PLASMA DYNAMICS

XII. PLASMA DYNAMICS

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XII. PLASMA DYNAMICS

A. Confinement Systems

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Physics of High-Temperature Plasmas

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

B. Coppi

An understanding of the physics of high-temperature plasmas is of primary importance in the solution of the problem of controlled thermonuclear fusion. One of the goals in this field of research is the magnetic confinement and heating of plasmas with densities of the order of 10^{14} particles/cm^3 and thermal energies between 5 keV and 10 keV. The macroscopic transport properties (e.g., particle diffusion, thermal conductivity, and electrical resistivity) of plasmas in these regimes are weakly affected by two-body collisions between particles. These plasmas are significantly influenced by the types of collective modes such as density fluctuations caused by microinstabilities that can be excited in them.

We have carried out a theoretical and experimental program in this general area during 1973 and presented relevant contributions at national and international conferences. Several papers have been published in professional journals. Our primary focus has been the experimental effort developed around the Alcator machine. Our purpose has been to realize plasmas capable of sustaining very high current densities (up to 1400 A/cm^2) without becoming macroscopically unstable, in order to achieve the highest possible rate of resistive heating of the plasma itself. The plasma operation of Alcator, initiated in November 1972, continued through May 1973. Plasma currents of 50 kA and 40-ms current pulses were achieved. In this phase of our work we gained valuable knowledge of problems connected with obtaining the macroscopic equilibrium of a toroidal plasma column and in applying a variety of plasma diagnostic techniques. These include the electrical diagnostic system and the microwave interferometer developed by colleagues at the Euraton-FOM Association at Jutphaas, the data-retrieving system developed by R. J. Taylor which has significantly enhanced the rate of utilization of the Alcator machine and increased the number of experiments on Alcator, and the HCN laser interferometer system developed by P. Brossier and his collaborators for plasma density measurements in the range 10^{14} particles/cm^3. The density measurements performed on Alcator with the HCN microwave source were, in fact, the first of their kind on a toroidal plasma.

In June 1973, the Alcator machine was made available to the engineering staff so that they could perform high magnetic field tests of the air-core transformer system and of the toroidal magnet with full cryogenic cooling of the entire machine, and install an improved vacuum system. The tests were successfully completed in September 1973. Fields higher than 100 kG were reached in the air-core transformer central elements and approximately 98 kG on the geometrical axis of the toroidal magnet, which corresponds to approximately 140 kG on the inner edge of the same magnet.

In August 1973 a low-cost auxiliary toroidal machine, later called "Versator," began to take shape in the basement of the Francis Bitter National Magnet Laboratory, developed by R. Taylor and a team of students, who used a spare chamber and other spare components of Alcator. This machine began plasma operation in October 1973, and showed all the major characteristic macroscopic phenomena of Tokamak plasmas.

In September 1973, at the Euratom-CNEN Laboratory in Frascati, work started on an accurate Thomson-scattering experiment, to be installed on Alcator.

B. Laser-Plasma Interactions

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

National Science Foundation (Grant GK-37979X)

E. V. George, H. A. Haus, A. Bers

We are studying the interaction of intense laser pulses with "low-density" target plasmas (n_e in the range 10^{14}-10^{16} cm^{-3}). In detecting these interactions it is important to choose suitable diagnostic tools. During the last several years we have developed experimental techniques for obtaining both spatially and temporally resolved emission line shapes from plasmas; hence, we have concentrated our diagnostic efforts in this direction. Our present interest is focused on detecting the strength of the interaction (laser-plasma) by using what are called optical satellites. In particular, we are interested in the time-dependent Stark effect first proposed by Baranger and Moser.[1] The salient features of this method, which is applicable to quadratically Stark-broadened systems (as in a helium plasma), may be outlined briefly as follows.

A typical three-level atom is illustrated in Fig. XII-1. Transitions from levels A to B and B to C are allowed by dipole selection rules, while a transition from A to C is forbidden. The allowed line has a frequency ω_{BC} and the forbidden line a frequency ω_{AC}. Time-dependent perturbation theory predicts that an intense ac electric field will cause two predominant changes in the emission spectra of this three-level system.

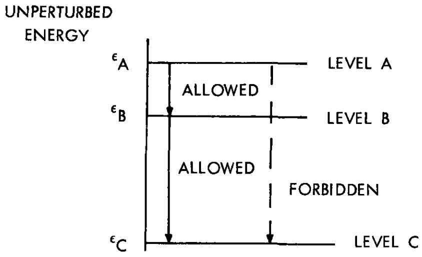

Fig. XII-1. Three-level atom model.

(i) The applied field (at frequency ω_ℓ) will cause a shift in the frequency of the allowed line.

(ii) The applied field will cause additional satellite lines at a frequency ω_s, where $\omega_s = \omega_{AC} \pm \omega_\ell$. Note that satellites may be induced by any oscillating field, including oscillations at ω_p (the plasma frequency).

The ratio of the intensities of the satellite lines to the allowed line is given by

$$S_\pm = \frac{E^2 e^2 a_o^2 R_{AB}}{6} \frac{1}{(\epsilon_A - \epsilon_B \pm \hbar\omega_\ell)^2},$$

where E is the electric field, a_o is the Bohr radius, ($a_o = \hbar^2/me^2$) is Planck's constant, R_{AB} is a numerical factor representing the dipole strength of transitions between levels A and B, and ϵ_A and ϵ_B represent the energy of levels A and B. Obviously, if levels could be found such that $\epsilon_A - \epsilon_B \approx \hbar\omega_\ell$, the satellite line would be greatly enhanced.

Notice the implications of these results. The presence of laser-induced plasma fluctuations at frequency ω_p can be detected by studying the so-called satellite lines, whose strength depends on the average plasma-field fluctuations, and the position of these lines yields the local electron density. We also feel that the shape of the satellite line when properly unfolded from its "natural" shape should yield the turbulent spectrum of the plasma fluctuations.

A prerequisite for using this technique is first, to ascertain the "natural" line shape of the satellite line(s) and second, to determine the effect on the emission spectra arising from the presence of a high-power CO_2 laser beam. Our work in this area has been successful and is nearly complete.

Before undertaking the various experiments described below, we decided that it was imperative to observe the satellites caused by the oscillating laser field $\omega_\ell = \omega_{CO_2}$ in a helium target plasma. From the results of this work we are developing the theoretical models to be used in detecting plasma satellites. The details of this experiment were reported in Quarterly Progress Report No. 110 (pp. 122-127). It suffices to say that we have observed the satellite line and the ac Stark-shifted allowed line, and that the agreement between theory and experiment is quite good.

We shall now discuss our proposed plasma experiments and the results that we have obtained thus far.

1. Optical Mixing in a Target Plasma

Both theoretical and experimental studies have been made of optical mixing in a target plasma. Kroll, Ron, and Rostoker[2] treated theoretically the coupling of two transverse electromagnetic waves to a longitudinal plasma oscillation (plasmon). More recently, Weyl[3] made calculations on optical mixing in a plasma. By using linearized theory it can be shown[3] that for the mixing of two laser transitions at ω_1 and ω_2 so that $\omega_1 - \omega_2 = \omega_p$ the density fluctuations at the plasma frequency are given by

$$\frac{n^{(2)}}{n_o} \sim 2\,\frac{v_{RF}}{v_{Th}}\,\frac{\omega_p}{\nu}\,f^2 \cos\theta,$$

where we have made use of the fact that $\omega_{\text{laser}} \gg \omega_p$ so that $\omega_1 \approx \omega_2$; θ is the angle between the incident wave vectors, $f \equiv k_pL_D < 1$ for weak Landau damping, and in this limit ν represents the collisional damping rate (either electron-atom or electron-ion collision frequency that dominates). Recently Stainsfield and his co-workers[4] have studied the optical mixing of two laser beams in a plasma jet, produced in a dual-cavity organic-dye laser, and pumped by a Q-switched ruby laser. By using a third laser beam, the presence of enhanced fluctuations is detected by scattering. With their experimental arrangement they could detect a fluctuation level of $\sim 2 \times 10^{-5}$.

There is some skepticism regarding strong absorption in these under-dense plasmas. For example, appreciable absorption is only possible if multiple scattering occurs, since only a fraction (ω_p/ω_1) of the photon energy is lost in a single scattering process. Therefore only those instabilities that produce small-angle forward scattering remain in resonance.[5] Also, these resonances could be destroyed by sufficiently strong density inhomogeneities.[6]

We have begun the experimental phase of this program and have constructed a low-density target plasma. A high repetition rate, multiline, CO_2 laser is under construction (developed under Joint Services Electronics Program sponsorship) and it should be operational in several months. We are also beginning construction of a slow-scan (~3 hours per free spectral range) Fabry-Perot interferometer. Such an instrument (developed by Professor T. Greytak and his students) is necessary to resolve adequately the spectral line shapes of the satellite lines.

2. Production of Plasmons by Stimulated Raman Scattering

The object of this work is to study with the use of lasers the enhancement (or supression) of plasma fluctuations.

Interest has developed in how to use lasers for plasma diagnostics. The great difficulty in using them is that the characteristic frequencies of laboratory plasmas are greatly different from those of lasers. Thus a nonlinear process must be considered as beating down the frequency of the laser to the frequency of the plasma. In most cases, the matrix elements for nonlinear processes are very small except under special circumstances.

The usual case considered is the mixing of two electromagnetic waves to produce a plasma oscillation at the difference frequency. This situation requires, however, two lasers of different frequencies that can be adjusted so that their difference frequency is near the plasma frequency. Also, in the plasma the beams must intersect at a proper angle so that the k-vector matching condition is satisfied. Taken together, this is a fairly restrictive set of conditions.

We are considering another type of nonlinear interaction of light with a plasma in which a less restrictive set of conditions must be satisfied. The interaction is a stimulated Raman process in which a photon from the laser beam is absorbed and a plasmon is emitted or absorbed by a neutral or partially ionized atom in the plasma. Since the atom mediates the interaction, it can absorb excess momentum so that a k-vector matching condition need not be satisfied. This interaction was suggested by Baranger and Mozer,[1] and work has been done on it by others.[6,7] An experiment has been performed by Burrell and Kunze[8] in which microwaves were used to create additional levels identical in nature to those that have been described earlier. These levels were then detected by using Raman-scattering technique with a tunable dye laser as the light source.[9]

The theory of the interaction is easily understood in terms of second-order time-dependent perturbation theory.[10]

We have completed the initial phase of our theoretical work and are now constructing the requisite dye laser system. A discharge tube (600 μm in diameter, 5 cm long) has been constructed and spectroscopic diagnostics has been developed for this study. We wish to acknowledge the important contribution with regard to the laser system given to us by Dr. M. Drake of Exxon Corporation, Everett, Mass.

3. Interactions with Solid Targets

During the past year we have initiated a theoretical analysis of the two-dimensional and three-dimensional evolution of unstable, nonlinear wave-wave interactions that are relevant to laser-pellet heating experiments.[11,12] With this work we hope to be able to explain the recently observed angular dependence of frequency mixing in the scattered light, and to design experiments for observing these phenomena in our laboratory.

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C. Symbolic Computation (MACSYMA) in Plasma Physics

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

National Science Foundation (Grants GK-28282X1 and GK-37979X)

A. Bers

During the past year we have achieved the first implementation of symbolic calculations by a computer system (MACSYMA) for studying nonlinear wave-wave interactions in a plasma. The nonlinear plasma model that we chose was multispecies hydrodynamic. The symbolic computation system has three major parts. The first part allows the calculation of linear wave characteristics from either a hydrodynamic or a Vlasov model. These characteristics include dispersion relations (giving propagation and damping), polarization characteristics, and energy density. The second part is a derivation of the nonlinear current in a plasma to second and third order in the electric field strength. In particular, the second-order current is derived and stored in a manner that allows each part of the final answer to be traced back to a particular nonlinear forcing term in the original equations of the plasma model. The third part contains various techniques for symbolic computation of the coupling coefficients and energy transfer rates of nonlinear wave-wave interactions.

The implementation of such symbolic computations on the MACSYMA system has been described in Quarterly Progress Reports No. 108 (pp. 167-185) and No. 110 (pp. 86-103) and in the Master's thesis of John L. Kulp.[1] The first major application of this system to an important nonlinear wave-coupling problem was carried out by C. F. F. Karney. He determined the parametric coupling of lower hybrid waves to ion-acoustic, ion-cyclotron, and magnetosonic waves at arbitrary angles to the magnetic field.[2,3] This will form the major part of his Master's thesis research. The complete theory of nonlinear wave interactions to third order has been formulated in a new fashion by D. C. Watson.[4] He has shown that to this order one can obtain in unified fashion all of the parametric interactions (which are second-order), the modified parametric interactions, and the so-called nonoscillatory interactions. This theory also contains formulations describing interacting wave packets, pump depletion, and higher order pump effects. This work will form the major part of his doctoral thesis research.

We have presented our work at several scientific conferences on plasma physics.[5-10] Recently, we joined the MACSYMA staff of Project MAC to hold at M.I.T. a Workshop on Symbolic Computation in Plasma Physics (October 29 and 30, 1973). Twenty-five research workers in plasmas from different parts of the country attended this workshop to become acquainted with the capabilities of the MACSYMA system for plasma physics problems.

During 1974 we plan to turn our attention to symbolic computations of nonlinear problems in weak turbulence. Our first aim is to implement on MACSYMA the symbolic computations associated with quasi-linear diffusion, resonance broadening, mode-mode coupling, and nonlinear Landau damping. In particular, we shall seek an implementation of those nonlinear calculations that will allow us to study the time-space evolution of weakly unstable plasma modes. This should allow us eventually to obtain a description of the transport properties of weakly turbulent plasmas.

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D. Intense Relativistic Beam-Plasma Interactions

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

National Science Foundation (Grants GK-28282X1 and GK-37979X)

G. Bekefi, A. Bers, J. E. McCune

This program involves experimental and theoretical studies of the interaction of intense relativistic electron beams with ambient plasmas. Our purpose is to understand the major mechanisms by which the plasma is heated by the incident beam. In parallel with this work we have begun preliminary investigations into generating intense fluxes of ion beams.

Our experimental program involves the study of intense relativistic electron beams interacting with ambient plasmas. The electron accelerator (COGEN III) generates reproducible solid and annular beams with an energy of approximately 250 kV and currents from 50 kA to 75 kA. A 2-3 kG axial magnetic field is used in guiding the beam to the interaction region. Injection of the beam into a mirror or a cusp magnetic field is available to us as an optional feature. The cusped field induces a rotation in the electron beam, an effect that would be expected to enhance the beam-plasma interaction. In the initial experiments, the ambient plasma will be generated by the relativistic beam itself. This occurs as a result of the ionization of the neutral gas into which the beam is being fired. To permit more controlled experiments, however, we have also constructed an independent plasma source of variable charged-particle density. It is a high-power CO_2 laser whose radiation is focused onto a solid target such as graphite. The plasma plume expands in vacuum away from the target surface and is partially confined by a mirror magnetic field. A detailed diagnosis of the plasma has already been carried out and the results have been reported at the American Physical Society, Division of Plasma Physics, Meeting, Philadelphia, October 31-November 3, 1973.[1]

Our main objective during the coming year is to study the energy deposition from the electron beam into a plasma confined in a mirror magnetic field as high as 30 kG. The plasma will be produced by the beam itself. The plasma energy will be diagnosed with diamagnetic loops, measurements of the x-ray Bremsstrahlung, and optical spectroscopy. The plasma heating will then be studied as a function of beam current, ambient gas pressure, and confining magnetic field.

We are also exploring the problem of producing intense fluxes of ion beams, using our Cogen III facility. Preliminary measurements show some promise. Suitable diodes, in which we shall attempt to suppress the electron current, are being constructed and will be tried out soon.

Our theoretical work during the past year was concerned with studying the evolution of the two-stream instability in the presence of plasma density gradients along the beam flow direction. We have completed such an analysis for the case of a cold beam and cold plasma model. The results of our analysis, together with computer experiments, show the following.

(a) In the presence of a plasma density gradient in the direction of beam flow the beam-plasma interaction is convectively unstable and the entire unstable pulse propagates essentially with the beam velocity.

(b) The nonlinear regime along the beam path is reached where the oscillating beam current density amplitude equals the dc beam current density.

(c) This, coupled with the results of steady-state noise amplification, in the presence of the plasma density gradient, can be used to estimate the constraints among plasma length and beam-plasma parameters that need to be satisfied for transferring energy from the beam to the plasma.

These results have been presented recently at the American Physical Society, Division of Plasma Physics, Meeting in Philadelphia,[2] and are being prepared for publication.

In the coming year we plan to complete the theoretical description of the two-stream instability in the presence of longitudinal plasma density gradients, including the effects of beam temperature and finite transverse beam dimensions.

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E. Fusion Technology Studies

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

P. A. Politzer, L. M. Lidsky

We shall continue to expand our work on the technological problems associated with the design and eventual construction of a controlled thermonuclear reactor. Our goals are to evaluate the engineering requirements for a fusion reactor, to assess the possible applications of this power source in our society, and to produce the engineering data required for the design of a reactor. We have in progress at present a study of the possibilities inherent in fission-fusion symbiosis. This concept envisions the use of fusion-generated neutrons for the production of fissionable fuels, as well as in the transmutation of radioactive waste products. Also in progress is an experimental study simulating the cyclic stresses that are expected in the first wall of a theta-pinch reactor. This program will determine the fatigue stress limits and fracture mechanisms for niobium and other first-wall candidate materials. We are also considering problems inherent in development of an intense 14-MeV neutron source which is needed for the testing of possible reactor materials in a high-flux neutron environment.

XII. PLASMA DYNAMICS

F. Experimental Studies – Waves, Turbulence, and Radiation

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Plasma Diagnostics

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

G. Bekefi

Our present objectives are focused on the use of optical and ultraviolet spectroscopy in the diagnosis of hot dense plasmas. In addition to the more mundane determination of plasma density and temperature, we are also very much interested in the study of turbulent plasmas. The shape and width of a Stark-broadened optical line is determined by the probability distribution of the electric microfield acting on the radiating atom. In a very turbulent plasma this microfield can be governed by collective oscillations that cause a change in the spectral line shape. Theoretical calculations have been carried out showing that the change in line shape is quite sensitive to the strength of the turbulence.

Experiments at optical and ultraviolet wavelength ranges have begun on M.I.T.'s small toroidal device (VERSATOR). These will continue during the coming year.

2. Scattering of 10.6 μm Radiation

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

L. M. Lidsky

An experiment is in progress to resolve and measure the "ion" portion of the spectrum of radiation scattered from a plasma. In a quiescent plasma this measurement permits determination of the temperature of the ions, and in a turbulent system it yields the spectral characteristics of the low-frequency waves. An extremely stable 10.6 μm CO_2 laser oscillator and amplifier system has been constructed for this experiment.

3. Linear Quadrupole Experiment (SLIM)

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

P. A. Politzer

Our experimental work on the stability and propagation characteristics of low-frequency waves in a two-dimensional magnetic field geometry continues. We have obtained significant results on trapped ion-driven drift wave instabilities and the theoretical effort on this problem is going forward. Experiments are also in progress to study the behavior of instabilities in the neighborhood of the neutral line, to investigate possible mechanisms for ion heating in an inhomogeneous magnetic geometry, and to determine the characteristics of echo pulses resulting from perturbations applied to the trapped electron population.

4. Wave Conversion near Lower Hybrid Resonance

National Science Foundation (Grant GK-37979X)

R. R. Parker

We plan to continue our study of wave interactions near the lower hybrid frequency. Work in progress has as its focus the study of the conversion of the cold-plasma Gould-Trivelpiece mode into a warm-plasma ion wave. This is being done by numerical solutions of the plasma fluid equations, linearized about a self-consistent nonuniform equilibrium. Identification of the modes involved is aided by solutions to the local dispersion relation. The primary goal of this work is to study the mechanism by which plasma heating takes place through linear mode conversion. A secondary goal will be to determine the structure of resonance cones in the presence of mode conversion. Additionally, the optimum experimental configuration in which to observe the (experimentally) elusive mode conversion effects will be defined.

5. Parametric Instabilities in Beam-Plasma Interaction

National Science Foundation (Grant GK-37979X)

R. R. Parker

We are continuing studies of parametrically induced instabilities generated by the linearly unstable interactions of beam-plasma systems. Following up our original discovery of a decay instability involving an ion-acoustic wave, we plan to investigate the role of such interactions on plasma heating and nonlinear stabilization of the beam-plasma instability. The experimental configuration will be improved by adopting a double-ended source which will reduce density gradients and, we hope, result in a more uniform interaction. Since the theoretical analysis thus far has dealt only with spatially periodic boundary conditions, a new direction for theoretical research will be an extension of the work to growth and decay in space. An additional goal of the theoretical work is to develop analytic criteria for the nonlinear stability of the multiwave system.

6. Nonlinear Saturation Experiments

National Science Foundation (Grant GK-37979X)

L. M. Lidsky

Nonlinear theory predicts that the growth rates and saturation levels of low-frequency plasma instabilities are affected by the presence of high-frequency turbulence. We are testing these predictions in our low-density fully ionized plasma column facility. In this column we can generate ion-acoustic and drift wave instabilities. We are measuring the effect of broadband ion-cyclotron frequency turbulence on the growth rates and saturation levels of these instabilities.

7. Trapped-Particle Experiment

National Science Foundation (Grant GK-37979X)

L. M. Lidsky

We are investigating the propagation characteristics and mode structure of trapped electron instabilities in our linear plasma facility. This facility has been modified by the installation of a periodic magnetic well in order to produce a trapped-electron population. On the basis of computer analysis of the linear theory we expect to observe electron waves localized in radial bands with frequencies near the bounce frequency.

8. Stabilized Mirror Experiment

National Science Foundation (Grant GK-37979X)

P. A. Politzer

The Ioffe bar stabilized magnetic mirror experiment has been reconstructed with the addition of a significantly higher magnetic mirror field capability. Using this system, we are beginning studies of the spatial and temporal development of the high-frequency velocity space instabilities which we expect to occur. We also intend to use our 337-μm HCN in conjunction with the fast-scanning Fabry-Perot interferometer that we have developed in order to obtain detailed information concerning the frequency and wave-number spectra of fluctuations in this plasma.

9. Wave-Particle Interaction

National Science Foundation (Grant GK-37979X)

P. A. Politzer

We are pursuing an experimental study of the effects of externally introduced electron-cyclotron frequency turbulence on a nonneutral counterstreaming electron-beam system. Since the apparatus allows precise determination of the time evolution of the electron distribution function, we shall be able to observe directly the nonlinear diffusion caused by the applied turbulent fields. We are also trying to determine the influence of turbulence on the growth and saturation of spontaneous instabilities in the electron-beam system.

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G. General Theory

RESEARCH OBJECTIVES AND SUMMARY OF RESEARCH

1. Collisional and Turbulent Transport in Toroidally Confined Plasmas

U.S. Atomic Energy Commission (Contract AT(11-1)-3070)

J. E. McCune, D. J. Sigmar

Our ongoing theoretical studies are concerned with two areas of research.

a. Neoclassical collisional diffusion provides a lower bound on cross-field transport in plasmas of the Tokamak type. While the theory for a simple electron-proton plasma has been worked out by Rosenbluth et al., the effects of impurity ions and neutral hydrogen (via charge exchange collisions) enhance the transport rates significantly and persist into the reactor regime.

b. This regime is characterized by the ordering collision frequency ≈ diamagnetic drift frequency and therefore requires a study of the collisional equilibrium distribution functions of all species in the banana regime, perturbed by drift- and trapped-particle mode turbulence caused by orbit diffusion.

2. Nonlinear and Turbulence Theory

National Science Foundation (Grant GK-37979X)

T. H. Dupree

The object of this research is to identify and develop analytic theories of strong turbulence effects such as clump and vortex formation. Effort is concentrated principally on those phenomena that are expected to play an important role in problems of practical interest, such as resistivity, heating, and transport across magnetic fields.