experiments in plasma physics, often in the form of verification of some of his own ideas. For instance, in developing a comprehensive theory for the evolution of the solar system, Alfvén intuitively proposed the concept of a critical relative velocity between a neutral gas and a magnetized plasma. Beyond this velocity the gas would ionize rapidly and the resulting plasma cloud would form the starting point for the process of condensation and accretion, leading to the formation of secondary bodies like planets and satellites. The value for the critical velocity was proposed to be $(2eV_i/M)^{1/2}$, where V_i and M are the ionization potential and mass of neutral atom. This limit has been experimentally verified in a number of experiments, including some carried out at the Royal Institute of Technology in Stockholm under his active encouragement. Likewise, he inspired a series of experiments and developments on the Marshall gun – a plasma device to create a minimum magnetic energy plasma configuration which he had theoretically proposed. This concept in the advanced form of a Spheromak configuration is today considered to be an attractive fusion confinement geometry. His original idea of intense electric field structures in space led to a large body of theoretical and experimental investigation into the so-called potential double-layer formations. Alfvén also helped inspire some early plasma physics work in India when he visited the Tata Institute of Fundamental Research, Bombay, in 1958 at the invitation of Homi Bhabha and gave a series of lectures on plasma physics to the then fledging plasma physics group.

Not all his ideas are accepted even today. He has put forward his own theory of cosmology, opposing the big bang model, and leaning towards the cosmology of Oscar Klien, with a universe oscillating between expansion and contraction. He believed that the universe was formed as an ambiplasma (i e. with equal amounts of matter and antimatter) and suggested clever mechanisms for their segregation into separate worlds. He also emphasized the importance of dust in the universe and talked long time ago about 'dusty' plasmas. Cast in the role of an iconoclast, during his early struggles with the established scientific views in space physics, Alfvén continued to question the established doctrine and always fought for his own 'wild' ideas. In the words of his friend and associate, Gustaf Arrhenius, Alfvén was a 'gentle wild man'. He was also an active campaigner against nuclear warfare and participated in the East–West 'Pugwash' conferences that sought to prevent such confrontations. Originally a strong promoter of nuclear power generation, he later grew apprehensive about the long-term safety of reactors and sought to highlight the problem of nuclear wastes. He continued to be active in research till fairly recently, sharing his time between the Royal Institute of Technology and the University of California in San Diego.

Alfvén was the recipient of several awards, including the Nobel Award in physics in 1970 (shared with Louis Neel), the Lomonosov Gold Medal of the Soviet Academy of Sciences, the Franklin Gold Medal of the Franklin Institute in Philadelphia and the Gold Medal of the Royal Astronomical Society, UK. He was a member of the National Academy of Sciences in the United States and a Fellow of the Royal Society in Britain. His books included: *Cosmical Electrodynamics*, 1950; *On the Origin of the Solar System*, 1954; *Cosmical Electrodynamics: Fundamental Principles* (with C. G. Fälthammar), 1963; *Worlds–Antiworlds*, 1966; *Structure and Evolutionary History of the Solar System* (with G. Arrhenius), 1975; *Cosmic Plasma* (monograph), 1981. He also wrote several popular scientific books, many of them in collaboration with his wife Kerstin Maria Erikson and often assuming the pen name of Olof Johannesson.

Alfvén has given the world of physics a rich legacy of ideas and tools. They have helped us reach out and understand many complex phenomena in the sun, the stars and the space beyond. They are also the basis on which one hopes to create the first star in the laboratory – and harness the energy of fusion reactions. Such is the power and reach of the field he helped create and which reflects in a striking way the true measure of his amazing genius.

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Remembering Hannes Alfvén and his work

'You know I love your country and I do Yoga everyday', Professor Hannes Alfvén was telling me this in a conversation in Gothenburg, Sweden, at a Plasma Physics conference in 1988. He further added, on seeing the book *The Alfvén Wave*, the first book on this topic written by Akira Hasegawa from Bell Laboratories, NJ, USA and myself and dedicated to him, 'You both seem to know more these waves than myself'. This was the highest complement coming from Hannes Alfvén, who discovered the Alfvén waves in 1942.

He can be justifiably considered as the father of space plasma physics and astrophysical plasmas. He originated many key theoretical ideas which opened a new vision in understanding of the plasma universe. Hannes Alfvén received his Doctorate from the University of Upsala in 1934 and was appointed as Professor of electromagnetic theory and electric measurements at the Royal Institute of Technology, Stockholm, in 1940, at the age of 32. From this date to almost the end of his life, Alfvén was an active scientist of this laboratory. His vigorous scientific and administrative activities led to the creation of several new departments within the Royal Institute of Technology. Three of these, Plasma Physics, Fusion Plasma Physics and Accelerator Technology Departments now constituted a separate entity called the Alfvén Laboratory. His own chair evolved correspondingly into electronics in 1945 and plasma physics in 1963.

From very early age, as a young boy Hannes Alfvén was intrigued by radio sets and radio electromagnetic waves. His vision about magnetic and electric fields and interaction with matter in the universe led him to discover the entirely new kind of waves in conducting fluids interacting with magnetic fields, which are now known as Alfvén waves. These waves have become a foundation stone in plasma physics and its applications to space physics, astrophysics and thermonuclear fusion plasma physics. In order to understand the theory of sunspots, Alfvén in a now famous letter to *Nature* gave a very simple mathematical formulation describing the mutual interaction between electromagnetic fields and conducting fluid motion and found that this interaction can give rise to a new wave phenomenon called electromagnetic-hydrodynamic waves.

Alfvén waves, as these waves are now known are low-frequency transverse waves propagating along the magnetic lines of force. Unlike sound waves, these are choosy about the direction of propagation. Closely related to the Alfvén waves is the concept of 'frozen in magnetic fields', also due to Alfvén. This concept simplifies greatly the physical reasoning about plasma phenomena but has its limitations. Using this concept it was very easy for Alfvén to draw an analogy with the theory of stretched strings. The magnetic tension arising due to parallel component of the Lorentz force along the magnetic field lines can lead to the possibility of transverse waves along the lines of force, with velocity ϑ_A given by

$$\vartheta_A = B_0/(\mu_0 \rho)^{1/2}$$

where ρ is the mass density of the fluid on which the field lines are imbedded.

The 'frozen in' concept, though simplifies greatly the physical reasoning about plasma phenomena, has its limitations. Alfvén himself cautioned the plasma physicists in using this concept without proper justification.

Incredibly, it took several years before the results arrived at by Alfvén were taken seriously. The experimental verification of Alfvén waves came still later due to technical difficulties. With the advent of space age now we have numerous number of satellite and spacecraft observations pointing out the omnipresence of Alfvén waves in space physical systems. The theoretical studies point out how various natural phenomena in nature can be explained as manifestation of the presence of Alfvén waves. In recent years the study of Alfvén waves in inhomogeneous magnetic fields have led to a considerable understanding e.g. of solar coronal heating, bending waves in galaxies, the characteristic features and origin of ULF waves in the magnetically organized systems, the magnetosphere, particle acceleration in auroras and so on.

The other natural phenomenon which attracted the attention of Hannes Alfvén

was the aurora. As we know auroras are a spectacular display of luminous radiation in the sky near polar regions. Auroras as we know from recent space experiments and theoretical developments are manifestation of the interaction of solar plasma with the earth's magnetic field. Much before these ideas were established Alfvén knew the key to the problem of understanding the auroral phenomena and in his very early years of research began to study the motion of charged particles in electric and magnetic fields. The guided centre approximation given by Alfvén to study the equations of motion of charged particles in electromagnetic fields led to the development of this subject and the important adiabatic theory for describing the mathematical models of plasma based on single charged particle motion. The importance of Alfvén work in this area can hardly be exaggerated.

Alfvén developed several other concepts regarding interaction of plasmas with magnetic and electric fields. Some of these were not well received initially but have later proved to be highly relevant and useful. For example, in a visionary paper published in 1958, he proposed auroral primary electrostatic potential drop along geomagnetic field lines. Such electric fields with huge potential drops were considered impossible at that time, but modern space probe measurements have established such electric fields and have also shown that this mechanism indeed plays a crucial role in the physics of aurora. Another example: as a part of a theory of the origin of the solar system, Alfvén introduced the daring hypothesis of 'critical velocity' in plasma–neutral gas interaction. Its experimental validation came years later, and it took many years more before the mechanism could be explained theoretically.

Carl G. Fälthammar, Alfvén's student and close associate mentioned that though it is not widely recognized that as early as 1937 Alfvén argued for the existence of a galactic magnetic field and by inference an ionized interstellar medium, both of which were at that time considered impossible but now, of course, are well established

As to the theory of the origin of the Universe, Alfvén had his favourite slogan: 'In the beginning there was plasma'. To understand the electricity and magnetism in space and the interaction of electromagnetic fields with conducting ionized matter in the plasma Universe was his passion which did not leave him till the very last days of his life.

Hannes Alfvén contributed towards the progress of space and astrophysical sciences not only through his work but by inspiring many students, colleagues and friends all over the world. I pay my homage to this great scientist and will miss his inspiring correspondence.

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