PLASMA DYNAMICS

A Symposium Report by ***R. Landshoff***

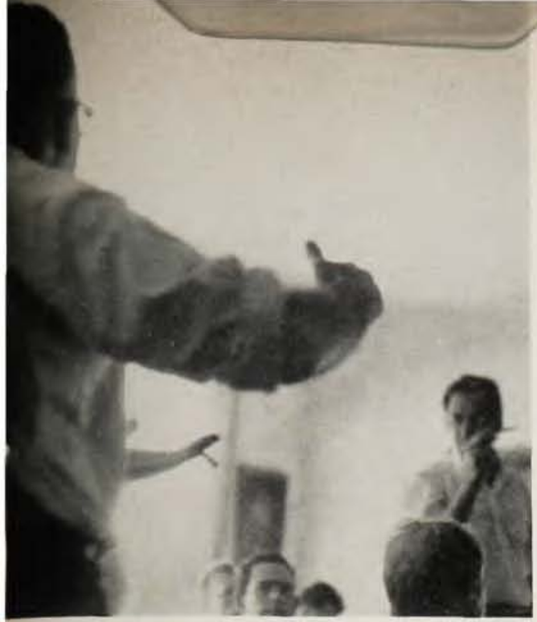
DURING the week of June 8th the National Academy of Sciences—National Research Council and the Air Research and Development Command sponsored an international symposium on plasma dynamics. The meetings took place on the beautiful Whitney Estate at Woods Hole on the southwest tip of Cape Cod. Attendance was limited to about fifty scientists actively engaged in research on plasma dynamics who were selected to represent all major aspects of this growing branch of physics. A number of participants came from England, Germany, and Sweden. To the regret of everyone, a simultaneous meeting of the Russian Academy kept scientists from that country away.

Only one session was held at a time, with everyone participating in each session. An introductory speaker outlined the topic and pointed out challenging areas of investigation. This was followed by a lively and fruitful exchange of ideas. A permanent record of all the discussions was secured, which is now being edited, and will soon be published by the Addison-Wesley Publishing Company.

Francis Clauser of Johns Hopkins, who was the general chairman of the symposium, scheduled the sessions for mornings and evenings, leaving the afternoons free for recreation or impromptu discussions. The highlight of the recreational activity was a beach party rewarding the participants with lobsters and other New England delicacies. The organization of this event and the thoughtful attention to details of every kind by John S. Coleman, executive secretary of the NAS-NRC Division of Physical Sciences, made our week at Woods Hole a very pleasant one.

There were nine sessions in all with generally clearly defined topics. However, the first and the last sessions had formal topics ("Summary of Physical Understanding Obtained from Experimental Plasma Dynamics" and "The Larger View of Plasma Dynamics") which were interpreted quite liberally as meaning experimental and theoretical results concerning the Sherwood program.

At the first session, James Tuck, who directs the Los Alamos Sherwood effort, introduced the conferees to several devices not previously published, which are used at Los Alamos to produce hot plasmas. Ixion, as one of them is called, is a magnetic mirror with a superimposed radial electric field. The cross fields cause a macroscopic drift of the plasma on circles around the mirror axis and a macroscopic gyration of the individual ions and electrons around the magnetic field lines. Scylla, another system, consists of a single coil shaped to produce a mirror field which is made to rise suddenly by connecting the coil to a high-voltage condenser. The induced tangential electric field ionizes the



Informal sessions punctuated by lively exchanges characterized the international symposium on plasma dynamics which was held last June at Little Harbor Farm, the Whitney estate at Woods Hole, Cape Cod.
(Photos by Davis)

gas which is then compressed by the magnetic field. Still another apparatus called Toxon produces puffs of ionized gas traveling at 40 km/sec.

It is obviously desirable to ascertain the velocity distribution of electrons in an accelerating electric field. Tuck pointed out in the first session that previous ideas on this, leading to an electrical conductivity going as $T^{3/2}$, do not seem to be born out by experiments, and introduced the concept of runaway electrons worked on by H. Dreicer. If the electric field exceeds a critical value—sufficient to accelerate electrons in one collision time to a speed, which is about equal to their thermal speed—the electron distribution in velocity space can "run away". The separation of electrons and ions in velocity space is, however, likely to be unstable and to lead to plasma oscillations. Tuck invoked a process analogous to the excitation of violin string vibrations by a bow. Reference was made to a mechanism to excite plasma vibration requiring some mobility of the ions as well as the electrons which has been worked out independently by O. Bunemann of Stanford and by M. Rosenbluth of General Atomics. The rate of build-up is $\sqrt[3]{m/M}$ times the plasma frequency of the electrons, which is very fast. Either instability would check runaway, increase the Maxwellization rate of the electrons and increase the resistance of the plasma. Evidence for a resistance which is higher than given by the $T^{3/2}$ formula has also been obtained at the Harwell Atomic Energy Establishment. Magnetic-field measurements reported by W. B. Thompson of Harwell indicate that currents are flowing much closer to the center line than one would have expected using the $T^{3/2}$ law with a temperature indicated by either Doppler shifts in the optical spectra or by neutron yields. At the same time there appears to be some doubt whether the Doppler shift is caused by thermal motion or by a flow pattern which is irregular on a small but macroscopic scale. Some semantic difficulties arose at that point between hydrodynamicists and other conferees as to the propriety of calling such irregularities turbulent.

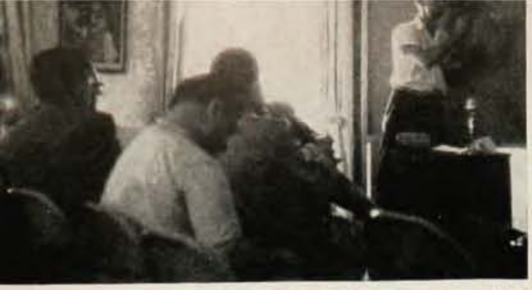
In the same context E. N. Parker of the Enrico Fermi Institute pointed to the need to invoke an acceleration mechanism for the ions to account for the observed fusion reactions in the absence of a sufficiently fast thermal motion. Parker, like others, proposed a Fermi-type acceleration which he supported by a model argument based on the Fokker-Planck equation. The model represented the irregularities by hard spheres, whose mean separations and velocities were picked intuitively, and this led to a critical speed of around 100 km/sec at which the Fermi mechanism would become operative in Zeta.

Richard F. Post (Livermore Laboratory) pointed out that in the process of producing and heating a plasma one must, energywise, get over a hump. This difficulty is caused by impurity atoms which radiate and therefore lose energy 10^6 times faster than ordinary bremsstrahlung of hydrogen.

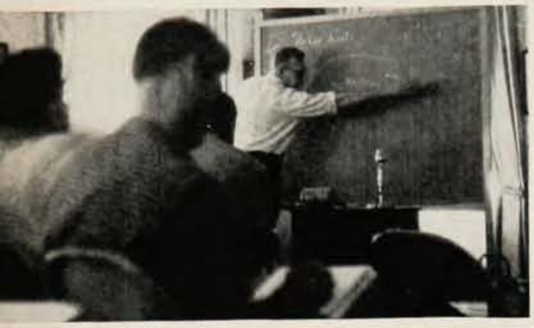
At plasma densities of interest in shock tubes and in controlled fusion research one is very far from radiative equilibrium and that has some surprising consequences. One feature of very low densities of, say, hydrogen is that very little foreign material (from the wall, for example) introduces an appreciable degree of impurity. If you calculate for a given temperature the degree of ionization of high z atoms such as oxygen, the Saha equation based on thermodynamic equilibrium would give complete stripping at 10 ev. To establish such an equilibrium would require a number of very slow processes such as three-body collisions, whereas the only processes which are anywhere near fast enough to establish a steady state are ionization by electron collision and radiative recombination. The consequence of this is a much lower degree of stripping than predicted by the Saha equation. There will therefore be plenty of impurity atoms in an ordinary discharge which are not completely stripped of electrons at the temperatures of interest.

Even this low degree of ionization takes some time to be established, possibly longer than the duration of the experiment, and one may be even further from the Saha distribution than in the steady state.

Rolf Landshoff is a consulting scientist at the Lockheed Missile Systems Division Laboratory in Palo Alto, Calif. A German-born mathematical physicist, Landshoff earned his PhD in physics at the University of Minnesota in 1938. Prior to joining Lockheed he was a member of the scientific staff at the Los Alamos Scientific Laboratory in New Mexico.



Lundquist



Krook

Chapman

Thomas

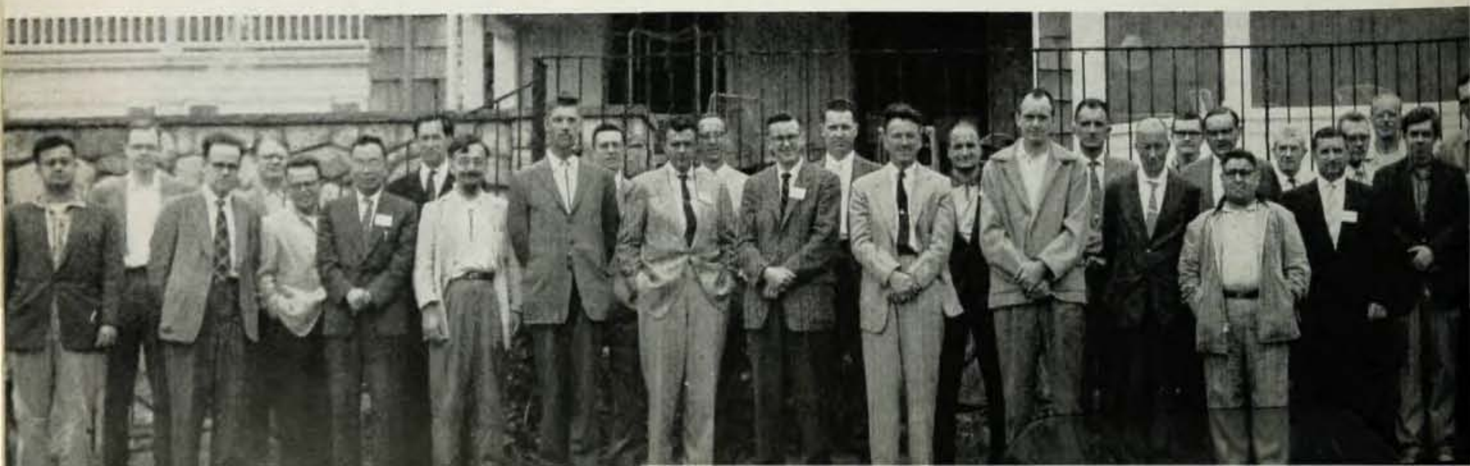
Parker

The presence of not completely stripped ions makes an important contribution to the radiation, as much perhaps as a megawatt per cm^3. If the size of the system is large enough the radiation intensity at the center of a line, and perhaps in some frequency interval around it, may add up to the Planck value and the line takes on a trapezoidal shape.

The Monday evening session dealt with the *dynamics of electron beams*. In this field one is interested in the gain of a signal modulating the beam. There are essentially three types of interaction which can give rise to an amplification. The electron stream can interact with another electron stream, with a slow wave circuit, or with ions. John Whinnery of the University of California (Berkeley) gave a survey of the most important cases that have been treated, basing the analysis on a simplified Boltzmann equation. The purpose of this discussion was not to learn about methods of amplification but rather to learn of the existence of well-analyzed phenomena which have an obvious bearing on other aspects of plasma physics.

Roy W. Gould of the California Institute of Technology described some experiments designed to measure electron densities in a plasma. By measuring the signal gain of a modulated electron beam passing through a plasma one obtains resonance at the plasma frequency and can calculate the electron density from this. A second method utilizes the scattering of an electromagnetic wave by a plasma column within a wave guide. In a third set of experiments one determines the propagation of slow space-charge waves along a plasma column. Finally, as an independent check, the density was measured by probes. The different density determinations were in reasonable agreement except for the electron-beam experiment, which differed from the others by a factor of three or four. The reason for this last discrepancy is not understood. The wave-propagation method promises to be a particularly useful tool for high-density thermonuclear plasmas because one can use frequencies much below the plasma frequency.

The third session considered theoretical investigations in the field of *statistical plasma dynamics*, which may proceed in two major directions. The first has as its aim the development of a statistical model and its mathematical formulation by starting from general principles and certain well-defined simplifying assumptions. The second uses such a model for the solution of macroscopic problems.



The assumption of one-particle distribution functions based on a self-consistent field idea can lead to the Boltzmann or the Fokker-Planck equation. Harold Grad of New York University discussed the validity of the Boltzmann equation and the notion of Debye screening which enters when one considers two-particle distribution functions.

C. M. Tchen of the National Bureau of Standards outlined the derivation of a kinetic equation, which is related to the Fokker-Planck equation, and its derivation from an assumption on how to express the three-particle distribution in terms of one- and two-particle distributions. An entirely different attack was proposed by Eugene Gross who showed how to reformulate the theory of plasmas by dealing with collective variables of charge fluctuation without reference to particle orbits.

Jan Burgers of the University of Maryland gave a discussion of the theory of transport phenomena based on the Boltzmann equation following, by and large, the ideas of Chapman and Enskog. Sidney Chapman of the University of Alaska's Geophysical Institute told of a recent application of his method leading to the discovery that highly charged ions will exhibit a very strong thermal diffusion towards hot regions. This phenomenon may be of great importance in the interpretation of spectra observed in the solar corona and in a Zeta-type discharge.

In all methods of solving the Boltzmann equation which rely on moments of the distribution function, one is faced with the necessity of getting rid of higher moments in order to obtain a closed set of equations. The Chapman-Enskog procedure is restricted to problems where one can apply equations which do not themselves depend on boundary conditions. Max Krook of the Smithsonian Astrophysical Observatory commented that, because of the large effective mean free paths of electrons in a plasma, one is often forced to adopt cutoff prescriptions which are determined by the boundary value. He favored a prescription which is a generalization of the Mott-Smith procedure.

Marshall Rosenbluth suggested a procedure specially adapted to stability problems which is based on a linearization of the Boltzmann equations and Kenneth M. Watson of the University of California at Berkeley outlined a technique for handling a wide class of hydrodynamic phenomena directly from the Schroedinger equation.

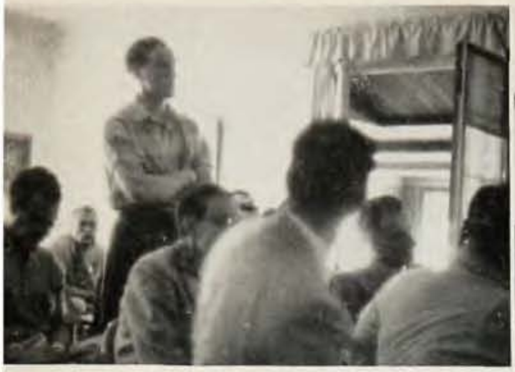
During the fourth session William Allis of the Massachusetts Institute of Technology discussed various *gaseous electron phenomena* which are related to plasma dynamics. He pointed out the fallacy of expecting electric fields in a plasma to be weak because of the low resistance. The physical conditions are usually such that there are regions both of low and of high plasma density. The density gradients give rise to diffusion currents which push both electrons and positive ions around until the electric fields created in this manner are sufficient to balance the diffusion forces. Depending on details of the arrangement, this may produce all sorts of phenomena such as single and double sheaths, tufted anodes, and striations moving through the plasma.

The fact that the electric field in a plasma is generally high and not necessarily uniform also influences the shape of the velocity distribution function of the electrons. In solving the Boltzmann equation for pure Coulomb collisions one finds, according to Allis, no steady-state solution unless the electric field is explicitly introduced. As you make the electric field go to zero the solution does not converge.

The fifth session was devoted to a discussion of the *continuum approach to plasma dynamics* which considers that the fluid is reasonably well described by the Navier-Stokes equations with terms added to express the interaction with the electromagnetic field. Even in ordinary hydrodynamics one is confronted with great difficulties in looking for solutions to the Navier-Stokes equations with boundary conditions representing actual physical conditions. According to Hans Liepmann of Caltech these difficulties stem from two sources: the nonlinear terms entering the equations and the presence of higher order derivatives in the viscous forces. An approximation procedure which often works, consists of combining solutions of the nonviscous equations connected by transition layers which are handled by perturbation methods. Among the nonviscous solutions are wavelike disturbances. In magnetohydrodynamics there is a larger variety of such waves including, for example, those discovered by Alfvén. These waves can be found by the method of characteristics. Liepmann discussed a number of special solutions. Harry Petschek of the Avco Research Labs compared one of these special solutions to an experiment carried out at Avco leading to ordinary as well as so-called switch-on shock waves. Alan Kolb at the Naval Research Laboratory studies the interaction of plasma flow of about Mach

Group photograph at Symposium on Plasma Dynamics. Left to right: 1. John S. Coleman; 2. Marshall N. Rosenbluth; 3. E. N. Parker; 4. F. D. Kahn; 5. Dwight Wennersten; 6. M. Mittleman; 7. C. M. Tchen; 8. W. B. Thompson; 9. Rolf Landshoff; 10. James L. Tuck; 11. Sherwood Githens; 12. John R. Whinnery; 13. S. Lundquist; 14. Roy W. Gould; 15. Richard G. Fowler; 16. Richard F. Post; 17. Richard N. Thomas; 18. Francis H. Clauser; 19. Adolph Buseman; 20. Johannes M. Burgers; 21. Joseph E. Byrne; 22. L. Biermann; 23. Milton Slawsky; 24. Sydney Chapman; 25. William J. Otting; 26. Hermann Haus; 27. William P. Allis; 28. Geoffrey Burbidge; 29. Alan C. Kolb; 30. Eugene P. Gross; 31. George Batchelor; 32. Kenneth M. Watson; 33. Edward Frieman; 34. Max Krook; 35. Walker Bleakney; 36. W. Marshall; 37. Harold Grad; 38. Hans W. Liepmann; 39. Winston Bostick; 40. Arthur Kantrowitz; 41. Julian Cole; 42. Harry Petschek. Not included in the picture are B. T. Chu, E. L. Resler, and William R. Sears.

(*Photo by Charles Spooner*)



Comment from the floor. Sessions were held in mornings and evenings with afternoons free for recreation, small group discussions, and preparation for forthcoming sessions.

Discussions continue during morning session coffee break.

100 with very strong external fields up to half a million Gauss and densities between 50 and 500 microns. Depending on the geometrical arrangement of the fields the plasma can be stopped or compressed by them. By means of a careful analysis of spectral line profiles Kolb hopes to obtain excitation temperatures.

With somewhat different timing Walker Bleakney at Princeton also observed a speeding up of the flow.

A discussion by L. Biermann (Max Planck Institute, Goettingen) of certain oscillating solutions led to a discussion of whether shock waves can exist in the absence of collisions. Rosenbluth emphasized the necessity for a damping mechanism to degrade the oscillating motion initiated by a high pressure front. He suggested a phase mixing of the particle orbits due to a small thermal velocity spread prior to the arrival of the front.

The sixth session was devoted to "*Aerodynamic Potentialities of Magnetohydrodynamics*". The main speaker, Arthur Kantrowitz of Avco Research Labs, outlined several ideas.

When the Larmor radius in an ionized gas flowing through a solenoid is comparable to the mean free path, the current tilts and the Lorentz force can cause a lift in addition to the drag. Magnetohydrodynamic forces could also be used to slow down an ICBM as it reenters the atmosphere, particularly if the conductivity is enhanced by squirting a little alkali vapor ahead of the flight path. Both these applications require electric power to energize the solenoid which produces the magnetic field. This electric power could possibly be derived from self-exciting generators which pick up the voltage from a couple of electrodes utilizing potential differences in the air flowing past the object. This, too, can be enhanced by "seeding" with alkali vapor.

The seventh session dealt with *solar, planetary, and interplanetary magnetohydrodynamics*. Sidney Chapman concluded that the sun's atmosphere extends beyond the Earth and that it must be very hot around the Earth. His calculation is based on a model assuming the solar atmosphere to be static and derives a temperature of 200 000 degrees K and a density of around 400 particles at the Earth's orbit. The temperature of this hot coronal gas cannot remain at 1500 degrees K at its outermost limit as had been thought until recently, but it must steadily increase.

This presents a heat flow problem from which Chapman infers that the Earth's atmosphere extends about 30 Earth radii and possibly more. Defining the limits of the Earth as the region where the density and temperature approach those of the interplanetary gas, the Earth is thus much bigger than it had previously been thought.

Chapman pointed out that the static condition assumed by him is clearly not fulfilled. An extension of this model to include a solar wind was proposed by L. Biermann. Observations of comet tails show that they experience an acceleration away from the sun which is much too large to be explained by light pressure. An acceleration of the right order can be explained by assuming that the solar atmosphere steadily streams outward with a wind velocity of perhaps 500 km/sec, rising to higher values during magnetic disturbances.

Parker discussed his hard-sphere model in more detail (see first session) and applied it to a number of astrophysical problems. According to Parker, one can explain the high-energy particles in a powerful solar flare as being generated by a region of about 1000 km agitated by eddies moving with a velocity of 230 km/sec.

Hydromagnetic shock waves which enter the coronal region from the considerably denser photosphere tend to speed up. Calculations by Parker indicate that this may be a mechanism which raises the coronal temperature to the exceedingly high temperatures which have been observed.

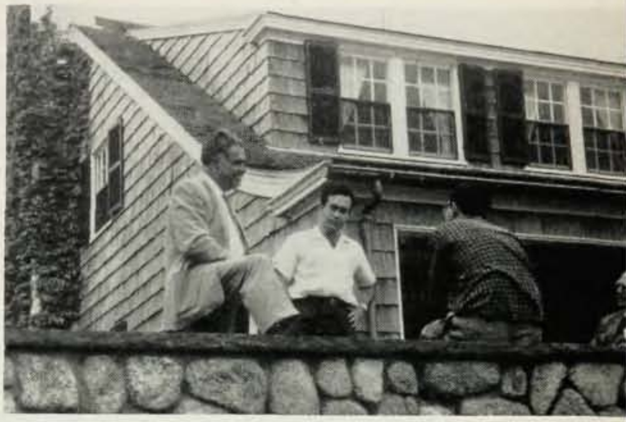
The solar wind tends to straighten the magnetic field lines coming from the sun up to a distance somewhat beyond the Earth's orbit where an instability develops. Beyond that region is a shell of disordered fields which provides a mechanism to trap cosmic rays from the sun. Such a trapping can be inferred from the slow decay of cosmic-ray activity following solar flares.

S. Lundquist, from the Swedish Royal Institute of Technology, reported on some recent work by Alfvén showing that the acceleration of cosmic-ray particles by fluctuating magnetic fields and their diffusion combine to lead very nearly to the observed momentum spectrum $p^{-2.6}$.

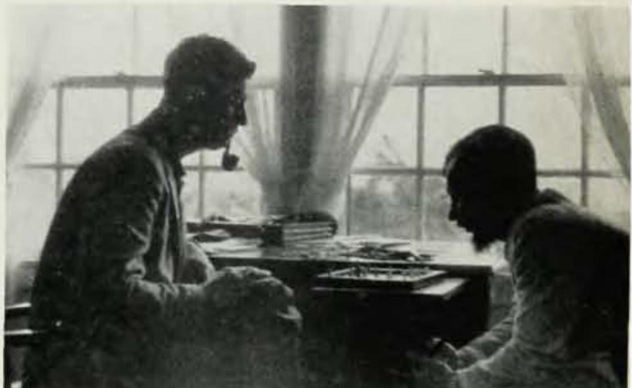
The interpretation of spectral line profiles in terms of temperature is difficult for two reasons. The observed

Participants were also occupied during their "free" time in writing up notes for the permanent record of the symposium, which is shortly to be published by Addison-Wesley. J. Tuck (above) and W. P. Allis (at left) are seen hard at work indoors on a sunny Cape Cod afternoon.

E. P. Gross and R. F. Post relax on glassed-in porch of Whitney summer home, which was leased for NAS–NRC summer program.



A. Kantrowitz, H. Petschek, A. C. Kolb, and W. Bleakney relax in sun. (A few hardy swimmers did their relaxing in the cold waters of Nantucket Sound.)



Meanwhile, back in the house, Tuck and Landshoff forgo relaxation to engage in a spirited game of chess. (Landshoff won.)

light comes from an optical depth about equal to one, so that the actual depth changes with frequency and the occupation of spectroscopic states is not in thermal equilibrium. Richard N. Thomas (NBS Boulder Labs), taking into account the rates of different types of excitation processes, arrives at a statistical equilibrium distribution of excited states and thus at a temperature-dependent source function for the emission of radiation. Substituting this into the radiation-transport equation he can now correlate line profiles with the temperature distribution.

The optical paths traversed are of the order of 10 000 km covering a density range from 10^8 to 10^{14} particles per cm^3 and a temperature ranging from 4000 to 2 million degrees K. This is entirely different from the laboratory situation, described by Post, where one has essentially constant conditions.

The Thursday evening session dealt with *magnetohydrodynamics on a galactic scale*. L. Biermann reviewed the observational evidence for the presence of magnetic fields and for the distribution and the state of motion of gas masses within our galaxy as well as others.

It has been suggested by Alfvén and Fermi that magnetic fields are responsible for cosmic rays and these fields have been estimated to be of the order of 5×10^{-6} gauss. Similar magnitudes are deducted from the observed scattering of the light from distant stars by cosmic dust particles which are lined up by magnetic fields. These fields appear to be correlated with the structure of the galaxy but there is not enough evidence to ascertain if the fields are, or are not, in the direction of the spiral arms.

A strong concentration of magnetic fields occurs in the Crab nebula which is the remnant of a supernova in our galaxy. The Crab nebula emits both highly polarized light and radio noise which can be interpreted as cyclotron radiation of high-energy electrons in a magnetic field.

When conventional spiral galaxies are looked at in the 10- to 100-cm wavelength region they often appear to be spherical. This radiation "halo" seems to be cyclotron radiation in a field of about 5×10^{-6} gauss.

A lobster and clam feast at a nearby Buzzards Bay beach was arranged one afternoon for participants in the symposium. Above (left) general chairman Clauser helps prepare clams; (center) chief chef Coleman serves clams; and (right) G. Burbidge is amused as bathers in background search anxiously for toe-nipping fish in the surf.

About 2 percent to 6 percent of the mass of a galaxy is present in the form of hydrogen gas. This gas is not distributed evenly but concentrates to form clouds. The hydrogen in these clouds is either completely ionized at around 10 000°K or not at all ionized and below 100°K. The displacement of spectral lines reveals a considerable amount of turbulent motion of the clouds and one can calculate a mean kinetic energy density of the same order as the energy density of the magnetic field, i.e., about 10^{-12} erg/cm^3.

It is believed that turbulent gas clouds are maintained by very hot stars which are born continuously. During their relatively short life of perhaps a million years these hot stars exert a very large pressure on the gas masses and provide the energy to set them into motion. The interaction with clouds of ionized gas which are in a state of turbulent motion tends to amplify weak magnetic fields. It is a question of considerable interest, which has not yet been settled, if such a "dynamo theory" mechanism can account for an equipartition of kinetic and magnetic energy.

In the last session of the symposium Marshall Rosenbluth covered some *aspects of plasma dynamics which have special importance for the Sherwood program.*

Most situations where one attempts to contain plasma tend strongly toward instability. There are basically two types of instabilities: the kink and the flute. Four basic approaches have been proposed to cure instabilities.

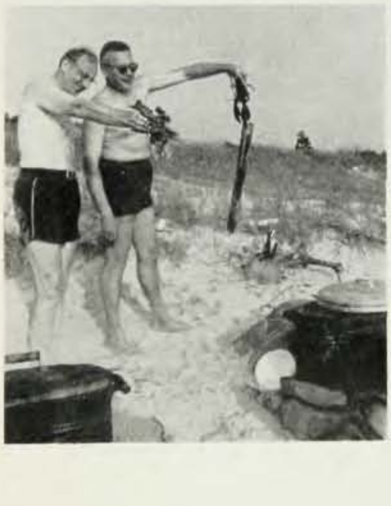
Rather generally a containment of plasma on the concave side of curved field lines is likely to be unstable. By arranging magnetic field lines coming out of cusps, so that the plasma in the interior looks at the convex side of the lines, one can obtain stability. However, the plasma will in this case leak out at the cusp, and the usefulness of such a scheme depends on the rate of this leakage.

Predictions concerning flute instability can be made by analyzing the effect of interchanging two bundles of flux lines together with the attached plasma. If any such interchange lowers the energy of the system, the initial configuration is unstable. By arranging field lines in a crosswise pattern to prevent the possibility of an interchange by a continuous displacement, one can obtain stabilization in the pinch and in the stellarator. In the first, the axial field on the inside is surrounded by the pinch field. In the second, the containing field is due entirely to external currents with a "rotational transform" preventing the interchange.

In the mirror machine, finally, one attempts to short out the flutes by placing conducting plates across the ends of the machine.

To produce a plasma one has to combat not only the energy losses by radiation, as pointed out by Post, but charge exchanges between cold neutrals and hot ions for which the cross sections are extremely large. Once plasma is produced it must be heated still further and methods which have been proposed utilize Ohmic heating, nonadiabatic pumping techniques, and the release of magnetic-field energy where two crossed magnetic fields in adjacent regions get mixed up. These methods all require some dissipative mechanism. In addition to collisions, which are inefficient at high temperatures, it is believed that "phase mixing" is able to randomize an initially coherent motion of the electrons and ions.

The growing field of plasma dynamics is rapidly branching out in many fruitful directions of research. The participants of the conference took with them a better understanding of each other's work as well as a broadened view of the entire field.



Plasma dynamicists Allis and Krook, with help of cooperative crustaceans, demonstrate pinch effect.