University. He received his Ph.D. in 1934 and then worked at Uppsala University and the Nobel Institute for Physics in Stockholm. In 1940, at the age of 32, Alfvén was appointed professor at the Royal Institute of Technology KTH, in Stockholm. From 1967 he shared his time between KTH and the University of California, San Diego in La Jolla and stayed scientifically active until after the age of 80. As a professor, Alfvén was a great inspiration to his students, several of whom later made significant contributions of their own to plasma physics, space physics, or both.

Early Scientific Work

Prominent among Alfvén’s early scientific interests was the origin of cosmic rays. All of his work is permeated by the principle that theories of cosmic phenomena must agree with results from laboratory experiments on Earth, so, characteristically, he dismissed earlier theories of the origin of cosmic radiation on the grounds that they did not appear to agree with recent experimental results.

In his study of cosmic rays Alfvén was led to the conclusion that there must exist a galactic magnetic field [*Alfvén*, 1937]. He believed such a field was needed to confine the cosmic ray distribution to galactic dimensions. This idea was generally disregarded because space was considered to be a vacuum, which could not possibly carry the electric current needed to generate a magnetic field. Much later, it was found empirically that the galactic magnetic field does exist but without recognition of Alfvén’s original proposal.

Discovery of Magnetohydrodynamic Waves

Alfvén’s scientific work reveals a profound physical insight and an intuition that

Fig. 1. (right) Hannes Alfvén receiving the 1970 Nobel Prize in Physics from (left) Gustaf VI Adolf, the king of Sweden.

By C.-G. Fälthammar

allowed him to derive results of great generality from specific problems. His most well-known discovery, of what are now called Alfvén waves, is typical of this. In this case the specific problem was the nature and origin of sunspots and the sunspot cycle. Alfvén formulated the mutual interaction between electromagnetic fields and fluid motion and described the resulting waves in an admirably simple and clear mathematical form in a letter to *Nature* [*Alfvén*, 1942a].

Incredibly, it took years before Alfvén's discovery was taken seriously. Some of his critics maintained that if such waves existed, they would have been discovered before. The breakthrough came in 1948, when Alfvén gave a seminar at the University of Chicago with the prominent physicist Enrico Fermi in the audience. After the seminar, Fermi nodded his head and said, "of course such waves could exist." According to Alfvén, the prestige of Fermi was such that "the next day every physicist nodded his head and said 'of course.'"

One reason for the initial nonacceptance of the new kind of waves was the fact that these waves, although elegantly described in theory, could not be demonstrated experimentally for several years. Although strongly damped waves could be generated in liquid metals [see *Lehnert*, 1954], it was not until around 1960 that Alfvén waves were demonstrated in plasmas. For example, *Wilcox et al.* [1960] generated Alfvén waves in a laboratory plasma and confirmed their predicted propagation velocity as well as their behavior when reflected at an obstacle.

Since then, Alfvén waves have become a well-known phenomenon in the laboratory as well as in space. They occur profusely in the Sun, the solar atmosphere, interplanetary space, and the magnetospheres of Earth and other planets. The model of sunspots and the solar cycle that Alfvén worked on was not successful, but the waves that he discovered in the process remain of crucial importance in solar physics as well as in the physics of all space and astrophysical plasmas.

Alfvén presented his understanding of magnetohydrodynamic waves and magnetohydrodynamics, as well as the guiding center approximation mentioned below, in a classic monograph, *Cosmical Electrodynamics* [*Alfvén*, 1950], and in a revised and extended version [*Alfvén and Fälthammar*, 1963].

Magnetohydrodynamics

The key to Alfvén's discovery was the combination of electromagnetic theory and hydrodynamics, which until then had been well established but in separate fields of physics. Their combination opened a new field of physics—magnetohydrodynamics.

At the time of its birth, magnetohydrodynamics had no applications. But in the 1950s the beginning thermonuclear research effort made it possible to generate high-temperature plasmas artificially in laboratories on Earth. For these plasmas, magnetohydrodynamics was of fundamental importance. In the same decade it became possible to send instruments into space. As almost all known matter beyond the Earth's atmosphere is in the state of a magnetized plasma, magnetohydrodynamics became an indispensable tool in the emerging field of space physics.

Frozen-In Magnetic Field

In a more comprehensive article published in a Swedish journal the same year as the letter to *Nature*, *Alfvén* [1942b] noted that in the new waves, "the matter of the liquid is 'fastened' to the lines of force." This is what in modern terminology is called a "frozen-in magnetic field" and is a basic feature of ideal magnetohydrodynamics, which greatly simplifies physical reasoning about magnetohydrodynamic problems.

The concept of frozen-in magnetic field is, however, based on idealized assumptions that are not always valid in a real plasma, especially in space. Alfvén's studies of the aurora convinced him that the use of the concept of frozen-in magnetic field lines can be misleading. Especially in his later years, he vigorously warned against unjustified use of the concept.

The Guiding Center Approximation and Adiabatic Invariance

Another contribution by Alfvén that has had far-reaching importance is the guiding center approximation for charged particle motion. The Norwegian mathematician Carl Størmer had studied the motion of electrons in the Earth's dipole field. These orbits were quite complicated, and for lack of computers it could take his assistants of the order of 2 weeks to calculate a single orbit.

By separating the motion of the particle into a gyration transverse to the local magnetic field and a drift of the center of this gyration, which he called the guiding center, *Alfvén* [1940] introduced an enormous simplification. While the advantage is clear in the example of the Størmer orbits, which apply at cosmic ray energies, it is still much greater at the lower energies that are mostly encountered in space plasma physics. There, the actual orbits would not only be cumbersome to calculate, even with modern computers, but would also be less relevant than the guiding center path because it is the average motion of the particles, rather than the small-scale gyrations superposed on it, that is relevant for behavior of the plasma.

In developing the guiding center approximation, Alfvén proved that the magnetic moment (a quantity that provides a measure of the magnetic effect of the particle's gyrating motion) of a gyrating particle is what is now called an adiabatic invariant (a property that does not change when the magnetic field changes very slowly on the time scale of the gyration). Since then, two more adiabatic invariants in charged particle motion have been found, and the adiabatic theory of charged particle motion has become an indispensable tool in plasma physics. The discovery of what is now usually called the first adiabatic invariant is another example of how results of great generality have resulted from Alfvén's consideration of a specific problem, in this case how the motion of charged particles in Earth's electric field creates the aurora.

Electric Fields

In the early years of the space age it was generally believed that space plasma could be described in terms of ideal magnetohydrodynamics (MHD), where the electric field is a quantity of little or no interest and can be neglected in calculations. Alfvén claimed that ideal MHD could not always be trusted, especially in space plasmas, and was the first to emphasize the importance of making direct measurements of electric fields in space.

Indeed, when direct measurements were finally made, it was found that the electric fields are different and much more complicated than foreseen in any theory. In particular, he believed that electric field components along the magnetic field could violate ideal MHD and the validity of the frozen field condition. Because such magnetic-field-aligned electric fields were considered impossible in contemporary theory, no attention was given to his suggestion that they exist above the ionosphere and cause the downward acceleration of auroral primary electrons [*Alfvén*, 1958]. But as soon as relevant in situ measurements were made in the space plasma, the first indications in support of Alfvén's idea were found [*McIlwain*, 1960]. Since then, the existence and importance of magnetic-field-aligned electric fields in space plasmas have become generally accepted.

Cosmogony and Cosmology

Developing a theory of the origin of planets and satellites, Alfvén postulated a new kind of interaction between plasma and neutral gas to take place at a certain relative speed, which he called the critical velocity. His cosmogonical theory has not been accepted, but the existence of the critical velocity was later confirmed both in the laboratory and in space and explained theoretically in terms of a previously unknown instability process [see *Brenning*, 1992].

In cosmology, Alfvén favored the concept of a symmetric universe consisting of both matter and antimatter. Alfvén tirelessly emphasized that in cosmic physics, plasma processes must be taken into account everywhere from Earth's ionosphere to the farthest reaches of the cosmos. He dramatized this point of view by proclaiming a new paradigm, which he called the Plasma Universe. This paradigm epitomizes the significance of plasma processes in the universe and is becoming increasingly recognized.

Contributions Beyond Science

Alfvén also took an active interest in matters related to the long-term fate of mankind, such as environment, population growth, and disarmament. During several years in the 1970s, Alfvén was president of the Pugwash movement in which eminent scientists from both the United States and the Soviet Union, as well as western Europe, Japan, and the third world, met annually, not as representatives of their countries but as concerned individuals. On the basis of his concern about nuclear proliferation and storage of nuclear waste, he became a pronounced opponent of nuclear energy and participated vigorously in the nuclear debate in Sweden.

A Lasting Heritage

Alfvén died on 2 April 1995. The scientific heritage of Alfvén is one with many facets. It includes new fields of research that he opened; powerful tools that he invented and that greatly facilitated scientific work in space and plasma physics; brave new concepts; stimulating, often controversial ideas; and the vision of a new paradigm in cosmic physics—the Plasma Universe. The frequency with which his name is still mentioned in any conference on space plasma physics is an indicator of how relevant his work is to the scientific community even today.

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