VILHELM BJERKNES[1]
March 14, 1862 — April 9, 1951

1. Family background. Education, student of Hertz.

BY OLAF DEVIK.

In his 63rd year Vilhelm Bjerknes published a biography of his father, Carl Anton Bjerknes, a book giving not only a narrative of the life and work of the principal person, but also a valuable contribution to Norwegian cultural history in the 19th Century. It demonstrates the difficulties and obstacles which in those days a student might encounter on his way to a university degree, particularly when his mind was bent upon research activity.

The life and work of Vilhelm Bjerknes had such a close connection with his father's ideas that a biography such as this one would be incomplete without due consideration of this fact.

In 1812 the father of C. A. Bjerknes obtained an official scholarship which enabled him to go to the University of Copenhagen. He qualified as a veterinary surgeon, settled down with his wife in Christiania, and here Carl Anton Bjerknes was born in 1825.

C. A. Bjerknes obtained a scholarship at the University, and later he spent the years 1855—57 abroad, drawing inspiration from leading mathematicians and physicists, first at Paris and then at Göttingen. Decisive for him became the lectures given in Göttingen by *Lejeune-Dirichlet* on the integration of differential equations with application to physical and hydrodynamical problems. Dirichlet demonstrated from his equations that in an ideal liquid a sphere would not be carried away by a uniform current. This result brought to C. A. Bjerknes the recollection of a book which had caught his imagination when he happened to read it in his student years. It was Euler's "Letters to a German Princess", published in 1770 in French and in 1792 in Danish. Even today it is sufficient to read a few of these 234 letters to get an impression of the brilliant capacity which Euler possessed to describe intelligibly a rather complicated matter.

[1] Edited by A. Eliassen and E. Høiland on the basis of original manuscripts by T. Bergeron, O. Devik and C. L. Godske.

Euler discussed thoroughly the forces of gravitation acting in space, and likewise the propagation of light, and he maintained that a so-called action at a distance in an empty space might in reality be due to the motion of a light medium (ether) filling the space.

The problem of whether Space is a Vacuum or a Plenum had fascinated the young student, and now the results obtained by Dirichlet seemed to support the ether hypothesis. Could not, Bjerknes asked himself, the invisible space-filling medium transfer hydrodynamic forces which would apparently move bodies as if they were exposed to forces acting at a distance through empty space? That the answer had to be found by studying the simultaneous motion of a number of spheres in a liquid was the immediate conclusion drawn by C. A. Bjerknes. This mathematical and experimental research program became his life's work.

On his return in 1857 from studies abroad C. A. Bjerknes continued his work at the University and was appointed professor of mathematics in 1866. In 1859 he had married Miss Alette Koren, daughter of a minister at Selje. They had four children, and number two was Vilhelm Bjerknes, born on the 14 March 1862. In the biography mentioned above he has described the home with great warmth and a keen sense of humour.

It happened during the first World War, in the summer of 1918, that the author of this article walked with Vilhelm Bjerknes to the outpost of Western Norway, Stadtlandet, and later on we visited the parsonage at Selje. Bjerknes then told me that we had walked the same way as his father and his mother had walked in their youthful days. The young scientist had charmed everybody in the parsonage, leaving science aside for a time.

Personally I never knew C. A. Bjerknes, but I have often met Mrs. Alette Bjerknes at the home of her son. The lively and wise old lady must have been a good and practical providence for her husband, absent-minded as he became and unpractical as he was. What a charming picture Vilhelm Bjerknes has drawn of the family circle when the day's work was ended and the professor read aloud from classical books, while the mother was busy with her needlework and Vilhelm kept to his hobby of cabinet-work. At family parties the learned father would reveal a well of inspiration which made him a perfect host and occasional orator.

In the book "The Students from 1880" Vilhelm Bjerknes states that it had been difficult for him to learn the art of reading and writing, and that in school lessons he was mostly engaged with his own thoughts and speculations. Reckoning with numbers was never his forte — he was often inclined to transpose the figures. When he was preparing his lessons at home he would sit with his father in the study, and he took no part in games and sports with his brother and other boys. Very early, however, he became fond of walking and skiing together with a friend, and this hobby he nurtured even at a great age.

He developed gradually what was in mature years to become his forte, the intense and methodical concentration of mind, focusing upon the importance of giving his thoughts a precise formulation with a clear physical connection.

Vilhelm Bjerknes passed the Matriculation examination in 1880 — Fridtjof Nansen was his fellow-student — and graduated in Science in 1889. During his student years he assisted his father in his researches in hydrodynamics, being greatly influenced by these works and the outlook they seemed to give upon fundamental problems in physics. As early as 1882, when he was 20 years old, his first publication appeared — a popular article on hydrodynamic investigations. The treatise contains a description of the different experimental demonstration apparatus which had been developed by the collaboration between father and son. In the preceding year, 1881, the instruments had been demonstrated at the first Electric World Exhibition in Paris, where the young Bjerknes performed the experiments and explained them to the visitors including nearly every leading physicist and electric engineer at that time. The demonstration was a perfect success and C. A. Bjerknes received one of the 11 Diplomes d'Honneur.

Such experience naturally strengthened the young student in the opinion that the field of research which his father had entered upon would be a promising one, and that it would be worth while to pursue to the ultimate end the analogy between the hydrodynamic fields of force and the fields of electricity and magnetism.

In the following years Vilhelm Bjerknes found it necessary to postpone his further occupation with his father's researches. He concentrated upon his university studies and passed his degree with distinction in 1889. Shortly afterwards he obtained a scholarship for studies abroad and went first to Paris to Poincaré who lectured on Maxwell's theory and also the electromagnetic waves which Hertz recently had produced in his laboratory at Bonn. Then Vilhelm Bjerknes in 1890 went to study the new waves as the first collaborator Heinrich Hertz had in his short life. He stayed there nearly two years, which proved to be most important to him, and all his life he kept a great attachment to Hertz, who died in 1893. Nor did he forget the widow of Hertz and his daughter. He assisted them 40 years later when the Third Reich would not acknowledge the name of Hertz so that mother and daughter had to find refuge in England.

Within the field of electromagnetic waves Vilhelm Bjerknes published a series of papers in the years 1891—1895, and his studies on electric resonance were of fundamental importance and belong to the classical papers in radio science. It is strange to realize that Vilhelm Bjerknes who lived to see television had himself worked together with Hertz when the electromagnetic waves were studied experimentally for the first time. One might ask why he left such a pioneer field. One reason may be that Hertz died so young; another may be the fact that the physicists turned their attention to other new discoveries: Cathode rays, Roentgen rays and radioactivity.

The wireless telegraph was developed in the industrial field and for a long period the technique was more or less an extention on a big scale of the laboratory experiments of Hertz.

During the First World War the Norwegian Telegraph Service built a big Marconi transmitting station near Stavanger to communicate with the U.S.A. It had a rotating spark transmitter which made a terrible noise in the machine-room. Bjerknes visited the station and found it amusing to discover all the parts which in his time belonged to an Hertzian oscillator and to his own resonance circuit, now enlarged to giant size.

Although Bjerknes left the experimental field of electromagnetic waves, he concentrated on the study of Maxwell's theory, and he also made an important acquaintance with the work of Oliver Heaviside, who was a pioneer in introducing vector analysis which greatly simplifies the use of mathematics in electrodynamics and hydrodynamics. A correspondence with Heaviside began in 1900, and Bjerknes made a special journey to see Heaviside who lived at Torquay in isolation and loneliness. I shall always remember the description he afterwards gave of this visit, which certainly was encouraging and helpful to Heaviside whom Bjerknes greatly admired.

These theoretical studies gave to Vilhelm Bjerknes an important tool for research both in Electrodynamics and Hydrodynamics, and when he in 1893 was appointed lecturer of Mechanics and later Professor of Physics at Stockholms Högskola, he could concentrate upon the systematic presentation and the fulfilment of his father's work, which was the theme of his lectures. In 1900—1902 these lectures were published in two volumes on *Hydrodynamic action at a distance according to C. A. Bjerknes' theory*. A generalization of the methods was presented in 1909 in a book *Fields of Force*. In this book the equations of motion of a fluid with special qualities were given in a form analogous to Maxwell's equations of the electromagnetic field.

In this way Vilhelm Bjerknes fulfilled the obligations he felt necessary to secure the completion of his father's work. In the memorial lecture which he gave 1903 after his father's death he aimed at giving a picture which might also be understood outside the circle of experts, and he wrote in a letter to the famous Norwegian poet and novelist Bjørnstjerne Bjørnson who was a friend of his father: "— not the usual picture of a scientist in full communication with his contemporaries, reaching within an inch ahead of now one, and now another prominent scientist in the same field, but the picture of the lonely one, without the stimulation by the competition of his contemporaries, having his inspiration from a distant past and working for a perhaps even more distant future. However, just for that purpose when time has given perspective, he will be seen as one of those who spiritually are building Norway and be heard as one of those who are calling her name through the future."

The conception of space, matter and energy were transformed radically through Einstein's Theory of Relativity, and it became no longer relevant to discuss a mechanical analogy to electromagnetic phenomena.

In 1893 Vilhelm Bjerknes married Miss Honoria Bonnevie, daughter of a prominent civil servant, for some years minister of education. The family Bonnevie had left Provence at the time of the persecution of the Huguenots and settled in Norway. Miss Bonnevie was a natural science student at the University and had followed the lectures of C. A. Bjerknes. They had fours sons. Mrs. Honoria Bjerknes followed the tradition of her mother-in-law, taking on her part all the duties of the household, she had the administration of the family's economy, and besides these tasks it was hers to see that the learned husband could work undisturbed in his study. With kind hospitality Mrs. Bjerknes received the many students and collaborators who were often their guests.

As mentioned above, Vilhelm Bjerknes was very handy in his youth. At his university office in Christiania he had his old lathe and his good vice for many years, and the latter stood in front of the book-shelf in his private study when he became professor emeritus. However, the zeal which once made the young professor indicate to his wife, that the living-room might be a suitable place for his lathe, — a proposal without sufficient resonance, did not last in the long run. By and by he would, like most professors, develop a sub-conscious understanding of the fact that it may be practical for an absent-minded person to be unpractical.

2. The Stockholm period.

BY TOR BERGERON.

In 1893, at the age of 31, Vilhelm Bjerknes got his first independant academic position, being appointed a lecturer in mechanics at the University of Stockholm (Stockholms Högskola). In 1895, he was installed as a full professor of mechanics and mathematical physics there, a foresighted initiative, for which Geophysics shall always have to be thankful. Here Bjerknes for the first time really came away from the paternal ties and obligations and got an entirely new sphere of activity. He also got intimate Swedish friends and pupils. All this was of great importance for his work, his comfort and development, and for his gradual transition to the geophysical sciences.

However, during his first time in Sweden he was as busy as ever following up his fathers ideas. The fact that his chair was one of Mechanics (and not Mathematics or Physics) went very well with that work. In this position he lectured over the entire field of Mechanics, and the purely mechanical aspect of the alleged analogy between hydrodynamic and electro-magnetic action at a distance became the central question. In the theoretical deliberations he replaced the solid bodies, pulsating and oscillating in the fluid, by fluid parcels of another density. V. Bjerknes was in this way led to the discovery of his two famous circulation theorems, which he first presented to his audience in his ordinary lectures at the University of Stockholm in April 1897. The first printed paper came in 1898. — V. Bjerknes saw the fruitful physical interpretation and the importance of his theoretical discovery. Vistas opened to him into an entirely new field of research, that of a physical hydrodynamics, where the idealising assumptions of classical hydrodynamics no longer are valid. L. Silberstein, of the University of Cracow, had published one of the two theorems already in 1896, however, without seeing its physical implications.

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A retrospect of two main fields within Physics at that epoch, will even better elucidate the great importance of Bjerknes' discovery of 1897. There existed at that time already a rational *hydrodynamics* and a *thermodynamics* of fluids and gases, *but the atmosphere and the oceans as a whole did not as yet belong to the field of these two disciplines.* In fact, the circulation theorems threw a bridge between classical hydrodynamics, whose fluids could not serve as a working substance within a thermodynamic machine, and classical thermodynamics, where one did not need to follow in detail the motion of the working substance. The foundations were laid for a *physical hydrodynamics*, by which the step could be taken from the writing desk of the theoretician, and from the laboratory of the experimentalist, out into reality: to the atmosphere and oceans of our rotating planet — and even to the atmospheres of other heavenly bodies — where vortices continually form, grow and decay.

With the circulation theorem as a starting point, Vilhelm Bjerknes managed to create a fruitful synthesis between these two main branches of Physics, which led to a huge extension of its field of applicability. The atmosphere and the oceans became accessible to a quantitative treatment based on rational physical principles, not only as to their small-scale states and motions — or under simplifying assumptions — but also concerning their general circulation and disturbances under quite realistic conditions. In fact, already in his paper of 1898, "Ueber einen hydrodynamischen Fundamentalsatz und seine Anwendung besonders auf die Mechanik der Atmosphäre und des Weltmeeres", Bjerknes demonstrated the application of the new theorems to such phenomena as ocean currents and ocean waves, trade winds and monsoons, the land- and sea-breeze, cyclones etc.

The greatness of Bjerknes' scientific achievement in this field does not only, or mainly, consist in the discovery of the circulation theorems themselves, but rather in the fact that he devoted a life-time to erecting, on the foundation of a physical hydrodynamics, a rational theoretical and practical Meteorology and Oceanography.

Now, 65 years later, we know that barotropy and conservation of vorticity are the dominating large-scale features of any atmosphere or hydrosphere, because of the rotation of all heavenly bodies. This return to classical hydrodynamics is, however, only apparent. In reality the baroclinic developments, i.e. the circulation accelerations, are the vital phenomena, nowadays being taken up again for study by the foremost theoreticians. These processes will, of course, eventually form the main concern of Dynamic Meteorology and Weather Forecasting.

However, before following this magnificent development further, we must go back to Vilhelm Bjerknes' time in Sweden, and take account of his scientific contacts there, which later proved to have been decisive for the development just hinted.

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Soon after he had moved to Sweden, Bjerknes established a firm friendship with his colleague at the Stockholm University, Svante Arrhenius, who almost at the same time as Bjerknes rose to fame in another Science, Physical Chemistry. This contact proved to be of great importance to V. Bjerknes and his family in many ways. Arrhenius was extremely broad-minded and mentally luxuriant personality, whose interests spread over practically all branches of natural sciences.

Through Arrhenius Bjerknes at an early stage got in contact with the Swedish meteorologist Nils Ekholm, with whom he discussed his pioneering meteorological plans and work. Ekholm had already in 1891 published some daily synoptic maps with lines of equal air density, isopycnics. Bjerknes was at that time still unfamiliar with the concrete atmospheric fields, among which the isobars and isosteres (the latter coinciding with the isopycnics) delineate the solenoids entering in his circulation theorems. Thus, according to Bjerknes' own statement in his above paper on the theorems, it was Ekholm's isopycnic maps that inspired him to applying the theorems to the atmosphere. Once more we witness a coincidence that may have been decisive for Bjerknes' further work.

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We have seen that Vilhelm Bjerknes already at an early stage envisaged wide perspectives for a new Geophysics. According to his own Bibliography in "Physikalische Hydrodynamik" (Berlin 1933), after 1897, the thought of trying to lay the foundation of a rational Dynamic Meteorology and Hydrography was always lurking at the back of his mind. However, he shrank from the enormous calculation and graphical work connected with such an undertaking. The contact with his first two Swedish pupils came to be decisive in this matter. — It is not the intention to enter here upon the great impact given to Geophysics by the works of these two eminent Swedish scientists. But the picture of their teacher and *his* life-work would be very incomplete without knowing how their collaboration came about and some of its salient features.

The dead-water phenomenon, well-known to seamen in high latitudes, but otherwise formerly regarded as a sailor's yarn, had been much felt by Fridtjof Nansen's ship "Fram" on his famous Polar expedition in 1893—96. V. Bjerknes' very first pupil, the young student V. W. Ekman, when confronted with the problem was able to explain it as the result of a wave-motion in a submarine surface of discontinuity, set up by the ship and thereby stealing momentum from it.

Among the results of Fridtjof Nansen's Polar expedition were also observations of the ice-drift in relation to the prevailing wind that seemed to contradict dynamic reasoning. When visiting Stockholm in 1900, Nansen discussed also this problem with his compatriot Bjerknes, who gave it to Ekman to study. The latter's swiftly working and mathematically well educated brain gave the answer the same evening: the well-known Ekman spiral. — Certainly, Ekman's result and its wide applicability, gradually showing up, must have strengthened Bjerknes' conviction as to his own mission in Geophysics, and stimulated his zeal for the great task he finally, in 1906, decided to take on. It also founded a life-long friendship and collaboration between these two scientists, of great mutual benefit to both.

The manner in which Bjerknes got in contact with, and for many years had as an assistant, the former mill hand J. W. Sandström — who proved a very useful collaborator at that stage of the development of Bjerknes' work — was naturally quite a different one. Since I am probably one of the few, if not the only one, now knowing how it came about, it may be permissible to retell the story here, the more as it came to have a considerable influence on Bjerknes' work, and also forms a contribution to the still unwritten biography of Sandström. The source of informations is a most reliable one: the outstanding mathematician Ivar Bendixon, professor at the Stockholm University during Bjerknes' period there, and later its Chancellor. This rather facetious story I heard from Bendixon as late as in 1922.

Sandström came from a small farm in northernmost Sweden and therefore — as Bjerknes later often liked to tell — had had no possibility of getting any regular school teaching at all. He came to the Stockholm University (where at that time anyone was admitted as a student without any previous exams) to study natural science with a stipend from benefactors at the industry where he had been a workman. Bendixon, being the supervisor of this stipendiate, had to summon him to report from time to time on the progress os his studies, but Sandström never appeared. At last, months having elapsed, he turned up at Bendixon's office with a huge of pile of .... Russian books and dictionaries! — "This is what has kept med so busy, professor", said the young promising student of natural science! — Evidently, Bendixon was a little shocked and did not like that turn of events too much. After having suitably reproached Sandström (as I knew Bendixon, certainly in very polite words), he turned to his friend Ekholm, who said that Bjerknes might need such an assistant, probably assuming that Bjerknes would be the right person to keep Sandströms' brains working along fruitful scientific lines. In fact, Bjerknes, having the Norwegian natural and straightforward ways, must have been much more apt to take care of that "uncut diamond" Sandström than the formal and circumstantial Swedish professors of those days. — Ekholm could hardly have guessed *how* right his judgement of Sandström was. The years with Bjerknes were probably Sandströms best scientifically speaking, although it is not sure that he realised that himself.

During this period Bjerknes got more and more convinced that Dynamic Meteorology had only one main, all-embracing task: to predict future atmospheric states. This problem, he meant, should then not be treated by sheer empiricism, i.e. cataloguing and memorising of isobaric patterns and weather types, as in the current weather forecasting of those days, but as a mathematically well-defined physical problem. He even thought of mechanical integration of the differential equations, i.e. numerical computation, when they were not analytically integrable.

His almost fanatic belief in Science at last goaded him into taking upon his shoulders the immense burden of trying to lay the foundations of a rational physical Meteorology and Oceanography, following the general principles of Laplace in his famous dictum of 1814. In Bjerknes' version of 1904, i.e. in his program for a Dynamic Meteorology, it might be expressed as follows:

Every purely mechanical atmospheric problem could be reduced to stating the present position and motion of all air-particles involved, and predicting their future state, position and motion at a given time by the laws of Physics — a problem which should in principle be solvable. The solution had to be carried through in three steps: (1) making the best possible diagnosis of atmospheric states, (2) finding the future position of all air parcels, (3) determining their future states in the new positions.

Next year, 1905, Bjerknes received an invitation to Columbia University in New York to give a series of lectures on hydrodynamic fields of force, and subsequently he was invited to Washington to give a lecture, the subject of which he chose to be his strategic plan for weather forecasting. "If at any time a lecture by me has been a success, it happened this time," said Bjerknes himself. As an immediate result The Carnegie Institution granted funds to enable him to employ assistants in his research work. This grant which was given yearly until 1941 has had a decisive importance for Bjerknes's research activity.

On the basis of his grand program Bjerknes could now already in Stockholm start to prepare the contents of his first great book in the new field: a "Dynamic Meteorology and Hydrography", aided by the very practical and ingenious Sandström. The latter had by now also acquired a good mathematical training and was familiar with Bjerknes' aims and general philosophy as to Geophysics. He became Bjerknes' first Carnegie assistant, and gladly undertook that part of the task which Bjerknes had shrunk from: the tedious and laborious calculation of tables and invention of graphical methods needed for the first volume of the planned great work. The result of their team work appeared later as the well-known volume I, "Statics", of the above book.

3. The years in Christiania (Oslo) and Leipzig.

BY OLAF DEVIK.

In the crisis leading to the dissolution in 1905 of the union between Norway and Sweden and in the following years Vilhelm Bjerknes began to consider his return to Norway, and in 1907 he was called to the University of Christiania. By 1910 and 1911 he published the first two volumes of an ambitious work *Dynamic meteorology and hydrography*, with the collaborators J. W. Sandström, Th. Hesselberg and O. Devik, who was succeeded by Harald U. Sverdrup. Bjerknes was the leader of the work and discussed every day with his assistants the results and the following plan, thereby giving his assistants a free hand. He was a brilliant and inspiring chief working with a team engaged in research, wise in his calls and generous in paying his tribute to the young collaborators. There was growth around him; the institutes which he directed in his long life were "Growing Points", to use a modern term.

To us who were science students when he started his lectures in 1907, they were extraordinary and stimulating. The problems which were presented continued to engage us when a lecture was ended. Vilhelm Bjerknes did not smooth out the difficulties, he let the matter keep its relief in a remarkable way. We had the feeling that he shaped it in the very moment, although it had been carefully prepared beforehand. And fascinating was the fact that some lectures also treated fields of research where Bjerknes himself was active.

It soon became obvious that a reformation of the whole meteorological service would be required if the theoretical studies and the mathematical treatment of the observational material should progress as planned. However, it was no easy task for an outsider — a physicist in a small country — to teach the meteorological experts around the world how to attack the problem of weather forecasting in a rational way. In 1912 when Bjerknes was offered a professor's chair at the University in Leipzig, and the direction of a new Geophysical Institute, he decided that he ought to accept this call.

He expected that it would require a limited time, and in his inaugural lecture at Leipzig he said that he would consider his task as accomplished, if in one year he could correctly calculate the change of weather during one day. "It may take a year to drill a tunnel through a mountain, but later others may make the passage with an express train," he said.

The new institute started under the best auspicies. Hesselberg and Sverdrup accompanied Bjerknes to Leipzig and in a short time the staff of the institute in addition included two assistants and 12 students working for the doctor's degree. Later from Norway came H. Solberg and J. Bjerknes. Two important series of publications had been created, when the war broke out in 1914, and soon the German assistants and the research students were called away.

When Bjerknes was appointed Professor and Geheimerat he stipulated that his sons should remain Norwegian citizens. When he was received in audience by the King of Sachsen, the King smilingly wondered why he would not accept German citizenship for his sons. "My sons will later decide for themselves" was the answer. Certainly he did not repent this reply.

In the "Kohlrübe" winter of 1916—17 food became so scarce that it was only the food parcels sent from relatives in Norway that made it possible to continue the work. Fridtjof Nansen happened to visit Leipzig then, and acted to obtain an invitation for Bjerknes to come back to Norway as soon as possible. When he accordingly was invited to go to Bergen, he found himself in a dilemma, but he decided in the end to accept the invitation to Bergen as soon as he had managed to assure the continued existence of the institute in Leipzig. R. Wenger was released from military service, and they agreed to collaborate when peace was restored.

The personality of Vilhelm Bjerknes attracted and stimulated his young collaborators. They were fascinated by his genius, and they will always remember his intellectual face and his sculpture-like head. Björnstjerne Björnson once said to Vilhelm Bjerknes, turning him around to see him better, just as an American had said to Björnson: "I like your head, Sir!"

4. The Bergen school.

BY TOR BERGERON.

The Geophysical Institute in Leipzig, which started so successfully in 1913 under the leadership of V. Bjerknes, worked under very difficult conditions. World War I entered into its fourth year, and the male German assistants were all called out. One of the most promising ones, H. Petzold, fell at Verdun; the elder Norwegian collaborators had returned to their country. The conditions of life in warfaring Germany became strenuous to Bjerknes' health. — Luckily, at this critical moment he was called back to his country, to found a Geophysical Institute in Bergen.

Here begins an epoch that in a way may be regarded as the most remarkable and brilliant part of Vilhelm Bjerknes' life-record. At the age of 55 his own scientific attitude was evidently stabilized. His research was focussed on carrying through the great plan that had led to the works produced at Stockholm and Christiania, and within the

Leipzig school. His own continued course was according to all probability already staked out.

Fortunately to Meteorology, Bjerknes had returned to Norway, the land of bold enterprises, landing at Bergen, on Europe's stormiest and meteorologically most eventful coast. There he was left with two pupils, about 20 years old: his son, Jack Bjerknes, and Halvor Solberg. Both had joined the Leipzig School during V. Bjerknes' last year there and had already acquired a certain theoretical training in the special kind of hydrodynamics and dynamic meteorology that interested V. Bjerknes. The philosophy and all the work of the Leipzig School evidently formed a necessary and sufficient condition for the budding of new and fruitful ideas in their receptive minds. On the other hand, they were not overburdened with general meteorological knowledge or trained in the current methods of weather forecasting. Therefore, in the years to come, they were able to study the concrete weather surrounding them and follow its development graphically on the daily maps with unbiassed eyes.

In the winter of 1917/18 and the following spring, the realistic strain in V. Bjerknes' character induced him to undertake a number of practical measures in order to improve the Norwegian Weather Service as an aid to the agriculture and fishing of his country during the last and most severe year of World War I. — Norway was at that time not only without food imports, but also cut off from most weather telegrams outside Scandinavia. — Already at Leipzig V. Bjerknes and Petzold had discussed the possible physical nature of the convergence lines observed in the field of flow. By using the densest obtainable network of observations in Central Europe, J. Bjerknes and Solberg had found that these lines seemed to be connected in a characteristic way to certain kinds of rain areas.

Pursuing this line of thought at Bergen, V. Bjerknes and his two young assistants became convinced that a very dense network of stations within Norway might enable the weather-men to trace and follow these apparently "weather-efficient" lines and, thereby, possibly also to get forebodings of weather processes from outside their own secluded country. — Therefore, V. Bjerknes now took the initiative to have the number of reporting stations in Southern Norway increased tenfold (from 9 to about 90 stations). Observations along the coast were evidently the most important ones since they would serve as outposts. They were also more representative, and the observers (in most cases old sailors) would be especially suitable. Not only the two assistants, but also V. Bjerknes himself, with due permission, went on Navy patrol boats along the coast and erected a chain of excellent stations there.

Later new elements were introduced in the reports, especially cloud observations, so as to furnish further data for a kind of indirect aerology. These new weather maps made it possible to analyse the wind field, and the distribution of clouds and weather connected with the former, in a hitherto unparalleled manner — thereby enabling the meteorologist to follow in detail the processes going on in the lower troposphere.

Moreover, V. Bjerknes — together with Th. Hesselberg, who already in 1916, on V. Bjerknes' recommendation, had become the director of the Meteorological

Institute at Christiania (Oslo) — managed to reorganize the administration of the Norwegian Weather Service, so that the two very young adepts of the new methods, J. Bjerknes and H. Solberg, became the superintendents of two new Weather Forecasting Divisions, one at Bergen, the other at Christiania.

Led by intuition and unimpeded by preconceived ideas, these two novices in Weather Forecasting could already in 1918 discover the true nature of the lines of convergence, or "fronts", and a new cyclone model. Other young Scandinavian collaborators gradually flocked to Bergen, several of them again being Swedes: in 1918 S. Rosseland; in 1919 T. Bergeron, E. Bjørkdal and C.-G. Rossby; later E. Palmén, Sv. Petterssen and others. The new findings were then extended into a complete system of main and secondary fronts and air-masses, a life-history of the frontal cyclone; and a good knowledge of the three-dimensional structure of these tropospheric entities was gradually acquired. It also became evident that these "organized models" generally were the carriers of the weather in the sense of Dove and FitzRoy. They formed the real "weather systems" rather than the different configurations of the continous fields of pressure, temperature, moisture and motion, which had constituted the base of all other synoptic studies inclusive those of the Leipzig School.

The achievements of the Bergen School in the period 1918—1930 are by now so far back in time that they can be stated to have established the new era in scientific weather forecasting foreshadowed at the turn of the century. They were based on considerable improvements of all the three necessary factors, observations, analysis technique and physical models of the atmosphere. They represent a final, successful fusion of the technique and concepts of Dove's *local* method and those of the *synoptic* method, based on a general physical understanding of the atmospheric processes, treated as fas as practicable from the Lagrangian aspect. Thus, they formed nothing less than a practical approximation to V. Bjerknes' own program.

Bjerknes was himself anxious to give the credit of the fundamental discoveries in this field, and its practical applications, to the young collaborators at Bergen. — Pertinently he once characterized his own rôle within the Bergen School as follows: "During 50 years meteorologists all over the world had looked at weather maps without discovering their most important features. I only gave the right kind of maps to the right young men, and they soon discovered the wrinkles in the face of Weather" — i.e. the fronst, vital to most weather systems.

In reality, however, Vilhelm Bjerknes' contribution to the Bergen School went much further than that. The meteorologically quite unknown youngsters at Bergen were not entitled to show the entire body of meteorological experts in Europe so many new fundamental facts within Synoptic Meteorology, which meteorologists could and ought to have seen half a century earlier. Especially in Central Europe authorities stood up against the new findings. At this critical period of the Bergen School, Vilhelm Bjerknes — always ready to take up the arms for a righteous cause — came to our rescue. All his fame and authority was needed to gain a willing ear in the meteorological world for the new concrete methods and findings.

It must be regarded as one of Vilhelm Bjerknes' most outstanding achievements, the way he — at the age of 60, and already through a lifetime trained to work along certain lines of stringent mathematical thinking — was able to such an extent to accept and assimilate the spirit of "the new deal" of his young collaborators. No doubt the use of the new entities, fronts and air-masses, represented a practical realisation of V. Bjerknes' old Lagrangian program: to find the future positions and states of all air particles. Therefore, these new concepts fitted well into his scheme of thought. On the other hand, our bold way of generalizing from a few synoptic maps might have appeared hazardous to an older generation and to a physicist, focussed either on mathematical analysis or on repeated physical experiments made under controlled conditions.

One reason for V. Bjerknes' faith in the group of young people at Bergen and their findings was, of course, the lucky fact that his own son was its leader; through him he was even more stimulated to enter into the spirit of that team. The two Bjerknes's, father and son, were in a way fused into one personality, possessing both the faculties and knowledge of a *theoretician* and of an *empiricist.* Accepting the thesis that the real advances in Science are achieved by such an intimate combination, this would offer a clue to the great break through at Bergen. — Another explanation lies in the pronounced dualism in Vilhelm Bjerknes' own personality. He was, indeed, already in himself both the theoretician and the experimentalist. As a proof of the latter ability we only need to think of the fundamental organising and practical work, described above, that he performed in Norway at the beginning of 1918. At the same time, he was the genuine scientist, always ready to accept new results or theories when they were sound.

During the most intense pioneer period of the Bergen School 1918—1920, there were no fixed office hours at the small Bergen Weather Service, where the main empirical advances were made — meaning that you might work as far into the night as you liked. We often sat alone, or several of the young meteorologists together, into early morning hours, reanalysing the maps of the past day, pondering over or discussing unexpected developments observed on the weather maps. These were utterly primitive according to present standards, with only 2 or 3 observational hours a day, a poor code, no aerology, hardly any ships, Iceland, Ireland and Spain being the Western outposts — provided that their cable telegrams did reach us in time! Only two features were even better than in many countries nowadays: the density of the network in Norway and the general reliability of the observations. — (As least within Norway most observers took a personal pride in helping both Science, shipping and agriculture. Also outside Norway the attitude of the observers — whose salary was hardly worth mentioning — was partly the same. Moreover, all the reports came by cable, either directly or after few retransmissions; thus telegraphic errors were rare.) — In such a night as that, V. Bjerknes might interrupt his *mathematical* analysis or his writing and turn up in the map-room with the eyes gleaming of expectation: "Are there any new discoveries tonight?"

This explains how V. Bjerknes, indeed, could take up the fight, in the meteorological world outside Norway, for all the novelties that were welling forth in the small map-room at Bergen. The episode just told also shows how this whole-hearted faith and optimism of the great master, must have encouraged his young adepts, and how it stimulated them to do their utmost.

At the same time, V. Bjerknes himself, together with H. Solberg tried to consolidate the new findings by rational mathematical-dynamic theory. — V. Bjerknes' own main contribution of this type was his classical paper of 1921, "On the Dynamics of the Circular Vortex with Applications to the Atmosphere and Atmospheric Vortex- and Wavemotion". Here also the first real outlines of the still unwritten volume III "Dynamics" began to take shape. — The main problem child, however, proved to be the dynamic theory of the frontal cyclone and its life history when taken up on a realistic basis, i.e. including the complications caused by the Coriolis force, and the lower boundary of the atmosphere: the earth's surface. This problem was at that time attacked purely dynamically and treated as the formation of a cyclonic vortex from a wave-like small-amplitude disturbance on a sloping discontinuity surface within a compressible medium, influenced by Coriolis forces but not by friction. — In all this work one could witness the afore-mentioned remarkable fact that among the theoreticians V. Bjerknes was the one who had the outstanding faculty of giving plausible physical interpretations of the mathematical results. We here again see the favourable dualism of his ingenium, and may also glimpse the influence of his big and admired early master: Heinrich Hertz.

We have now already witnessed Bjerknes' extraordinary "School creating" talent, which manifested itself at all the universities where he was active. At the same time it is difficult to state what are the necessary and sufficient components to make up such a talent in general, or even what they were in his case. — At least in his later days, Bjerknes was on the whole reticent and withdrawing, but on the other hand he would never hold back when fight was needed for a just cause, not least when called to help his followers. — His mental and corporal structure was the one that has been regarded as typical of the creative mind, i.e. rather on the edged and astenic side than on the round and pycnic one. He had the sound discontent with the achievements reached within his science, and also by himself, and never sat down to rest on his laurels. This power is necessary in order to be stimulated, and to excite others, to a continued and always deeper searching for better solutions. — He had also all the curiosity of the true scientist, and the faculty of putting the right questions to nature, not common among theoreticians, and not giving in until he got satisfactory answers. More especially, he had a paragon of seeking and finding fruitful concrete interpretations of the mathematical results arrived at. Thus, Bjerknes was the one who had the infallible eye for the plausible physical interpretation of the formulae produced by his theoretical team. — We are then back at the dualism in his personality and training, alluded to above; he was in fact a theoretician and experimentalist in one person — a very rare and valuable combination.

To Bjerknes Science was the first thing in life, other cravings having to submit, when necessary, to its demands. He always concentrated on the solution of one task at a time — an advice from Hertz — and strove to focus all his own and his collaborators' time and forces on reaching this solution. His own strong pathos for the goal he had set up was intensely transferred to the people around him, and thus he could give them a remarkably free rein.

The qualities just described, with an ordinary, only theoretically working scientist, might have formed a dry, rather inhuman and pedantic person. The fine sense of humour that V. Bjerknes possessed, together with his genius, his farsightedness, increased during a long and migrating career, and his practical interests, made him a very human individual.

Therefore, also as a teacher, Bjerknes had few peers, in spite of the fact that he did not speak with facility. More than once I heard him state that he never learned or created easily, that he lacked the natural ability for easily communicating his thoughts verbally or in writing, that he had to be a hard worker — and certainly he *was* one. Those who had the good fortune of hearing his masterly speeches at solemn occasions certainly would admire his "faculty of improvisation", but his secretary could tell about the great amount of preparatory work behind it. — In my opinion, this partly gives the clue to his pedagogic skill and good results with pupils: he could understand and handle also the apparently slow intellects.

Vilhelm Bjerknes' friends will always remember his dignified bearing and fine face — often with a shy, tolerant or humoristic smile on it — getting even more refined with age. He had not only a keen sense of humour, but also many good stories to tell. To a great extent they emanated from his young days at Bonn and in Sweden. When remembering these times, his reticence often would give way to reciting German student songs or telling anecdotes. Judging from the latter, his humour had been especially stimulated by the often quite drastic wit of the famous Swedish cartoonist and writer Albert Engström. — V. Bjerknes being a non-synoptician and the present writer a non-theoretician, this Swedish humour was one of the channels through which we could have a good mental contact.

5. Back in Oslo.

BY CARL LUDVIG GODSKE.

On June 11, 1926, an extra-ordinary professorship in mechanics and mathematical physics at the University of Oslo was offered Vilhelm Bjerknes. He moved over to Oslo and became the first leader of the theoretical division of the physical institute of the university. Even after his retirement in 1932, he remained the leader of the institute, until 1937. He continued his scientific activity almost until his death.

The new professor in mathematical physics started the work with his characteristic energy. Lectures were to be given, introducing advanced students to diverse branches of theoretical physics. This science had, during V. Bjerknes' long "pilgrimage" into geophysics, had a rapid development. Bjerknes, however, concentrated upon classical physics — the field where he felt most at home and where he had himself given fundamental contributions. The more recent developments in physics he wisely left to others. Like many older people he was somewhat sceptical about "science à la mode", and with a smile often quoted Heaviside's words about "Einstein's distorted nothingness".

Bjerknes's lectures and even more his colloquia were inspiring to the young students. Questions and criticism from the students were not only tolerated, but welcomed as signs of interest and independent reasoning. To bring these lectures into book form was one of Bjerknes' chief problems during the Oslo years. Volume I, containing vector analysis and kinematics, was published in 1929. Vector analysis at that time was not the standard part of mathematical physics which it has now become. In fact, V. Bjerknes was the pioneer for introducing vector analysis in Norway; this explained his somewhat cautious and elaborate introduction of vector notation. He choose the terminology of Heaviside-Gibbs (the fact that this terminology today dominates geophysics is to a large extent due to Bjerknes and his pupils.) Not only did he consider Heaviside-Gibbs notation the most logical, but he also had a strong admiration for the original thinker Heaviside, and a personal weakness for the lonely hermit who never felt at home in scientific circles, and whom he had visited many years earlier.

The second and most important part of the planned book was never finished. A great difficulty was the inclusion of "hydromagnetic theory", explaining the experimental results of his father C. A. Bjerknes. Again and again with never tiring patience V. Bjerknes started rewriting the most difficult chapters, but never arrived at a final formulation which could satisfy him and his young collaborator Einar Høiland, who became his Carnegie assistant in 1935. The manuscript on theoretical physics by Bjerknes—Høiland certainly would be worth publishing, containing as it does important parts of classical physics in an original and inspiring form.

October 24, 1925 was the centenary of the birth of C. A. Bjerknes, the father, teacher and friend of Vilhelm. This event led to an interesting biography of C. A. Bjerknes by his son. It was not merely a biography, but a contribution to the history of the young Norwegian nation and its science and culture — charming reading, with clear pictures of persons and institutions by a skilled writer. Some years later (1929) Vilhelm Bjerknes published a new edition of C. A. Bjerknes's biography of the mathematician Niels Henrik Abel, probably the greatest genius Norway has ever fostered. Once more Bjerknes gave his attention to the scientific development and policy of our country in the 19th century. This naturally brought him in contact with today's problems. He became vitally interested in many current questions, such as the ecduation of teachers for elementary and high school. With never failing enthusiasm, and without asking whether his ideas were popular in official circles (often they were not) he wrote, lectured, talked and fought for his ideas, whose essence can be characterized as *quality in culture*.

The "pilgrimage" into geophysics was not finished when Bjerknes became professor of physics. The grants from the Carnegie institution continued. Bjerknes renewed his contact with H. Solberg, who was his assistant until 1930, when he became professor of theoretical meteorology at the University of Oslo. Somewhat later J. Holmboe (now professor of meteorology at the University of California in Los Angeles) became his Carnegie assistant, succeeded first by C. L. Godske (now professor in V. Bjerknes' old chair in Bergen) and finally by E. Høiland (now professor in hydro- and aerodynamics at the University of Oslo). They not only became his Carnegie assistants, but also his collaborators, and his good friends, full of veneration and respect for the "grand old man", albeit sometimes with an indulgent smile when the old professor was too "young" and enthusiastic.

In order to follow the work done by Bjerknes in theoretical meteorology we must go back to the Bergen years, and to the question of cyclogenesis as a wave problem. Atmospheric waves had already been studied by many scientists. Thus Helmholtz in 1888 had studied gravity waves in sliding layers and applied his results to explain the formation of billow clouds. These waves are so short and have such short periods that they are not influenced by the earth's rotation. Extremely long waves, on the other hand, essentially influenced by the rotation, had already been studied by Laplace (1775) and the results applied to explain tidal phenomena in the ocean and the atmosphere. Waves which may be utilized as models of frontal cyclones have to be intermediate in scale between Helmholtz waves and Laplace's waves; as wave generating factors have to be considered not only gravity and inertial forces, but even elastic forces. Thus the problem is a very complicated one and has to be approached in a systematic way. Characteristic of most wave studies is the hypothesis of small amplitudes, through which the non-linear hydrodynamical equations reduce to a linear system. Thus it becomes possible to arrive at general solutions by means of the super-position of simple ones. A systematic procedure for linearization of the hydrodynamical equation would therefore be of great use for the investigation of general atmospheric waves. Moreover, for finding models, realistic and at the same time tractable from the mathematical point of view, it is necessary to define simple fundamental states and motions which could depict average atmospheric conditions and upon which a principle of linearization could be applied.

The problem of the fundamental state was attacked in V. Bjerknes' paper of 1921, "On the Dynamics of the Circular Vortex with Application to the Atmosphere and to Atmospheric Vortex- and Wavemotions", perhaps the most fundamental and also the most elegant and inspiring paper he has ever written. The paper gives much more than the title promises, presenting a detailed introduction into the physical hydrodynamics which is characteristic of baroclinic fluids, and which originated with the discovery of the circulation theorems in 1898. Moreover, the theory of the discontinuities, which had been such useful entities on the maps, is presented together with a consideration of the close similarity between waves and vortices, in theory and on weather maps. The following quotation gives, in a nut shell, the description of the evolution of the cyclones observed on the maps:

"This violent transformation of wave to vortex is, as emphasized already, the ultimate result of the same tendency which for more moderate values of the sliding velocity leads to the formation of surface waves. The tendency is to produce a mixture of the two fluid strata, the formation of the waves is a first attempt to attain this result, the transformation of wave to vortex the concluding step".

The concept of a vortex is of particular importance in dynamic meteorology. In fact, in an absolute system of coordinates the atmosphere of the earth (and of other planets and stars) is in first approximation a circular vortex. Moreover, the circular vortex can also (in absolute and relative coordinates) be used as a model of cyclones and anticyclones. A discussion of the general properties of the simpler types of vortices —baroclinic and barotropic, "cold" and "warm" as given by Bjerknes — is of fundamental importance. Moreover, Bjerknes presents in the same paper the main practical results of the Bergen school as to cyclone evolution, and also gives a model of the general atmospheric circulation.

Many of the results of the "Circular Vortex" are today classical and almost self-evident; many of the problems announced have been taken up by his pupils, including the problems connected with the stability of the vortex. The lucid and elegant style of the "classical" paper ought to inspire even today's students and scientists; in this paper they will find mathematical and physical considerations synthesized in such a harmonious way that the old term "natural philosophy" can be applied.

The problem of the systematic study of waves is announced in the "Circular Vortex". In a paper five years later Bjerknes gives, for the first time, the general principle of linearization, leading to the *equations of perturbation* necessary for a mathematical discussion of the waves. The equations can be deduced according to two different methods, the Eulerian (field) method and the Lagrangean method, the relative merits of which often were discussed by Bjerknes. From the dynamical point of view, the Eulerian approach is the most simple; it is also the natural method for the practical meteorologists working with a network of stations fixed in space. However, the thermodynamical transformations always refer to individual physical particles, and thus favour the use of the Lagrangean method. Which of the methods should be chosen in physical hydrodynamics? Bjerknes chose — both. In his first paper he was concerned only with Eulerian equations, but in 1929 he extended his perturbation principle to the Lagrangean system. In fact, he hoped that this system would prove the better, and applied it in 1933 in the book written together with J. Bjerknes, H. Solberg and T. Bergeron (Hydrodynamique physique avec applications à la météorologie dynamique). However, after this book was finished, it was discovered that the Lagrangean perturbations studied by V. Bjerknes were not sufficiently general; the improvements introduced by J. V. Mieghem (Sur les équations de perturbations des fluides parfait piézotropes, 1935) led to fairly complicated equations, so that today the Eulerian field method again is considered preferable for most purposes in dynamic meteorology.

The discussion of solutions of the perturbation equations was started by V. Bjerknes already in 1923; at that time he introduced the quasi-static hypothesis, generally accepted in tidal theory. According to this hypothesis, one substitutes for the vertical component of the equation of motion the simple equilibrium equation. For a practical meteorologist the substitution is quite natural, considering that practically all aerological data are evaluated quasi-statically. However, it is much more difficult to defend from a dynamical point of view the substitution of a diagnostic equation for a prognostic one, making impossible a direct computation of the acceleration (and the "evolution") along the vertical. Later, therefore, V. Bjerknes and also H. Solberg, who made the most systematic attack on the atmospheric wave problem, applied the dynamical equation along the vertical, although this led to a great increase in mathematical difficulties. The model selected by V. Bjerknes and H. Solberg was directly inspired by the practical results of the Bergen school. The fundamental state contains a sloping discontinuity surface separating a lower cold air layer from an upper warm air layer; both layers were assumed in translatory motion, but with different speeds. In Solbergs first paper (1928) the two layers were assumed to be homogeneous and incompressible, later (Hydrodynamiqie physique 1933) an internal stability was assumed to exist within the layers. Only the simplest harmonic waves were discussed, but even they were fairly complicated, depending on static stability within the layers and at the surface of discontinuity, on shearing instability at the surface, on rotational stability and on elastic forces. The aim was to select, among all the wave solutions possible within such a system, one which had a sufficiently strong resemblance to the observed cyclone wave. Thus, the selected wave ought to have a wave length of the order of 1000 km, an increasing amplitude, and a velocity of propagation not differing too much from the velocity within the fluid layers. One cannot say that the attempt was an unconditional success. Quite recently the frontal model has been revived by a younger generation of meteorologists, including E. Eliasen in Denmark and E. Riis in Norway; results have been found that have led to a renewed interest in the wave problem of V. Bjerknes and H. Solberg.

Looking back upon the scientific activity of V. Bjerknes, we may summarize the results as follows:

1. The work concerned with the mathematical formulation of C. A. Bjerknes's theory took a great del of V. Bjerknes's time during most of his life. Perhaps he himself did consider that part of his work as the most important. However, at least today one has the feeling that this field of investigation may be characterized as an interesting blind alley. But, to quote a Danish clown philosopher: "It is difficult to prophesy, especially about the future."

2. Fundamental contributions were given by V. Bjerknes in his younger days to the theory of radio-waves.

3. The creation of a new branch of science, physical hydrodynamics, by introducing of the circulation theorems, and the application of this science to dynamical meteorology and physical oceanography must be considered the life work of Vilhelm Bjerknes.

4. Last, but not least, we must remember Vilhelm Bjerknes as the incomparable team leader, the enthusiastic and inspired stimulator, the brilliant lecturer — and the good and kind man with a variety of cultural interests.