REVIEWS OF MODERN PHYSICS VOLUME 32, NUMBER 4 OCTOBER, 1960

Relations between Plasma Physics and Astrophysics*

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THE most general observation, in introduction of the subject matter herein, is the obvious one that most of the matter in the universe exists in the form of a plasma; celestial bodies like the earth and the other planets contribute, as far as we know, only a minor fraction by mass. This aspect receives additional emphasis by the recent observations, according to which large scale magnetic fields pervade interstellar space and at least parts of interplanetary space, while the magnetic fields on stars, especially on the sun, have been known somewhat longer; the interaction of the interstellar, the interplanetary and the stellar material with these cosmic magnetic fields belongs to the most interesting applications of plasma physics and magnetofluid dynamics to astrophysics.

We begin by collecting by some figures and relations from plasma physics as a background of the subsequent discussion. The plasma-oscillation frequency (n electron density)

$$\omega_p=(4\pi ne/m)^{\frac{1}{2}}=(10^{9.5}n)^{\frac{1}{2}} \tag{1}$$

ranges from values around $10^4\cdots10^6$ sec^{-1} in interstellar or interplanetary space to $10^7\cdots10^9$ in the solar corona and up to 10^{11}–10^{12} in the atmospheres of ordinary stars. In view of the respective values of the thermal velocity v_e of the electrons—$10^7\cdots10^8$ cm/sec in most of the regions mentioned, only in the solar corona values around 10^9 being reached—the Debye length λ_D, essentially the ratio of the two quantities, is readily seen to be quite small on the astronomical scale. The statistical fluctuations of the (essentially equal) electron and ion densities can therefore be disregarded for most purposes, though not for all; in particular the possibility has become apparent recently, that under nonthermal conditions "microscopic" instabilities, i.e., instabilities not derivable from the macroscopic equations, which express the balance of mass of momentum and of energy, greatly enhance these fluctuations.

It is known that some of the theoretical difficulties arising from the behavior of charged particles in magnetic fields, especially if the frequency of collisions is smaller than the gyration frequency of the electrons, can be solved by using the so-called two-fluid model of a plasma for the case of full ionization (or a multifluid model in more general cases); in this representation the plasma is visualized as composed of two fluids, the ion gas and the electron gas, coupled together by a friction term. It is found that Ohm's law can still be expressed in the form ($\mathbf{j}$ current density, $\mathbf{E}^c$ electric field measured in a comoving system, $\mathbf{E}^i$ "impressed" electromotive force, p_i ion pressure, m_i ion mass, $\mathbf{g}$ acceleration of gravity, v mass velocity)

$$\mathbf{E}^c\equiv\mathbf{E}+\left[\frac{\mathbf{v}}{c}\times\mathbf{B}\right]$$

$$\mathbf{j}=\frac{1}{\eta}(\mathbf{E}^c+\mathbf{E}^i) \tag{2}$$

$$e\mathbf{E}^i=-\frac{1}{n}\operatorname{grad}p_i+m_i\left(\mathbf{g}-\frac{d\mathbf{v}}{dt}\right)$$

with a scalar resistivity η. Hence combination with the law of induction and with Maxwell's first equation yields the familiar equation of telegraphy $(1\equiv\delta/\delta t)$

$$\mathbf{B}'-\operatorname{curl}[\mathbf{v}\times\mathbf{B}]=-c\cdot\operatorname{curl}\mathbf{E}^c$$

$$=\frac{1}{4\pi}c^2\eta\nabla^2\mathbf{B}\quad(\text{for }\nabla\eta=0\text{ and curl }\mathbf{E}^i=0). \tag{3}$$

In a moving fluid, the expression on the left-hand side measures the rate of change with time of the magnetic flux through a closed curve moving with the fluid; owing to the finite values of η and especially to the large dimensions usually involved in astrophysical applications, which make the time scale defined by dividing the right-hand side by $|B|$ very long, one can often regard the left-hand side as zero to a first approximation, i.e.,

$$\mathbf{B}'-\operatorname{curl}[\mathbf{v}\times\mathbf{B}]\ll\mathbf{B}'\quad\text{or}\quad\operatorname{curl}[\mathbf{v}\times\mathbf{B}] \tag{4}$$

and likewise

$$\mathbf{E}^c\ll\mathbf{E}\quad\text{or}\quad(1/c)[\mathbf{v}\times\mathbf{B}] \tag{5}$$

an approximation defining the range of "magnetohydrodynamics" with zero resistivity. Equation (3) expresses the strong coupling between the velocity and the magnetic field, which in the equation of mass motion appears in the form of the Lorentz volume force $(1/c)[\mathbf{j}\times\mathbf{B}]$ and furthermore results in the appearance of an additional characteristic velocity of waves:

$$\mathbf{v}_A=(1/4\pi\rho)^{\frac{1}{2}}\mathbf{B} \tag{6}$$

first discovered by Alfvén. With this definition the momentum equation may be brought into a form exhibiting a certain degree of symmetry in $\mathbf{v}$ and $\mathbf{v}_A$, and thereby the strong interaction between velocity and magnetic fields in plasmas of sufficient extent and/or sufficiently low resistivity.

We turn now to some of the applications of these results to astrophysical problems. In view of the

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* The author wishes to dedicate this paper to his former teacher, Professor H. Kienle, Heidelberg, in honor of his 65th birthday.

lectures, which are to follow this afternoon, the main emphasis will be given to problems of solar physics and of interplanetary space.

Magnetic fields of considerable strength—1 to 4 kgauss—are observed in sunspots. Their observed lifetime—of a week or some weeks up to some months—is quite short compared to the time scale derived from Eq. (3), the magnetic fields therefore must have been brought to the surface by convection. Recent work of Babcock has indeed revealed that the magnetic flux associated with a spot tends to persist in magnetic areas of much lower field strength, but correspondingly larger diameter. The energy density of a large spot (of some 10^5 erg/cm^3) is of the same order as the density of thermal energy in the photospheric level outside spots, one would therefore expect an influence of the magnetic field on the stratification of the solar atmospheric material, e.g., in the form of a difference in level between a spot and the surrounding regions. When, on the other hand, we compare the energy density of the magnetic fields in spots with that of the turbulent mass motions, the observed velocity of which is of the order of 1 km/sec, the latter is found to be smaller even in small spots. This fact, together with the long time scale of changes of the magnetic flux referred to already, has led to hypothesis (first proposed in 1941), that the fundamental physical feature of a spot is the magnetic field, and that the local low temperature producing the ordinary appearance has to be understood as a local inhibition of the energy flux from the deep interior. The energy transport in the layers immediately below the visible surface—in the so-called hydrogen-convection zone—is believed to be effected by convection; the magnetic field is thought to inhibit this mechanism owing to its large energy density. This part of the hypothesis has not yet been accessible to a real check beyond very rough theoretical estimates; recent observational work at Princeton and elsewhere has indicated the presence of considerable structure and of velocities also in the umbras of spots, though their characteristics seem to differ from those outside spots. The theoretical consistency of the whole picture can also be checked by investigating the internal structure of a spot, that is the distribution of pressure and density inside; specifically it may be asked whether the deduced structure of a spot is compatible with the boundary conditions imposed by the structure outside the spot regions. This problem has been investigated at Göttingen, and more recently at Munich. The results obtained so far suggest that the picture of a spot referred to is indeed consistent with our general knowledge of the structure of the regions outside spots.

The turbulent mass motions outside and in spots, the velocity of which near the surface is a finite fraction $(\frac{1}{5}\cdots\frac{1}{3})$ of the velocity of sound v_s has the further consequence that part of the turbulent energy, which is continuously dissipated, mainly into heat, is used to generate progressive waves. Outside spots, where v_A according to (6) is but a small fraction of the velocity of sound v_s, these waves are essentially sound waves, the frequency of which has a lower limit determined by v_s and the local scale height; near and in spots, however, these waves are largely hydromagnetic. In both cases they transport mechanical energy outwards, which, according to ideas first developed around 1947, maintain the temperature equilibrium of the solar chromosphere and the corona. The temperature of the chromosphere is $\approx 10^4$, that of the corona $\approx 10^6$, with a fairly sharp transition near the pressure level 10^{-1} d/cm^2. The local magnetic fields on the sun outside spot regions have an energy density of the same order; the theory of waves in a plasma shows that at and above this level the magnetic fields affect the behavior of the waves and also the dissipation of their energy to a considerable extent. Mechanisms related to the so-called magnetic pumping, which is used in devices for controlled thermonuclear fusion, appear to be operative in addition to ordinary dissipation by viscosity; this is due to the fact that in the middle corona the ion collision frequency is of the same order as the characteristic frequency of hydromagnetic disturbances coming from below.

The main features of the energy balance of the solar corona are probably understood: In addition to radiative recombination of heavy ions (like Mg XII and Fe XV) and energy loss by heat conduction, the normal flow of corpuscular radiation (to be discussed later) appears to require a major part of the total, while during violent disturbances the relative amounts going into other forms of nonthermal energy become significant. We can only mention in passing the problems connected with the acceleration of charged particles—to energies in the Mev to the Gev range—in the changing magnetic fields above active sunspots, which is now known to occur very much more frequently than was supposed only a few years ago, and those related to the mechanisms of emission of plasma streams or clouds, which give rise to the several components of the corpuscular radiation.

The question of how far the magnetic fields of the sun and of the earth and those of other planets extend into interplanetary space is not easily answered for the following reasons. As explained in the following there appears to be sufficient ionized material in interplanetary space to make the electric conductivity rather high ($\geqq 10^{13}$ esu). Now the sun and the planets rotate, and their magnetic fields would constrain, at least in a stationary state, the interplanetary material to rotate with them, as far as the magnetic lines of force reach. To the extent to which these fields are of poloidal character, there would be magnetic lines of force reaching to very great distances if there were no currents outside the sun or the planet; on the other hand, such currents, if they existed, should not exert volume forces, since these (at least their azimuthal components) could not be balanced. This raises the interesting question of the characteristics of magnetic fields with

$$[\mathbf{j}\times\mathbf{B}]=0,\quad \mathbf{j}\neq 0$$

or, with Maxwell's first law

$$[\mathbf{B}\times\mathrm{curl}\,\mathbf{B}]=0$$

the "force-free" fields, an analog to the "Beltrami-fields" of ordinary hydrodynamics, or of fields with rotational symmetry with

$$[\mathbf{B}\times\mathrm{curl}\,\mathbf{B}]_{\mathrm{az}}=0.$$

Three-dimensional solutions of these equations, which show how a poloidal magnetic field could be shielded against outer space by currents flowing $\|\mathbf{B}$, have been found by Lüst and Schlüter. For several reasons one should not expect any close agreement between the computed and the actual magnetic fields, in particular because of the solar corpuscular radiation which should be of great influence both on the sun and on the earth, but the theoretical results seem to indicate at least that the magnetic fields should reach to distances large compared to the extent of the corona or the exosphere of the earth, but probably small compared to the distance between sun and earth. In view of the experimental results now becoming available from satellite and space-probe measurements this appears to be a particularly fruitful area for future research.

We turn now to the physics of interplanetary space. There are up to now mainly the following sources of observational information: The zodiacal light, the comets, cosmic rays, and finally the information which can be derived from the characteristics of geomagnetic (and ionospheric) disturbances. To take the evidence last-mentioned first, it strongly suggests that geomagnetic disturbances are due to plasma clouds emitted from the sun with velocities of the order of some hundred or a thousand up to almost 2000 km/sec. This refers not only to the violent magnetic storms, but also to the less intense, but recurrent phenomena, which are ascribed to plasma streams emitted continuously from certain ("*M*"-) regions on the sun, the lifetime of which is of the order of several solar rotations (of 27 days each, as viewed from the earth) or up to a year; the fact that on polar stations disturbances are observed practically without interruption, indicates furthermore, that a certain level of corpuscular intensity ("solar wind") is always present. Some of the problems in this area have been dealt with in lectures by Professor Ferraro[1] and Dr. Vestine.[2]

Geophysical observations necessarily yield information only about what is going on in the vicinity of the earth, it is fortunate therefore that certain comets—between a third and half of the brighter objects with tails—have been recognized as a sort of probes, which not only confirm the general picture suggested by the geomagnetic observations, but give additional data, in particular regarding the actual value of the particle intensity. The comet tails in question, which are all directed nearly radially away from the sun, are composed of a plasma having molecular ions like CO^+ and N_2^+ as ionic constituent. Not only do these tails show a much higher degree of general activity, but also their extent and the motion of individual structures indicate that the accelerating forces are much larger, in some case even of a different order of magnitude that those acting on the tails composed of nonionized molecules (CN, C_2, and others) and of dust. The forces acting on the latter can be accounted for by ordinary light pressure, whereas the much stronger forces acting on the former were unexplained until it was recognized (in 1951) that the interaction between the plasma clouds—the solar plasma streaming by with the velocity of the order of 10^8 cm/sec and the tail plasma ordinarily moving with a velocity of $\lesssim 10^7$ cm/sec may give rise to these large accelerations. Correlations between pronounced geomagnetic activity and exceptional accelerations in the tails of comets were indeed observed in the cases in which the geometrical conditions were favorable (i.e., the angle comet-sun-earth being not too large). The angle between the main axis of such tails and the radius joining the sun with the comet is usually small, of the order of some degrees, the sign of it being such, that the tail lags a little bit behind, against the sense of the comets orbital motion around the sun.

There are several possibilities for the mechanism of this interaction. The simplest is the transfer of momentum by the electrons; this was worked out in some detail in 1951, and it was found, that with an assumed particle density of 10^3 cm^{-3} in the solar stream, an acceleration of 10^2 cm/sec^2 should result if the electron temperature was of the order of 10^4. The coupling between the solar and the cometary ions could be enhanced in at least two ways: first if magnetic fields of suitable properties were present, second by fluctuations of the local electric microfields of superthermal amplitude, which are likely to be caused by instabilities of the kind, which are currently discussed in connection with the problems of controlled thermonuclear fusion. The fact mentioned before, that these tails usually lag behind the radius by a small angle, is about what one would expect on the basis of simple transfer of momentum, but there are, at the same time, indications, that magnetic fields are present at least on certain occasions. While, therefore, it is difficult to be more specific about the actual mechanism of the transfer of momentum, it seems clear, that there is no difficulty in accounting for the observed magnitude of the acceleration.

Two conclusions may immediately be drawn from the foregoing discussions:

(1) With the exception of the transient plasma tails of comets, there should be no interplanetary plasma

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[1] V. C. A. Ferraro (unpublished).

[2] E. H. Vestine, Revs. Modern Phys. 32, 1020 (1960), this issue.

different from the solar corpuscular radiation, since such an assumed medium would be accelerated as is observed for the comets (any gaseous medium would be ionized out to at least several astronomical units distance from the sun).

(2) The solar corpuscular radiation travels approximately radially through interplanetary space. It differs from the outer solar atmosphere both by its total (kinetic+potential) energy and its rotational momentum. Whereas the corona rotates with the sun and as a whole has a negative energy, the contrary is the case for the interplanetary plasma.

Some further observational facts are of interest in this connection: If a comet is once observed to have a tail of the kind under discussion (type I in the Bredichin classification), it seems to have it for the whole period of time during which this would be expected on the basis of its distance from the sun. Such comets have been observed at all levels of solar activity, during periods of minimum activity as well as of medium or high activity, though with some dependence on the heliocentric latitude of its perihelium, as one would expect. Furthermore the appearance of such tails usually changes from night to night; during periods of high activity ion structures appear at times within less than one hour. This raises the important question of the mechanism of ionization.

The ionization potentials of CO and N_2 are ≈ 14 ev, and it is readily seen that an effective contribution of photoionization is unlikely in view of the observed low intensity of the part in question of the solar spectrum: With an effective ionization cross section of 10^{-17} cm^2, which is possibly an overestimate, $10^{13.5}$ quanta/cm^2 sec corresponding to $\gtrsim 10^{3.0}$ erg/cm^2 sec would be required for a time scale of 0.9 h, found in instances of rather high activity, and 10^{12} quanta/cm^2 sec or $\gtrsim 10^{1.5}$ erg/cm^2 sec for periods of normal (low) activity (time scale of ionization $\approx 10^5$ sec; owing to the uncertainties of the figures used the possibility of photoionization cannot strictly be ruled out for the low activity case, though also then it does not appear likely). As an alternative the mechanism of exchange of charge has been proposed: In the range of proton velocities between 200 and 1000 km/sec (0.2–5 kev) the cross section in question is as high as $3\cdot 10^{-15}$ cm^2, hence the particle intensities required are 10^{11} and $10^{9.5}$ p/cm^2 sec, respectively. These values would correspond to $\approx 10^3$ and $\lesssim 10^2$ p/cm^3, respectively, the lower figure being perhaps still too large, since it is based on somewhat less precise evidence than the former.

It is fair to point out that the picture which emerges for periods of low solar activity rests on the collective evidence provided by the observations of a still rather small number of comets scattered over a long period of time. The total number of comets known to have had a plasma tail is around 30; there is no conspicuous correlation of the appearance of such a tail with the general level of solar activity. As far as the comets are concerned, the possibility still cannot be ruled out that the base level of solar activity may be at times still lower than has been deduced above; this might imply, however, that the geomagnetic observations at high-latitude stations referred to above are explained on a different basis.

Lastly we turn to the evidence obtained or obtainable from the other sources mentioned earlier. The first accurate measurement of the polarized component of zodiacal light seemed to point to electron densities in interplanetary space of the order of some 10^2 cm^{-3} for 1952. More recent work, in particular by Blackwell, has shown, however, that the observational position is more complex than had appeared at first. As yet no simple interpretation of his (still mostly unpublished) results seems available. Of the cosmic-ray observations the most relevant part, in the present connection, are those referring to the time dependence of the additional radiation often produced on the sun in connection with flares, which yield important informations on the magnetic fields in interplanetary space. These phenomena have been studied in great detail by a number of groups in this country and abroad (e.g., by the Chicago group under J. Simpson). Since the measurements from satellites and space probes are just about to enlarge the observational evidence very rapidly, we will not try to summarize the data here. Their interpretation belongs without doubt to the most important applications of plasma physics to astrophysical problems.

In closing we would like to say that a number of important other examples exist, which could not be touched upon at all, in the fields of the dynamics of the interstellar gas, its interaction with the interstellar magnetic fields and the related problems of the origin and the propagation of cosmic radiation. Much relevant work has given a number of interesting results, though the number of open questions certainly exceeds very much the number of those which have received satisfactory answers.

For references the reader is referred to the lectures given by the author at the Varenna Summer School of 1958; see *Nuovo cimento Supplemento* **13**, No. 1 (1959).