Royal Swedish Academy of Engineering Sciences

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A Tribute to the Memory of

Svante Arrhenius

(1859–1927)

A scientist ahead of his time

by Gustaf Arrhenius, Karin Caldwell and Svante Wold

Royal Swedish Academy of Engineering Sciences (IVA)

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Presented at the 2008 Annual Meeting
of the Royal Swedish Academy of Engineering Sciences

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Foreword

Every year, the Royal Academy of Engineering Sciences (IVA) produces a booklet commemorating a person whose scientific, engineering, economic or industrial achievements were of significant benefit to the society of his or her day. The Commemorative Booklet is published in conjunction with the Academy's Annual Meeting.

This year the Commemorative Booklet is to honour Svante August Arrhenius (1859-1927) a Swedish scientist awarded the Nobel Prize in Chemistry (1903), for his discovery of electrolytic dissociation. He is also known as a prescient atmospheric physicist as he already in 1896 demonstrated the effect of radiatively active gases on planetary surface temperatures and made an attempt to quantify what he called the "greenhouse effect" especially of carbon dioxide on the earth's climate. His scientific career encompassed three distinct specialties within the broad fields of physics and chemistry: physical chemistry, cosmic physics, and the chemistry of immunology. Popularization of science was of great concern to Arrhenius throughout his career.

We wish to give our sincere thanks to the authors, Gustaf Arrhenius, Karin Caldwell and Svante Wold, who are all grandchildren of Svante Arrhenius, for the work they have devoted to this year's Commemorative Booklet.

Björn O. Nilsson
President of the Academy

Mauritz Sahlin
Chairman of the Medals Committee

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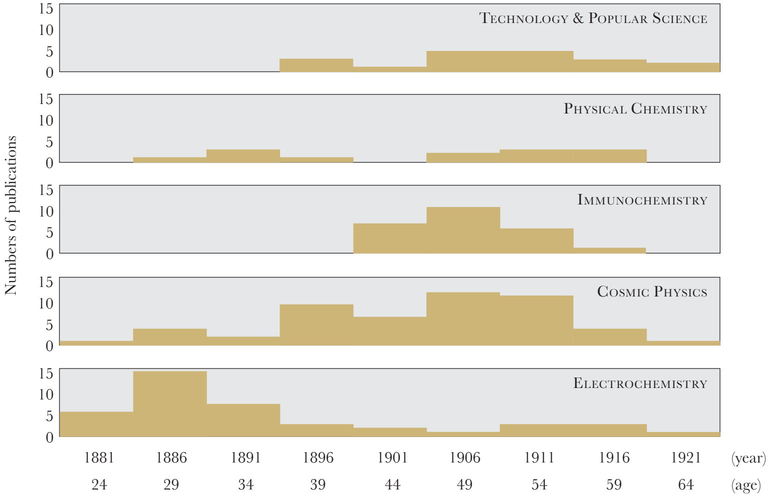
Introduction

Svante Arrhenius was an extremely talented man with an expansive range of interests, both inside and outside the academic domain. His early work with the dissociation of ionic substances, which was presented in his doctoral thesis (1884), earned him the Nobel Prize in Chemistry in 1903, twenty years after his first ideas in this area had been presented orally to a very sceptical and even scornful academic supervisor. The theory of electrolytic dissociation and his kinetic "law" – the Arrhenius equation – made Arrhenius one of the founders of modern Physical Chemistry.

Early on, he became interested in electricity as a source of energy for homes, industry, transport and more. He pointed out the economic advantages of hydroelectric power generation. The main energy source in the Scandinavian countries at the time was coal; extraction from insignificant deposits was costly. Acting on a royal commission, Arrhenius chaired a committee of experts to investigate the potential of using hydroelectric power for the electrification of railways in Sweden. He was also instrumental in starting Örebro Elektriska AB which later formed part of ASEA (now ABB), and the chemical company Jon (ion), which became part of Kebo-Grave. Although Jon was primarily created to secure the supply of acceptably pure research chemicals, it also became an international exporter of bulk chemicals, such as acetic acid.

Convinced of their general validity, he applied physicochemical principles to immunology and thereby came to be the founder of immunochemistry. Many physiologists disagreed on whether these principles applied to biological systems.



Svante Arrhenius' publication record with time and age. Arrhenius took a keen interest in spreading information about new scientific discoveries and accomplished a large number of publications within various fields of research ,the most numerous in what he called "Cosmic Physics".

Arrhenius' interests in planetary physics led him to discovery of the molecularly selective atmospheric radiation filtering referred to as "the greenhouse effect" which today so greatly concerns our society. His fascination with cosmic physics drove him to formulate numerous new ideas whose validities are still being explored. His proposal that life is spread through the universe by means of small spores, travelling through space pushed by radiation pressure and particle charge (his version of the "panspermic theory") generated considerable interest.

Like many scientists Arrhenius was deeply shocked by the First World War and afterwards worked tirelessly to mend the relationships between scientists from combatant countries, relationships that had been badly damaged by the war.

He enthusiastically participated in academic debates on chemistry, biology, astronomy and astrophysics, and geophysics as well as in public debates on how science and technology, if used correctly, would contribute to the building of a better world. He took a keen interest in spreading information about new scientific discoveries and how they might affect mankind. He accomplished this by authoring numerous popular science articles and books that received international attention and were translated into many languages.

Family and childhood

Svante Arrhenius' family descended from farmers in the neighbouring villages of Årena and Klövdala in Småland in south eastern Sweden. Around 1830, Arrhenius' uncle, Johan Petter, and father, Svante Gustaf, both sought to further their education (Eksjö, Linköping Gymnasium, Uppsala University), and moved "to town." Johan Petter received a PhD degree and made a career in agricultural research, which culminated in the positions of President of the new Agricultural University in Uppsala, and Secretary of the Swedish Academy of Agricultural Sciences. Svante Gustaf studied to become a surveyor and graduated in 1834. He started working as a surveyor in Kalmar County (län) in 1836 and became the manager of the university's estates in western Uppland in 1847. After marrying his cousin Carolina Thunberg in 1855 he took a second position as caretaker of the Vik estate outside Uppsala to improve his family's finances. The family soon moved into the town of Uppsala where Svante Gustaf became "akademifogde" (approximately rent collector for the university). Four children were born: Johan (Janne, 1857), Svante (19 Feb. 1859), Sigrid (1860), and Robert (1862). The latter died at the age of three. Svante was the only one to marry (twice), and he had four children: Olof, Sven, Ester and Anna-Lisa.

Svante Arrhenius was a clearly gifted child, learning to read by listening to the lessons given to his older brother Janne and learning arithmetic by watching his father checking the various accounts for which he was responsible. At the age of eight after a number of years of home schooling, Arrhenius was tested and accepted into the second grade in "realskolan" at Uppsala Högre Allmänna Läroverk. The age of the boys at this school varied between eight and fourteen with an average of eleven. He excelled in mathematics, physics and chemistry, but showed little interest in other subjects. He graduated from the "gymnasium" (upper secondary school) in 1876 with good grades but not at the top of his class.

Svante Arrhenius at the beginning of his research career, 1878.

University studies

In the autumn of 1876, Svante registered at Uppsala University with mathematics, physics and chemistry as main subjects, to which he added history, mineralogy and geology, botany and Latin as secondary subjects. He earned his diploma in January 1878 after only a year and a half of studying, a record at the time.

After a summer journey to Paris, Arrhenius began his graduate studies in the autumn of 1878. These started with lectures in mathematics and laboratory work in chemistry. Following this introductory period, Arrhenius decided to register for physics as his main subject with the intention of conducting experimental work in the borderland between physics and chemistry. His physics professor found this unnecessary and even somewhat ridiculous and urged him to choose chemistry as his main subject. As a result, Svante Arrhenius and his friend Klas Mebius, who had been given a similar recommendation, travelled to Stockholm (70 km south) and asked Erik Edlund, physicist at the Royal Swedish Academy of Sciences, if he would be their physics supervisor. He accepted and Arrhenius, Mebius and a third graduate student, Lukas Homén, were assigned to help Edlund with his investigations into the inherent power of electrical sparks.

Meanwhile, Arrhenius embraced student life in Uppsala. He became responsible for organizing social events at his fraternity, Uplands Nation, in 1880 and fondly remembered this time as giving him practical and valuable experience of aspects of life other than academic studies.

In the spring of 1882 Edlund invited the three young men to continue their studies in his laboratory, provided that they worked independently on subjects of their own choice. Arrhenius chose to work on a way to determine the molecular weight of chemical compounds in solution, and later the same year began his work on the conductivity of electrolyte solutions which would lead to his Nobel Prize 21 years later. The experimental results together with the new theory of the dissociation of ionic substances upon their dissolution in water – which he discovered on 17 May 1883 – was written up and edited to become a completed thesis in June 1883. He received little encouragement from his Uppsala chemistry professor, but Otto Pettersson, professor of chemistry at the new Stockholm University College (Stockholms Högskola), read the document and wrote Arrhenius two very encouraging letters. Arrhenius' revised thesis included some of Pettersson's proposed changes to format and focus and his dissertation was finally presented on 26 May 1884.

Dissertation controversy, Ostwald intervention

The thesis and dissertation were given passing grades that were too low for Arrhenius to become a docent, thereby almost closing the door to an academic career. Arrhenius never forgot this humiliation.

After its publication, Arrhenius sent his thesis to two of the leading physical chemists at the time, Jacobus van't Hoff in Amsterdam and Wilhelm Ostwald in Riga. After some correspondence, Ostwald travelled from Riga to Uppsala to visit Arrhenius who met him at the railway station. To identify himself, he carried a copy of Ostwald's latest publication with its easily recognizable blue cover.

Ostwald offered Arrhenius a docent position in Riga, which Arrhenius declined. To allow Arrhenius to continue his scientific work in Sweden, the Uppsala faculty now offered him an unpaid docent position in physical chemistry, a new branch of science. One year later the Royal Swedish Academy of Sciences gave Arrhenius a three-year travel grant totalling SEK 4,500 to visit Europe's leading physical scientists, Ostwald, Friedrich Kohlrausch, Ludwig Boltzmann, van't Hoff and others.

Ludwig Boltzmann and students from the Institute of Physics University of Graz Summer 1887. Standing to the left Walter Nernst, at the table Ludwig Boltzmann and behind him to the right Svante Arrhenius.

Physical Chemistry – A New Discipline

The 19th century brought with it an extraordinary expansion of the natural sciences, due in part to strong industrial growth. The initial mastery of synthetic organic chemistry had led to a wave of commercial developments centred around the production of new structural materials, textiles, dyes, fertilizers and other much coveted goods. Small wonder, then, that organic chemists found their discipline to be productive and progressing well without much support from other areas of chemical science.

At the same time, the formulation of thermodynamic principles gave chemists the tools to carry out precise determinations of properties such as molecular weights and acidities of synthesized compounds, and to predict relationships between temperature and pressure in reacting systems. Although such studies were of obvious value, they were plagued by not belonging to the realm of either physics or chemistry. Reported observations were generally buried deep inside chemical journals, and audiences at the chemists' professional meetings were very small when subjects of this nature were presented.

In 1887 those working in the field found the situation unbearable. Ostwald in Riga and van't Hoff in Amsterdam therefore initiated the publication of a new journal to be called *Zeitschrift für Physikalische Chemie*. This initiative was immensely important for the young discipline of physical chemistry as it provided legitimacy to observations that, despite a difficult start, have come to be fully accepted even in elementary courses in chemistry.

Upon its presentation, Arrhenius' dissertation had not met with broad approval, and had it not been for Ostwald's strong support, the idea that salts upon dissolution dissociate into ions would have had a much slower road to acceptance.

Fortuitously, in 1886 van't Hoff had begun a search for analogies be-

The major portion of "the wild herd of ionists", Ostwald and Arrhenius, here in conversation with Richard Abegg.

tween the behaviour of compounds in dilute solutions and gases at normal pressure. To test this analogy, he had made a series of osmotic pressure measurements for an array of compounds dissolved in water. Although, in general, solution pressures were found to be proportional to the molar solute concentrations as expected, a vexing departure from this rule was noted for some compounds. Despite these obvious deviations the study was meritorious and the work was published.

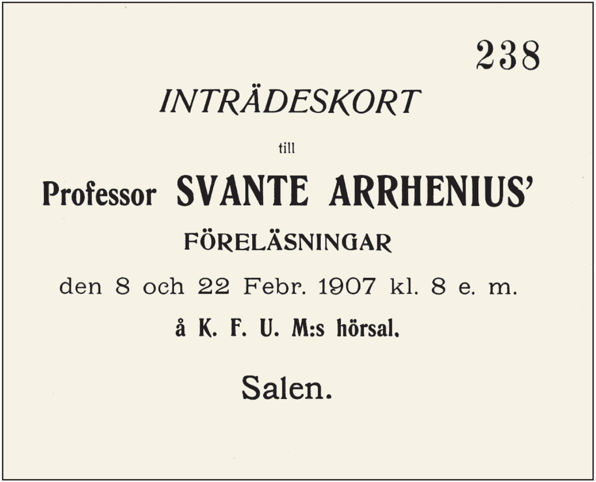
In March 1887 the author forwarded a copy to Svante Arrhenius for review. After some pondering Arrhenius realised that the deviations appeared specifically for solutions of salts and that they were nearly proportional to the number of ions constituting the salt molecule in question. Here, suddenly, was the perfect proof of the mechanism that Arrhenius had proposed in his doctoral thesis to explain the observed electrical conductivity of salt solutions. The publication of his findings in the first volume of the Zeitschrift marks the beginning of a life-long friendship between Ostwald, van't Hoff and Arrhenius. The trio came to be known by their numerous scientific enemies as "The wild herd of ionists."

Two years later, the *Zeitschrift* published another one of Arrhenius' articles; this one outlining the effect of temperature on the rate of a chemical reaction. Although modern textbooks in physical chemistry take the dissociation of salts into ions as being self-evident without the need to identify an inventor, the "Arrhenius rate law" is, to this day, an important and frequently cited model ofreactivity widely used also as a tool in the engineering sciences.

Physics at Stockholms Högskola

Following his dissertation, nearly a decade passed before Arrhenius was able to take up an academic position in Sweden, when he was appointed physics lecturer at the young university, Stockholms Högskola. In the interim he had not been idle; he had spent valuable sojourns in Riga and Leipzig with Ostwald, in Amsterdam with van't Hoff, in Würtzburg with Kohlrausch, a pivotal figure in the study of the electrical properties of solutions, and with Boltzmann in Graz. All this, coupled with his friendly and personable style, gave him a network of international contacts – something that was unusual in Sweden at the time.

Among his Swedish peers, however, there were still lingering doubts about his qualifications as a physicist. Indeed, when the professorial chair in Physics became vacant a few years later, a veritable war broke out between supporters of Arrhenius' candidacy and those who, at all cost, wanted to prevent him from claiming the title Professor of Physics. The battles were fought in the open arena offered by the daily press and left many scars among all involved. Nevertheless, in 1895 the chair was his and two years later he was appointed Vice Chancellor of Stockholms Högskola. Under his leadership the Physics programme blossomed, not least through his creation of the Physics Society which arranged public lectures and presented topics of current interest advertised in the local press. Typical topics included geophysics, vulcanology, the origins of the Northern Lights and other cosmic phenomena (see below). Another topic of great interest was the generation of hydroelectric power, including transporting power over long distances. Arrhenius gave most of the lectures himself, and due to his skills as a lecturer, the sessions attracted large crowds.



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INTRÄDESKORT

till

Professor SVANTE ARRHENIUS'

FÖRELÄSNINGAR

den 8 och 22 Febr. 1907 kl. 8 e. m.

å K. F. U. M:s hörsal.

Salen.

Arrhenius was a popular lecturer and an admission ticket was required to attend his classes.

Contribution to popular science

The technical and scientific optimism of the period around 1900 did indeed generate strong popular interest in the progress of science and technology. Many of the greatest scientists at the time participated in the lively debate about the positive consequences of scientific and technical inventions, and Arrhenius took part with great enthusiasm. Between 1906 and 1925 he wrote eleven books popularizing science and summarizing scientific progress. They were translated into all major languages, including Russian, Chinese and Japanese; some of the most widespread were "Världarnas utveckling," "Människan inför världsgåtan," "Stjärnornas öden," "Kemien och det moderna livet." and "Planeternas Atmosfärer". In English these selected titles appeared as "Worlds in the Making", "Cosmogonic Ideas through the Ages", " The Destinies of the Stars", "Chemistry in Modern Life" and "The Atmospheres of the Planets" came to the fore in 1913 when a limited epidemic of smallpox hit Stockholm. Arrhenius became strongly engaged in encouraging massive vaccination against the disease. To counter the vaccination opponents he wrote engaging historically and statistically well documented book on smallpox,"Smittkopporna och deras bekämpning" which would translate as "Smallpox and its Combat". In a clear and readable way he explained to the general public what was at stake, citing recent extraordinary fatality levels in all central European countries except Prussia, where Bismarck had introduced a general vaccination in 1874 and where consequently the fatalities were very few. Mercifully, the Swedish epidemic ended without an extensive death toll.

Svante Arrhenius' first popular book, Worlds in the Making, generated enormous interest and was one of the two best selling books in Sweden in 1906. Here Arrhenius presented current scientific views of the universe – infinite and ageless – and the origin of life on earth and potentially on other habitable planets seeded by spores travelling through space from one planet system to another driven by the radiation pressure of the stars (see below). This version of the panspermic theory, which was immediately attacked by Darwinists and conservatives, stimulated the debate about science and creation. This book, like others, was published in several editions and Arrhenius put much effort into continually updating the material to include the latest results in natural sciences.

The First World War marked the end of scientific and technological optimism and Arrhenius was shaken by the hostilities that affected his scientific colleagues. But he did not abandon his hope for a better future and after the war he actively participated in rebuilding Europe by restoring contacts between scientists in different countries. He was also an active supporter of the League of Nations.

The Will of Alfred Nobel and its implementation

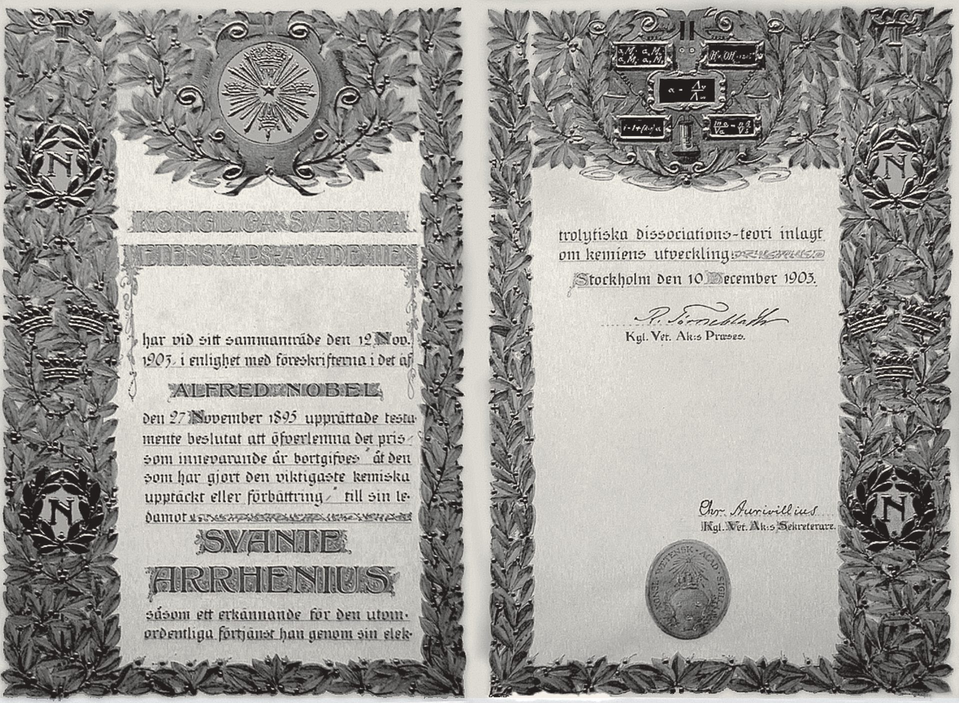
In 1897 the passing of Alfred Nobel had left the Swedish scientific establishment with the arduous task of devising suitable ways of handling the unusual financial legacy he had left behind. Nobel's expressed intentions had been to support mankind through the recognition of extraordinary findings in physics, chemistry and medicine as well as in literary art and in the promotion of peace. The task of crafting procedures for how this was to be accomplished was left to the executors of the will. If, in the end, the handling of this task had been anything but skilful, the Nobel prizes could well have become nothing more than research grants in support of the Swedish scientific establishment. Instead, and with "the battle at Stockholms Högskola" in fresh memory, it was realised that Sweden was too small to alone shoulder the selection of the most outstanding scientific contributions for the annual award. Instead, elaborate networks of international experts were identified, very much thanks to Arrhenius and the mathematician Gösta Mittag-Leffler, who were both well connected internationally by Swedish standards of the end of the 19th century. It is clear from the established networks and from the adopted selection rules that Arrhenius had a strong hand in designing the procedures for what developed into the most prestigious international scientific award, a distinction that has endured for more than a century.

The Nobel Institute of Physical Chemistry, situated in Frescati north of Stockholm, was designed by Svante Arrhenius. It became a focal point for social life among Swedish scientists and foreign guests. The picture below was taken at the inaguration of the Nobel Institute in 1909.

The Chemistry Prize of 1903 and the Nobel Institute of Physical Chemistry

The first Nobel Prize ceremony was held in 1901. Although a number of network delegates had proposed Arrhenius for a chemistry prize this first time around, the final choice was his colleague van't Hoff. The following year the chemistry award went to the renowned German carbohydrate chemist Emil Fischer. In 1903 it was Arrhenius' turn. Even though the prize was awarded for chemistry, and not physics as he would have preferred, the award was a significant recognition of the work that had begun with his ill-fated doctoral thesis nearly twenty years earlier.

Despite this recognition his employment situation in Stockholm, especially with respect to laboratory facilities, was highly unsatisfactory. When Arrhenius was offered a professorial chair in Berlin a year later he was tempted to accept. Thanks to the intervention by King Oscar II, financial resources from the Nobel Foundation that had been set aside to build so-called "Nobel Institutes," were used to establish a research facility for Arrhenius and his invited foreign colleagues. The Nobel Institute for Physical Chemistry designed by Arrhenius was inaugurated in 1909. It was located in Frescati, north of Stockholm just a stone's throw from the Academy of Sciences, and became a focal point for the social life of the Academy and its foreign guests.



KONGLIGA SVENSKA
VETENSKAPS-AKADEMIEN

har vid sitt sammanträde den 12 Nov. 1903 i enlighet med föreskrifterna i det af

ALFRED NOBEL

den 27 November 1895 upprättade testamente beslutat att öfverlemna det pris som innevarande år bortgifves åt den som har gjort den viktigaste kemiska upptäckt eller förbättring till sin ledamot

SVANTE
ARRHENIUS

såsom ett erkännande för den utomordentliga förtjänst han genom sin elektrolytiska dissociations-teori inlagt om kemiens utveckling.

Stockholm den 10 December 1903.

R. Törnebladh
Kgl. Vet. Ak:s Præses.

Chr. Aurivillius
Kgl. Vet. Ak:s Sekreterare.

Hydroelectric Power and the Electrification of Swedish Railways

In 1900 the Swedish Government began contemplating the exploitation of its large hydroelectric power resources as a substitute for the large quantities of coal being imported for power generation, primarily from Great Britain. The feasibility of utilising hydroelectric power to operate the railway system was of particular interest. As a first step in this investigation, a royal commission was issued whereby Svante Arrhenius would chair a small task force of four experts in engineering and economics. The group was given six weeks to travel around central Europe and gather information regarding the practicality of utilising hydroelectric power for the railway system, with a particular focus on power generation and storage, and the cost per kWh at various geographical locations. Special emphasis was placed on the acquisition of legal rights to use a valuable resource (falling water) which, until only a couple of years before, had been without commercial value. The task force's findings are summarised by Arrhenius in the short but fact-laden "Report from the Royal Department of Agriculture, No. 1, 1901." The report was exemplary in its clarity. It stated unequivocally that Sweden had abundant developable hydroelectric power. Yet the costs (in the year 1900) associated with electrification of the railway would be prohibitive, considering that power transmission over distances greater than 150 km was not yet technologically feasible and that an extensive power grid would be needed to service the rail system in our long country. Another argument against the electrification of the rail system at the time was the intermittent demand for power which would make the cost per kWh prohibitively high. A more constant rate of consumption, such as that by industries with round-the-clock operation, would significantly reduce the cost per kWh and favour hydroelectric over steam power. A far more attractive savings initiative would therefore be to reduce the need for the portion of the SEK 64 million for annual coal imports, which served the country's growing production industry, and replace it with hydroelectric power.

Örebro Elektriska AB, and Örebro Pappersbruk

The fast progress of the natural sciences and the related technology in the beginning of the 20th century made Arrhenius and many others feel a great sense of optimism about the world's future. This optimism, combined with his social and technical interests, resulted in his participation in several industrial projects, including the hydroelectric power plant Örebro Elektriska AB and a couple of years later (1901) in the pulp and paper mill, Örebro Pappersbruk. The latter was built close to the power plant to be a good electric power customer, thereby improving the somewhat unstable finances of the former. The pulp and paper mill's location close to the centre of the town of Örebro caused many complaints about pollution and bad odours, and resulted in a lengthy legal battle (1904-1911). Subsequently great efforts were made to improve and clean up the pulping process. This must have concerned Arrhenius and made him realise that industrial economic developments also carried problematic aspects. In his book "Chemistry in Modern Life" (1919) he held out the great potential that modern chemistry was offering for Swedish industry and global developments. Still, he wrote a popular book about "Chemistry and Modern Life" (1919) where he emphasized the great potential modern chemistry would have for Swedish industry.

Svante Arrhenius participated in several industrial projects. This diploma is proof of appreciation from the hydroelectric power plant Örebro Elektriska AB.

Among the many scientists that joined Arrhenius at the Nobel Institute was Thorwald Madsen from the Danish Serum Institute in Copenhagen who wanted to apply the new physical chemistry arguments to shed light on the ”toxin-antitoxin” affinity reaction. This reaction was observed when a serum sample from an infected patient was added to a suspension of the micro-organisms that had caused the infection. The affinity question was raised at a time when our knowledge of proteins and their complex architecture was non-existent.

The serological studies by the two colleagues met with opposition from those who opined that chemical models were inappropriate to explain the intricate processes of life. The opponents included supporters of the highly regarded physiologist Paul Ehrlich in Frankfurt, who had formulated the so-called “side-chain theory” of the immune response which postulated that the reaction involved a sequential formation and secretion of a series of complex reactive vesicles. This stood in stark contrast to the Arrhenius concept of the existence of a well-defined binding equilibrium between two entities, in turn considered to be a ridiculously simplistic notion by the opponents. The “Arrhenius-Ehrlich controversy” became quite a cause célèbre in the scientific community and the debate initiated by the two scientists raged for several years after the turn of the century.

The "Arrhenius-Ehrlich controversy" was widely debated among the scientific community. In this picture from 1903 you find Ehrlich on the left at the table, with his dog on his lap, debating with Svante Arrhenius.

Arrhenius, who was always ready to express himself clearly in his writings supplemented by considerable experimental data, compiled a series of research reports that he had presented at the University of California, Berkeley in 1904, into a volume that he published under the title "Immunochemistry." By his insistence that chemical principles were at work even in physiological reactions he became the recognised father of an entirely new discipline.

Arrhenius contributed importantly to many fields, but his foremost interest throughout his life was what he called "cosmic physics", collectively what we today would call geophysics, planetary and space physics, and cosmology. As shown in fig.1, his productivity in this field extended from his first to his last publication and in volume they outnumbered those in any other field, a fact not generally recognized.

Some of his interpretations of astrophysical data have been overtaken by modern measurements with vastly increased resolution. On the other hand, the effects of the atmospheres of planets on their energy balance has become a major issue in contemporary world politics.

The discovery of electrolytic dissociation which, like his reaction rate theory, has been eponymously named after Arrhenius, played an important role in his innovative thinking for only a decade after the breakthrough. The trailing end of related papers mostly represents work indirectly intended to strengthen the concept of partial ionization against conceptual modifications by a new generation of physical chemists. Instead his creative enthusiasm was for the rest of his life focused on "cosmic physics," biochemical and technological issues.

Structure of the universe and the distribution of life

For Arrhenius as for other leading contemporaries such as Lord Kelvin, Maxwell and Boltzmann, the infinity of the universe in space and time was self evident, although admittedly purely a philosophically based assumption. Against this background, the question of the origin of life was also meaningless; life had always existed. Since stars and planetary systems were seen to form and perish, a basic question was how life could propagate in space, moving from doomed environments to populate new habitable regions.

While Lord Kelvin proposed impact as a source of fragments carrying spores of life, Arrhenius objected on the basis of the destructiveness of collisions between celestial bodies and the low speed of ejecta compared to interstellar distances to be traversed. He therefore took up the centuries old idea of panspermia – microscopic life dispersed through space. What was missing was a theory for the lifting off of such spores from their home planets, their acceleration to necessary velocities and their survival during millennia in the harsh space environment.

For propagation he found a tool in radiation pressure recently discovered by Lebedev and Hull. Liftoff would be achieved by the spores being by solar corpuscular radiation and being repulsed by the net planetary charge, a concept similar to the now known phenomenon of "polar wind." For survival, Arrhenius could invoke his chemical reaction rate law which, at close to absolute zero in space, would ensure biomolecular integrity.

With the modern development of the concepts of a finite age of our universe and experimentally based theories for the origin of life, Arrhenius' panspermia went out of fashion for a while but has generated occasional interest due to a small group of prominent astrophysicists, heretically opposing the "big bang" cosmogonic model. A modern IVA based analysis of the panspermia concept was carried out by Curt Mileikowsky.

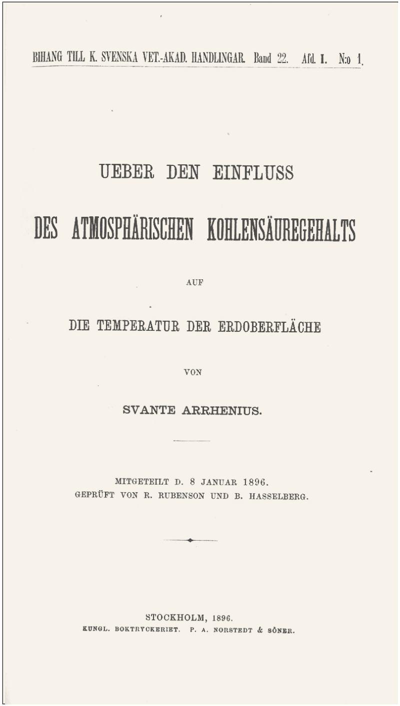
Nature's energy balance and global warming

As a forum for interdisciplinary debate on cosmic physics, Arrhenius founded the Physics Society active at Stockholms Högskola (see above). One of the contributions that attracted his attention in particular was a demonstration by the geologist Arvid Högbom of the geochemical cycle of carbon dioxide with volcanism as input and weathering, organic growth and burial as removal mechanisms.

Arrhenius became fascinated by what he saw as the role of carbon dioxide, water vapour and clouds as variable infrared active components in planetary atmospheres, leading to retention of solar heat and thus climate control. This "greenhouse effect" was found to be particularly important on Earth, Mars and Venus. He thought that long-term variations in volcanic activity, the main source of carbon dioxide in the atmosphere, would likely be responsible for the Quaternary ice ages and interglacials.

In order to test this hypothesis Arrhenius set out on a detailed calculation of the magnitude and regionality of global warming and cooling caused by changes in CO_2 content and related atmospheric variables. He approached this Herculean task using what in modern engineering practice is known as "finite element analysis", dividing the Earth's surface from 70 deg N to 60 deg S into small segments and calculating the radiative balance for each of them for day and night in four different seasons under four different assumptions about atmospheric CO_2 concentration. Doing this without the aid of a computer consumed the better part of a year – the most tedious task he had ever undertaken.

The reward was a quantitative demonstration of temperature effects, affecting particularly the high latitudes and of such magnitude that Arrhenius felt his glacial climatic theory vindicated. He now went a step further and turned his attention to the similarly caused warming that would result from the accelerating industrial injection of CO_2 by fossil



BIHANG TILL K. SVENSKA VET.-AKAD. HANDLINGAR. Band 22. Afd. I. N:o 1.

UEBER DEN EINFLUSS

DES ATMOSPHÄRISCHEN KOHLENSÄUREGEHALTS

AUF

DIE TEMPERATUR DER ERDOBERFLÄCHE

VON

SVANTE ARRHENIUS.

MITGETEILT D. 8 JANUAR 1896.
GEPRÜFT VON R. RUBENSON UND B. HASSELBERG.

STOCKHOLM, 1896.
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER.

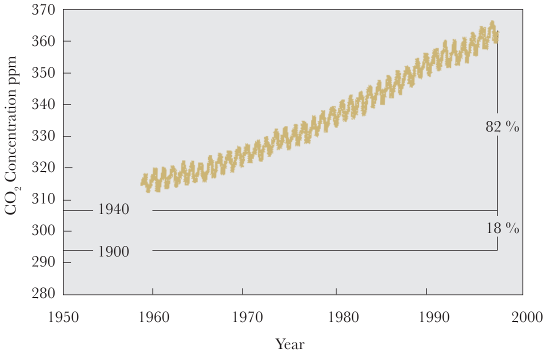
First publication on what has become known as "the green house effect" was in February 1896.

coal burning and cement manufacture, the latter by release of CO_2 bound in limestone. In the perspective of the inclement Nordic weather, Arrhenius as a "cultural optimist" considered this warming as an attractive prospect, with an increased abundance of the plant nutrient carbon dioxide also promising improved harvests. In this context he pointed to the benign effects of climatic optima in recent geological and cultural history.

It is remarkable that Arrhenius' laborious analysis gave thermal results close to those later obtained by hundreds of hours of calculations carried out with powerful digital computers. However his time perspective was off – the time required in Arrhenius' calculations to reach a three to four degree average increase in temperature of the atmosphere was on the order of 3000 years instead of the much shorter times now considered. This discrepancy was likely due to an overestimation of the net rate of uptake of CO_2 by the ocean, not realising at the time the inhibition of ocean mixing by a warm surface layer effectively in the short term sealing off the main body of potentially CO_2 absorbing deep ocean water. Arrhenius also greatly underestimated the magnitude and acceleration of future man-induced CO_2 emission and regretted that the beneficial effects would only be enjoyed by our remote descendants.

While Arrhenius' prediction received great public interest, this typically waned in time but was revived as an important global mechanism by the great atmospheric physicist Carl Gustaf Rossby who initiated atmospheric CO_2 measurements in Sweden in the 1950s. Thanks to the efforts of Rossby, Roger Revelle, the Director of Scripps Institution of Oceanography (SIO) and Harry Wexler at the U.S. Weather Bureau, the question of Arrhenius' greenhouse effect was taken up as a major topic for the International Geophysical Year 1957-1958. As a continuation of this project, permanent CO_2 measurements were initiated under the leadership of Charles D. Keeling at SIO. These were carried out with improved precision and in locations (the top of Mauna Loa in Hawaii and in the Antarctic) ensuring sampling of a well mixed atmosphere and eliminating the local, vegetation induced variations that had hampered the early Swedish measurements. Thanks to Keeling's persistence and skill we now have a five-

Until C.D.Keeling had completed high precision measurements of carbon dioxide in the atmosphere over a meaningful time period the highly political question of a global increase of carbon dioxide, indicated by Arrhenius as a basis for global warming, could not be confirmed experimentally.



decade record of the growth of atmospheric carbon dioxide, placing beyond doubt the man-made increase in atmospheric concentration predicted by Arrhenius.

To the initiators of this effort the now quantitatively known spike of CO_2 input represented a global one-time, and therefore unique, experiment that would shed light on the unknowns in Arrhenius' model: the rate of streaming of carbon dioxide between its natural reservoirs, the industrial sources, fossil carbonate and carbon, and the sinks – weathering silicate rocks, uptake by the ocean, burial of organic carbon and an expanding biosphere; only the first of these were known by Arrhenius with some precision. With a better grip on the major variables it would eventually, with the help of the new atmospheric observations, be possible to assess the time perspective of global warming, which had eluded Arrhenius.

With the publicity surrounding these developments, public interest and concern has come to be focused on the ultimate global warming aspect. Here, another variable – natural secular climatic changes – further complicates the evaluation of the changes caused by human activities, giving rise to fierce political polarisation with respect to the need for global remedial action.

Also here, Arrhenius' viewpoint serves as a guide. He strongly advocated remedies to stop the indiscriminate waste of fossil energy and chemical resources, oil, gas and coal. He was a strong proponent of societal action for alternative energy sources and was appointed by the Swedish Government as an advisor in the national development of hydroelectric power at the turn of the twentieth century (see above). He made a positive evaluation of the efficiency of "solar machines" for the production of electric energy in and from low latitude regions, and argued for a reliance on wind power generation at higher latitudes.

Such developments are now driven by the rapidly rising direct and indirect costs of fossil carbon consumption while at the same time mitigating the destabilising effects of man-made global warming. Arrhenius' opening of this field over a hundred years ago has probably become his most lasting political and socio-economic legacy.

Geophysical phenomena

Arrhenius' work was characterised by his considerable ability to interpret seemingly complex phenomena in terms of physical laws. Both practical and scientific demands turned this ability to an asset. One example of practical importance was his straightforward explanation of salt domes, a then poorly understood geological formation of importance in the prospecting and exploitation of oil and gas deposits. They consist of large mushroom-like sedimentary evaporites protruding through clastic sandstones and clays, and serve as impermeable barriers, stopping and accumulating migrating hydrocarbons and preventing them from leaking to the surface and being lost.

When studying the geometry of the deposits, Arrhenius came to the simple conclusion that the domes were the result of the release of a Rayleigh instability, a stratification of a denser laminar body (the clastic sediment layer) on top of a lower density material (the salt layer). Upon a disturbance of a magnitude determined by the theory, the instability is released and the low density material erupts through the overlying high density stratum and in the geological case freezes in the observed shape. Hence oil and gas prospecting has come to depend much on remote density (gravity) measurements, a subject that was also of interest to Arrhenius as a general geophysical technique.

In other cases Arrhenius' attempts at interpreting natural phenomena were even bolder and were not at that time completely accepted by the scientific community. This category includes his application of osmotic theory, a tool of fundamental importance in his dissociation theory to the cause and nature of volcanism. Drawing on the observation that volcanoes are heavily concentrated on the continental rims, particularly in the Indo-Pacific region (the "Ring of Fire"), Arrhenius proposed that the sediments separating the magma reservoirs from the sea water act as a semipermeable membrane with the silicic acid in the melt drawing in water and thus exerting an osmotic pressure, forcing the magma to rise in the volcanic vent. His calculation of the height of the resulting lava column was sufficiently close to the altitude of the Andean volcanoes.

Although the theory as a whole has hardly won support among geoscientists, it contains elements of interest in the interaction of volcanic source magma with water and the subduction of seafloor rocks and sediments under the continental edge. It is not impossible, as often with Arrhenius' theories, that this one will reappear in a relevant modern form. A case in point is his theory on molecular interaction in immunochemistry (see above), originally regarded as the folly of an otherwise recognised scientist and now an experimentally verified basic concept.

Arrhenius' contributions to cosmic physics are too numerous to be described in detail in this context, but a selection has been provided here of subjects that strongly attracted his interest and dominated his published record over his productive lifetime – from his first publication in 1881 on ball lightning to his last in 1927 expanding on interplanetary transport of life.

The jovial scientist enjoying life.

Epilogue

The first international scholar to join Svante Arrhenius' young research team at Stockholms Högskola was Hans von Euler, later recipient of the Nobel Prize in Chemistry (1929). He characterises his mentor as follows:

"Above all, it was his ability to grasp the great problems and confine himself to their essentials in treating them that gave his versatile scientific work an individual and brilliant character. An unusual intuitive sense had often carried him in the right direction. He was also, in science and in life in general, a pronounced optimist…. His solid intelligence made him unprejudiced even in questions which lay outside his field of knowledge. As a man he was a good-hearted, integrated personality who kept his balance under all circumstances."

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