THE COSMIC DYNAMO: FROM $t = -\infty$ TO COWLING'S THEOREM

A REVIEW ON HISTORY

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Abstract. An attempt is made to present a review as well on the historical development of knowledge on cosmic magnetic fields as on the development of our understanding of this phenomenon.

1. Introduction

The view backwards has two aspects: First we learn how our understanding of a certain phenomenon has developed in time. On the other side we get knowledge about this phenomenon and get so insight in the time behaviour on larger scales, decennia, centuries or even much longer. For cosmic phenomena, which in most cases develope on time-scales much longer than human life, we find so an important source of information.

The terrestrial magnetism is known since about two-thousand years. Research in paleomagnetism reveiled knowledge on a long-time behaviour of the Earth's magnetic field of interest: The Earth reverses its magnetic polarity in time intervals of irregular length from some hundreds of thousands of years upwards.

Means for detecting extraterrestrial magnetic fields have been developed in this century, however, phenomena closely related to magnetic fields or even caused by magnetic fields have been in some cases observed for long. In this way some insight in the time behaviour with the scales of centuries is possible.

In connection with the question for the origin it soon became clear that only the dynamo effect can provide for an answer, however, a convincing solution of this problem has met with heavy difficulties. Now we know the reason: the cosmic dynamo is closely connected with turbulence and so deeply anchored in nonlinear physics. A final answer to the questions raised by observations is still out of access even for the best up-to-date computers.

2. The Earth's Magnetic Field

The "south-pointing carriage", with the help of which the emperor Huan Tin (~ -2700) found his enemies under the cover of night and fog is traditional in legends of old China (Chapman and Bartels 1940), however, it is now generally believed that the construction of this device, if ever it really existed, was based on a non-magnetic principle: It was a self-regulating device, involving a system of gear-wheels such that a pointer would maintain an originally fixed direction by continually compensating for any excursions of the vehicle away from that direction (Needham 1962).

What we now can take for shure is that the attractive power of the loadstone was known, as well in China as in India, Arabia and Greece, from early time, about the

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middle of the -1st millenium. The earliest observations on the magnet are supposed to have been made by Thales (-6th century). According to Lukrez ((-99 - (-55)) the name magnet is due to the "Magnesia Hills" in Asia Minor, whereas from Plinius is traditional the "Nicanda-Legend" according to which a shepherd named Magnus carried iron mountings on his boots and on his stick which had been attracted by stones. The Chinese literature, from the -3th to the +6th century, is as full of references to the attractive power of the magnet as the European.

The directive power, however, was certainly first understood and used in China. The original Chinese compass was probably a kind of spoon carefully carved from loadstone and revolving on the smooth surface of a diviner's board (Fig. 1). This original form was certainly known and used in the +1st century, and may go back, as a secret of magicians, to the -2nd century (Needham 1962). The ubiquity of the Earth's magnetic field was the reason for this mysterious directive power and so we may consider this as the first time people discovered the Earth's magnetic field.

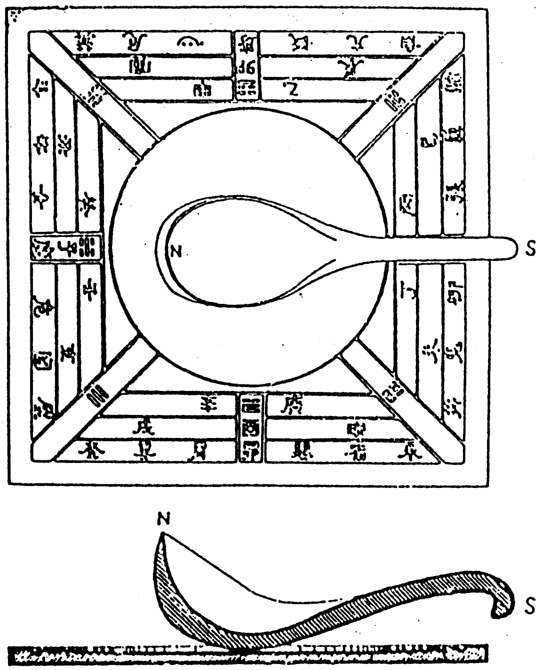

Fig. 1. Draft of an diviner's board with a loadstone spoon (Needham 1962)

The first Chinese text clearly describing the magnetic needle compass dates from + 1088. Worth noting, that already the declination, i.e. the failure of the magnetic needle to point to the astronomical north, has been mentioned there. One century later one finds the compass described in Europe. In his famous letters dating from + 1269 Pierre Peregrini introduced the notions Northpole and Southpole, gave practical advises for the determination of the poles of natural magnets and constructed ships compasses.

So far we mainly dealed with the discovery of magnetism. In the following people became aware that, indeed, the Earth is a magnet or, better to say, the Earth has a magnetic field. First of all we have to mention William Gilbert, the physican in ordinary to Queen Elizabeth, who got carved a sphere out of magnetic rock (Gilbert 1600, cf. Chapman and Bartels 1940). He measured the magnetic field around this sphere and concluded: *Magnus magnes ipse est globus terrestris*. The terrestrial globe is a large magnet. With the conception of the "Terrella" (Fig. 2) Gilbert was in contrast to the contemporary opinion that the polar star attracts the magnetic needle which especially has been advocated by Pierre Peregrini (Zilsel 1941).

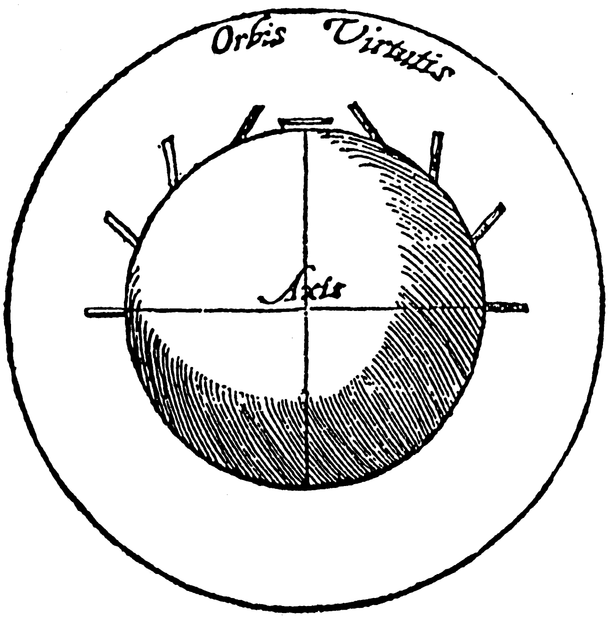

Fig. 2. Gilbert's Terella: Variety in the declinations of iron spikes at various latitudes

The growth of knowledge is now accelerating: Soon after Gilbert created his conception of the large magnet the secular variations of the Earth magnetic field

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have been discovered (Halley 1692) and so the knowledge that the magnetic field as a whole system migrates in westward direction, a phenomenon which cannot be in agreement with the conception of Gilbert's terella.

The discovery that the Earth's magnetic field is a quantity which is not rigidly connected with the Earth's globe is crucial for our concern. This property has been more pronounced by a discovery of this century: Paleomagnetic investigations revealed that the magnetic field of the Earth has even reversed its polarity: in time periods from some hundreds of thousands of years upwards the field changes the polarity. There have been recorded 174 reversals during the last 100 million of years (Lowrie and Alvarez 1981).

In this way the magnetic field of the Earth is a somewhat tender entity anchored in the Earth's core with a tendency to instability but with the ability of a permanent reproduction.

3. The Exploration of the Solar Magnetism

The discovery of extraterrestrial magnetic fields is a matter of this century. However, some phenomena caused by or closely related the the presence of magnetic fields have been observed and described for long. Without doubt the best known example are the sunspots.

It is generally believed that the discovery of the sunspots came soon after the invention of the telescope and that Johann Fabricius, Galileo Galilei and Christian Scheiner are the first who observed and described this phenomenon. Probably is Johann Fabricius's *"Narratio"*, where he describes his observation of sunspots on the June 13, 1611, the first European publication on this subject (cf. Rüdiger 1989).

Also in this case Chinese descriptions have been much earlier: In the Encyclopaedia of Ma Twan Lin a list of sunspot observations is published with the first event dating from October 20, 301 (Williams 1873). There are numerous references to this phenomenon in the Chinese literature with probably the first one dating from the year -28 (Needham 1959). The sunspots have been described by a term which means "black" as well as "crow". There was seen a "three-legged crow" in the Sun, or spots "large, like a hen's egg" (November 7, 354), "like a peach" (April 4, 355) or "as large as a chestnut" (May 3, 1112).

From the begin of the 17th century sunspots have been extensively observed and described. The next date worth to note here is the year 1844 when Heinrich Schwabe, chemist in Dessau, published his records of sunspot observations over a period of about 15 years (Schwabe 1844, cf. Rüdiger 1989). He noticed the strong variations of the number of sunspots and concluded that probably there is a period of about 10 years. Worth noting also that the old Chinese records are so numerous that an estimate of this period is possible (DeMoidry 1904).

In the following the sunspot phenomenon has extensively been studied. Let be mentioned R.C. Carrington who revealed by his thorough records that the sunspots appear only in bands characterized by the heliographic latitudes $\pm(6^o - 35^o)$ and that, especially, their diurnal motions in longitude are subject to a wellmarket law of variation depending on the longitude: Carrington discovered the differential rotation of the Sun! Independly of Carrington the distribution of sunspots has been studied by Gustav Spörer in Potsdam. Spörer confirmed Carrington's observations and found especially the zonal migration of the sunspot phenomenon towards the equator during the course of a cycle. Spörer recognized the strangest phenomenon of the solar cycle: the Maunder Minimum, i.e. that in the second half of the 17th century nearly no sunspots have been observed (Spörer 1887, Eddy 1976, cf. Rüdiger 1989).

Without doubt the decisive discovery is that by G.E. Hale in 1908, who detected the Zeeman effect in sunspots and provided thus observational evidence for the existence of strong magnetic fields, up to 3000 Gauss, in these regions of the Sun. Moreover, Hale found the characteristic polarity laws, i.e. the opposite magnetic polarities of, in the sense of rotation, preceding and following spots in a spot group, and the opposite polarities of corresponding spots in the northern and southern hemisphere of the Sun. Finally, the continuation of these observations over the following decennia revealed that the magnetic polarity of the whole sunspot phenomenon changes from one activity cycle to the next one: the magnetic cycle of the Sun has a period of 22 years.

Already at this point the outline of the basic structure of the solar magnetic field became visible: A temporal oscillating field with a period of about 22 years, symmetric with respect to the axis of rotation and antisymmetric with respect to the equatorial plane. The latter could be concluded from the spatial distribution of the sunspot phenomenon over the Sun's surface, which found their manifestation in the observed appearance in certain latitudinal belts, best represented in Maunder's butterfly diagramm (Maunder 1922).

It is worth noting that the electromagnetic character of the sunspot phenomenon has been already anticipated 1868 by Wilhelm Foerster, director of the 'Berliner Sternwarte', in the second half of the foregoing century (cf. Foerster 1911). Foerster stated in his memorandum for the foundation of the Astrophysical Observatory Potsdam that *there must be an electromagnetic coupling between Sun and Earth which has to be one of the problems the new observatory has to investigate.* The background for this proposal was the already realized temporal coincidence of the appearance of sunspots, northern lights and magnetic storms. By the way, the first attempt for the foundation of this observatory has been rejected, since this proposal looked suspicious to the old-fashion astronomers.

4. The Discovery of Magnetic Fields Outside the Solar System

The detection of magnetic fields outside the solar system is clearly a matter of the second half of this century, however, again phenomena caused by magnetic fields have been in most cases observed before.

In the middle of this century H.D. Babcock developed the observational means for detecting magnetic fields in stars (Babcock 1947) and discovered the "magnetic stars" (Babcock 1958). This term "magnetic stars" has been introduced for those objects, of which the magnetic fields are detectable by line shifts between light of opposite polarization. For this to occur Babcock estimated a field strength of about the order of 10^3 Gauss is needed. In this sense the Sun is not a magnetic star, since its average field, of the order of 0.3 Gauss, is far too weak.

Nearly all magnetic stars are Ap-stars, that is to say peculiar A-stars. The pecularity consists of unusual spectral line intensity ratios, variations of the integral light and variations of the spectrum. Because of this the discovery of the Ap-stars came much earlier than that of their magnetic character. Ludendorff (1906) and Belopolsky (1913) described the light and spectral variations of the star $\alpha^2 CVn$, which is still one of the most thoroughly investigated magnetic stars, while Ludendorff (1913) and Guthnick and Prager (1918) discovered similar properties of the star ϵUMa.

The variations are strictly periodic and the periods amount to some days. It is now generally believed that these variations originate in structures on the surfaces of these stars which strongly deviate from the symmetry about the rotation axis. According to this idea the surface of magnetic stars is spotted while the magnetic field is highly asymmetric about the rotation axis. The temporal variations of quantities measured from the Earth stem from the fact that during the star's rotation different parts of its surface become visible. Hence we can infer from these observations that the pecularities – and with them the magnetic fields – have shown a strictly periodic behaviour over the last 70 years, although there were no observational methods at that time to detect magnetic fields.

Although new methods have been developed to extend optical observations to measure magnetic fields (Landstreet 1992), one hardly can detect magnetic fields on solar-type stars. However, there are other activity phenomena which can be used as indicators for the presence of magnetic fields. In this way Wilson (1978) found by measuring chromospheric variations in main sequence stars indeed cyclic variations at some late-type stars. Already Karl Schwarzschild realized this possibiltity to detect solar-like activity cycles: On over-exposed plates of some stars (Arcturus, Aldebaran, Geminorum) he found reversals of H and K lines of calcium. In conclusion was stated "*it remains to be shown whether the emission lines of the star have a possible variation in intensity analogues to the sunspot period*" (Eberhard and Schwarzschild 1913).

Pulsars and our Galaxy are further objects, where the existence of magnetic fields have been predicted for theoretical reasons some time before their observational detection.

Pulsars have been discovered in 1968 and it was soon clear that this phenomenon can only be explained by the presence of a strong magnetic field. The detection of the magnetic field of the order of 10^{12} Gauss came only 1978 (Trümper et al. 1978).

The existence of the magnetic field of our Galaxy was predicted by Alfvén et al. (1949) and Fermi (1949), for there was no other possibility to explain the observed isotropy of the cosmic radiation in the neighbourhood of our Earth. Even a correct estimate of the field strength, of 10^{-6} Gauss, has been given (Biermann 1952, Schlüter and Biermann 1950).

The observational detection came about ten years later by radio observations of (i) the polarization of radio sources and their Faraday rotation (Mayer et al. 1962, Bracewell et al. 1962, Cooper and Price 1962), (ii) the polarized non-thermal radio emission (synchrotron radiation) of the Galaxy (Wielebinski et al. 1962, Westerhout et al. 1962) and (iii) the Zeeman-splitting of the 21cm-line in HI- and OH-regions (Verschuur 1968).

Let at the end of these consideration be mentioned the detection of magnetic fields in some nearby galaxies. Even these observations provided for a new stimulation of dynamo theory. It need not to be here described in detail, since this is mainly a matter of the last ten years and a number of contributions in this volume will be dedicated to this subject.

5. The Question for the Origin of Cosmic Magnetic Fields

Schuster (1912) examined the causes of the terrestrial magnetism and presented an explanation on the basis of the hypothesis that any rotating neutral masses generate magnetic fields. Also Einstein (1924) considered a relation of this kind as a possible explanation. However, in this way an understanding of the tilt of the geomagnetic axis as well as for the secular variations, or even the solar magnetic cycle is not possible. And, moreover, Schuster's hypothesis would mean an extension of the basic laws of physics.

The idea that the magnetic field of a cosmical object may be of dynamo origin has been presented first time, when Sir Joseph Larmor read his paper "*How could a Rotating Body such as the Sun become a Magnet?*" at the seventh meeting of the British Association for the Advancement of Science on September 9, 1919. He analyzed the question for the origin with the conclusion that "*it is possible for the internal cyclic motions to act after the manner of the cycle of a self-exciting dynamo, and maintain a permanent magnetic field from insignificant beginnings, at the expense of some energy of the internal motions*".

In case of the Sun internal motions are indicated by surface phenomena. For the Earth, however, Larmor saw the discrepancy in the "*almost fixity of length of the astronomical day*" and "*the very extraordinary feature of the Earth's magnetic field, i.e. its great and rapid changes*". The dynamo "*would account for magnetic change, sudden or gradual*" and would "*require fluidity and residual circulation in deep-seated regions*".

In addition to the possible origin of the geomagnetic field we find here the conclusion that deep in the Earth must be fluid regions, and that the fluid carries out circulations. The final observational evidence for the fluid core of the Earth, however, was provided about ten years late (Lange 1930).

6. The Self-Excited Dynamo

The self-excited dynamo is an invention of the second half of the last century, without doubt one of the most important for the development of the human society, since it provided the means for producing electromagnetic energy in a large scale.

In December 1866 Werner von Siemens showed the physicist of the Berlin Akademie his invention, the self-excited dynamo: "*The Berlin physicists, among them Magnus, Dove, du Bois-Reymond have been very surprised when I in December 1866 showed them .... that a small electromagnetic machine without battery and permanent magnets, which could be turned in one direction without power at any velocity, the opposite rotation a resistance presented, which was hardly to overcome,* *and produced besides such a strong electric current that the wires become soon very hot*" (von Siemens 1889).

Magnus presented the paper of Werner Siemens in the session of the Prussian Academy on January 17, 1867 (Werner Siemens 1867). Siemens already has been conscious of the importance of his invention: "*The technic have now been given the means to produce electric currents of unlimited strength in a cheap and comfortable way at any place where working power is available*".

William Siemens communicated on February 14, 1867 a short paper to the Royal Society, describing the dynamo-electric principle of action, the conception which he attributed to his brother Werner: "*When the paper was read, another paper followed by Sir Charles Wheatstone (sent in on the 24th February) also describing this principle of action, thus showing that the same line of thought had occupied that eminent philosopher*".

Fig. 3. Werner v. Siemens

He presented in december 1866 the physicists of Berlin his invention: the self-excited dynamo

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It is worth to mention that the paper, by which the above is documented, is entitled: "*On the dynamo-electric current, and on certain means to improve its steadiness*" (William Siemens 1880). We see already here that the tendency to unstability is obviously an immanent property of the self-excited dynamo. That concerns the technical realization as well as the cosmical dynamo, indicated here by the reversals of the terrestrial magnetic field and the long-time variations of the solar cycle.

At that time research in the field of electromagnetic induction was clearly a fascinating matter. A paper of H. Wilde, mechanics of Michael Faraday, may stand for all. Wilde describes "*a new and powerfull Generator of Dynamic Electricity*" (Wilde 1867). It represents a highly complex device, where the field of a permanent magnet is amplified by rotational motion. However, here we have amplification, i.e. a given field (e.g. by permanent magnetism of iron) is amplified by the motion of electrically conducting material. The ratio of the amplified field to the given field is represented by the product of a characteristic number and the rotational velocity. The construction of more and more sophisticated devices can only increase the characteristic number, the induced field is in any case limited by the rotational velocity.

For self-excitation, in contrast to amplification, the initial field is unimportant. If self-excitation is realized by a certain motion of an electrically conducting material an initial field will grow exponential with time up to a value which is limited only by the available force for maintaining the dynamo active motion.

Thus the self-excited dynamo is a manifestation of self-organization which contributes to the evolution to the universe: because of the self-excited dynamo a new structure, a magnetic field, growth from an insignificant background.

7. The Dynamo Problem

Most inventions of mankind have been invented before by nature. There is one famous exception: the wheel. For nearly one century it looked like being the same for the dynamo. Larmor in 1919 anticipated that the dynamo might be already realized in the cosmos, however, evidence was provided not before half a century later.

It was T.G. Cowling who, following the suggestion of Larmor, tried to explain the sudden appearance of sunspots by dynamo generation (Cowling 1934). It is now well known that Cowling's attempt was without success, however, he found his famous theorem: An axisymmetric magnetic field cannot be maintained by dynamo action.

This statement is indeed crucial. In general it means that dynamo excitation cannot be realized in simple two-dimensional configurations. At that time, where electronic computers have not yet been invented, theoretical physics demonstrated its achievements mainly by presenting examples in simple geometries or by investigating integrable systems. Cowling's theorem elucidated why the realization of a dynamo on cosmic conditions was, at least for some time, out of access.

Without doubt Cowling's theorem was a challenge to theoreticians to provide an existence theorem for the "homogeneous" dynamo, i.e. a dynamo without insulating sheets. Let be reminded that the technical dynamo rests on a simple principle but is realized in a topological complicated geometry: Electrically conducting material covered with insulating material is arranged in a special way in order to fullfill the requirements of the dynamo principle. The cosmic dynamo, however, has to be realized in a simple connecting region without any insulating sheets.

The attempts to solve the "dynamo problem" followed two lines:

On the one side more complex motions as those of axisymmetry have been checked whether they could provide for self-excitation. Elsasser elaborated a systematic approach to the dynamo problem (Elsasser 1946a,b, 1947, 1950). Bullard (1949) investigated a certain pattern of convective motions which could be expected in the Earth's liquid core. This was the first time electronic computers have been used to overcome the mathematical difficulties. There is an indication that self-excitation may appear for sufficiently large values of a certain parameter (cf. Bullard and Gellman 1954).

The most convincing proof for the existence of a homogeneous dynamo was elaborated by Herzenberg (1958), who considered a model which consists of a rotating sphere embedded in another sphere. He was able to show that this model under certain conditions works as a self-excited dynamo. Worth to mention that the first experimental realization of a homogeneous dynamo followed Herzenberg's concept: Two rotating cylinders embedded in a block of the same material (Low and Wilkinson 1963). Worth noting here also the two-disc dynamo of Rikitake (1958), which has been developed for explaining the, obviously randomly appearing, reversals of the Earth's magnetic field. This model demonstrates the unstability of a self-excited dynamo in the nonlinear regime, and anticipates already certain developments of the physics of nonlinear processes (Cook and Roberts 1970).

On the other side one can find considerations about which motions may provide for dynamo excitation in the cosmos. Because of their artificial structures the models of homogeneous dynamos mentioned above could not be representative for cosmic objects. Hints in the right direction, namely that the irregular, turbulent motions in the convection zone of the Sun, may be responsible for dynamo excitation, came from Frenkel (1945) and Gurevich and Lebedinski (1945).

However, it looked strange that even turbulent motions should produce well ordered large scale magnetic fields. The notion "inverse cascade" was unknown at that time. It was Biermann (1951) who showed, in connection with an explanation of the differential rotation of the Sun, that turbulent convection on a rotating star may provide for this phenomenon. That was probably the first time turbulence has been thought to be the cause for the formation of a large scale structure.

Cowling (1953) noticed first that the induction action of the differential rotation may explain some details of the observed solar magnetic field: if a dipole-like poloidal magnetic field with the field lines in the meridional planes is assumed, then by the action of the differential rotation two toroidal magnetic field belts above and below the equatorial plane will be formed in the course of time. If parts of these magnetic field belts emerge to the solar surface to form sunspot groups, all observational findings by Carrington, Spörer and Hale find a simple explanation.

In this way Cowling discovered the mechanism which forms the toroidal field from a prescribed poloidal field, however, the question for the feedback, i.e. the formation of a poloidal field of opposite direction from the toroidal one remains open. This mechanism proved to be closely connected with turbulence and was first indicated by Eugen Parker's "cyclonic turbulence" (Parker 1955). Parker showed that turbulent motions under the influence of an overall rotation provide for a mean induction action, which in combination with differential rotation can provide for dynamo excitation. The cyclonic turbulence found about ten years later a foundation in a general theory, the mean-field magnetohydrodynamic.

The key role for dynamo excitation in frame of mean-field magnetohydrodynamics plays the α-effect, i.e. a mean electromotive force $\mathcal{E}$ parallel to the mean magnetic field $\mathbf{B}$ – $\mathcal{E} = \alpha\mathbf{B}$ with the pseudoscalar α – , which is formed in turbulences lacking reflection-symmetry (Steenbeck et al. 1966). Experimental evidence for the α-effect was provided by an experiment in liquid sodium (α-yashtchik) (Steenbeck et al. 1967, cf. Krause and Rädler 1980).

Lack of reflection-symmetry means that one type of helical motions, either righthanded or lefthanded, appears with a higher probability: the average of the scalar product of the velocity and its vorticity, $\overline{\mathbf{u}\cdot \mathit{curl}\,\mathbf{u}}$, is unequal zero. The turbulence has helicity (Moffatt 1970).

In rotating ($\boldsymbol{\Omega}$), stratified ($\mathbf{g}$) turbulent layers a non-zero helicity is formed by the action of Coriolis forces and $\alpha = \alpha_0(\boldsymbol{\Omega}\cdot\mathbf{g}) \neq 0$. Thus magnetic fields are a quite natural attribute of nearly all cosmical objects.

8. Final Remarks

Also today the investigations on dynamo theory follow mainly two directions: The one is that based on the mean-field aspect, the other is the attempt to solve the problem by numerical simulations.

The first one is apparently useful for solving the problems at the border to the non-linear region, i.e. the problem of finding situations which are typical for self-excitation. Mean-field theories apparently run into difficulties, if the state of saturation is considered, since in that case especially nonlinear relations between the turbulent electromotive force $\mathcal{E}$ and the mean magnetic field $\mathbf{B}$ of complex structure have to be taken into account.

The other direction, numeric simulations, is so far not in a position to present models which are close to real cosmical objects, however, the rapid development of computer technics and related numerical codes is promising for the near future.

I would like to close these considerations with a story which I have been told (P.H. Roberts, 1991):

Walter Elsasser and Einstein were friends in Germany before they both emigrated to the US in the 1930s. Several years after Elsasser had settled there (in the late 1930s in fact), he became interested in the origin of the geomagnetic field. Einstein paid him a visit, and (as people do) asked "What are you working on these days?". Elsasser told him, and Einstein invited him to explain dynamo theory to him. Elsasser set up the problem and then told Einstein about Cowling's theorem. Einstein's response was, "If such simple solutions are impossible, self-excited fluid dynamos cannot exist". For once, the great man's craving for simplicity seems to have misled him.

Mean-field magnetohydrodynamics, which opened the way to simple solutions for the self-excited fluid dynamo, came more than ten years later.

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