43. PLASMAS AND MAGNETOHYDRODYNAMICS IN ASTROPHYSICS (PLASMAS ET MAGNÉTO-HYDRODYNAMIQUE EN ASTROPHYSIQUE)

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A. INTRODUCTION

This report emphasizes selected problems in plasma physics and magnetohydrodynamics that appear to be of substantial future interest in astrophysics. Because of space limitations, complete coverage is impossible and bibliographical references are drastically curtailed. More complete references to the papers in Sections B and C are available on application to the undersigned. Additional references should be easily available in the well known abstracting and review journals. I am grateful to the members of Commission 43 who supplied the information on which this report is based. I am particularly grateful to Professors Mestel, Lüst, and Kaplan for writing the three main sections of this report.

LEVERETT DAVIS, JR.
President of the Commission

B. PLASMA IN THE SUN AND STARS

(by L. Mestel)

1. *Origin of stellar magnetism*

Masses condensing from magnetic gas clouds should retain some primeval flux. Models of rotating magnetic stars (Davies, 1968; Wright, 1969) suggest that even those with the strongest surface fields have a total flux less than one percent of the virial theorem limit. This may be due to field leakage during formation, or possibly to hydromagnetic instability: an analogue of the "sausage" mode in laboratory plasma theory may cause a more rapid contraction of poloidal flux-tubes into a neutral line than does decay in a stationary medium. Non-adiabatic modes, analogous to those discussed for rotating stars (see Commission 35 report) may yield a slow but steady motion of flux-tubes to the surface. Completely stable fields may require toroidal flux linking poloidal loops.

The Biermann "battery" process uses the non-irrotational partial pressure gradient per electron in a non-uniformly rotating star to drive poloidal currents which maintain a toroidal field. The process may stop if the centrifugal field relaxes rapidly into an irrotational state, but this is still under debate (see report for Commission 35). A weak primeval poloidal field constrains the rotation field sufficiently to kill the process except in stars where radiation pressure is significant (Kato and Nakagawa, 1969).

A slowly-decaying field in an Ap star or a pulsar need not be a primeval "fossil" but could be the relic of a dynamo-built field from e.g. the Hayashi convective phase. There remains uncertainty as to whether strictly isotropic turbulence can generate a large-scale field (Kraichnan and Nagarajan, 1967; Parker, 1969). New work by Moffatt (1969) and Leorat (1969) confirms the earlier result of Steenbeck, Krause and Rädler that turbulence which lacks reflection symmetry with respect to a plane generates a large-scale field with the same helicity as the turbulence. Steenbeck and Krause (1969) argue that their model is applicable to the solar and terrestrial dynamos. Numerical work by Roberts (1970) suggests that a *non*-axisymmetric field (without Cowling-type singular lines) may be maintainable against Ohmic decay by axisymmetric motions.

2. *The strongly magnetic stars*

The low rotations of the Ap stars may be due to magnetic braking, especially through coupling with a stellar wind (Mestel, 1966, 1968). The oblique rotator model of magnetic variables requires a large mutual inclination of the rotation and magnetic axes (Preston, 1967). The same coupling with a stellar wind rotates the rotation axis through the star (Mestel, 1968), but whether so as to increase or decrease the inclination depends critically on the detailed flux distribution over the stellar surface (Mestel and Selley, 1970) which in turn depends on internal magnetohydrodynamics. Sufficiently powerful laminar circulation in a rapidly rotating star can prevent flux from appearing above the surface (Mestel, 1967; Maheswaran, 1969; Wright, 1969). More work could be done to see which distributions of flux and which angles of inclination are consistent with observed Zeeman shifts and cross-over effects (Böhm-Vitense, 1967; Preston, 1967; Steinitz, 1969; Landstreet, 1969).

3. *Magnetism and stellar evolution*

A primeval field would need to be improbably strong in order to suppress convection over the bulk of a star in e.g. the Hayashi phase (Moss and Tayler, 1969), though convective efficiency may be affected. Numerical studies (Moss, 1970) confirm that even without turbulent dynamo action a field of energy much less than that of the turbulence will not be completely expelled from the zone; some of the flux will remain, concentrated into filaments. There could be a moderately strong primeval field in the solar radiative core, which would probably couple together the rotations of the core and the convective envelope. Gurm and Wentzel (1967) and Finzi and Wolf (1969) have suggested that magnetic blobs generated in convective cores may become buoyant and cause mixing with the radiative layers.

4. *Sunspots and the solar cycle*

The observed concentration of magnetic flux at the supergranular junctions is a confirmation of theoretical predictions. The clustering of active magnetic regions into complexes with a scale ten times the supergranular scale (Bumba, 1967) is a possible clue to the "giant cells" of Simon and Weiss (1968). Local magnetic interference with convective heat transport accounts qualitatively for the formation of pores and sunspots, but most sunspot models (e.g. Chitre and Shaviv, 1967) require radiative transport to be supplemented by a reduced but finite convective transport. Alfvén waves and also overstable sound waves (Syrovatskii and Zhugzhda, 1968) can develop, but it is not clear how the consequent energy transport is related to the observed umbral dots and the umbral flashes (Beckers and Tallant, 1969). Wilson (1968) has emphasized the theoretical importance of the penumbra in the energy deficit problem.

Cowling's objections to sunspot decay through Ohmic effects appear to remain valid (Altschuter, 1967), though Kopecký (1969) has emphasized the excess dissipation in the fine structure of the field. The computation by Altschuter *et al.* (1968) of an Evershed flow with a component perpendicular to the field lines suggests a dynamic model of sunspot destruction.

Following Babcock, Leighton (1969) has constructed a mathematical model of the solar cycle as a periodic dynamo, its main features being the twisting of a poloidal field by the non-uniform rotation, eruption of the consequent strong toroidal field to form sunspots, and Leighton's random-walk dispersal process. With an eye on the solar dynamo, the H.A.O. group (e.g. Nakagawa and Swarztrauber, 1969) have studied the hydromagnetics of axisymmetric, incompressible, differentially rotating systems, with and without dissipation. This work underlines the need for a dynamical theory of the differential rotation (see report to Commission 35): one theory (Gilman, 1968) simultaneously develops a solar dynamo model.

The solar cycle as the prototype of stellar magnetic variability (e.g. Tuominen and Tuominen, 1967; Godoli, 1967) is a less plausible rival to the oblique rotator model, now that the Ap stars are thought to be intrinsically slow rotators.

No theoretical model seems able yet to cope with the observed complex solar field, especially the sector structure corresponding to the interplanetary field (Wilcox and Howard, 1968). Viewed as a magnetic star, the sun has a general field currently varying with half the rotation period (Severny, 1969).

5. *Solar and stellar atmospheres*

Besides the gravitationally-modified sound waves, the solar convection zone generates coupled gravity and Alfvèn waves with no frequency limits on propagation (Lighthill, 1967). However, Kuperus (1969) concludes that most of the upward energy flux responsible for the heating of the solar corona is acoustic, though uncertainties in the turbulence spectrum in the convection zone can cause errors by an order of magnitude (Stein, 1968). More work on wave propagation and damping is needed to decide the range of stellar surface temperature and gravity for which hot coronas are formed. With only acoustic input, de Loore (1969) found no corona until the contracting sun had reached the bottom of the Hayashi track, but this may be altered if the star has a dynamo-built magnetic field, especially as the field can lead to dipole or monopole emission of acoustic waves.

Accretion heating – once suggested for the solar corona – has been revived as the energy supply for X-ray sources (Hayakawa and Sugimoto, 1968; Sakashita, 1968). Zeldovich and Shakura (1969) predict a non-Planckian spectrum.

The magnetic field channels heat conduction from the corona into the strongly magnetic chromospheric regions above the supergranular junctions. Kuperus and Athay explain spicules as due to the consequent local over-heating and hydrostatic breakdown. Pikel'ner (1969) argues that the Sweet-Petschek-Sturrock picture of the pinching-off of field lines is inadequate to explain flares, but will yield spicules (see also Uchida, 1969). Kuperus emphasizes that ultraviolet spectra and magnetic data should enable us to decide between different models of the chromosphere-coronal interface.

A strong local field with closed lines restricts solar wind expansion. If the heat input exceeds the radiation loss, a domed "helmet" structure evolves into a "cusped helmet", becoming ultimately a coronal streamer (Pneuman, 1968; Sturrock and Smith, 1968).

Most authors agree that the energy of solar flares comes from the convective zone, to be stored as the energy of non-potential magnetic fields until explosively released. Filaments modelled as cylindrical force-free fields are hydromagnetically unstable to formation of helical structures, which may therefore be more plausible pre-flare states (Anzer, 1968). The Kippenhahn-Schlüter filament model is unstable if the current density increases with height (Anzer, 1969). The tearing-mode resistive instability and its non-linear development e.g. into Petschek's mode needs further study. Yeh and Axford (1969) argue for a reconnection rate determined completely by external flow, and not even logarithmically dependent on resistivity. Syrovatskii (1969) emphasizes collisionless dissipation and the associated acceleration of runaway particles as the origin of the X-ray, optical and radio emission. The Moreton wave emitted by flares has been interpreted by Uchida (1968) as a fast-mode m.h.d. wave.

The gravitationally-distorted magnetic fields that arise naturally during condensation from the interstellar or intergalactic medium should cause large-scale flares as they relax to a lower-energy state, possibly yielding radio galaxies or quasars (Sturrock, 1969).

Zaitsev (1969) has studied shock-wave generation of type-II radio bursts. The C.S.I.R.O. group (Smerd, 1968) emphasize the continuing difficulties of the high brightness temperatures, and the need for a non-linear theory of the stabilization of radiative instabilities before meaningful comparisons with observation can be made.

6. *Pulsars*

Goldreich and Julian (1969) have followed up Gold's suggestion (1968, 1969) and studied the hydromagnetics of an axisymmetric rotating magnetic neutron star. In their model, the approximately corotating magnetosphere (of negligible thermal scale-height) is held up by the electrostatic forces associated with almost complete charge separation. The field is quasi-dipolar near the star, but field-lines from near the poles extend beyond the light-cylinder, enabling charges to be accelerated outwards to high energies in an "electrostatic wind" (although synchrotron losses are a difficulty (Chiu, 1969)).

Following Pacini (1968), Ostriker and Gunn (1969) adopt an oblique rotator model. Beyond the light cylinder the time-varying magnetic field becomes a low-frequency electromagnetic wave, as the conduction current is limited by the finite electron velocity. The wave is very efficient at accelerating particles arriving from the Goldreich-Julian magnetosphere. Emphasis is laid on the rotational braking associated with the radiation, and (Davis and Goldstein, 1970) a possible change in the mutual inclination of the rotation and dipole axes.

The work of Chiu *et al.* (Chiu, 1969) concentrates on the emission mechanism rather than on cosmic ray production. They explain the enormous brightness temperatures as laser radiation from electron bremsstrahlung in a magnetic field, with the population inversion achieved by the magnetospheric electric field. They also argue that neutron stars may be permanently magnetized, due to the moments of electrons moving in Landau orbits.

Ginzburg *et al.* (1969) discuss both the laser process and the conversion of part of the energy of amplified plasma waves into electromagnetic waves. They suggest that the second period observed in the radio pulses is a neutron star pulsation period, though this appears to conflict with computed periods of neutron star models.

C. INTERPLANETARY PLASMA

(by R. Lüst)

Remarkable progress has been made recently in our understanding of the interplanetary plasma, the solar wind. The great extent of new observations has stimulated theoretical investigations of a variety of problems which can be compared with the measurements. But at the same time observations and theories have opened new areas not yet well understood. In most cases further progress requires both theoretical and observational work. The basic theory of the dynamical behaviour of the plasma and the magnetic field as developed by Parker in 1958 has been confirmed by the observations. The currently important problems of the interplanetary plasma may be categorised under six headings:

1. *Description of the large-scale properties*

As Parker has shown the large-scale properties of the solar wind can be described by a fluid model. A number of different one and two fluid models have been solved numerically in order to improve the comparison between theoretical predictions and observed quantities like velocity, density and temperature. These calculations have shown in particular that thermal conduction alone is not sufficient for supplying the necessary energy (Hartle and Sturrock, 1968). They lead to too high an electron temperature and too low an ion temperature. Furthermore, when in such one and two fluid hydrodynamic models the only energy transport from the base of the corona is conduction and convection, the calculated density of the wind at 1 A.U. tends to be too high and the velocity too low to agree with observations.

As a consequence, other forms of energy transport must be operative too; during quiet conditions they should be effective out to at least $r = 3\ R_\odot$. During active periods which are indicated by higher temperatures but also by high density and wind velocity, the energy input should be enhanced out to the orbit of earth. The additional energy is presumably delivered by waves or turbulence. Near to the sun the mechanism responsible for heating the solar corona could be effective also in the outer corona, since not all energy in the shock waves will be absorbed in the inner corona. But in addition other waves might be responsible. For heating the solar wind near the sun during quiet times the fast mode of magnetoacoustic waves could be effective (Barnes, 1968, 1969).

These waves with long wavelength (about 2×10^{11} cmo r 10^{-2} A.U.) which are generated in the solar corona as remnants of processes occurring in the solar photosphere, such as the granulation or spicules, will have damped out before they reach the orbit of earth. Therefore the waves we are observing at the orbit of earth – in particular the ones with wavelengths less than 10×10^6 km – are generated in the solar wind and do not directly reflect processes occurring at the surface of the sun. The wavelength spectrum at the orbit of the earth may reflect some sort of equilibrium between generation and decay of hydromagnetic waves. The strong damping of waves provides a significant heat source for the solar wind.

However, waves generated by internal plasma instabilities cannot heat the wind, since they contribute only to the equalization of the anisotropies, and probably do not produce the long wavelength waves of interest. However, the interaction between streams, or sectors, of differing solar wind velocity distributed in solar longitude would provide a dominant source for long wavelength waves heating of the plasma (Jokipii and Davis, 1969). The velocity differences observed in such streams represent an energy source in the frame of the average solar wind corresponding to a thermal velocity of a few hundred km/s which is certainly adequate to maintain the solar wind temperature of the order of some 10^5 K and which has the required property of being variable. In addition, this mechanism would heat the particles proportionally to their mass, since the interaction produces equal velocity spreads. Therefore we would expect that during perturbed times the ion temperatures are proportional to their mass. This would indeed explain the fact that the temperature of the α-particles is about 4 times that of the protons during active times while the temperatures are more nearly equal during the times when the solar wind is cold and quiet.

Important problems are: (a) the explanation of the non-Maxwellian velocity distribution functions of the ions and the electrons and, in particular, the reason why they are different; (b) the dependence of these functions on distance from the sun and ecliptic latitude; (c) the important instabilities in the wind and the mechanisms for wave particle interactions; (d) knowledge of the abundances of the different ions in the solar wind and an understanding of any differences from the elemental abundances of the solar atmosphere. In particular, observations reported by Hundhausen (1968) and Hundhausen *et al.* (1968) of He^+, He^{++}, O^{+5}, O^{+6}, and O^{+7} give direct evidence of the temperature of the coronal gas expanding to produce the wind, a key parameter in most models.

2. *The interaction with the solar magnetic field and the transport of angular momentum*

The basic theoretical picture (as developed by Parker) of the spiral pattern of the magnetic field extending from the sun through interplanetary space is well substantiated by the observations of the field in space. Weber and Davis (1967) have taken into account the influence of the magnetic field on the motion of the solar wind. They evaluated also the transport of angular momentum by the magnetic field and by the azimuthal motion of the solar wind caused by the interaction with the magnetic field. The predicted value of the azimuthal velocity seems to be smaller by almost one order of magnitude than the observed value at certain periods. The difference might be due to viscosity and anisotropic pressure (Meyer and Pfirsch, 1969; Weber and Davis, 1970), or due to the interaction of fast and slow streams. The torque exerted by the magnetic field and the azimuthal motion may be sufficient to halve the rotation of the entire sun in about 10^{10} yr and of the outer part of the convection zone in about 10^9 yr.

3. *Fluctuations, discontinuities and waves*

Many more detailed observations are now available about the fluctuations in the plasma and in the magnetic fields, in particular the power spectra (Coleman, 1966; Holzer and McLeod, 1966; Burlaga *et al.*, 1969). Jokipii and Hollweg (1970) have studied the connection of the correlation length observed for scintillations of point radio sources with the power spectra of the magnetic field. The longer wavelengths (lower frequencies) may be of solar origin, but the rest of the spectrum observed near the orbit of earth must originate in space. The basis for proposed generation mechanisms is the observed variation in the wind velocity. Coleman (1968) suggests that the large-scale shear in the wind leads to something like hydrodynamic turbulence. Jokipii and Davis (1969) propose that the fluctuations are produced more directly by the collision of fast and slow streams (see Subsection 1). Another mechanism (only for higher frequencies) is based on the thermal anisotropies in the wind (Parker, 1958). The calculations and a summary of Kennel and Scarf (1968) show that the strength and nature of the dominant instabilities in the solar wind depend on a number of parameters, including the pressures of both the electrons and ions relative to the magnetic field pressures and on the mode which one considers.

Individual fluctuations can now be compared with theory. Shock transitions have been studied in some detail by Razdan *et al.* (1967), Schubert and Cummings (1967), and Nishida (1968). Dryer and Jones (1968) investigated the problem of heating the solar wind by shock waves generated in a solar flare disturbance. Hundhausen and Gentry (1969) have studied the propagation of shock waves through the interplanetary space.

Besides shocks, many individual fluctuations are of the nature of shear planes (McCracken and Ness, 1966; McCracken *et al.* (1968), Burlaga, 1968, Meyer and Pfirsch, 1969). The shear planes are separated by distances of a few times 10^{11} cm, suggesting that they may be related to the super granulation and related solar motions (Gosling *et al.*, 1968).

4. *Modulation of galactic cosmic rays and propagation of energetic solar particles*

Progress has been made too in the understanding of the modulation of galactic cosmic rays by the solar wind and of the propagation of energetic solar particles (Gosling *et al.*, 1968; Jokipii and Parker, 1967, 1968 and 1969; Parker, 1967 and 1968; Axford, 1967; Jokipii, 1967 and 1968; Jokipii and Coleman, 1968; Noerdlinger, 1968). A theoretical connection between the cosmic-ray diffusion tensor and the power spectrum of the small-scale irregularities in the interplanetary magnetic field has been established.

A comparison of theory with observation indicates that the fluctuations in the interplanetary field die out with increasing distance from the sun, so that cosmic rays propagate more freely beyond 5–10 A.U. than at the orbit of earth (Simpson and Wang, 1967; Bachlet *et al.*, 1967; O'Gallagher, 1967; O'Gallagher and Simpson, 1967). The conditions inside the orbit of earth and out of the ecliptic plane have also been theoretically investigated (Gosling *et al.*, 1968). Three distinct effects combine to produce the anisotropy of cosmic rays. One is the adiabatic deceleration of cosmic-ray particles in the field carried in the expanding solar wind gas, another is Fermi acceleration and solar production, and the third is the variations with solar latitude of the ratio of the solar wind velocity to the diffusion coefficient. A comparison of theory and observations of cosmic ray anisotropy suggests tentatively, that, compared to conditions observed at the orbit of earth, the wind is less turbulent nearer to the sun and/or faster or more turbulent at higher solar latitudes, particularly at sunspot latitudes.

5. *The transition into interstellar space*

The supersonic solar wind will reach interstellar space after undergoing a shock transition. This shock transition should occur about 30 to 300 A.U. from the sun, the uncertainty being due to our uncertain knowledge of the interstellar pressure and of the effects of charge neutralisation of the solar wind particles due to charge exchange with the interstellar hydrogen atoms. Also the relative motion of the sun with respect to the neighboring interstellar gas must be considered.

More detailed studies of this transition should be of great interest. The charge exchange interaction between solar wind ions and interstellar neutral atoms followed by the sweeping up of all newly created ions by the solar wind magnetic field must contribute to the deceleration and heating of the solar wind. Within a transition region of radius of order 10^3 A.U. the electrons and ions may largely recombine and the lines of force of the solar magnetic field merge with those of the interstellar field. Presumably plasma instabilities are important here.

6. *The interaction of the solar wind with the earth, moon, and planets*

The main features of the interaction of the solar wind with the geomagnetic field to form a bow shock, magnetosheath, magnetosphere, and tail have become reasonably well understood but many features require further study. It is expected that the interaction with Jupiter will be similar. The moon appears to have so little intrinsic magnetic field and such a low conductivity that the solar wind impinges directly on its surface and leaves an empty wake, occupied by a largely undisturbed interplanetary magnetic field just behind. Venus and Mars appear to have no significant intrinsic magnetic fields but to have an ionosphere with high enough pressure and conductivity that the solar wind cannot easily penetrate it. Thus there is a bow shock and an as yet very poorly understood wake and interface between solar wind and atmosphere.

REVIEW PAPERS

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D. MAJOR PROBLEMS IN PLASMA ASTROPHYSICS AND MAGNETOHYDRODYNAMICS

(by S. A. Kaplan)

This report reviews the main directions of work currently done in the U.S.S.R. on the astronomically significant problems of plasma astrophysics and magnetohydrodynamics. The only references are to books or review papers; in addition, names of authors are given for some cases where essential results were obtained.

1. *Theory of plasma turbulence*

Much attention is paid to the general theory of wave turbulence in collisionless plasma. Different plasma instabilities excite different modes of plasma wave turbulence. Computations of increments of plasma instabilities, the various coefficients of interaction between the same and different waves and the coefficients of decay of turbulence are now in progress (B. B. Kadomtsev, R. S. Sagdeev, V. I. Karpman, V. N. Tsytovich, S. A. Kaplan, V. Yu. Trakhtengertz, V. V. Zaitsev, A. S. Chikhachev etc.).

Among the problems of plasma turbulence which are most important for plasma astrophysics are:

a. *Interactions between plasma waves and electromagnetic waves*

(i) Plasma waves of different modes are converted into electromagnetic waves both at the plasma frequencies and at higher frequencies. This is due to the nonlinear and Compton scattering of plasma waves on thermal, superthermal and relativistic electrons and ions, making possible the observation of plasma turbulence.

(ii) Coalescence of plasma and electromagnetic waves gives a number of effects which also have made possible the observation of plasma turbulence. These are: angular scattering of electromagnetic waves (increasing, in particular, the angular sizes of sources); changes of electromagnetic frequency (increasing, in particular, the width of emission spectral radio-lines). Coalescence of the same and different modes of plasma waves can also lead to the generation of electromagnetic waves with combination frequencies.

(iii) Induced conversion of plasma waves into electromagnetic waves due to nonlinear and Compton scattering on anisotropically distributed fast charged particles made possible the occurrence under cosmic conditions of maser-effects. It was shown that this process may lead to the very fast transformation of nearly all the energy of relativistic electrons into electromagnetic waves.

A summary of theoretical investigations of the interaction between plasma and electromagnetic waves is given in the review article "Plasma mechanism of radiation in astrophysics" (S. A. Kaplan, V. N. Tsytovich, *Usp. fiz. Nauk*, **97**, 77, 1969) and in the book under the preparation by the same authors.

Knowledge of different probabilities of interaction between waves of one or different modes makes it possible to calculate the spectra of plasma turbulence (distribution of energy between various modes and between waves with different wave numbers of the same mode). Only a few data of this kind are now known and further investigation is needed for the classification of other physical aspects of the effect of plasma turbulence (B. B. Kadomtsev, S. B. Pikel'ner, V. N. Tsytovich).

b. *Interaction between plasma wave turbulence and charged particles*

(i) Streams of fast particles with anisotropic velocity distributions are the most common source of plasma turbulence (especially on high frequency modes) in cosmic conditions. Many of these effects are observable now, e.g. sporadic solar radiobursts of type III. In exciting the plasma turbulence, the streams usually decay and anisotropy vanishes but in some cases there is a stabilization of the streams.

(ii) Plasma waves of different modes accelerate charged particles and even neutrinos. It has been shown that in many cases that the plasma acceleration is much more effective than the well known Fermi mechanism and can also lead to power-law spectra.

(iii) The high degree of isotropy of cosmic rays may be attributed to plasma instabilities. Any significant anisotropy is removed by the generation of Alfvèn and magnetosound waves with a time scale of some hundred years.

A review of plasma acceleration was given by B. B. Kadomtsev and V. N. Tsytovich at the VIth Joint IAU/IUTAM Symposium (*IAU Symposium* no. 39) held in Crimea 8–19 September 1969 (to be published soon).

(iv) The effect of synchrotron instability due to cold plasma in radiosources with a high concentration of relativistic particles is proposed and investigated (V. V. Zheleznyakov, E. V. Suvorov).

(v) Many papers are devoted to the plasma instability and interaction of plasma and different wave modes inside and outside the magnetosphere of the Earth (V. Tu. Trakhtengerz). Here the most important are the plasma waves connected with magnetic fields.

c. *Influence of plasma turbulence on the physical and dynamical state of the cosmic medium*

The occurrence of plasma turbulence in the cosmic medium changes the gas motion and leads to new effects in the usual hydromagnetic flow.

(i) Plasma turbulence makes possible the formation of shock waves in collisionless plasma, both in plasma with high magnetic pressure and in plasma with no magnetic fields. The stability conditions for tangential discontinuity are also changed by the presence of plasma turbulence.

(ii) There are many problems which must be solved by using hydromagnetic and plasma turbulence equations together; such problems must be formulated in a self-consistent way. These are (besides the shock structure): flow of gas around bodies with magnetic fields, annihilation of magnetic field in the regions near neutral lines, instability of electric current sheets, etc. In these investigations, it is necessary to use the tensors of viscosity, electric and thermal conductivity, stress and so on in the hydromagnetic equations for plasma with strong turbulence. This has not been done yet in part because of the complexity of the nonlinear equations for plasma turbulence.

2. *Hydromagnetics of solar and stellar winds*

One of the main problems of modern Hydromagnetics and Plasma Astrophysics is the study of gas motions around stars and the Sun. The possibility of observational and experimental investigations using cosmic probes makes such work particularly significant.

a. *The collisionless shock*

The possibility of a shock having a scale much less than the collision mean free path, particularly where a magnetic field provides a mechanism for particle interaction or where plasma turbulence and the interaction of waves substitutes for particle collisions, has been studied ever since it was realized that many of the very low density gas flows in astrophysics were supersonic. Such shocks very probably exist in interstellar space where they may maintain the isotropy of galactic cosmic rays and may heat the gas in H I regions. They definitely exist in interplanetary space, where they can be studied with space probes. Space probe observations give us much information on the structure of the magnetic field, the gas density and velocity, etc. on both sides of the Earth's bow shock. Both theory and observation show that the shock thickness is of the order of the ion Larmor radius. The magnetic fields and other features of the shock are very irregular. All ions are heated more than electrons and fluctuating electric fields are found.

It is believed that the plasma turbulence excited in the fronts may serve as a mechanism of increasing entropy. Such turbulence also accelerates charged particles.

The theory of collisionless shocks may also explain some features of solar radio activity. No review is available on the theory of collisionless shocks but many papers have been published by R. Z. Sagdeev, V. V. Zaitsev and others.

b. *The flow of solar wind around the Earth*

(i) This flow, including the stability of the gas motion, the position of the shock, and the directions of stream lines, may be studied using phenomenological hydromagnetic equations. Such studies have been made by M. V. Samokhin and, for the flow around a comet, by Z. M. Jaffe.

(ii) Alternatively, the kinetic equations for the state of plasma turbulence in and around the magnetosphere may be studied, some progress having been achieved by R. Z. Sagdeev, A. I. Beresin, and V. Yu. Trakhtengerz.

c. *Modelling of plasma flow in interstellar space*

Laboratory modelling of cosmic plasma phenomena gives information which is difficult to obtain by any other means. The principle of similitude points out phenomena which may be reproduced in the laboratory with different parameters. For instance, it is possible to modulate the collisionless shocks and the tail (or wake) of the Earth's magnetosphere. The experiments have shown the micropulsations and other features in accordance with theory. The modelling of plasma flow around the Moon and planets is planned. A review article is "Physics of interplanetary plasma and laboratory experiments" (R. Z. Sagdeev, I. M. Podgorny, *Usp. fiz. Nauk.*, **98**, 411, 1969).

3. *Hydromagnetics of stellar interiors and surfaces*

a. *Theory of hydromagnetic convection, generation of stellar and solar magnetic fields*

Convective transport of energy inside stars plays an important role in the determination of stellar structure and stellar (solar) activity. The presence of magnetic fields can drastically change the whole character of convection and turbulence. Thus the problem of thermal convection and turbulence in hydromagnetics is one of the most important.

(i) Generalization of the Schwarzschild criteria for convective instability for the hydromagnetic case shows that external magnetic fields usually impede the convection but that it is possible to find conditions in which the magnetic field relieves the convection. Special cases are the vibrational convection in strong magnetic fields with transfer of energy by waves, and the heating of the solar corona by the transport of energy from the convective zone by Alfvén and magnetoacoustic waves. No review is available but there are many papers of S. A. Kaplan, N. S. Petruchin, S. B. Pikelner, S. I. Syrovatsky, Yu. I. Zhugzhda and others.

(ii) It is now believed that the magnetic fields of stars are created by internal motions (dynamo-model). Many modes of convective, circular or meridional motions of gas inside stars are investigated and it is shown that it is possible to explain the occurrence of stellar magnetic fields. The general method of calculation of the dynamo-model was developed by S. I. Braginsky. Some papers are published by E. M. Drobyshevsky, A. I. Kipper, R. S. Iroshnikov and others.

(iii) In usual stars, magnetic fields are irrelevant for the equilibrium or stability. But the magnetic field may have an important role in supermassive configurations which now are attributed to the quasars. For instance, the magnetohydrodynamics turbulence and pulsations can prevent collapse of such supermassive objects (L. M. Ozernoy, Ya. B. Zeldovich, V. V. Vandakurov).

b. *Behaviour of the magnetic fields in neutron stars and pulsars*

It is now widely believed that pulsars are rotating and pulsating neutron stars with very strong magnetic fields.

(i) Possibly superconductivity may occur during the collapse thus influencing the formation of a pulsar magnetic field (V. L. Ginzburg, D. A. Kirznitz).

(ii) The rotation of a pulsar with a strong magnetic field must lead to the generation of longwave electromagnetic radiation. If the velocity of motion of the poles of the magnetic field is relativistic, this longwave radiation is concentrated into a comparatively narrow beam in which the acceleration of electrons causes the generation of high-frequency radiation (S. A. Kaplan, V. Ya. Eidman).

(iii) The magnetospheres of pulsars have a great influence on the motion of nearby charged particles. Concentration of relativistic particles to the rotating equatorial plane of a pulsar magnetosphere can explain the pulsed nature of its radiation (review article on magnetic models of pulsars by V. I. Ginzburg, V. V. Zheleznyakov, V. V. Zaitsev "Coherent mechanisms of cosmic radiation and magnetic model of pulsars", *Usp. fiz. Nauk*, **98**, 201, 1969).

(iv) It is now assumed that the main sources of cosmic rays are pulsars (I. S. Shklovsky).

E. COSMIC RAYS

(by L. Davis)

A number of significant astrophysical problems are related to cosmic rays. The mechanisms by which cosmic rays are accelerated, an understanding of their isotopic abundances, a determination of the regions in which galactic cosmic rays are stored, their relationship to the various recently discovered highly energetic objects, the way they diffuse in the solar system are all important both as cosmic ray problems and for their relation to basic problems in other areas of astronomy. Surveys of, and extensive references for, these topics may be found in recent reviews listed below. A detailed account of recent work is given in the Proceedings of the 11th International Conference on Cosmic Rays, Budapest, 1969 (in press).

In some of these problems the plasma properties of the cosmic ray gas are significant and there are important interactions between cosmic rays and lower energy plasmas. Plasma instabilities appear to hold the net flux of cosmic rays throughout the Galaxy to a very low value and hence require near isotropy of cosmic rays. The balance between cosmic ray pressure, gravitation on gas, and magnetic forces determines the large scale structure of gas and field; instabilities in this balance should be involved in many of the irregularities and condensations of the structure. Energy derived from very low energy cosmic rays may be significant in the temperature balance of H I regions (Spitzer and Scott, 1969; Goldsmith, Habing, and Field, 1969).

REVIEWS

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