43. COMMISSION DE LA MAGNETO-HYDRODYNAMIQUE ET DE LA PHYSIQUE DES GAZ IONISES

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INTRODUCTION

At the IAU meeting in Moscow the new Commission 43 for Magneto-hydrodynamics and the Physics of Ionized Gases was constituted. Consequently no report on the development in this field has been given earlier to the IAU. As a symposium on 'Electromagnetic phenomena in cosmical physics' was organized by the IAU (in collaboration with IUPAP and IUGG) in 1956, the present report will make reference to the transactions of this symposium (**1**) and concentrate on development after 1956.

The essential purpose of the Commission is to study the phenomena produced by the coupling between hydrodynamic and electro-magnetic phenomena, especially in ionized gases. If a medium with mass density ρ and electric conductivity σ is magnetized by a field H, this coupling is important if (**2**)

$$l > \rho^{1/2} H^{-1} \sigma^{-1} c^2$$

where l is the characteristic length of the phenomenon (*e.g.* wave-length, or linear dimension of the considered body). This inequality defines the border between magneto-hydrodynamics (**3-9**) and ordinary hydrodynamics. If it is satisfied we cannot generally treat the motion of the medium without taking account of electro-magnetic phenomena. If it is not satisfied, electromagnetic phenomena on one hand, and hydrodynamic motions on the other can usually be treated independently.

In the lower parts of the planetary atmospheres (below the ionosphere) the electric conductivity σ has an extremely low value ($\sigma/c^2 = 10^{-24}$) so that the above inequality cannot be satisfied. Neither does it hold in the terrestrial oceans and lakes ($\sigma/c^2 = 4 \times 10^{-11}$) and in corresponding formations, if any, on other planets. With these exceptions, however, it seems to be satisfied for large-scale phenomena everywhere in the universe (**3-9, 15-19**). On the other hand it is not always satisfied for small-scale phenomena.

The inequality mentioned defines what we mean by 'large-scale phenomena' in this connection. For example, in the ionosphere ordinary radio waves, say $\lambda = 1$ m, are not coupled with mass motion, nor does the motion of a mass of air of the linear extension of 1 m there produce any noticeable electromagnetic phenomena; but oscillations of the whole ionosphere with periods of the order of seconds are of magneto-hydrodynamic character (**10-14, 18**).

GENERAL STATE OF THE SUBJECT

The field of magneto-hydrodynamics and the physics of ionized gases is a combination of three different fields of research which until recently have been developed independently. If we combine *classical hydrodynamics* with *classical electrodynamics* we obtain magneto-hydrodynamics (synonyms: hydromagnetics, magneto-fluid dynamics), by which we can treat the behaviour of an electrically conducting fluid (*e.g.* mercury or liquid sodium) in the presence of a strong magnetic field. However, the astrophysical application is confined to the liquid cores of planets. For other astrophysical applications we must combine magneto-hydrodynamics with *the physics of ionized gases* (**3-9, 15-22**).

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The first development of the magneto-hydrodynamics of ionized gases was a result of a combination of formulae from these fields, *viz.* Maxwell's equations, the hydrodynamic equations, and the formula for the conductivity of an ionized gas. This formal procedure gave many important results, but led in some cases to serious difficulties. The enormous complexity of a field of research which is a combination of three fields, all very complex, gave rise to laborious mathematical problems. In order to cope with these it was necessary to include in the treatment only a few effects which were thought to be the most important. But as different authors selected these effects in different ways, this led to a number of co-existing theories, which were applied to astrophysics. Because of our limited ability to study the astrophysical phenomena in detail, a decision between the theories is often difficult.

Fortunately in this deadlock there have come two new very important factors: '*thermo-nuclear*' *work* (**23, 24**) has stimulated the experimental check of theoretical magneto-hydromagnetics, and *space research* (**25-30**) has given us new tools to observe astrophysical phenomena.

As a result of the new technique of producing hot magnetized plasmas, magneto-hydrodynamics is entering a new phase in which the theories can be checked experimentally and new, and theoretically unexpected, phenomena be discovered. Space research gives us direct measurements of, for example, magnetic fields in inter-planetary space which could earlier only be the subject of speculative theories. It has also opened the possibility to carry out experiments on a planetary scale (*e.g.* 'Argus') (**31**).

CONTENT OF THE PRESENT REPORT

In cosmical physics magneto-hydrodynamics is applicable to the following subjects.

(*a*) *The origin of the geomagnetic field.* In the *liquid core of the Earth* the most important problem is *the origin of the geomagnetic field* and its secular variations. This question is intimately associated with the origin of the magnetism of other planets or stars, and possibly also of inter-stellar clouds and of the galaxies.

(*b*) *Electromagnetic state of the exosphere and inter-planetary space.* Magneto-hydrodynamic phenomena in the exosphere (and also in the ionosphere) are basic for the understanding of magnetic storms and aurorae. There is an intimate connection between these phenomena and the *radiation belts* surrounding the Earth. The electromagnetic conditions there depend on the conditions in *inter-planetary space*, especially the corpuscular radiation of the Sun.

(*c*) *Solar physics.* Electromagnetic phenomena are very important in the Sun, and without much exaggeration one may say that *solar activity* in general is a display of magneto-hydrodynamic phenomena.

(*d*) *Stellar physics.* Special magneto-hydrodynamic phenomena occur in the *magnetically variable stars* and possibly in many other stars too.

(*e*) *The physics of inter-stellar matter.* The *dynamics of inter-stellar clouds* is probably affected very much by magnetic fields. Whether such fields also are important for the rotation and translational motion of galaxies is an open question.

To these five main fields of application one could add the following more special, but still very important, problems, which will not be treated in detail here.

The origin of *cosmic rays* (**32**) is probably found in part in stellar atmospheres, in part in inter-planetary, inter-stellar, and possibly inter-galactic space. The *time-variations* (**33**) of the radiation provide an important tool for exploring the electromagnetic state of inter-planetary space. The subject of cosmic rays has been discussed recently at a conference in Moscow (**34**).

The *cosmic radio noise* is in part produced by plasma phenomena in stellar atmospheres and in space. (Phenomena of this kind are dealt with by Commission 40.)

The *origin of the solar system* is a fascinating but necessarily speculative problem, which like the dynamics of inter-stellar clouds and the formation of proto-stars belongs to the field of magneto-hydrodynamics and the physics of ionized gases (**35**).

Concerning the *field of research covered by this report* it should be observed that solar physics is covered by Commissions 10 and 12, and that there are other Commissions devoted to stellar constitution (**35**) inter-stellar matter (**34**) and to radio astronomy (**40**). Commission 43 should be complementary to these and include such papers from these fields as are of a more general interest from the point of view of magneto-hydrodynamics and the physics of ionized gases.

This is one reason why the present report to some extent concentrates on the exosphere and inter-planetary space. A second reason is that this field is likely to develop very rapidly with the introduction of the rocket technique. It may be hoped that such studies will clarify the basic properties of magnetized ionized atmospheres, and inter-stellar matter, with far-reaching consequences for the whole field of this Commission.

It is difficult to draw the border-line between astronomy and geophysics. In this report phenomena like the oscillations of the ionosphere, whistlers and the dynamo theories of magnetic storms have been excluded, but the origin of the geomagnetic field is included because of its importance to the generation of magnetic fields in celestial bodies in general.

The attached list of references contains a large number of articles but is still far from covering completely all the work done in this large and rapidly expanding field of research.

1. THE ORIGIN OF THE GEOMAGNETIC FIELD

Surveys of the state of this field of research in 1955 were given by Cowling (**101**) and by Inglis (**102**). The central problem is how a poloidal field can be amplified in spite of Cowling's theorem, which states that this cannot be achieved by any symmetrical and stationary process. Two different models have been examined.

(*a*) *The self-exciting dynamo model*

This is a stationary but unsymmetric model in which a number of uni-polar inductors produce currents, each of which magnetizes the next inductor in a circular sequence. After Inglis' review the following contributions are of interest.

Backus and Chandrasekhar (**103**) have analysed mathematically the conditions for Cowling's theorem about the impossibility of an axisymmetric stationary dynamo.

Elsasser (**104**) has reviewed the conditions which a dynamo theory must satisfy, and pointed out that the feed-back from a toroidal to a poloidal field is the critical point. He has shown that a number of small-scale eddies can produce this feed-back, but only under the condition that they have rather special properties. Elsasser has suggested that sunspots may be eddies which are of importance for the maintenance of the general magnetic field of the Sun.

Cowling (**105**) has made a closer study of the cases in which dynamo maintenance of a steady field is impossible. He suggests that these cases are likely to be a very restricted group.

A review of dynamo theories is given by Colombo (**106**).

Chandrasekhar (**107**) has discussed the decay of a magnetic field in a fluid body and concluded that certain patterns of fluid motion may prolong the time of decay by orders of magni-

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tude. The decay time of the Earth's magnetic field, which without internal motions is estimated to 14 000 years, may thus be as long as 500 000 years.

This result was questioned by Spitzer (**108**) who demonstrated that the decay rate is not greatly affected by axisymmetric motion in a sphere. On the other hand the large-scale field inside the fluid is much reduced in the presence of strong convection.

Backus (**109**) has also treated the same problem and his conclusions agree with Spitzer's. He found that axisymmetric motions cannot lengthen the decay time of the dipole moment by more than a factor of four.

A remarkable investigation has been made by Herzenberg (**110**). Compare also Herzenberg and Lowes (**111, 112**), who have demonstrated that two rotating conducting spheres embedded in a conducting medium may act as a self-exciting dynamo under certain conditions. The model is reasonably simple, but it remains still to be shown by what mechanism two whirls of the required configuration can be produced in the Earth's interior.

Palaeo-magnetic data indicate that reversals of the geomagnetic field may have taken place (**113**). This would make the Earth analogous in some respects to a magnetically variable star. A dynamo model studied mathematically by Rikitake (**114**) and Allan (**115**) also exhibits reversals of polarity.

(b) The kink instability model

This is a non-stationary model in which an initial poloidal field gets a toroidal component by hydrodynamic motion. The field configuration becomes unstable for kinks and produces an amplified poloidal field.

In a plasma experiment Lindberg and Jacobsen (**116**) have found that a poloidal field is easily amplified in the presence of a toroidal field. The phenomenon has been studied in detail and it appears that the flux amplification is due to a kink instability. A phenomenon possibly related to this has been studied by Bickerton (**117**). According to Alfvén (**118**) the same mechanism may magnetize the Earth (and other planets), the stars and possibly also inter-stellar clouds and galaxies.

There is not yet any conclusive evidence of magnetic fields on other planets, but observations of radio noise from Jupiter has been interpreted by Franklin and Burke (**119**) and by Barrow (**120, 121**) as an indication of a magnetic field, and this interpretation is supported by recent observations by Radakrishnan and Roberts (**119a**) of polarization in the 31 cm radiation emitted by Jupiter.

2. ELECTROMAGNETIC STATE OF THE EXOSPHERE AND INTER-PLANETARY SPACE

General state of the theories

Before rockets were sent out into inter-planetary space the conclusions about the electro-magnetic state there were based on studies of the following subjects:

(*a*) The outer parts of the solar corona.

(*b*) Geomagnetic storms.

(*c*) Cosmic radiation.

In the hands of different investigators these studies have resulted in two completely different pictures:

A. In the environment of the Sun out to at least one astronomical unit there are no magnetic fields (**201-3**), either because there is no solar or galactic field, or because the fields are swept away by the ejection from the Sun of non-magnetized ionized matter.

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B. Inter-planetary matter is magnetized (**204-11**) and the Sun emits beams or clouds with frozen-in fields which, when the plasma reaches the Earth's orbit, are of the order 10^{-4} to 10^{-6} gauss.

Picture A is intimately connected with the Chapman-Ferraro theory of magnetic storms (**201, 212-15**), according to which the storms are produced by non-magnetized beams emitted from the Sun. Against picture A some general objections have been raised:

There seems to be no reason why non-magnetized clouds should influence the cosmic radiation. The Forbush decreases (**216**) and the 27-day variation (**217**) of cosmic radiation are difficult to reconcile with this picture. The possibility that they are local events in the immediate vicinity of the Earth (**218**) suggested by Chapman (**201**) long ago and later taken up again by Parker (**218**), is definitely ruled out by rocket measurements (**320, 321**) which show that a Forbush decrease affects a very large region around the Earth.

Picture B implies that the Sun emits ionized gas clouds or beams which are magnetized either by the Sun's general magnetic field or by local sunspot fields at their origin in the solar atmosphere (**204-211**). As they move with a velocity of $v \approx 10^8$ cm/sec they are also electrically polarized (seen from a fixed co-ordinate system), the electric field being of the order $E = 1$ to 100 μ volt/cm if $H = 10^{-6}$ to 10^{-4} gauss. With a characteristic breadth of 10^{13} cm near the Earth's orbit this means a voltage of 10^7 to 10^9 volts, which is sufficient to influence cosmic rays. The electric field is also thought to be of decisive importance for the understanding of magnetic storms and aurorae (**3**).

There is no general agreement about the density and temperature of inter-planetary matter. The density is usually supposed to be about 10^3 particles/cm^3, a value which is essentially based on Siedentopf's (**219**) measurements of the polarization of the zodiacal light. It may be much smaller, and a value of 1 particle/cm^3 or less is indicated by some phenomena (**208**). Compare also van de Hulst's (**220**), Blackwell's (**221**), Redman's (**222**) and Nikolsky's (**222a**) discussions of zodiacal light.

The scarcity of empirical data leaves the field open to speculations, and the foundations of many theoretical investigations are rather poor.

The physics of the exosphere has been discussed at a recent symposium (**223**).

In the theoretical treatment of the phenomena occurring when the solar plasma reaches the terrestrial exosphere, two different approaches have been employed:

(*a*) A hydrodynamic or magneto-hydrodynamic treatment has been used in a number of papers (related to picture A) by, among others, Chapman-Ferraro (**201, 212-15**), Piddington (**224**), Dessler and Parker (**225**) and Akasofu-Chapman (**226**).

(*b*) Investigations starting from the motions of individual particles have been carried out by Alfvén (**3, 205, 227**), Block (**228, 229**) and Singer (**230, 231**) (all essentially based on picture B above).

The former group of theories run into well-known difficulties concerning the inability of the cloud to penetrate into the geomagnetic field, and the difficulty of understanding how the ring-current and the aurorae are produced. These difficulties do not exist in the latter approach. Experiments (**228**) show that a low-density plasma behaves as it should according to the latter view, and there are indications that also a high-density plasma does so, although a proof of this is not yet given.

In principle it should be possible to treat the phenomenon either from the hydrodynamic or the particle view, and both methods should give the same result. When comparing the two groups of theories more closely one finds that according to the particle treatment some essential phenomena—such as the formation of a ring-current and the occurrence of aurorae—are due to the finite *temperature* of the injected solar plasma. In fact if the temperature is put equal to zero, the particle theory gives neither ring-current nor aurora.

This indicates that one of the reasons why many present theories fail to describe essential phenomena is that they neglect the temperature of the plasma and hence the vigorous spiralling of the particles.

From what is said can be concluded that for future theoretical work the following points should be observed:

(*a*) it is essential to take account of the fact, recently established by rocket experiments, that the solar plasma is magnetized;

(*b*) the temperature of the plasma must not be neglected;

(*c*) further theories should be developed in close contact with plasma experiments;

(*d*) a consequent particle-description of the whole complex of phenomena is preferable to a hydromagnetic treatment, which in any case must be combined with a particle-description of the aurora and the radiation belts.

We shall now turn our attention to a number of special subjects in the field of exospheric and inter-planetary physics.

Rotation of the exosphere

The state of rotation of the matter in, and above, the ionosphere is discussed by Maeda (**232, 233**), Gold (**234**) and Hines (**235**). According to Ferraro's theorem of iso-rotation there should be a coupling between the ionosphere and the inter-planetary gas. On the other hand, as the atmosphere is a very good insulator there is no electromagnetic coupling between the ionosphere and the Earth's crust. Gold and Hines conclude that the ionosphere and the matter above it may rotate with an angular velocity different from that of the Earth. There are no conclusive observational results related to these theoretical predictions (**236**).

Auroral mechanisms

A review of auroral theories has been given by Chamberlain (**237**). Compare also the contributions by Vegard (**238**), Bennett (**239**) and Reid (**240**). Recently Akasofu and Chapman (**226**) have tried to develop the Chapman-Ferraro theory to include also the aurora. They assume that 'neutral lines' are formed in the Earth's magnetic field and that the aurora should be associated with such lines. There is no observational evidence that neutral lines exist, and from what is known about plasmas there is little reason to suppose that, even if there were neutral lines, their existence should produce a phenomenon like the aurora.

Propagation of geomagnetic disturbances through the exosphere

A problem of great interest is the transmission of sudden commencements of magnetic storms through the exosphere. Dessler (**241**) has given a theory of this propagation, but observations by Gerard (**242**) show that the delay times are much shorter than predicted by this theory and, according to Gerard, agree better with Singer's (**230, 231**) shock-wave theory. Dessler's theory has later been modified and developed (**243, 244**). Williams (**245**) has observed that sudden commencements begin preferably in high latitudes which is in agreement with Singer's picture.

The ring-current hypothesis for the explanation of the main phase of geomagnetic storms was criticized by Parker (**246**), who argued that the disturbance field could not penetrate the highly-conductive exosphere in a reasonable short time. This view was refuted by Hines and Storey in the discussion that followed (**247-52**). Recent papers by Dessler and Parker (**225**), Akasofu (**253**), Dvoryashin (**254**), and Dvoryashin and Pikelner (**255**) on magnetic storm theory should be mentioned in this connection.

With a somewhat different approach Piddington (**256, 224**) has given a detailed theory of the propagation of a disturbance through the exosphere.

Inter-planetary space

The state of inter-planetary matter has been treated as an extrapolation of the solar corona by Chapman (**257**) and by Pottash (**258**). The calculations hold only if the inter-planetary magnetic field is negligible ('picture A'), and a magnetic field would affect the thermal conductivity very much. Some problems concerning the inter-planetary medium have also been discussed by Shklovsky (**259**). In the inter-planetary space there are obviously regions ('beams' or 'streams' or 'winds') with a rapid outflow of plasma. The properties of such beams are discussed by several authors (**260-64b**). Even outside the beams there may be a general outflow in all directions, a 'corpuscular radiation' as supposed by Biermann (**265-71**), but it is also possible that outside the beams there is a slow inflow of matter to the Sun (**208, 273**).

Different models have been proposed for the inter-planetary magnetic field. A number of authors (**208-10, 273-6**) assume that it derives from the solar field, which is blown up by beams ejected from the sun-spot zones. The field near the equatorial plane should have a predominantly radial direction. Obviously the field cannot be very regular. Dorman (**277**) has investigated the onset of turbulence in solar streams carrying frozen-in fields, and Parker (**278**) has discussed some instabilities of a tenous ionized gas in a magnetic field.

The conclusions about the inter-planetary magnetic field are mainly based on cosmic ray research. The cosmic radiation emitted during solar flares travels to the Earth along paths which are determined by the inter-planetary magnetic field (**276, 279-81**). The Forbush decreases, the 27-day variation and the diurnal variation reveal other properties of the magnetic and also electric field around us (**282-9, 319**). These problems will be discussed at a cosmic ray conference in Tokyo 1961.

The phenomena occurring when the beams reach the Earth's magnetic field have been discussed theoretically in a number of papers (**290-98**). Compare also the section on *Auroral mechanisms* above. There are indications that certain types of radio bursts from Jupiter may be the effects of solar beams incident on that planet (**299**).

Observational results on the relations between solar activity and geomagnetic disturbances have been presented in a number of papers (**300-304b**).

Rocket measurements

Recently the development of artificial Earth satellites and cosmic rockets has provided an extremely powerful source of information about the exosphere and inter-planetary space.

One of the first major accomplishments was the discovery of a very intense radiation of high-energy particles (**305**), which was found to occupy two different regions, the radiation belts (van Allen belts) (**306, 307**). These belts have been interpreted in different ways. Singer (**308, 309**) had concluded that, besides trapped solar particles, the Earth's field should contain trapped particles secondary to cosmic radiation. The observation of the belts might be a confirmation of his theory, but there are also a number of other views. The particles of solar origin may be accelerated by some mechanism near the Earth, perhaps the same mechanism

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that in other regions of space produces the cosmic radiation (310, 311). A bibliography of the work on trapped radiation up to October 1960 has been given by van Allen (312).

The study of the radiation belts may shed light on which conditions in space are essential for the production of high-energy particles, and the knowledge thus obtained may be applicable to the generation of cosmic radiation and also to the production of high-energy particles in supernova explosions etc.

Rocket measurements of magnetic fields are very important, but the interpretation of measurements which refer only to the component perpendicular to the spinning axis of the space vehicle requires care. In the geomagnetic field considerable deviations from a dipole field have been observed (313-17), which seem to be correlated with magnetic storms, as expected. There is apparently a smooth transition between the geomagnetic field and the inter-planetary magnetic field. So far no indication has been found of the marked transition between the geomagnetic field and a non-magnetized plasma invading from outside, that is required by the Chapman-Ferraro theory. The inter-planetary field reported by Coleman, Davis and Sonett (318) is normally about 25 μ gauss, but increases at intervals by one power of ten. These values are consistent with the field strength deduced by Venkatesan (319) from studies of Forbush decreases in cosmic radiation.

Instruments carried by the space probes Pioneer V and Explorer VI have recorded Forbush decreases in cosmic ray intensity at great distances from the Earth (more than 1 000 Earth radii in the case of Explorer VI) (320-21). This definitely rules out the geocentric theories of Forbush decreases. The measurements give support to picture B above and seem to be very difficult to reconcile with the Chapman-Ferraro theory of magnetic storms.

In addition to the study of naturally-occurring phenomena, the rocket technique can be used for producing related phenomena artificially under controlled conditions (31). Thus in 'project Argus' an atomic bomb exploding beyond the atmosphere produced an artificial shell of electrons between the two naturally occurring radiation belts (322, 323, 312). The experiment gave valuable information about the exosphere and especially about the dynamics of the natural radiation belts. Artificial aurora was observed in connection with 'Argus' and has also been produced by high-altitude thermo-nuclear weapons tests (324-6, 312).

Rocket measurements of the magnetic field of the Moon indicate that the surface field should be less than 600 μ gauss (327). The interpretation of this measurement has been discussed by Neugebauer (328).

3. SOLAR PHYSICS

The whole Sun is a magneto-hydrodynamic plasma (401, 402), but as Commissions 10 and 12 cover solar physics in general, we shall here only report a few phenomena of special interest.

The general magnetic field and sunspots

The remarkable technique developed by Babcock and others has made it possible to measure very small Zeeman effect displacements (403). If these displacements are interpreted as a measure of the average magnetic field, one obtains a field with remarkable properties; it is very far from a dipole field and it changes sign with time, apparently connected with the sun-spot cycle (404-6). An interpretation based on a magneto-hydrodynamic model has been given by Babcock (406).

Concerning sunspots, it seems now to be generally agreed that the cause of a sunspot is a strong magnetic field in the photosphere, but there is no general agreement on the primary

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cause of the spot-producing fields. Bjerknes' old theory that sunspots are products of the non-uniform rotation of the Sun has been revived in a hydromagnetic version by Babcock (**406**) in connection with his theory of the variation of the general magnetic field. A somewhat similar model has been suggested by Allen (**407**).

Some objections have been raised against this general picture. As there does not exist any detailed theory of the Zeeman effect in a turbulent atmosphere, the measured Zeeman effect cannot immediately be interpreted as a measure of the average field (**408, 409**). In this connection it is interesting to note that Leighton (**410**) finds that the Zeeman effect of the calcium-line $\lambda 6102{\cdot}8$ gives unexpectedly high values in extensive areas. Further it is not quite clear from where the sunspots draw their energy. The total energy stored in the non-uniform rotation of the Sun will suffice to produce the magneto-static energy of sunspots only during 1 000 – 10 000 years (**411**). Hence we require a mechanism which constantly pours energy into the non-uniform rotation, or else we must conclude that sunspots and presumably all solar activity represent a rapidly passing state in the history of the Sun.

The opinion about the Sun's general magnetic field has changed many times already from Hale's initial report of a 50-gauss field to the present views. As the problem is very difficult, there may still be new drastic changes of the views in the future.

Solar flares

Severny (**412, 413**) and Bumba (**414**) have reported that solar flares usually occur in 'neutral points', *i.e.* in regions where the magnetic field in the solar atmosphere is zero. Severny also outlines a theory of flare production in neutral points (**412, 415-18**). A discussion of related problems has also been given by Dungey (**6**). Another theory of solar flares has been proposed by Gold and Hoyle (**419**).

Streamers in the corona

The relation between the observed polar rays and the general magnetic field is discussed by Shimoda (**420**), Saito (**421**), Bachmann (**422**), Dzyubenko (**423**), and Bugoslavskaya (**424**). Their results seem to be that the shape of the polar rays is in a reasonably good agreement with magnetic field lines from a dipole field.

Streamers or filamentary structure very far out in the corona have been investigated by Vitkevitch (**425, 426**), Hewish (**427**) and Högbom (**428**) who measure the scattering of radio star radiation when it passes the outer corona. They conclude that there are filaments ('super-corona') as far out as 10–30 solar radii, and one may ask whether filamentary structure is a general property of inter-planetary substance. The production of such a filamentary structure may be related to the condensations in prominences, a problem which is discussed by Lüst and Zirin (**429**), Jensen (**430**), Brown (**431**) and Kippenhahn and Schlüter (**432**).

4. STELLAR PHYSICS

Magnetic stars and their variations have been further studied by Babcock (**501, 502**). He has observed an A-type star with a field of as much as 34 000 gauss (**503**). As the magneto-static pressure of this field is $H^2/8\pi \approx 50 \times 10^6$ dynes/cm² or about 50 atmospheres, this demonstrates how very important magnetic forces may be for the equilibrium and motions in stellar atmospheres. A review of observations and theories of stellar magnetic fields has been given by Deutsch (**503a**).

The equilibrium of magnetic stars and their oscillations is treated by many authors. The equilibrium of magnetic stars is treated by Wenzel (**503b**) and by Prendergast (**504**), who finds that the simplified model he uses gets unstable when the magnetic energy exceeds two-fifths of the gravitational energy. According to Cowling (**505**), however, Prendergast's model is always unstable, and the instability will lead to a re-adjustment of the field but not to an explosion. Ledoux and his associates have treated the oscillations of cylindrical and spherical bodies under the influence of their own gravity and a magnetic field (**506-11**). Chopra (**512**), Agostinelli (**513**), De (**514**), Rikitake (**515**), Talwar (**516**), Oki (**517**), Ramamoorty and Chakraborty (**518**), Tandon (**518a**) and Woltjer (**519**) also discuss a number of theoretical problems of importance for magnetic stars. A critical review of the calculation of the electric conductivity (which is important in this connection) is given by Oster (**520**). The Eighth International Astrophysical Colloquium on stars with emission lines (**521**) contains much information of interest in connection with magnetic stars.

Runcorn (**522**) and Ferraro (**523**) discuss different ways of explaining the magnetically variable stars. The variation may in special cases either be due to magneto-hydrodynamic oscillations of the star or to the effect of an 'oblique rotor'. However, Babcock (**502**), raises serious doubts against the oblique rotor model.

5. THE PHYSICS OF INTER-STELLAR MATTER

For the understanding of the magneto-hydrodynamic properties of inter-stellar space it is essential to know the strength and direction of inter-stellar magnetic fields. Unfortunately there is still no reliable method of measuring the *strength* of the fields and the usual estimates ($H \approx 0{\cdot}1$ to $10\ \mu$ gauss) are obtained by indirect methods which are not very certain (**601**). Conclusions about the *direction* of the magnetic fields may be drawn if it is assumed that the *galactic polarization* is caused by the directive effect of a magnetic field on rotating dust grains. This problem has been studied by Spitzer and Tukey (**602**) and by Davis and Greenstein (**603**).

Summaries of the present state of observations and theories are given by Hiltner (**604**) and by Davis (**605**). Davis (**606**) and Henry (**607**) have also made more detailed calculations of the alignment of particles by weak magnetic fields.

An attempt to measure a galactic magnetic field by Zeeman splitting of the hydrogen line is reported by Davies, Slater, Shuter and Wild (**608**), who find no magnetic field in excess of the error of measurements, which is in one case $7\ \mu$ gauss. As this refers to the average field component in the line of sight, however, much stronger local fields are not excluded.

In this connection it is of interest to note that *filamentary structure* may be important also for inter-stellar matter. As has been mentioned earlier the filamentary structure of the solar corona is traced very far out. The filamentary structure of gas nebulae is a related phenomenon which has been studied by Pikelner and Gershberg (**609**).

An interesting and far-reaching problem is how galactic motion affects the *structure of galactic magnetic fields*, and also whether magnetic fields play an important role for the structure of the galaxy. Especially in the galactic halo magnetic fields may be important. These problems are discussed by Pikelner and Shklovsky (**610**), Biermann and Davis (**611**), Razin (**612**), Korchak (**613**) and Hoyle and Ireland (**614, 615**). The formation of spiral arms by magneto-gravitational instability is investigated by Pacholczyk and Stodolkiewicz (**616-621**).

When two magnetized gas clouds collide, a number of interesting phenomena are likely to occur, including generation of strong magnetic fields, acceleration of charged particles and emission of radio noise. These problems have been studied by Kahn (**622**), Kaplan (**623-6**), Harris (**627**), Pikelner (**628**), Piddington (**629**). They have also been discussed at a symposium in Cambridge, Massachusetts in 1957 (**630**).

Of special interest are the phenomena which take place when the gaseous shell of a nova or super-nova pentrates the inter-stellar gas, a problem which has been treated by Sedov (**631**). For the studies of the *Crab nebula*, the production of radiation by electromagnetic effects, the connection between magnetic fields and filaments, and a number of other problems are important, and these have been investigated by Piddington (**632**), Savedoff (**633**), Marshall (**634**), Münch (**635**), Mayer, McCullough and Sloanaker (**637**), Thiessen (**638**) and Burbidge (**639-40**), Gurzadian (**641-4**), Gordon and Pichakhchi (**645**), Serkowski (**646**), and Parker (**648**) (with a number of valuable references).

As a summary one may state that the theories of colliding plasmas are still in a rather speculative state. It may be hoped that laboratory experiments will soon give a clearer picture of what is actually happening when magnetized plasmas collide and this may give a firmer basis for further advance in this field.

A mechanism for the generation of relativistic electrons in cosmic space is proposed by Veksler (**649**); Erickson (**650**) suggests that swiftly rotating dust grains may emit appreciably at radio frequencies.

Attention should be paid to a number of investigations on *force-free magnetic fields* (**651-9**). Such fields are of interest for the understanding of inter-stellar magnetism, and also for stellar magnetic fields. Further, the general properties of the inter-stellar plasma (**660-61**) are of basic importance also in this connection.

Star formation may be influenced in a decisive way by magnetic fields. The influence of large-scale magnetic fields on the formation and dynamics of stars in a galaxy has been investigated by Elvius and Lindblad (**662**) and by Elvius and Herlofson (**663**). Magneto-gravitational instability has been treated in a number of papers by Pacholczyk and collaborators (**616-21**), by Debye (**664, 665**) and by Oganesian (**666**). The gravitational condensation leading to star formation is influenced by a magnetic field (Mestel and Spitzer (**667**), Mestel (**668-671**), Meadows (**672**)). The magnetic field tends on the one hand to counteract the contraction of a protostar, but on the other hand it facilitates the dissipation of angular momentum through a hydromagnetic transfer to the surroundings.

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President of the Commission

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