Plasma Physics from Laboratory to Cosmos—The Life and Achievements of Hannes Alfvén

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(Invited Paper)

***Abstract*—Hannes Alfvén, Lifetime Fellow of IEEE and 1970 Nobel Laureate for Physics, passed away on April 2, 1995 after a life of exceptional scientific achievement. His discoveries laid the foundations of major parts of modern plasma physics and its applications in areas as diverse as industrial processes, thermonuclear research, space physics, astrophysics, and cosmology. From a family background of high achievers and stimulating childhood experiences he went through an extremely rapid academic career, and his intense scientific activity lasted from his early twenties well into his eighties. His scientific work reveals a profound physical insight and an astounding intuition which allowed him to extract results of great importance and generality from specific problems. His most fundamental discoveries were those which opened a new field of physics, *magnetohydrodynamics*, and provided plasma physics with powerful new tools. His discovery of a new kind of waves, now called *Alfvén waves*, was initially met with disbelief and accepted only years later. With the evolution of plasma physics, and especially space plasma physics, the significance of this discovery has grown to the extent that Alfvén waves, and related terms such as Alfvén velocity, Alfvén number, etc., have become among the most frequently used terms in plasma physics. His introduction of the *guiding center* concept vastly simplified the analysis of charged particle motion in electric and magnetic fields and was the embryo from which grew the highly sophisticated adiabatic theory of particle motion. In addition to his most fundamental discoveries, Hannes Alfvén made numerous important contributions to the physics of (what we now call) the magnetosphere, especially auroras and magnetic storms, as well as to solar and interplanetary physics, astrophysics, and cosmology. Often his contributions were initially disregarded or opposed but vindicated later, often as a result of new experiments in the laboratory or measurements in space. Some of his ideas remain unaccepted or controversial even today. Finally, it is worth emphasizing that Hannes Alfvén contributed to the progress of science not only by his own work but also by the extraordinary inspiration that he gave to his many students as well as to colleagues all over the world.**

***Index Terms*—Commemorative biography, Hannes Alfvén.**

I. Introduction

On April 2, 1995, one of the great pioneers of plasma physics, Hannes Alfvén, passed away after a life of exceptional scientific achievement.

When he received the 1970 Nobel Prize for Physics, the citation read "for his contributions and fundamental discover-

Fig. 1. Hannes Alfvén 1908–1995.

ies in magnetohydrodynamics and their fruitful applications in different areas of plasma physics."

These discoveries opened a whole new field in physics, namely magnetohydrodynamics, and initiated the adiabatic theory of charged particle motion. They form a significant part of the foundations of modern plasma physics, as well as its applications in areas as diverse as industrial processes, thermonuclear research, space physics, astrophysics, and cosmology.

How significant his contributions have been is to some extent indicated by how often concepts bearing his name are mentioned at any conference in this field of science—such as Alfvén waves, Alfvén number, Alfvén layer, etc.—but only to some extent, because he also made important contributions of which his role as originator is not widely known.

Hannes Alfvén was born on May 30, 1908, in the town of Norrköping, in Sweden. Both heritage and environmental circumstances contributed to make him capable of his achievements. Heritage, because he came from a family of high achievers, including a mother who was a pioneer as one of the first female physicians in Sweden and an uncle

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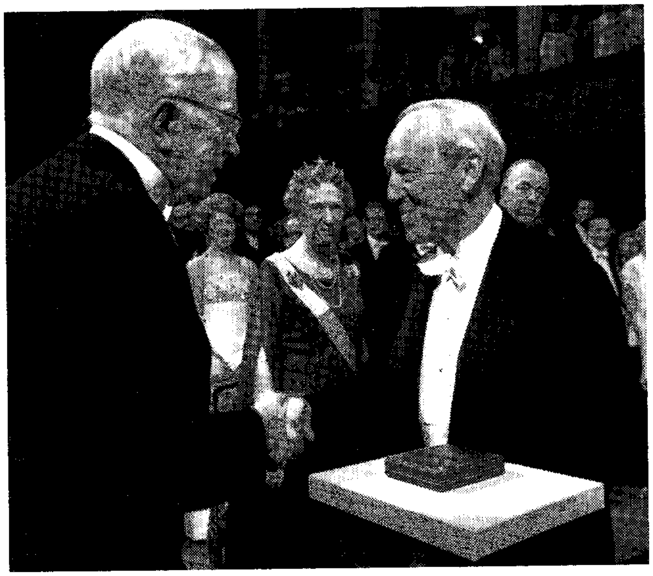

Fig. 2. Hannes Alfvén receiving the insignia of his 1970 Nobel Prize for physics.

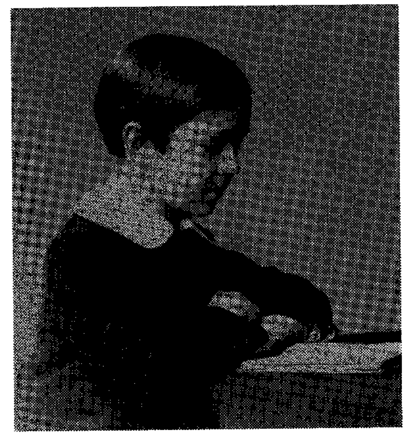

Fig. 3. Hannes Alfvén as a young boy reading Camille Flammarion's popular book on astronomy.

who was a famous composer. Environmental factors, because two childhood experiences had a significant influence on his intellectual development and scientific career. One was a popular book on astronomy by Camille Flammarion, which he was given at a young age and which kindled a lifelong fascination with astronomy and astrophysics. The other was the school's radio club where he was an active member and built radio receivers. This instilled in him a profound interest in electronics.

It is a striking fact that the fresh perspective that he had by approaching astrophysical problems from an electromagnetic point of view was a valuable asset in his scientific work. In fact, when his book *Cosmical Electrodynamics* was published in 1950, he was referred to in one review (written by T. G. Cowling) as "an electrical engineer in Stockholm."

All of his scientific work reveals a profound physical insight and an intuition that allowed him to derive results of great generality from specific problems. He published a paper in *Nature*, at the age of 23, on cosmic rays, which reflects a principle that he adhered to in all of his work: theories of cosmical phenomena must agree with what is known from laboratory experiments on the Earth, because the same laws of nature must apply everywhere.

His rapid academic career was marked by a doctor's degree at the age of 24 and, at 32, an appointment as full professor at the Royal Institute of Technology in Stockholm. He was given many honors, including membership in the Scientific Academies in Sweden, the United States, and the Soviet Union, as well as many gold medals.

As a professor he was an exceptionally inspiring and generous leader, spreading fruitful ideas around him without any claim to co-authorship of publications deriving from them. His vigorous scientific activity led to the creation of a number of new professorships and departments. The three departments that most directly trace their origin to his work now form a separate entity within the Royal Institute of Technology, the *Alfvén Laboratory*, founded in 1990.

II. Alfvén Waves

His most well-known discovery, what we now call *Alfvén waves*, is in many ways typical of his ability to achieve important general results from the consideration of specific problems. In this case the specific problem was the nature and origin of sunspots and the sunspot cycle, but it led to his discovery of a new kind of waves and to the opening of a whole new field of research: *magnetohydrodynamics*.

Until then electromagnetic theory and fluid dynamics had been well established but separate fields of physics. But as an "electrical engineer" Hannes Alfvén realized that the magnetic fields observed in the sunspots must derive from electrical currents in the solar plasma and that the currents and magnetic fields together must give rise to forces that affect the motion of this plasma, which in turn induces electric fields. He formulated this mutual interaction between electromagnetic fields and fluid motion, and the resulting waves, in an admirably simple and clear mathematical form in a letter to *Nature* published in 1942.

Incredible as it may seem today, it took years before this discovery was taken seriously. Some of his critics maintained that if such waves existed, Maxwell would have discovered them. As Hannes Alfvén told it, he received letters from colleagues asking whether he had not understood that his paper about a new kind of waves was nonsense. The breakthrough came in 1948, when after a seminar by Hannes Alfvén in Chicago, Enrico Fermi nodded his head and said "of course such waves could exist," and again according to Hannes Alfvén's own account, the prestige of Enrico Fermi was such that "the next day every physicist nodded his head and said 'of course'."

A circumstance contributing to the long nonacceptance may have been the fact that the waves, theoretically conceived, were not demonstrated experimentally until several years later, when in Alfvén's laboratory Stig Lundquist proved their existence in mercury and Bo Lehnert in liquid sodium. But the waves in liquid metal were very strongly damped, and it vas not until around 1960 that Alfvén waves were observed in plasma, about at the same time in the United States and the United Kingdom.

Existence of Electromagnetic-Hydrodynamic Waves

If a conducting liquid is placed in a constant magnetic field, every motion of the liquid gives rise to an E.M.F. which produces electric currents. Owing to the magnetic field, these currents give mechanical forces which change the state of motion of the liquid. Thus a kind of combined electromagnetic-hydrodynamic wave is produced which, so far as I know, has as yet attracted no attention.

The phenomenon may be described by the electrodynamic equations

$$\text{rot } H = \frac{4\pi}{c} i$$

$$\text{rot } E = -\frac{1}{c}\frac{dB}{dt}$$

$$B = \mu H$$

$$i = \sigma(E + \frac{v}{c} \times B);$$

together with the hydrodynamic equation

$$\partial \frac{dv}{dt} = \frac{1}{c}(i \times B) - \text{grad } p,$$

where σ is the electric conductivity, μ the permeability, ∂ the mass density of the liquid, i the electric current, v the velocity of the liquid, and p the pressure.

Consider the simple case when $\sigma = \infty$, $\mu = 1$ and the imposed constant magnetic field H_0 is homogeneous and parallel to the z-axis. In order to study a plane wave we assume that all variables depend upon the time t and z only. If the velocity v is parallel to the x-axis, the current i is parallel to the y-axis and produces a variable magnetic field H' in the x-direction. By elementary calculation we obtain

$$\frac{d^2H'}{dz^2} = \frac{4\pi\partial}{H_0^2}\cdot\frac{d^2H'}{dt^2},$$

which means a wave in the direction of the z-axis with the velocity

$$V = \frac{H_0}{\sqrt{4\pi\partial}}.$$

Waves of this sort may be of importance in solar physics. As the sun has a general magnetic field, and as solar matter is a good conductor, the conditions for the existence of electromagnetic-hydrodynamic waves are satisfied. If in a region of the sun we have $H_0 = 15$ gauss and $\partial = 0{\cdot}005$ gm. cm.$^{-3}$, the velocity of the waves amounts to

$$V \sim 60 \text{ cm. sec.}^{-1}.$$

This is about the velocity with which the sunspot zone moves towards the equator during the sunspot cycle. The above values of H_0 and ∂ refer to a distance of about 10^{10} cm. below the solar surface where the original cause of the sunspots may be found. Thus it is possible that the sunspots are associated with a magnetic and mechanical disturbance proceeding as an electromagnetic-hydrodynamic wave.

The matter is further discussed in a paper which will appear in *Arkiv för matematik, astronomi och fysik*.

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Fig. 4. Hannes Alfvén's letter to *Nature* describing what is nowadays called Alfvén Waves ("Existence of Electromagnetic-Hydrodynamic Waves," *Nature*, vol. 150, p. 405, 1942).

Since then they have become a well-known phenomenon in the laboratory as well as in space and indeed a key concept in plasma physics and its applications. In space physics they play a very important role. For example, Alfvén waves occur profusely in the sun, the solar atmosphere, interplanetary space, and the magnetospheres of the Earth and other planets.

III. MAGNETOHYDRODYNAMICS

But the 1942 letter to *Nature* meant much more than the discovery of a new kind of waves. It meant the opening of a whole new field of physics—that of magnetohydrodynamics. At the time of its discovery, there were no known applications. The reason is that plasmas rarely occur naturally on the Earth. And the technology of the 1940's had very limited capability of producing them artificially—hence the difficulty of even demonstrating the existence of Alfvén waves.

But this situation was soon to change. In the 1950's the beginning of the thermonuclear research effort led to technological developments that made it possible to generate high temperature plasmas artificially in laboratories on the Earth. And for these plasmas magnetohydrodynamics was of fundamental importance. In the same decade it became possible for man to send instruments into space. As almost all 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.

As far as the problem of sunspots and the sunspot cycle is concerned, the particular solution that Hannes Alfvén worked out has not been widely accepted, but the waves that he discovered in the process, and the field of magnetohydrodynamics that this opened, are of fundamental importance not only to solar physics but to the whole field of space and astrophysical plasmas.

IV. FROZEN-IN MAGNETIC FIELD LINES

In the case of sufficiently high electrical conductivity, one corollary of magnetohydrodynamics is the concept of *frozen-in magnetic field lines*. This well-known concept greatly simplifies physical reasoning about plasma physical problems and is used profusely, but it is perhaps not always recognized as due to Alfvén.

It is a seductive concept, which has often led to careless reasoning in terms of "moving magnetic field lines." As often stressed by Hannes Alfvén the motion of magnetic field lines is an intrinsically meaningless concept, which can be used only under very restrictive conditions and with utter caution.

In a rigorous definition, a state of frozen-in magnetic field lines is one where any two elements of the medium that are at one instant on a common magnetic field line will be on a common magnetic field line at any other instant. This definition does not rely on the concept of motion of magnetic field lines, but where the frozen condition in this sense holds, it can be used to "label" field lines and then define their "motion."

How high the conductivity needs to be for the frozen-in condition to hold depends on the spatial scale in such a way that it should be easily satisfied in practically all space and astrophysical plasmas—as long as classical conductivity formulas apply. Hannes Alfvén realized, however, that the classical theory of plasma conductivity may not always apply in space plasmas. In particular, his

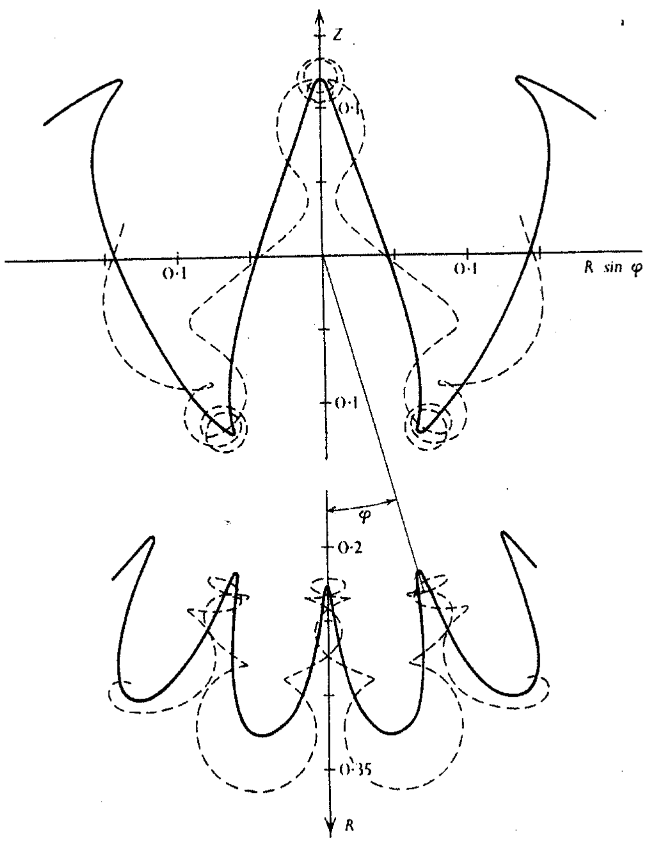

Fig. 5. Størmer orbit (dashed line) and guiding center path (solid line) for a high energy particle in the Earth's magnetic field (From H. Alfvén, "On the Motion of a Charged Particle in a Magnetic Field," *Arkiv för Matemaatik, Astronomi och Fysik*, vol. 27A, no. 22, 1940.)

study of the aurora convinced him that the use of the concept of frozen-in magnetic field lines can sometimes be unjustified and dangerously misleading. In his later years he vigorously warned of unjustified use of the concept.

V. The Guiding Center Approximation

Another contribution of 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. His objective was to explain the auroral zones by tracing electron orbits from the sun to the Earth. These orbits were quite complicated, and for lack of computers it could take his assistants up to two weeks to calculate a single orbit.

Hannes Alfvén introduced the guiding center approximation by separating the motion of the particle into two superposed parts: 1) a gyration transverse to the local magnetic field and 2) a drift of the center of this gyration, which he called the guiding center. For most purposes it is sufficient to know the motion of the guiding center, which represents the average motion of the particle. It is much simpler than that of the actual particle and can be calculated much more easily.

The advantage of the guiding center approximation, however, is usually much greater than in the case of the Størmer orbits. The reason is that the Størmer orbits apply for particles of very high energy. At the relatively low energy, say a few keV, of electrons that cause the aurora, the orbits are vastly more complicated and make many thousands or even millions of turns before they reach the upper atmosphere. In this case the actual orbit would not only be cumbersome to calculate, even with modern computers, but it would also be less relevant than the guiding center path.

In developing the guiding center approximation, Hannes Alfvén proved that the *magnetic moment* of the gyrating particle is what we now call an adiabatic invariant. This became the starting point of what has since developed into the adiabatic theory of charged particle motion, which has reached a high degree of sophistication and become an indispensable tool in plasma physics. Thus this is another example of how results of great generality have resulted from Hannes Alfvén's consideration of a specific problem, in this case the aurora.

Using his guiding center approximation Hannes Alfvén analyzed the concept of a *ring current* in the Earth's magnetic field. It is now well known that the ring current is an important structural feature of the magnetosphere. But when he tried to publish his result, it was rejected by the leading journal at that time, *Terrestrial Magnetism and Atmospheric Electricity*, on the grounds that it did not agree with generally accepted theories.

VI. The Critical Ionization Velocity

A concept introduced by Hannes Alfvén, but not widely known, is the *critical ionization velocity*, often referred to as CIV. In developing a theory of how planets formed around the sun, and satellites around some planets, he made a strange postulate. Considering neutral atoms falling toward the primordial sun, he postulated that when a particle reached a speed such that its kinetic energy was equal to its ionization energy, it would suddenly become ionized. He called this velocity the critical velocity. The ion formed from the neutral atom would then be trapped in the magnetic field and remain at that distance from the sun where it reached its critical velocity.

The strangeness of the postulate becomes obvious from realizing that when the neutral atom in the above scenario collides with a resident particle (essentially at rest), the energy in the center of mass system is less than the ionization energy and ionization therefore energetically impossible. (Even at higher energies the ionization yield of collisions between atoms and ions is small).

Not surprisingly, the concept was met with massive disregard. But years later, experiments carried out by Block and Fahleson with plasma and neutral gas in relative motion showed that as the relative speed reached a certain value, the neutral gas was rapidly ionized [6]. And this value of the relative speed turned out to be the one postulated by Alfvén. Since then, the phenomenon has been found to occur in plasma experiments of many configurations and at least in one case in space.

It took years before the phenomenon was explained theoretically. The explanation is, essentially, that an instability transfers part of the energy residing in the relative motion into energy of the electrons, which can then ionize very efficiently.

The critical velocity phenomenon has manifested itself as a velocity limitation in early fusion experiments and has been invoked in a number of space and astrophysical contexts. For example, the impact on the moon of the Apollo 13 carrier rocket generated a dust and gas cloud, which was found to become ionized very rapidly. The only explanation so far of this observation is that it was caused by the critical velocity phenomenon. It has also been proposed that this phenomenon plays a role in the interaction of the solar wind with the surrounding interstellar gas.

VII. 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). As a consequence it was thought that the electric field, in case anyone was interested, could be calculated from the MHD equations. This view was challenged by Hannes Alfvén, who seems to have been the first to emphasize the importance of making direct measurements of electric fields in space. And indeed, when direct measurements were finally made, it was found that the electric fields were much more complicated than foreseen in any theory.

In particular, Hannes Alfvén emphasized that ideal magnetohydrodynamics and the validity of the frozen field condition could be violated locally by electric field components parallel to the magnetic field. The existence of such components used to be considered impossible, because the essentially collisionless motion of electrons and ions in dilute space plasmas would cause any such components to be "shorted out."

Therefore, no attention was given to his suggestion, first published in 1958, that magnetic field aligned electric fields, perhaps in structures called electric double layers, exist above the ionosphere, and cause the downward acceleration of auroral primary electrons. In this case the suggestion had an empirical basis, because the double layer phenomenon was known, even if not well understood, from laboratory experiments by Schönhuber and from current disruptions in mercury rectifiers. Only after very extensive evidence from space measurements and active experiments did the existence of magnetic-field aligned electric fields became generally accepted.

VIII. Partial Corotation

Some of Hannes Alfvén's ideas are still unaccepted or controversial. One example is the concept of a special kind of *partial corotation* (at a velocity equal to two-thirds of the Kepler velocity). He introduced this concept primarily in an attempt to explain in great detail the structure of the Saturnian ring system. But it also led him to predict that Uranus would prove to have a ring system. He was unable to have this prediction accepted for publication, but the prediction proved correct. Another example is *symmetric cosmology*, which implies that the universe may consist of equal amounts of plasma and antiplasma, separated by thin boundary layers, where intense annihilation takes place. The radiation from this annihilation is unobservable, because the low density and small spatial size of the boundary regions make the resulting radiation too weak to be detected at the position of the Earth. These regions are analogous to the Leidenfrost layer formed under a drop of water on a hotplate.

IX. Extra-Scientific Interests

Hannes Alfvén also took an active interest in important matters outside science, especially matters related to the long-term fate of mankind, such as environment, population growth, and disarmament. One result of such interests was a fascinating book, *Living on the Third Planet,* which he wrote with his wife [4].

For several years in the 1970's he was President of the Pugwash movement. This is an activity initiated by Albert Einstein and Bertrand Russell and named after a small Canadian fishing village, where the first meeting was held and where the Einstein–Russell Manifesto was generated. In this movement, eminent scientists from both of the superpowers as well as Western Europe, Japan, and the Third World met annually, not as representatives of their countries but as concerned individuals.

In his extra-scientific endeavors, too, Hannes Alfvén had a mind of his own. On the basis of his concern about nuclear proliferation and storage of nuclear waste he became a pronounced opponent of nuclear energy, participating vigorously in the nuclear debate, and made a significant impact on nuclear policy in Sweden.

In 1966 he published, under the pseudonym Olof Johannesson (his middle name was Olof, and his father's name was Johannes), a very amusing satiric book. In its 1968 English version the title is *The Tale of the Big Computer* [7]. This book caricatures politicians in a brilliant but not very flattering way. At that time Hannes Alfvén was a Member of the Prime Minister's Advisory Council for Science. Soon the true identity of the author became known, and the Prime Minister asked for a copy of the book, which Hannes gladly agreed to give him. So he did, and his handwritten dedication in the Prime Minister's copy read "To Tage Erlander [the name of the Prime Minister] from Hannes Alfvén, *with thanks for inspiration.*" The Prime Minister had a good sense of humor and did not take offense.

X. Concluding Remark

Returning to Hannes Alfvén's scientific achievements, it is worth emphasizing that he contributed to the progress of science not only by his own work, but also through the extraordinary inspiration that he gave to his many students as well as to colleagues all over the world.

When he passed away, his many friends were left with a feeling of great loss but also of deep gratitude for all that he has meant as a scientist and as a friend. And his scientific contributions will remain a lasting heritage.

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Carl-Gunne Fälthammar (M'91) was born in Markaryd, Sweden, on December 4, 1931. He received the degree of Civilingenjör (graduate engineer) in 1956, the Tekn. lic (approximately the Ph.D. degree) in 1960, and the Docent (approximately assistant professor) in 1966, from the Royal Institute of Technology (KTH), Stockholm, Sweden.

In 1969, he was appointed Associate Professor of Plasma Physics at the Royal Institute of Technology. In 1975, he succeeded Hannes Alfvén as Professor of Plasma Physics. Since 1967, he has been Chairman of the Department of Plasma Physics at the Royal Institute of Technology, which, since 1990, has been a Division of the Alfvén Laboratory. His research interests include fundamental aspects of plasma electrodynamics, with application to space and astrophysical plasmas, especially in the context of auroral and magnetospheric physics.

Dr. Fälthammar has served in several international scientific organizations, including the Executive Committee of IAGA, the Space Science Committee of the European Science Foundation, the Council of the European Geophysical Society, and the Board of the European Physical Society Plasma Physics Division. He was Topical Editor of *Annales Geophysicae* 1991–1995. He is currently Associate Editor of *Astrophysics and Space Science* and a member of the Editorial Board of *Space Science Reviews*. Since 1975, he has been a full member (Fellow) of the Royal Swedish Academy of Sciences, and he is also a full member of International Academy of Astronautics, Academia Europaea, and European Academy of Arts, Sciences and Humanities. In 1989, he was awarded an Honorary Doctor's degree by the Faculty of Science of the University of Oulu, Finland. He is also a recipient of the Golden Badge Award of the European Geophysical Society and of the Basic Sciences Award of the International Academy of Astronautics.