accompanying the production of shock waves has become another area of interest in fluid dynamics. Sharp luminous lines have been observed in what appears to be the collision of interstellar clouds, and the violent turbulent motion involving shock waves is thought to be at its origin. These magnetofluid-dynamic shock waves are but one example of a large area of phenomena combining magnetic forces with flowing and conducting media. The influence of a magnetic field on wave propagation, boundary-layer flow, shock-tube flows and other fluid flows has become the subject of extensive studies.

Statistics

Several big steps forward have been made in the statistical-mechanical formulation of fluid-dynamics equations and other transport equations. One of these is the development of the correlation-function method, in which the assumptions are more clearly seen than by previous techniques using the Boltzmann equation. Interest in rarefied-gas flow has been increasing continuously. A whole range of conditions, from continuum at one extreme to free-molecule (collisionless) flow at the other and embracing a large number of problems in the region between those two extremes, now occupies a number of fluid dynamicists.

Geophysical fluid dynamics

Interaction between classical fluid dynamics and high-speed computing methods has been particularly important to meteorology and oceanography. Most of the problems in meteorology involve laws of fluid dynamics; however, meteorological applications require extremely long computations. Thus meteorology is a somewhat special discipline based in part on known physical laws and in large part on insight gained from long experience. Many complex flow problems can now be treated with fast computers. There is, too, an increasing interaction between fluid dynamicists and meteorologists. Fluid instabilities, convection phenomena and problems involving rotating fluids were the subject of a variety of studies related to the field of geophysical fluid dynamics.

Superfluids

20 years ago the theoretical description of liquid helium by Lev Landau was suspect. It has described the properties of the strange fluid below 4.2°K so successfully that it now forms one very satisfactory approach. The superfluid properties of no viscosity and no thermal resistance then known have been augmented by the discovery of quantized vortices. A bucket of superfluid cannot have a range of values of angular momentum. Discrete vortices are detected by their effect on the motion of tiny bubbles surrounding electrons moving in an electric field. An alternative theory starting from Bose statistics furnishes a description of the properties of a superfluid condensate. The amalgamation of the two approaches is a recent exciting development.

Outlook

Since fluids, including plasmas, essentially constitute the entire content of the universe, with solids but a trace impurity, it might appear that for all but a few exceptions natural phenomena would be within the domain of the physics of fluids. Of course only a fraction of the activity in physics is organized under this topical heading, and this probably represents our inability to handle the complexities of large and complicated motions. Laws governing subnuclear, nuclear and atomic "particles" are believed to provide for the behavior of collections of "particles." However, the ensemble of particles that constitutes a fluid produces many phenomena that are not always expected from these laws.

Will the evident and recurrent processes going on about us all the time be understood better by frontal attacks from macroscopic fluid dynamics? We wonder if high-speed computer studies of nonlinear problems in the next 20 years will bring us to an understanding of the big unanswered problems in our surroundings. It is possible that emphasis on understanding small phenomena may decrease and that more attention to organized systems will constitute our new era of progress. In any case it is interesting to raise the question. □

TWENTY YEARS OF PHYSICS

PLASMAS

By MELVIN B. GOTTLIEB

TWENTY YEARS AGO the study of plasmas occupied a relatively minor role in physics: The wide variety of plasma phenomena remained unexplored. The field had its origin early in this century in the study of the gas discharge, a relatively dense, slightly ionized plasma regime where the dominant effects are ionization, excitation, recombination and other atomic collision processes. Irving Langmuir initiated modern plasma physics through his discovery of plasma electrostatic oscillations and his realization that this was an aspect of collective particle motion. It is these collective motions which, generating and interacting with electric and magnetic fields, are responsible for the wealth of physical phenomena that take place in a plasma and make it so different from ordinary fluids.

Astrophysical and geophysical studies also played an important early role. Edward Appleton, in his ionospheric studies, correctly described (in the thirties) the propagation of electromagnetic waves in a plasma, including the effect of static magnetic fields. Sydney Chapman and Vincenzo Ferraro developed their theory of the interaction of plasma streams with the earth's magnetic field. Willard Bennett, in 1934, predicted the pinch effect, which was to give rise to major experimental efforts 25 years later.

Hannes Alfvén, in 1941, with the publication of *Cosmical Electrodynamics,* brought collective effects once more to the foreground, and in particular first described the wave processes named for him.

Kinetic theory of plasmas had an even earlier start. Lev Landau, in 1934, derived the Fokker–Planck approximation for the collision integral. Chapman and Thomas Cowling, in *The Mathematical Theory of Nonuniform Gases,* showed that the Boltzmann equation could be simply adapted to the plasma problem. The classic papers of Landau, in 1945–46, on phase mixing, and of A.A. Vlasov, setting up the so-called collisionless Boltzmann equation, laid the necessary foundations though the need for rigorous proofs remained.

The first strong impetus for modern plasma physics came with the realization, about 1950, that the successful release of controlled energy from the fusion reaction would probably involve a hot plasma interacting with a magnetic field. Within a few years plasma physics received an added stimulus from the discovery of the important role played by the solar-produced plasma in interplanetary space. In the subsequent period there has been a rapid expansion in our knowledge.

Plasma theory

In essence plasma physics is a many-body problem, in which the basic interactions (electromagnetic) are well known and where, in addition, quantum effects are often negligible. Thus, the equilibrium statistical mechanics of these systems is a trivial problem; but, due to the subtle, long-range nature of the forces involved, the dynamics is very rich—many kinds of collective motions are possible. A key advance of theory in the last decade has been to make a rigorous derivation (from the many-body equations) of a slightly modified form of the Boltzmann, or Fokker–Planck, equation which, together with Maxwell's equations, governs plasma behavior. Thus the fundamental dynamics takes place in six-dimensional phase space. Two further great simplifications are often relevant. For distances larger than the Debye length and frequencies less than $(4\pi ne^2/m)^{1/2}$, the plasma frequency, any motions must preserve quasineutrality. For distances greater than the gyroradius and frequencies less than the gyrofrequency, a simplified form of particle equation of motion is applicable, and consequently the "guiding-center" approximation to the Boltzmann equation is valid. From this approximation, the appropriate conditions under which fluid theory (magnetohydrodynamics) is correct have been determined, and also a whole new class of waves at lower frequency—drift waves—has been predicted theoretically and observed experimentally.

The physical content of the guiding-center approximation is that particles move across the magnetic field in accordance with the drift $\mathbf{E} \times \mathbf{B}/B^2$, which is also the velocity of the field lines themselves. Therefore $\mathbf{E} + \mathbf{V} \times \mathbf{B} = 0$; the electric field vanishes in the moving coördinate system. At the same time particles are accelerated freely along the field lines by the component of **E** parallel to **B**. In the absence of this parallel motion they would move strictly with the field lines, and plasma and magnetic field would remain frozen together, which is the distinguishing characteristic of infinite-conductivity fluid theory. On the other hand when the phase velocity of the wave along the magnetic field is slower than the particle velocity this transverse motion becomes averaged out. When this condition applies for electrons, the powerful constraint of being frozen to field lines is removed, and under these conditions a larger class of dynamics—specifically, drift waves—becomes possible.

Thus low-frequency waves and consequent instabilities can be studied in the guiding-center approximation; but at higher frequencies, where characteristic distances are very short, geometrical effects are not too important. The theory is then concerned primarily with motions in velocity space, where anisotropies often supply an energetic source for instabilities.

As in other branches of physics, while the behavior of linearized waves is now reasonably well understood, their nonlinear behavior is both complex and often of crucial importance. This study is, in some ways, similar to classical Navier–Stokes turbulence. At first sight it would appear to be much more complicated, since the nonlinear interaction of many kinds of waves is involved and particle distributions in six-dimensional phase space need to be considered. However, it turns out that there are often enough constraints present (for example Liouville's theorem, conservation of adiabatic invariants, etc.) that fully turbulent motion is not to be expected, but stabilization at low amplitudes may occur, leading to such effects as anomalous diffusion across the magnetic field such as that conjectured by David Bohm in 1945.

This study of the "weak turbulence" regime is one of the main tasks of theorists today, as is the continuing search for a definite answer to the key problem of thermonuclear research: Will we find a sufficiently stable confined equilibrium?

Laboratory plasmas

In the period 1948–58, extensive classified work on plasmas got under way in the US, the UK and the USSR. The simple fluid theory of plasmas was applied to the dynamics of pinches and to their major instabilities, as well as to the realization of grossly stable toroidal-pinch configurations with extended lifetimes. This period also saw the invention of other basic toroidal magnetic bottles (stellarators and tokamaks) and the verification of a gross correspondence of torus stability with the predictions of the fluid theory.

Experimenters demonstrated effec-

Melvin B. Gottlieb took his PhD at the University of Chicago and was on the faculty at the University of Iowa during 1950–54. He then joined Princeton and became director of the Plasma Physics Laboratory and professor of astrophysical science in 1961. He was the first chairman of the APS plasma physics division, formed in 1959.

tive mirror confinement of hot plasmas and developed the physics of rotating plasmas, plasma accelerators, and collisional plasma shocks. The laboratory study of plasma waves and their application to plasma heating also began in this period.

These experiments on the fluidlike behavior of plasmas were conducted mostly in the lower part of the temperature range 10^4–10^7°K and at densities of 10^{14}–10^{17} cm^{-3}. Plasmas were generated principally by ohmic heating and magnetic compression. Effective plasma diagnostics, by visible, ultraviolet, and x-ray spectroscopy, microwave interferometry, and multiprobe techniques, were evolving.

International coöperation in controlled-fusion research began with the 1958 Geneva Conference. At that time the anomalies with respect to simple plasma theory were just beginning to emerge. The decade 1958–68 has provided a body of far more sophisticated theory and experiment, and some of the major anomalies have been resolved.

Studies of the nonfluidlike behavior of hot plasmas progressed mainly in the context of mirror machines. Long-time, single-particle confinement in complex magnetic fields was verified and shown to correspond to the theory of adiabatic invariants. When beam-injected plasmas in the 10^7–10^9°K range were built up into the 10^8–10^{10} cm^{-3} density range, excitation of high-frequency instabilities began to show up, and the limitation of plasma confinement by instability-related velocity-space diffusion was established.

The detailed experimental study of velocity-space stability problems was initially limited by the additional presence of fluidlike instabilities in the simple mirror machine. The introduction of minimum-B magnetic-field shaping both documented the nature of these instabilities and effectively removed them. Then the discovery of Lorentz dissociation of neutral-atom beams in a magnetic field provided a highly controllable method for trapping energetic ions, and the detailed structure and parameter dependence of high-frequency modes began to be explored. On the theoretical side, a rich spectrum of high-frequency modes is now established, and the infinite-medium theory has been extended to include finite-geometry effects. A substantial degree of quantitative experimental–theoretical agreement exists.

The understanding of the fluidlike behavior of finite plasmas has, in turn, been extended to include more complex plasma dynamics. The validity of the infinite-conductivity-fluid treatment of plasma stability was first disproved by experiments on pinches with internal conductors. Finite-resistivity stability theory emerged, and has provided a more realistic guide to both laboratory and astrophysical phenomena. Next to be introduced and experimentally verified were gyroviscous effects, which in turn led to the extremely important discovery of drift waves and the associated density and temperature-gradient instabilities.

Stellarator experiments provided a way to measure the detailed parameter dependence of anomalous diffusion in toruses, and empirically confirmed Bohm's conjecture ($D = ckT/16eB$), within the short-mean-free-path regime. Theoretically the diffusion anomaly now became understandable in terms of resistive and drift-type instabilities, and conditions were derived for plasma stabilization by magnetic-field-shaping techniques (shear and minimum-average-B), and by a shift to long-mean-free-path regimes.

Experiments with axisymmetric internal-conductor toruses (multipoles, levitrons), and more recently with stellarators, have borne out these theoretical predictions qualitatively, and substantial advances relative to Bohm's diffusion formula have been realized. In the large tokamak experiments plasmas of 10^6–10^7°K and 10^{12}–10^{13} cm^{-3} have been reported to show improvement factors of 10–30 relative to Bohm diffusion.

Some of the most basic plasma experiments have used simple linear geometry instead of the complex magnetic-field configurations that have come to characterize the long-time plasma containers. Alkali-metal plasmas (Q machines) have been used for the experimental realization of drift waves and ion-acoustic waves. Experiments with electrostatic wave-generation in steady-state, low-density, hydrogen plasma columns have verified the details of the Landau damping and excitation process, and the existence of wave echoes.

The most important of the linear experiments, from the point of view of controlled-fusion research, has been the transient containment (in theta pinches) of plasmas in the temperature range 10^7–10^8°K at densities of 10^{16}–10^{17} cm^{-3} and plasma pressures comparable to that of the magnetic field. The simple fluid instabilities are substantially controllable, and an upper limit on anomalous diffusion has been shown not to exceed the Bohm range. Theta-pinch geometry also serves for the production and study of collisionless shocks, thus providing laboratory verification for the theory of this important space phenomenon.

The feasibility of stable, coherent rings of relativistic electrons, forming plasmalike entities, has been demonstrated. While these rings need further increases in ring current before they can form closed magnetic bottles for controlled fusion (Astron), their application in collective, high-energy accelerators has recently emerged as an immediate practical prospect (see PHYSICS TODAY, February, page 51).

Laser technology has interacted significantly with the plasma field. Lasers are used in diagnostic techniques such as interferometry, Faraday rotation, and Thomson scattering, and high-powered lasers provide virtually instantaneous point sources of energetic plasma by completely ionizing small levitated targets.

Space plasma

During the past 20 years plasma physics has played an increasingly important role in astrophysics and a nearly dominant role in space physics.

In 1958 the first US space vehicle, Explorer X, carried instruments that detected high-energy, charged particles trapped by the magnetic-mirror effect of the earth's field. These particles oscillate back and forth along a line of force, reflected by the increasing magnetic field near the earth, and, in addition, drift around the earth due to the inhomogeneous magnetic field and the earth's rotation. The detailed understanding of the particles' motion was made extremely simple by application of the ideas of adiabatic invariance, which were dramatically confirmed by the Argus experiment in which an atomic bomb was exploded above the atmosphere and an artificial belt appeared whose development could be followed with the passage of time.

In the early 1960's, satellites found that the sun continually emits a plasma at a high velocity—the solar wind:

SIMULATION OF THE SOLAR WIND interacting with the earth's magnetic field. This picture was made at the NASA Lewis Research Center, Cleveland, Ohio, in a 4.6×20-meter vacuum chamber with a magnetoplasmadynamic thruster (right) standing in for the sun. Thrustors such as this one being studied at Lewis have produced exhaust velocities of nearly 48 km/sec. Radiation belts are to scale.

This emission had been predicted earlier from the theories of equilibrium of the sun's corona to explain the origin of comet tails. Since the solar wind is highly conducting, it can not penetrate the earth's field and has to flow around it, creating the geomagnetic cavity or magnetosphere where we find the Van Allen radiation belts. The boundary of this cavity was determined in detail in 1961 and its shape and position in the solar direction was found to satisfy a simple theory based on a balance of the solar wind pressure by magnetic pressure. The Imp I satellite found in 1965 that the cavity formed a cylinder stretched many hundreds of earth radii away from the earth (in the antisolar direction), forming a magnetic tail. In this tail the field is parallel to the cylinder, taking one direction in the northern half and another in the southern half, with a neutral sheet in between; plasma instabilities in this sheet may be responsible for the violent aurora and magnetic storms. The origin of the magnetic tail is still uncertain.

The solar wind is essentially collisionless, so it was a great triumph for plasma theory when Imp I (in 1964) found a stand-off shock in front of the earth. This was the first established observation of a collisionless shock. Further collisionless shocks in the solar wind have been observed by the Mariner probes, sent to Venus in 1962. These shocks are presumably blast waves arising from strong perturbations of the solar wind by flares on the surface of the sun.

The solar wind contains a weak magnetic field that originates in lines of force radiating from the photosphere. Because of solar rotation they are expected to be carried into Archimedean spirals by the radial motion of the solar wind. Measurement of the predicted angle of the field at the earth (≈ 45 deg to the earth–sun line) confirmed the idea that flux lines are carried by conducting fluid. This was further substantiated by a correlation of the polarity of the field with areas of the photosphere of corresponding polarity.

In 1963 the Alouette satellite first observed the electrostatic modes perpendicular to $\mathbf{B}$, in the ionosphere, by excitation with a burst of rf and observation of ringing at the predicted frequencies. Radar experiments at Arecibo show collective effects in the backscattering of microwaves from the ionosphere. In these observations, the main spread is due to ion doppler frequencies in agreement with plasma kinetic theory, rather than electron doppler frequencies. The scattering from plasma-frequency oscillations excited by photoelectrons has also been detected and agrees with theory.

If the next 20 years are as fruitful as the past 20, we may look forward to a highly developed understanding of the plasma state—by far the dominant state of matter in the universe.

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This article was written in consultation with Harold Furth, Russell M. Kulsrud and Marshall N. Rosenbluth. □