REVIEWS

Electromagnetic Phenomena in Cosmical Physics. Edited by B. LEHNERT. Cambridge University Press, 1958. 545 pp. £2. 10*s*.

Magnetohydrodynamics. Edited by R. K. M. LANDSHOFF. Stanford University Press, 1957. 115 pp. $4.00 or £1. 12*s*.

The Plasma in a Magnetic Field. Edited by R. K. M. LANDSHOFF. Stanford University Press, 1958. 130 pp. $4.50.

The Magnetodynamics of Conducting Fluids. Edited by D. BERSHADER. Stanford University Press, 1959. 145 pp. $4.50.

Magnetohydrodynamics, with its partner, plasma physics, is now becoming a fully fledged branch of fluid mechanics. Already it occupies a sizeable fraction of this *Journal*'s space. And yet ten or fifteen years ago it was the concern only of a few astrophysicists and isolated scientists and engineers to whom the unity and ramifications of the new field was barely apparent. It is interesting to speculate why the subject has suddenly undergone an exponential eruption after being so long quiescent. After all, most of the essential facts were known to Faraday's generation. In 1832 Faraday* himself records speculations such as the possibility that motions of the electrically conducting oceans might be responsible for the observed distortions of the earth's magnetic field, and in the same year Ritchie* records how he caused water to move by subjecting it to an electric current perpendicular to a magnetic field and wonders whether this action might be the cause of ocean currents. Here we have the two vital ideas of magnetohydrodynamics, the mutual interactions between the velocity field and the electromagnetic field. One might have expected such giants as Maxwell and Rayleigh to take these ideas up, but for a long time the only activity was the invention of various gadgets to measure pressure, velocity or current or to pump mercury by exploitation of the magnetohydrodynamic interaction. Hints of things to come were the observation of the pinch effect in liquid metals by Hering and Northrup* in 1907 and Larmor's* suggestion of solar dynamo action in 1919, but not until about a century after Faraday did the subject begin to gain adherents, with Cowling exploring the dynamo problem, and Bennett the pinch effect, and Williams and Hartmann making experiments on pipe flow under transverse fields. Although Ferraro, Biermann and others explored the subject a little further, there was still a surprising time lag before the subject really found its feet early in World War II with the advent of Alfvén's waves, characterized by a fully mutual coupling of the magnetic and flow fields. The vital idea that the fluid and field may 'freeze' together was clearly realized at last.

The post-war period has seen the astrophysical and geophysical implications fully appreciated and the early, limited practical applications to liquid metals

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* M. Faraday, *Phil. Trans.* (1832), p. 176. W. Ritchie, *Phil. Trans.* (1832), p. 295. E. F. Northrup, *Phys. Rev.* **24**, (1907), p. 474. J. Larmor, *Engineering, Lond.*, **108**, (1919), p. 461.

transcended by the tantalizing prospect of applications to controlled fusion, plasma technology, aeronautics and astronautics.

What then provided the impetus which caused the subject finally to develop? It seems that the major factor was the realization by astronomers that conducting matter and magnetic fields are commonplace in the universe. As van de Hulst remarks in the first volume under review, the observation of unexplained novelties in the cosmos was a great spur to the development of the subject. To astrophysicists goes the credit for taking over the subject from the gadgeteers, and setting it on a respectable formal basis. It has since mellowed in the hands of fluid dynamicists and others who have applied it to laboratory and technical problems, more closely specified than the typical cosmic application.

The subject has not entirely avoided the failing of early fluid mechanics, the cleavage between ideal hydrodynamics and empirical hydraulics, even though such pioneers of the formal subject as Alfvén are experimentalists at heart. There are still very large gaps between observed fact and idealized theory, and still a deplorable tendency for magnetohydrodynamics to be treated as a playground for applied mathematicians. The temptation lies in the fact that, if ordinary fluid mechanics offers infinite scope, its generalization to conducting fluids is at least doubly infinite. It is so easy to find new theoretical problems in the field that one must plead for a self-imposed discipline that only problems with some conceivable relevance to real phenomena be pursued. Only by this means can the present torrent of papers be kept to reasonable proportions.

One sign of adult vigour in the subject is the number of conferences and symposia being devoted to it all over the world, ever since the 1949 I.A.U. meeting in Paris. Notable among these have been the three annual ones sponsored by the Lockheed Missiles and Space Division since 1956. At these latter symposia the topics have in no way been confined to applications to aviation and space flight. In fact there has obviously been considerable effort to make the coverage of topics sufficiently basic and catholic to justify the general titles borne by the published proceedings of these symposia, *Magnetohydrodynamics* (held in 1956), *The Plasma in a Magnetic Field* (held in 1957), and *The Magnetodynamics of Conducting Fluids* (held in 1958). These titles indicate that the books aim to function as primers in the subject, but this is not entirely achieved. Nevertheless, they are welcome additions to a literature in which such few books as exist are predominantly astrophysical in tone. Their chief value lies in the inclusion of one or two authoritative articles. Many of the other contributions were of transient interest only or were abbreviated previews of work which has since been presented more comprehensively in regular journals.

The 6th I.A.U. Symposium, held in Stockholm in 1956, has recently had its lengthy proceedings published in full, thanks to the diligence of B. Lehnert, as a volume entitled *Electromagnetic Phenomena in Cosmical Physics*. In this case the title tends to give a false impression, for many of the papers are of general interest and some even are more relevant to applied science than to the cosmos. Into this last class fall the contributions in German from the Russian fusion delegates. These three papers, incidentally, had already appeared in the regular Russian journals in 1956, and in English in *Journal of Nuclear Energy* in 1957.

In this review it is obviously impossible to comment on more than a few of the papers in these four volumes. In choosing papers for comment here, the obvious principle to adopt is to select work of sustained rather than transient interest (particularly since two of the symposia took place as long ago as 1956) and work of general fluid-mechanical rather than astrophysical significance.

The Stockholm symposium proceedings are split into parts dealing in turn with general, solar, stellar and experimental problems, etc. Several of these parts begin with historical review articles, of which the one by Cowling on solar electrodynamics is particularly noteworthy. Another valuable review is provided by Lehnert, who discusses the practicability of experiments with plasmas or liquid metals with a view chiefly to simulating cosmic phenomena. The conclusion is pessimistic, but, be it noted, the point is that cosmic simulation is all but impossible, not that general magnetohydrodynamic experimentation is futile. Indeed such experiments for their own sake can be very rewarding.

Lehnert and Baños (who extends his work on magnetohydrodynamic waves to fluids with viscosity and thermal conductivity) state energy equations in various rival forms which may tend to cause confusion. One reason for this is that both authors show a strange reluctance to mention entropy and to relate its creation to heat transfer and viscous and ohmic dissipation. One way in which Lehnert's energy equation differs from Baños' version is that it is a purely thermodynamic or material one and does not include magnetic energy. The electrical energy supply to the material is $\mathbf{E}.\mathbf{j}$ in the usual notation. Baños's equation uses the Poynting flux, whose divergence represents the total energy supply to the material and the electromagnetic field. Lehnert's review is confined to cases where kinetic energy and magnetic energy densities are comparable, with the result that a Lundquist number (of the form length multiplied by Alfvén wave velocity divided by diffusivity of field, momentum or heat) becomes the dominant parameter. There are of course many interesting magnetohydrodynamic phenomena where the two energies are not comparable and consequently other dimensionless groups are important.

Schlüter and Åström make useful contributions to plasma theory. Schlüter discusses generalized Ohm's laws for partially and full ionized gases, while Åström examines the effective permeability and permittivity of collision-free plasma in a magnetic field. Some generalization of thermodynamics for this case seems to be called for.

Bostick's entertainingly illustrated contribution to the book consists of a salvo of plasmoids (if that is the appropriate collective noun). Much of the other discharge work described by Pease and the Russians has been overtaken by events, particularly by the great release of information at the 1958 Geneva Conference on peaceful uses of atomic energy. The central mass of the book deals with specifically astrophysical matters, but it ends with a miscellany which includes Sweet on magnetohydrostatic equilibrium, Kaplan on magnetoturbulence and Kopecký on the conductivity of partially ionized gas.

We turn next to the Lockheed Symposium volumes. The first one, *Magnetohydrodynamics*, opens with Kantrowitz and Petschek's valuable classification of domains in plasma physics, presented very clearly in a diagram for the case of deuterium under a magnetic field whose pressure equals the gas pressure. This is almost the same as setting the Alfvén wave and sound velocities equal. Elsasser and, later in the book, Landshoff, discuss the important dimensionless ratios in magnetohydrodynamics, and Elsasser reproduces some of his work on dynamo action. He uses the unfortunate term 'magnetic viscosity', which since the publication of Hartmann's work has taken on many conflicting meanings. The term diffusivity is to be preferred for all quantities of dimensions L^2/T which measure the rate of diffusion per unit gradient of intensity, whether of magnetic field, momentum, heat, neutrons or anything else. The ratio of the diffusivities for momentum and magnetic field, $\mu\sigma\nu$ (in M.K.S. units), has not yet acquired a name or regular symbol, but certainly deserves them. One possibility, the term *magnetic Prandtl number*, has already been interpreted by Zhigulev as the ratio of the magnetic and *thermal* diffusivities, $\rho C_p/\mu\sigma K$, instead. The quantity $\mu\sigma\nu$ is particularly important in boundary-layer problems (such as the one studied by Carrier and Greenspan in the third Lockheed volume).

Burgers's contribution is to consider the penetration of a shock into plasma at rest in a dipole field. The most interesting section is his simple study of the structure of a plane shock in a relatively poor conductor in which the magnetic diffusity exceeds all others. Rosenbluth concludes this section with his simplified theory of the fast pinch and some discussion of the Boltzmann equation.

The second half of the book deals with experimental work, mostly with shock tubes, apart from Colgate's scantily described experiment on the instability of a shell of liquid sodium accelerated inwards by a magnetic field, and Newcomb's scheme for exciting magnetohydrodynamic waves in plasma contained within a cylindrical tube or wave guide. There is a full description of work with T-tubes by Kolb and by Kash, but the AVCO shock tube work is more fully described elsewhere.

The title of the second Lockheed volume, *The Plasma in a Magnetic Field*, reflects the trend towards plasma physics, although pure magnetohydrodynamics, governed by classical continuum equations, is not entirely excluded. The book is in three parts, of which the first deals with basic plasma physics. In this Chandrasekhar studies single particles and gives a sophisticated theory of adiabatic invariants, while Rosenbluth takes particles by the swarm and investigates the validity of the hydrodynamic approximation for the collision-free case. The second section is a mixed bag, ranging from Colgate's brief but illuminating explanation of the generation of neutrons in unstable pinches to Weibel's fully detailed solution for the case of a plasma column confined by the pressure of electromagnetic waves excited between the plasma and a concentric conductor. Karr gives a thorough account of some of the Los Alamos observations on pinches. The last section is also motley, although interesting. The work described by Blackman and Niblett on shocks produced by an electrodeless discharge has been reported in this and other journals. The next paper is by the home team from Lockheed, Kash *et al.*, and deals with shock-speed measurement. There follows Los Alamos work on shock tubes with axial fields, and the book ends with Liepmann outlining the work of Bleviss and Chester on Couette and Stokes flow, recently published in full elsewhere.

With the third Lockheed volume, *The Magnetodynamics of Conducting Fluids*, Landshoff hands over the editorship of the Lockheed series to Bershader. The change in terminology in the title is not significant; the five words employed are synonymous with 'magnetohydrodynamics'. This volume is in several ways different from its two predecessors. Nearly all the work is theoretical, and most is presented in detail at some length. The continuum approximation is used throughout. The book is more homogeneous, more even in quality than the earlier two. Most of the basic ideas presented are already familiar, however. This is partly due to the fact that, apart from Busemann's contribution, all the papers had received at least limited circulation in whole or part before this Lockheed publication ensured the wide currency that most of them deserve. Typifying this class is Grad's authoritative contribution on the propagation of undamped magnetohydrodynamic waves from localized or point sources in compressible fluids. The only experimental study is that presented by the AVCO contingent, who used a shock tube to generate ionized gas flow past and through a transverse solenoid. Together with the attendant analysis, this constitutes a fine achievement, remarkable for the successful development of flow-visualization techniques appropriate to plasma motions.

Busemann's paper is the most novel and stimulating one, though poorly written. He tackles one of magnetohydrodynamics' major idiosyncrasies, the fact that, given perfect conductivity, compressible fluids can undergo free surface motions, confinement being achieved by surface current sheets. He considers configurations in internal and external aerodynamics where the fluid and fields occupy different regions of space. An example is the well-known case of potential flow past a line of transverse magnetic dipoles. The crucial question as to whether these flows of a perfect conductor have any counterpart in the case of high but finite conductivity is not discussed. An interesting lack of uniqueness occurs in the case of flows past purely magnetic obstacles if the ionization is produced in a bow shock. The fluid has the alternative of flowing un-ionized past the obstacle without any interaction at all.

Cole discusses magnetohydrodynamic shocks generated by a moving piston. Mitchner goes into great detail on one- and two-dimensional flows in the case where the field is transverse and proportional to the density. The Cornell work on linearized theory for gas flows with finite conductivity is surveyed by Resler and McCune. Finally, Carrier and Greenspan give a condensed, approximate version of their work, already published in this *Journal*, on flat-plate boundary layers. The essential mechanics of the flow is well conveyed.

All the four books here reviewed ought to be available to workers in the fields of magnetohydrodynamics and plasma physics, as all four contain a fraction of permanently valuable and fully described work. Needless to say, the definitive text on magnetohydrodynamics still remains to be written, but at the moment it would be premature. Though magnetohydrodynamics has come of age, it is still too youthful and volatile at this stage for such a text to be timely. When truly consolidated text-books begin to emerge, we can reckon that magnetohydrodynamics has become middle-aged and respectable.

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