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# "ESTABLISHMENT OF AN INSTITUTE FOR FUSION STUDIES"

Technical Progress Report

November 1, 1994 - October 31, 1995



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# Technical Progress Report for the Grant DE-FG05-80ET53088 "Establishment of an Institute for Fusion Studies" for the period November 1, 1994 to October 31, 1995

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## OVERVIEW

The Institute for Fusion Studies is a national center for theoretical fusion plasma physics research. Its purposes are to (1) conduct research on theoretical questions concerning the achievement of controlled fusion energy by means of magnetic confinement—including both fundamental problems of long-range significance, as well as shorter-term issues; (2) serve as a national and international center for information exchange by hosting exchange visits, conferences, and workshops; and (3) train students and postdoctoral research personnel for the fusion energy program and plasma physics research areas.

The theoretical research results obtained by the Institute contribute to the progress of nuclear fusion research, whose goal is the development of fusion power as a basic energy source. Close collaborative relationships have been developed with other university and national laboratory fusion groups, both in the US and abroad. In addition to its primary focus on mainstream fusion physics, the Institute is also involved with broader range research in related fields, such as advanced computing techniques, nonlinear dynamics, space plasmas and astrophysics, statistical mechanics, fluid dynamics, and accelerator physics.

The diversity of the research performed at the Institute is reflected in the list of recent IFS publications, given in the third section of this report. Last year IFS scientists published 66 scientific articles in technical journals and monographs. Also, two major review papers were published: "Solitary Waves and Homoclinic Orbits," by N. J. Balmforth, Ann. Rev. Fluid Mech. **27**, 335 (1995); and "Hamiltonian Description of the Ideal Fluid," by P.J. Morrison, *Geophysical Fluid Dynamics,* R. Salmon and B. Ewing-Deremer, eds., Woods Hole Oceanographic Institution, Woods Hole, MA (1994), WHOI-94-12. One book was published: *Physics of High Energy*

*Particles in Toroidal Systems*, edited by T. Tajima and M. Okamoto (American Institute of Physics Press, New York), 362 pages.

The work of IFS scientists continued to receive national and international recognition. At the 1994 APS Division of Plasma Physics Meeting, an invited paper was presented by M. Kotschenreuther on "Detailed Comparisons of Nonlinear Gyrofluid ITG Simulations and Experiment." At the 15th IAEA International Conference on Plasma Physics and Controlled Nuclear Fusion Research (1994), IFS scientists presented three papers: R. Fitzpatrick, "Stabilization of External Kink Modes in Advanced Tokamaks"; B. Breizman, H. Berk, S. Mahajan, M. Pekker, J. Van Dam, V. Wong, S. Sharapov, M.S. Chu, R.R. Mett, M. Rosenbluth, and J. Candy, "Nonlinear Evolution of Unstable Alfvén Waves Interacting with Energetic Alpha Particles in Ignition Tokamak Plasmas"; and W. Dorland, W. Horton, M. Kotschenreuther, J.-Q. Dong, T. Tajima, M.J. Lebrun, M.A. Beer, R.E. Waltz, and R. Dominguez, "Comparisons of Nonlinear Toroidal Turbulence Simulations with Experiment"; and were co-authors on several other papers. At the 1995 International Sherwood Controlled Fusion Theory Conference, two invited papers were presented: "Resistive MHD Stability in Small Aspect Ratio Tokamaks" by A. Aydemir, and "Turbulence and Transport Simulations" by W. Dorland. Numerous other invited talks were also given during the past year at various conferences and workshops in the US and abroad.

The Institute actively sponsors collaborative research programs with laboratories and universities in the US and throughout the world. This past year, the IFS hosted 9 long-term visitors (i.e., one month or more) and 34 short-term visitors. A complete list of visitors is appended to this report. On behalf of the Department of Energy, the IFS also organizes the exchange activities of the US.-Japan Joint Institute for Fusion Theory and is their principal site in the United States. Last year this program sponsored two workshops in the US and two in Japan, four exchange scientist visits, and 12 joint computational projects. The IFS has also continued to be active in the US-Russian Federation exchange program.

A few specific examples may be cited of collaborations in which the IFS is involved. The Joint Program in Divertor Physics, which the IFS helped establish, organizes collaborations among scientists at IFS, MIT, and Culham on the theoretical physics of tokamak edge plasmas, and also, in general, disseminates information and stimulates research in this area. Several IFS scientists are working to develop and apply sophisticated computational codes for simulating tokamak behavior, as part of the "grand-challenge" Numerical Tokamak Project, a national collaborative effort among half a dozen research institutions, which is part of the federally-funded High Performance Computing and Communication Program. An IFS scientist spent the 1995 spring semester at the Institute of Theoretical Physics (UC Santa Barbara), collaborating with other visiting scientists on the fundamental theoretical description of plasma turbulence. Also, various IFS scientists have spent extended periods visiting General Atomics to study MHD stability problems; collaborated on-site at PPPL to analyze the resistive wall stability of the proposed TPX tokamak; visited JET and JAERI to work on alpha particle physics problems; and interacted with the ITER Joint Central Team in San Diego to investigate transport and confinement properties for the ITER design—to mention only a few such collaborations.

In addition to its research activities, the IFS has an important educational function. This past year 16 graduate students worked on fusion and plasma physics doctoral-degree thesis projects under the supervision of senior IFS scientists, several of whom also teach on the faculty of the Department of Physics. Six (6) of these students graduated with Ph.D. degrees last year. As part of its educational role, the Institute also has a postdoctoral training program, which involved four postdoctoral fellows last year.

IFS scientists are also active in various forms of service to the scientific community. A number of these may be listed: associate editor for *Reviews of Modern Physics*; vice-chair and chair-elect, APS Division of Plasma Physics; member of the ITER U.S. Home Team Steering Committee; chairman of the US Theory Coordinating Committee; chairman of the PPPL Theory Advisory Board; chairman of the MIT Plasma Fusion Center Theory Advisory Board; member of the DOE Strategic Planning Panel for Fusion Theory Program; co-organizer of the Joint Program in Divertor Physics; member of the Science Advisory Board for the La Jolla International School of Physics; member of the National Research Council, National Academy of Science; member of the US DOE Edge Physics Working Group; member of the Sherwood Conference Steering Committee; member of the TPX Program Advisory Committee; ITER liaison for the TTF Fast Particle Working Group; member of the ITER Expert Group on Energetic Particles, Heating, and Current Drive; member of the Steering Committee for the Numerical Tokamak Project. One IFS scientist serves part-time as the director of the plasma physics group at the International Centre for Theoretical Physics (Trieste, Italy), and another leads the charged particle many-body systems group at the new Advanced Science Research Center of the Japan Atomic Energy Research Institute. Also, one IFS scientist was the organizer for a conference at The University of Texas entitled, "The Future of Accelerator Physics: The Tamura Symposium", November 14-16, 1994. The IFS director was a co-author of "Strategic Plan for US Fusion Theory Program," a recent report commissioned by the US Department of Energy and also presented a talk before the Texas Atomic Energy Research Foundation, Washington, DC entitled "The US Fusion Program and Fundamental Physics".

In August of 1994, the IFS was reviewed by a DOE panel of experts, in connection with the proposal for its next five-year extension (FY 1996-2000). This panel gave a strong endorsement of the IFS achievements. At the same time, The University of Texas committed to continue its matching of DOE support.

## TECHNICAL PROGRESS AND RESULTS

During FY 1995, a number of significant scientific advances were achieved at the IFS, both in long-range fundamental problems as well as in near-term strategic issues, consistent with the Institute's mandate. Examples of these achievements include, for example, tokamak edge physics, analytical and computational studies of ion-temperature-gradient-driven turbulent transport, alpha-particle-excited toroidal Alfvén eigenmode nonlinear behavior, sophisticated simulations for the Numerical Tokamak Project, and a variety of non-tokamak and non-fusion basic plasma physics applications. Many of these projects were done in collaboration with scientists from other institutions. Research discoveries are briefly described in what follows.

### Tokamak fluid dynamics

The study of macroscopic instabilities is especially important for designing the next generation of tokamak devices, since control of these modes extends hope for improving tokamak performance. Guided by recent experimental results, IFS has made key contributions to recent advances in the understanding of advanced tokamak operation, sawteeth, resistive wall stabilization, sheared flow effects, and low aspect ratio behavior.

**Stabilization of the resistive shell mode**—Advanced tokamak scenarios (e.g., those proposed for TPX and, increasingly, ITER) only work if pressure-driven external kink modes can be stabilized by the presence of a close fitting conducting shell. Conventional theory says that this is impossible if the shell has finite resistivity, due to the existence of an instability known as the "resistive shell mode." This instability can possibly be suppressed by plasma rotation. A model was developed that elucidates the physics underlying the stabilization of the resistive shell mode. This allows the prediction of the level of plasma rotation and the optimum position for the shell required to stabilize the mode. In particular, it was found that extremely close fitting shells (e.g., as in ITER) are not effective for stabilizing the resistive shell mode. Somewhat paradoxically, this situation can be remedied by cutting holes in the shell.

**Control of shear flow profiles by external velocity perturbations**—Over the last few years a great deal of progress has been made in understanding the interaction of magnetic perturbations with high temperature plasmas. This work has been used to develop a theory which determines the maximum error field a tokamak plasma can be subjected to without deleterious effects. It is also possible to spin a tokamak plasma using rotating magnetic perturbations, and even to affect plasma turbulence. Recent DIII-D experiments have shown that externally applied helical magnetic perturbations can be used to control the plasma toroidal rotation profile, which has a significant effect on transport in VH-mode plasmas. Theoretically, it turns out that the basic equations which describe the interaction of a magnetic perturbation with a tokamak plasma are very similar to those which describe the interaction of a velocity perturbation with high Reynolds number shear flow. Thus, many of the ideas and results obtained in tokamak plasma physics are also applicable to hydrodynamics. A theory was developed that describes the response of a fluid to external velocity perturbations. Such perturbations can be used to probe the relationship between the equilibrium velocity profile and fluid turbulence in a controlled manner.

**Momentum injection via Alfvén waves**—Strong shear flow is advantageous in a tokamak plasma for two main reasons. Firstly, it decouples MHD modes with different poloidal mode numbers, and also decouples the plasma from any external structures such as a conducting shell or an error field, thereby contributing to the overall MHD stability of the plasma. Secondly, it suppresses plasma turbulence, thereby improving the energy confinement. Present-day tokamaks achieve strong shear flow by means of unbalanced neutral beam injection. Unfortunately, this scheme is not reactor relevant. It is possible to spin the plasma with the use of slowly rotating magnetic perturbations. However, this scheme is intrinsically hazardous because of the danger of driving magnetic reconnection inside the plasma and thereby ruining the confinement. It is also possible to spin the plasma by injecting phased Alfvén waves, without any danger of driving magnetic reconnection. A theory of this type of momentum injection has been developed.

**MHD stability in small aspect ratio tokamaks**—Initial experimental results for tight aspect ratio tokamaks (or spherical tori) have indicated the possibility of quiescent operation at high beta. Here, the nonlinear MHD code CTD is used to generate equilibria of arbitrary aspect ratio and cross section, including self-consistent toroidal equilibrium flows (if desired), which are then checked for linear and nonlinear stability against ideal and resistive modes. Whereas earlier theoretical studies had considered external kink and ballooning modes, the present work has focused on the $n=1$ internal kink mode, expected to be unstable in some of the high current, low-q operating scenarios. At low beta, decreasing the aspect ratio is found to be highly stabilizing for the resistive $n=1$ mode, although these gains are nearly erased when the elongation increases, as naturally occurs in small aspect ratio devices. Triangularity has a weaker effect. Nonlinear studies are now underway.

**Stability of the m=1 "top"**—Experimental beta limits are accurately predicted by ideal MHD theory when the safety factor exceeds unity. However, high-beta discharges in DIII-D and TFTR generally violate the ideal $m=1$ internal kink stability criterion when $q < 1$. The effect of plasma rotation on the ideal stability of the $m=1$ mode was evaluated. In the presence, the Coriolis force component has a stabilizing effect on the mode, analogous to that found in a spinning Lagrange top. It was found that the mode can be stabilized by toroidal rotation velocities in the sonic range.

**Helical temperature perturbations associated with tearing modes**—The conventional picture of electron temperature perturbations associated with tearing modes is that they are flattened inside the separatrix due to finite parallel thermal conductivity and stagnation of magnetic field lines in the vicinity of the rational surface. This picture becomes invalid when the magnetic island width is smaller than a critical value. It was found that there is no temperature flattening in this case, and that such islands are not destabilized by the perturbed bootstrap current. This theory may explain experimental results concerning error-field-induced magnetic reconnection. The critical island width is estimated to be fairly substantial in typical tokamak plasmas.

**Onset of the sawtooth crash**—The nonlinear evolution of the magnetic island at the q=1 surface plays a key role in determining the onset conditions for the sawtooth crash. Two island widths are identified. Below the first critical width, the perturbed Pfirsch-Schlüter current stabilizes the tearing mode. Above the second critical width, the current-diffusion region collapses and the island coagulates due to the self-attraction of the current. The parameter variation of both critical widths was derived.

## Edge physics

The study of edge plasma physics is an area of much attention, with particular relevance to L- to H-mode confinement transitions, divertor design for ITER and TPX, and other urgent topics.

**Orbits and transport in the scrape-off region of a divertor tokamak**—It was discovered that the mobility coefficient, which vanishes by momentum conservation in the tokamak core, has appreciable magnitude in the edge region due to charge exchange. This new interaction between particle motion and the radial electric field has been studied in detail.

**Consistent kinetic theory in the edge region**—Conventional transport orderings employed in the core of a tokamak plasma allow large divergence-free flows in flux surfaces, but only weak radially diffusive flows. However, alternate orderings are required in the edge region where radial diffusion must balance the rapid loss due to free-streaming to divertor plates or limiters. Kinetic equations commonly used to study the plasma core do not allow such a balance and are, therefore, inapplicable in the plasma edge. Similarly, core transport formulae cannot be extended to the edge region without major, qualitative alteration. A novel kinetic equation was solved in order to construct distinctive transport laws for the plasma edge. In particular, a surprising form was found for parallel transport in the scrape-off layer, in which the parallel flow of particles, heat and viscous stress are driven by a combination of the conventional parallel density and temperature gradients, as well as new terms involving second-order radial derivatives. The new terms are not relatively small, and thus could affect understanding of limiter and divertor operation. For simplicity, radial diffusion resulting from classical Coulomb collisions is assumed; however, the most striking features of these results would persist even if classical transport were replaced by some anomalous or turbulent diffusion process.

**MARFES in tokamak edge plasma**—A simplified two-dimensional nonlinear fluid model was developed to explain the basic mechanism of the formation of multifaceted asymmetric radiation from the edge of tokamak plasmas (MARFE). In the framework of a mixed Eulerian-Lagrangian description, the problem was reduced to a reaction-diffusion type of equation with nonlocality, which obeys the constraints of length constancy and mass conservation along the magnetic field. With sufficient radiative cooling, this model predicts formation of MARFE-like plasma condensations from a variety of initial conditions.

## Turbulence and transport

Understanding the physical processes that control particle, momentum, and energy transport in thermonuclear plasmas is of fundamental scientific interest and practical importance. Presently unresolved confinement physics issues are critically relevant to the ITER design and thus to any fusion power plant. A principal goal of IFS research is to obtain a sound understanding of the varied and competing transport mechanisms, and to produce reliable predictions for transport in specific geometry and plasma parameter regimes. In this effort, new algorithms and modeling tools for large-scale, self-consistent kinetic simulations have been developed by IFS scientists.

**Simulation-based models for anomalous transport**—IFS work, in collaboration with PPPL, has showed that first-principles simulation models are able to quantitatively describe thermal transport in the core region of TFTR L-mode plasmas. Recently, more stringent experimental tests of this model were performed, the theory was extended to be capable of describing thermal transport all the way to the plasma edge, and comparisons were made with nonlinear gyrokinetic simulations. Specific results include the following: A long-wavelength mode was identified that is likely responsible for anomalous thermal conduction near the edge in TFTR L-modes. The role of the carbon-based ITG mode in core supershot confinement was clarified. Simulations of $\rho^*$ scans in TFTR and DIII-D were performed. Off-axis heating experiments in TFTR and DIII-D were simulated. More than 70 TFTR L-mode discharges have been successfully simulated, yielding good agreement with gyrofluid/gyrokinetic interpolation predictions.

**Extrapolated performance of fusion reactors**—Estimates of the performance of future tokamak fusion reactors have usually been based on empirical extrapolations, without insight into the underlying physics and how it may differ for various reactors. In this work, recently developed first-principles calculations of the thermal transport from ion-temperature-gradient turbulence were applied to predict the confinement in proposed devices such as ITER. An upper bound on L-mode performance can be obtained, from which a lower bound on the confinement enhancement (the H factor) needed for ignition is calculated. A quantitative assessment can be obtained of the heating power required for velocity shear stabilization of ITG modes.

**Inertial-range scaling laws for two- and three-dimensional turbulence**—A correction was derived for Kraichnan's logarithmically corrected two-dimensional enstrophy-range law that removes the divergence at the injection wave number. A related modification was found for Kolmogorov's well-known energy cascade law in the energy inertial range . A linear frequency term, like the drift-wave term in the Hasegawa-Mima equation, was also incorporated. The significance of these new corrections has been illustrated with steady-state energy spectra from high-resolution numerical computations of closure for a test-field model.

**Spectral reduction method for turbulence simulations**—A new technique, based on statistical closures, is being developed for turbulence simulations, which can dramatically reduce the number of Fourier modes required for direct numerical simulation of two-dimensional turbulence. Such a tool could be used to assess the effect of various dissipation mechanisms in large-eddy simulations.

**Neoclassical turbulent transport**—Due to the need to determine the fluctuation-driven components of velocity shear in toroidal geometry, a new neoclassical kinetic theory transport calculation was completed that takes into account the role of electrostatic drift wave fluctuations. The new transport formulas, while complicated, are shown to satisfy the Onsager symmetries. The transport reduces to collisional transport for a sufficiently low level of fluctuations, first in the parallel transport formulas and then in the cross-field transport formulas.

**Pressure-gradient-driven shear flow**—Microscopic turbulence theories are extended to show the detailed mechanism by which ion pressure-gradient-driven turbulence can drive sheared mass flows. New multiple-state confinement models were derived and investigated in detail for the dynamics of the transitions between states with different transport properties. The model provides an explanation for the L-mode, H-mode, and ELMy confinement states observed in tokamaks.

**Ion temperature gradient driven turbulence**—Theoretical studies of the mode coupling show how turbulent energy is transported from the short wavelengths to large scales where ion-transit effects absorb most of the fluctuation energy. The model predicts a new mixing-length formula which enables the profiles of diffusivity to be brought into closer correlation with the power balance diffusivities. The new formulas are currently being evaluated by the JET transport analysis group. Also, modes due to impurities and turbulence driven by combined impurity gradient and ion temperature gradient were investigated extensively. The isotope effect and the difference in confinement properties that occur with mixtures of low-Z impurities, especially carbon and oxygen, were determined with a complete kinetic-toroidal stability analysis.

**Advanced particle simulations of microturbulence**—A new kinetic particle-in-cell code, the Generalized Tokamak Simulator, is being developed, which provides an environment for kinetic plasma simulation of drift wave turbulence and other physics models relevant to the Numerical Tokamak Project. This code is being extended for capability of parallel execution on local area multicomputers or massively parallel computers. At the same time, a parallel gyrokinetic field solver is being constructed for use with the GTS, in order to study plasma confinement and instabilities in a general toroidal metric.

**Plasma transport barriers**—An off-diagonal term in the transport matrix that is due to shear in the toroidal flow velocity and which can give energy inflow has been analyzed in addition to the usual outflow diffusion terms that depend on the ion temperature gradient. The new term can be an explanation of the barrier for ion thermal energy transport observed in record high-temperature experiments in JT-60U.

**Generalization of self-organized critical gradient model**—An L-mode transport model based on a critical gradient model of the ion temperature gradient mode was generalized to include both toroidal and poloidal shear flows. The dynamical equations for the state variables yield the L- to H-mode transition, the critical momentum input power, and the L-H transport ratio. The theory is compared with simulation results from a toroidal particle code.

**Electron energy transport due to electron plasma waves**—In a magnetized plasma, all electrons with parallel velocities above the thermal speed emit plasma waves with frequency close to the electron plasma frequency. With the use of results obtained for the wake of such an electron and a Fokker-Planck operator for the emission and absorption of such waves, the energy loss has been calculated for realistic tokamak conditions. Large enhancements are found to be caused by magnetic shear, magnetic field curvature, and the enlarged non-Maxwellian tail due to the current. This theory may offer a simple explanation for profile consistency and the inward electron heat flow with off-axis heating.

## Alpha particle physics

The physics of alpha particles, especially their collective interaction with Alfvén waves in burning plasmas, has assumed importance in connection with the deuterium-tritium experiments being performed currently on the TFTR tokamak and with the design effort for the ITER device. IFS work in this area is being carried out with various inter-institutional collaborations, as well as through the TTF Fast Particle Working Group.

**Core-localized toroidal Alfvén eigenmodes**—The inclusion of additional finite aspect ratio effects was shown to lead to the existence of a new ideal TAE mode, localized in the low-shear, core region of the plasma. Since fusion-product alpha particles tend to be concentrated in the same region and since this mode has negligible radiation damping, it could be a candidate in the search for TAE instability in the TFTR deuterium-tritium campaign. As values for the shear, pressure gradient, and aspect ratio parameters vary, it is shown how this mode can convert to a kinetic TAE mode. Numerical results from a two-dimensional eigenvalue code for realistic tokamak equilibrium profiles confirm these predictions.

**Simulations of nonlinear alpha particle-TAE wave dynamics**—A numerical code for simulating the self-consistent dynamics of energetic alpha particles, which had been previously tested in simulations of the bump-on-tail instability model, has been applied to study a multiple set of unstable discrete shear-Alfvén TAE modes in a tokamak. The code has a Hamiltonian structure for the mode-particle coupling, with wave damping, particle source, and classical relaxation processes superimposed. Transition is observed from single-mode nonlinear saturation, to mode overlap and global quasilinear diffusion. The average level of the nonlinear wave energy pulsations is found to scale with the drive in agreement with analytical predictions. The effect of global diffusion on the loss of energetic particles has been demonstrated, including the experimentally observed bursts in the outgoing particle flux.

**Extended quasilinear model of energetic particle-Alfvén wave interaction**—The usual formulation of quasilinear theory does not describe a triggering effect of the mode amplitude for the onset of global diffusion. A model that takes this effect into account has been developed. This is critical to determine whether mode overlap conditions during the nonlinear fast particle interaction with Alfvén waves are fulfilled. It is shown that, when parameters are varied, both steady-state and pulsating nonlinear behavior can be predicted, along with local and also global diffusion. These results will be compared with experimental data.

**Mode overlap resonance for TAE growth rates**—The condition for resonant interaction of energetic alpha particles with toroidal Alfvén eigenmodes defines a resonance surface in particle phase space. The width of the resonant region is proportional to the growth of the unstable mode. The rate of energy transfer from passing and trapped particles to the TAE modes and the corresponding mode growth rates were calculated and then used to map out the resonance lines. This allows an assessment of whether the instabilities have growth rates large enough to cause mode overlap and, consequently, global particle diffusion.

## Basic plasma physics

Basic plasma physics is a broad category that includes fundamental discoveries as well as numerical techniques for describing plasma experiments. Particular emphasis of the research listed below concerns the application and development of methods in nonlinear Hamiltonian dynamics.

**Thermodynamic aspects of fluid dynamics**—A thermodynamic formalism was developed that allows reversible and irreversible transfer of kinetic, internal, and magnetic energies. The equations are written in manifestly covariant form, which leads naturally to a covariant statement of Onsager symmetry, so that it can be represented with different choices of variables. This is desirable since dynamical variables need not possess symmetry under time translation.

**Noncanonical Hamiltonian perturbation theory**—Whereas in canonical perturbation theory the nonlinear corrections to linearization about an equilibrium arise only from the Hamiltonian of the system, in a noncanonical Lie-Poisson system the Poisson bracket (cosymplectic form) also contributes to the nonlinearity. A perturbation formalism was developed for noncanonical Hamiltonian systems, in particular for the prototype rigid-body model. This captures the primary features of Eulerian theories of matter, such as plasma physics (i.e., Vlasov-Poisson equation and MHD) and also inviscid fluid dynamics.

**Nonlinear stability criteria for noncanonical Hamiltonian dynamics**—The energy-Casimir method is applied to the problem of symmetric stability in the context of a compressible, hydrostatic planetary atmosphere with a general equation of state. Stability criteria for symmetric disturbances to a zonally symmetric baroclinic flow are obtained. Also, finite amplitude stability conditions are obtained that provide an upper bound on a certain positive-definite measure of disturbance amplitude.

**Numerical studies of nonneutral plasmas**—Computational techniques based on low-noise particle-in-cell algorithms were used to study the linear and nonlinear evolution of pure electron plasmas in cylindrical and toroidal geometries. Linearly unstable diocotron modes in non-monotonic density profiles and the vortices nonlinearly generated by them were examined by following either the full particle orbits or only the guiding center drifts, in a finite-temperature electron plasma.

**Relabeling symmetry and Ertel's theorem**—Ertel's theorem in hydrodynamics was shown to be a generalized Bianchi identity by deriving it from a symmetry of the fluid Lagrangian. The particular symmetry is a transformation that relabels the Lagrangian fluid elements while leaving the fluid Lagrangian invariant. This approach was also extended to the case of MHD.

**Diagonalization and canonization of the linearized Maxwell-Vlasov system**—After linearization, the usual moment approach was used to separate out the longitudinal and transverse motion in the Maxwell-Vlasov system of equations. A noncanonical bracket and Hamiltonian (essentially the Kruskal-Oberman energy) are derived, and it is shown that both of them can be brought into diagonal form. Such diagonalization is essentially a transformation to linear action-angle variables for this infinite-dimension Hamiltonian system.

**Lyapunov exponents in nonequilibrium statistical mechanical systems**—A theoretical formalism was developed for using Lyapunov exponents as a window on the microscopic state of a fluid far from equilibrium where traditional thermodynamic quantities such as temperature and pressure cease to be meaningful. The Lyapunov exponent measures the sensitivity of the evolution of a chaotic system to small variations in starting conditions (the so-called "butterfly effect" in chaos theory). Two achievements have been: to define an instantaneous Lyapunov microscopic exponent and show that it mirrors macroscopic changes in the system; and to construct a complete theoretical connection between the Lyapunov exponent of a dilute gas near equilibrium and its response functions and transport coefficients. A major success of this latter theory was the prediction that quantities such as the diffusion constant are proportional to the cube of the Lyapunov exponent. This prediction was decisively verified in simulations of a one-component plasma performed at the Institute for Laser Engineering (Osaka).

## Advanced ideas and interdisciplinary research

**Tokamak disruptions predicted by neural net**—The technique of neural net was applied to predict minor and major disruptions in TEXT tokamak discharges. Under the assumption that the tokamak can be modeled as a low-dimensionality dynamic system, past values of the magnetic fluctuation signal as measured by a mirror coil were used to predict future values of the fluctuating signal. The time step employed corresponds intrinsically to the experimental data sampling rate. The feed-forward neural net code was constructed with one hidden layer, and it was trained through the back-propagation algorithm with inertial terms.

**Singular eigenfunctions for shear flow in fluid dynamics**—General methods related to Van Kampen's treatment of the oscillations in a homogeneous plasma were applied to study the continuous eigenvalue spectra of perturbations for the case of sheared, plane parallel flow in an ideal fluid.

**Laser wakefield excitation**—One- and two-dimensional numerical simulations were performed to study the wakefield microstructure generated ponderomotively by a tunnel-ionized plasma produced by ultrafast, ultra-intense sub-100 femtosecond pulses from a table-top terrawatt laser system. Comparison with experimental results shows accurate prediction of the frequency shifts for photon acceleration in the low density regime. Also, methods to enhance pulse modulation with forward Raman scattering and to decrease the time required for self-modulation to occur were investigated. Simulations permit a comparison of these techniques for effectiveness of modulation and quality of wakefield production.

**Beat wave cooling**—Non-Hamiltonian manipulation of the internal structure of the phase space of charged particle beams can result in much faster cooling than the conventional method of stochastic cooling. It was found that the longitudinal emittance reduction can be accomplished by the ponderomotive force of the beat between the undulator and the laser adjusted appropriately in its broadband spectrum through feedback at each turn.

**Electron-neutrino phase separation instability**—Based on Weinberg-Salam electroweak theory, a Boltzmann equation and subsequent fluid equations were derived for the primordial electron-positron-neutrino-photon plasma. A collective instability that separates the phases of electrons and positrons, and neutrinos and anti-neutrinos, was analyzed.

**Global dynamics of magnetic flux tubes in the sun**—The global structure of solar X-ray corona as observed by Yohkoh and other satellites may be interpreted as an indication that large-scale magnetic flux tubes in solar active regions are in fact those that have emerged from deep in the convective zone. Three-dimensional simulations were carried out of the evolution of the flux tube in an elastic approximation in gravitationally stratified plasma. It was found that the flux tube becomes unstable against kink instability and forms a coil structure. The upper portion of the coil rises due to buoyancy and forms a characteristic pattern of kinked series of active regions.

**Relativistic magnetized plasma equilibria**—Equilibrium configurations were computed for a magnetized plasma in a general relativistic spacetime, which can represent possible configurations of a black hole atmosphere. The equilibria are governed by a generalized Grad-Shafranov equation. Two spacetimes were considered: the Schwarzschild metric, representing a static black hole, and the Kerr metric, representing a rigidly rotating black hole.

**Parallel computation for Monte-Carlo simulation code**—The parallelization algorithm can be applied to the Monte-Carlo simulation code, since the movement of particles is independent in this code. A parallel computation code for Monte-Carlo simulations used to study plasma dynamics and transport processes in toroidal geometry was developed on a parallel computer. Numerical results show that the parallel computational efficiency is very high for this code.

**An exactly conservative integrator for nonlinear dynamical systems**—Traditional numerical discretizations of conservative systems generically yield an artificial secular drift of any nonlinear invariants. These algorithms are based on polynomial functions of the time step. A new class of nontraditional algorithms has been developed that exactly conserve the nonlinear invariants to all orders in the time step.

**Nonlinear integration algorithms with exact linear evolution**—A new algorithm, based on a variable integrating factor, was developed for integrating dynamics when both a linear and nonlinear time scale are involved. If a dynamically-adjusted variable time step is used, the scheme can speed up realistic forced-dissipative turbulence computations by many orders of magnitude. It is particularly advantageous in the dissipation range, where the linear time scale is short compared to the nonlinear time.

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# IFS VISITORS - 1994-95

| Name | Institution | Dates of Visit |
|---|---|---|
| BERNSTEIN, Ira | Yale University | August 30-31, 1994 |
| BICKERTON, Roy | JET, United Kingdom | April 14-21, 1995 |
| BOOZER, David | University of Virginia | June 25-Aug. 25, 1995 |
| CANDY, Jeff | Univ. of California, San Diego | November 14-18, 1994<br>May 4-11, 1995 |
| CATTO, Peter | MIT Plasma Fusion Center | October 17-22, 1994<br>May 1-5, 1995 |
| CHOI, Duk-In | K.A.I.S.T. — Korea | November 12-19, 1994 |
| CRANDALL, David | U.S. Department of Energy | October 26-27, 1994 |
| DEBENHAM, Phil | U.S. Department of Energy | April 28, 1995 |
| DONG, Jiaqi | Southwest Inst. of Physics—China | March 6-April 8, 1995 |
| DURFEE, C. | University of Maryland | April 24, 1995 |
| FITZPATRICK, Joseph | Lawrence Berkeley Lab | October 10-14, 1994<br>January-August, 1995 |
| FUKUDA, Takeshi | JAERI — Japan | November 14-15, 1994 |
| HIRAMOTO, Kazuo | Hitachi, Japan | April 26-29, 1995 |
| ICHIGUCHI, Katsuji | NIFS, Nagoya — Japan | March 2-9, 1995 |
| ICHIMARU, Setsuo | University of Tokyo — Japan | September 18-23, 1994<br>April 17-18, 1995 |
| ILGISONIS, Victor | Kurchatov IAE, Moscow | November 11-19, 1994 |
| KIM, J.Y. | Kyoto University — Japan | September 12-13, 1994 |
| KISHIMOTO, Y. | JAERI — Japan | November 17-18, 1994 |
| KOGA, James | JAERI — Japan | November 17-18, 1994 |
| KONDOH, Yoshiomi | Gunma University — Japan | July 26-October 25, 1994 |
| LACKMAN, Jon | Amherst College | June 25-Aug. 25, 1995 |
| MATSUMOTO, Ryoji | Chiba University — Japan | Sept. 1-October 1, 1994 |
| MCGUIRE, Kevin | Princeton Plasma Physics Lab | November 16, 1994 |
| MEACHAM, Steve | Florida State University | March 29-April 2, 1995 |
| MEERSON, Baruch | Hebrew University — Israel | February 7-28, 1995 |
| MOUROU, Gerard | University of Michigan | January 18-19, 1995 |
| NEBEL, Rick | Los Alamos National Lab | January 26-27, 1995 |

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## (continued)

| Name | Institution | Dates of Visit |
|---|---|---|
| PASTUKHOV, Vladimir | Kurchatov Inst., Moscow | April 8-15, 1995<br>June 16-July 24, 1995 |
| PORCELLI, Franco | ITER-San Diego | February 6-10, 1995 |
| REM, Dr. | The Netherlands | April 24, 1995 |
| SIGMAR, Dieter | MIT Plasma Fusion Center | November 23, 1994 |
| TAYLOR, Bryan | UKAEA Fusion, Culham Lab | April 6-19, 1995 |
| VANICEK, Jiri | Harvard University | June 25-Aug. 25, 1995 |
| WARE, Andrew | Univ. of Wisconsin-Madison | August 29-Sept. 2, 1994<br>October 3-7, 1994 |
| YAMADA, Masaaki | Princeton Plasma Phys Lab | October 30-Nov. 1, 1994 |
| YAMAKAWA, K. | JAERI, Japan | November 17-18, 1994 |
| ZABUSKY, Norman | TICAM, UT Austin | March 13-17, 1995 |
| ZHANG, Y.Z. | ICTP — Trieste, Italy | Aug. 23-October 9, 1994<br>April 3-May 15, 1995 |

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IFSR #667

## Hybrid model in general geometry

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### Abstract

We propose hybrid model equations in toroidal (or more general) geometry for magnetically confined plasmas. This is suitable for low frequency toroidal modes, for example, the trapped electron and current diffusive ballooning instabilities. This model consists of fluid ions and drift kinetic electrons. We discuss the numerical algorithm of these model equations. The linear dispersion relation of this model equations that defines the requirements of the model for describing these modes is also discussed.

IFSR #668

## Wake fields in semiconductor plasmas

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It is shown that an intense short laser pulse propagating through a semiconductor plasma will generate longitudinal Langmuir waves in its wake. The measurable wake field can be used as a diagnostic to study nonlinear optical phenomena. For narrow gap semiconductors (for example InSb) with Kane-type dispersion relation, the system can simulate, at currently available laser powers, the physics underlying wake-field accelerators.

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IFSR #669

## Nonlinear symmetric stability of planetary atmospheres

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The energy–Casimir method is applied to the problem of symmetric stability in the context of a compressible, hydrostatic planetary atmosphere with a general equation of state. Linear stability criteria for symmetric disturbances to a zonally symmetric baroclinic flow are obtained. In the special case of a perfect gas the results of Stevens (1983) are recovered. Nonlinear stability conditions are also obtained that, in addition to implying linear stability, provide an upper bound on a certain positive-definite measure of disturbance amplitude.

IFSR #670

## A wavenumber-partitioning scheme for two-dimensional statistical closures

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A technique of wavenumber partitioning that conserves both energy and enstrophy is developed for two-dimensional statistical closures. Coupled with a new time-stepping scheme based on a variable integrating factor, this advance facilitates the computation of energy spectra over seven wavenumber decades, a task that will clearly remain outside the realm of conventional numerical simulations for the foreseeable future. Within the context of the test-field model, the method is used to demonstrate Kraichnan's logarithmically-corrected scaling for the enstrophy inertial range and to make a quantitative assessment of the effect of replacing the physical Laplacian viscosity with an enhanced hyperviscosity.

IFSR #671

# Energetic particle drive for toroidicity-induced Alfvén eigenmodes and kinetic toroidicity-induced Alfvén eigenmodes in a low-shear tokamak


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## Abstract

We analyze the structure of toroidicity-induced Alfvén eigenmodes (TAE) and kinetic TAE (KTAE) with large mode numbers and calculate the linear power transfer from energetic particles to these modes in the low shear limit when each mode is localized near a single gap within an interval whose total width $\Delta^{out}$ is much smaller than the radius $r_m$ of the mode location. Near its peak where most of the mode energy is concentrated, the mode has an inner scalelength $\Delta^{in}$, which is much smaller than $\Delta^{out}$. The scale $\Delta^{in}$ is determined by toroidicity and kinetic effects, which eliminate the singularity of the potential at the resonant surface. In this work we examine the case when the drift orbit width of energetic particles $\Delta_b$ is much larger than the inner scalelength $\Delta^{in}$, but arbitrary compared to the total width of the mode. It is shown that the particle-to-wave linear power transfer is comparable for the TAE and KTAE modes in this case. The ratio of the energetic particle contributions to the growth rates of the TAE and KTAE modes is then roughly equal to the inverse ratio of the mode energies. Our results indicate that, in the low shear limit the growth rate of the KTAE modes can be larger than that for the TAE modes.


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IFSR #672

# Generalized relaxation theory and vortices in plasmas


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We present a generalization of the relaxation theory based in the canonical momentum of each species fluid in a multicomponent plasma. The generalized helicity, as a topological quantity, has a lifetime larger than the lifetime of the energy. The proposed variational principle suggests vortices structures. We study localized solutions, assuming the existence of a separatrix. Two-dimensional and three-dimensional solutions are studied for an electron-positron-proton plasma. Ideal magnetohydrodynamic (MHD) three-dimensional localized vortices are studied as well. Possible cosmological implications are discussed.

IFSR #673

## Impurity effects on linear and nonlinear ion temperature gradient driven modes

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### Abstract

Linear and nonlinear stages in the development of the ion-temperature-gradient driven drift-wave instability are studied analytically in the presence of shear flows, magnetic shear, inhomogeneity, and curvature. In the linear regime, it is shown that the toroidal $\eta_i$ mode can be destabilized by a small amount of impurities only if there exists an impurity build-up at the plasma edge. The slab $\eta_i$ mode is destabilized by a small amount of inhomogeneities, and stabilized by a larger impurity content when the inhomogeneity and main ions density profiles are close to each other. In the nonlinear regime two types of coherent structures are found: generalized Hasegawa-Mima dipole vortex in the weak magnetic shear case, and a periodic, vortex-chain solution in the strong shear case, which corresponds to the saturated, large amplitude drift-tearing mode.

IFSR #674

## Potentials and Bound States

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August 2, 1994

### Abstract

We discuss several quantum mechanical potential problems, focusing on those which highlight commonly held misconceptions about the existence of bound states. We present a proof, based on the variational principle, that certain one dimensional potentials always support at least one bound state, regardless of the potential's strength. We examine arguments concerning the existence of bound states based on the uncertainty principle and demonstrate, by explicit calculations, that such arguments must be viewed with skepticism.

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IFSR #675

# TWO-DIMENSIONAL BALLOONING TRANSFORMATION WITH APPLICATIONS TO TOROIDAL ALFVÉN EIGENMODES

Publication No. ____________

Xiao-Dong Zhang, Ph.D.

The University of Texas at Austin, 1994

Supervisor: Richard D. Hazeltine

A general formulation for high-$n$ ($n$ is the toroidal mode number) modes in an axisymmetric toroidal plasma is presented, based on the two dimensional (2-D) ballooning transformation. It is shown that this formulation is more general than the conventional ballooning theory, and reduces to the conventional theory in a special case.

Toroidal Alfvén waves are studied using the 2-D ballooning formulation. A perturbation theory is systematically developed for the continuum damping of the toroidal Alfvén eigenmode (TAE). A formula, similar to the Fermi golden rule for decaying systems in quantum mechanics, is derived for the continuum damping rate of the TAE; the decay (damping) rate is expressed explicitly in terms of the coupling of the TAE to the continuum spectrum. Numerical results are obtained and compared to previous calculations.

Kinetic effects on toroidal Alfvén waves are studied. Multiple-gap coupling is included automatically by the 2-D ballooning formulation. A new branch of modes, the kinetic toroidal Alfvén eigenmodes (KTAE), emerges as a result of kinetic effects. This mode resides just above the toroidal shear Alfvén gap, and has a structure similar to the TAE. Numerical results for the kinetic damping rates for the TAE and the KTAE are obtained, and multiple-gap coupling effects are studied by comparing with the single gap theory of Mett and Mahajan [Phys. Fluids B 4 2885 (1992)].

IFSR #676

# Neural net prediction of tokamak plasma disruptions

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## Abstract

The computation based on neural net algorithms in predicting minor and major disruptions in TEXT tokamak discharges has been performed. Future values of the fluctuating magnetic signal are predicted based on $L$ past values of the magnetic fluctuation signal, measured by a single Mirnov coil. The time step used (= 0.04 ms) corresponds to the experimental data sampling rate. Two kinds of approaches are adopted for the task, the contiguous future prediction and the multi-timescale prediction. Results are shown for comparison. Both networks are trained through the back-propagation algorithm with inertial terms. The degree of this success indicates that the magnetic fluctuations associated with tokamak disruptions may be characterized by a relatively low-dimensional dynamical system.

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IFSR #677

## Comparisons of nonlinear toroidal turbulence simulations with experiment

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### Abstract

The anomalously large thermal transport observed in tokamak experiments is the outstanding physics-based obstacle in the path to a commercially viable fusion reactor. Although decades of experimental and theoretical work indicate that anomalous transport and collective instabilities in the gyrokinetic regime are linked, no widely accepted description of this transport yet exists. Here, detailed comparisons of first-principles gyrofluid and gyrokinetic simulations of tokamak microinstabilities with experimental data are presented. With no adjustable parameters, more than 50 TFTR L-mode discharges have been simulated with encouraging success. Given the local plasma parameters and the temperatures at $r/a \simeq 0.8$, the simulations typically predict $T_i(r)$ and $T_e(r)$ within ±25% throughout the core and confinement zones. In these zones, the predicted thermal diffusivity increases with minor radius robustly. For parameters typical of $r/a > 0.8$, toroidal stability studies confirm the importance of impurity density gradients as a source of free energy potentially strong enough to explain the large edge thermal diffusivity, as first emphasized by Coppi, *et al.* Advanced confinement discharges have also been simulated. The dramatic increase of $T_i(0)$ observed in Supershots (from 5 keV to 30 keV) is recovered by our model for dozens of simulated experiments. Finally, simulations of VH and PEP mode-like plasmas show that velocity-shear stabilization of toroidal microinstabilities is quantitatively significant for realistic experimental parameters.

IFSR #678

## $1/f$ Noise in Two-Dimensional Fluids

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### Abstract

We derive an exact result on the velocity fluctuation power spectrum of an incompressible two-dimensional fluid. Employing the fluctuation-dissipation relationship and the enstrophy conservation, we obtain the frequency spectrum of a $1/f$ form.

IFSR #680

# DYNAMICS AND TRANSPORT IN ROTATING FLUIDS AND TRANSITION TO CHAOS IN AREA PRESERVING NONTWIST MAPS

Publication No. ________

Diego del Castillo Negrete, Ph.D.

The University of Texas at Austin, 1994

Supervisor: P. J. MORRISON

Dynamics and transport in rotating fluids in general, and in a rotating annulus experiment in particular, are studied. A derivation of the quasigeostrophic equation for the rotating annulus experiment is presented, followed by a discussion of exact time-independent axisymmetric solutions. Linear quasigeostrophic theory is used to study both the instability of axisymmetric solutions and the propagation of Rossby waves in the experiment. Transport of passive scalars by waves in shear flow is studied using few degrees-of-freedom Hamiltonian models. Two transport problems are considered: the destruction of transport barriers and the statistical description of particle motion. The first problem is studied using the resonance overlap criterion and a criterion for separatrix reconnection. Both criteria are compared with numerical and experimental results. For the second problem, the statistical description of particle motion, the variance of the particle displacement is computed and evidence of anomalous diffusion is presented. The probability distribution functions of trapping and flight events are computed and shown to exhibit power law behavior. The transport results obtained in the models are compared with the experimental results. It is shown that the general Hamiltonian for traveling waves in symmetric shear flow is degenerate and, thus, exhibits topological changes in phase space due to separatrix reconnection. From this general Hamiltonian, an area preserving map called the *standard nontwist map* is constructed. This map violates the twist condition along a curve called the shearless curve. Using the method of approximating KAM curves by periodic orbits and the residue criterion, a numerical study of the destruction of the shearless curve is presented. This is a novel problem for which KAM theory and other important results can *not* be applied, due to the violation of the twist condition. The results obtained are interpreted in light of the renormalization group and it is concluded that the destruction of the shearless KAM curve with winding number equal to the inverse golden mean is described by a period-six fixed point of the renormalization group operator. This new fixed point defines a new universality class for the transition to chaos in Hamiltonian systems.

IFSR #679

Analytical Studies of the Effects of
Charge-Exchange on a Magnetized Plasma

Publication No. ____________

Mark Darren Calvin, Ph.D.
The University of Texas at Austin, 1994

Supervisor: Claude W. Horton

We analytically calculate the neutral particle distribution and its effects on ion heat and momentum transport in three dimensional magnetized plasmas with arbitrary temperature and density profiles. A general variational principle taking advantage of the simplicity of the charge-exchange (CX) operator is derived to solve self-consistently the neutral-plasma interaction problem. To facilitate an extremal solution, we use the short CX mean-free-path ($\lambda_x$) ordering. Further, a non-variational, analytical solution providing a full set of transport coefficients is derived by making the realistic assumption that the product of the CX cross-section with relative velocity is constant. The effects of neutrals on plasma energy loss and rotation appear in simple, sensible forms. The presence of ionized impurities in the plasma are also considered, and the effects of CX drag and ion-impurity collisions on plasma flows in the short $\lambda_x$ regime are presented. Finally, the long $\lambda_x$ regime is analyzed in slab geometry by finding an appropriate Green's function for the neutral kinetic equation and by solving recursively for the neutral distribution function. Our results are found to agree favorably with previous work.

IFSR #681

# Analytical and numerical studies of ion mobility near the tokamak plasma edge

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## Abstract

The effects of radial electric field on charged particle motion and transport in a toroidal magnetic system have been studied both analytically and numerically. We examine the effects of radial electric field on particle orbits, allowing for the relatively large and strongly sheared field observed in some experiments. We find that ion radial mobility due to the combined effects of radial electric field and charge exchange collisions can dramatically affect the ion transport and orbit loss near the tokamak edge. These properties may help us understand the formation of transport barrier near the H mode plasma edge and explain the asymmetry between bias voltage and confinement in biased-electrode-induced H mode.

IFSR #682

# Nonlinear instability and chaos in plasma wave-wave interactions. I. introduction

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## Abstract

Conventional linear stability analyses may fail for fluid systems with an indefinite free energy functional. When such a system is linearly stable, it is said to possess negative energy modes. Instability may then occur either via dissipation of the negative energy modes, or nonlinearly via resonant wave-wave coupling, leading to explosive growth. In the dissipationless case, it is conjectured that intrinsic chaotic behavior may allow initially nonresonant systems to reach resonance by diffusion in phase space. In this and a companion paper [submitted to Physics of Plasmas], this phenomenon is demonstrated for a simple equilibrium involving cold counterstreaming ions. The system is described in the fluid approximation by a Hamiltonian functional and associated noncanonical Poisson bracket. By Fourier decomposition and appropriate coordinate transformations, the Hamiltonian for the perturbed energy is expressed in action-angle form. The normal modes correspond to Doppler-shifted ion-acoustic waves of positive and negative energy. Nonlinear coupling leads to decay instability via two-wave interactions, and to either decay or explosive instability via three-wave interactions. These instabilities are described for various (integrable) systems of waves interacting via single nonlinear terms. This discussion provides the foundation for the treatment of nonintegrable systems in the companion paper.

IFSR #683

# Envelope evolution of a laser pulse in an active medium

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## Abstract

We show that the envelope velocity, $v_{env}$, of a short laser pulse can, via propagation in an active medium, be made less than, equal to, or even greater than $c$, the vacuum phase velocity of light. Simulation results, based on moving frame propagation equations coupling the laser pulse, active medium and plasma, are presented, as well as equations that determines the design value of super- and sub-luminous $v_{env}$. In this simulation the laser pulse evolves in time in a moving frame as opposed to our earlier work where the profile was fixed. The elimination of phase slippage and pump depletion effects in the laser wakefield accelerator is discussed as a particular application. Finally we discuss media properties necessary for an experimental realization of this technique.

IFSR #684

# MAGNETIC VISCOSITY BY LOCALIZED SHEAR FLOW INSTABILITY IN MAGNETIZED ACCRETION DISKS

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(Received Aug. 18, 1993 ; accepted Dec., 1994 )

January 9, 1995

**Abstract**

Differentially rotating disks are subject to the axisymmetric instability for perfectly conducting plasma in the presence of poloidal magnetic fields (Balbus & Hawley 1991). For nonaxisymmetric perturbations, we find localized unstable eigenmodes whose eigenfunction is confined between two Alfvén singularities at $\omega_d = \pm\omega_A$, where $\omega_d$ is the Doppler-shifted wave frequency, and $\omega_A = k_\parallel v_A$ is the Alfvén frequency. The radial width of the unstable eigenfunction is $\Delta x \sim \omega_A/(Ak_y)$, where $A$ is the Oort's constant, and $k_y$ is the azimuthal wave number. The growth rate of the fundamental mode is larger for smaller value of $k_y/k_z$. The maximum growth rate when $k_y/k_z \sim 0.1$ is $\sim 0.2\Omega$ for the Keplerian disk with local angular velocity $\Omega$. It is found that the purely growing mode disappears when $k_y/k_z > 0.12$. In a perfectly conducting disk, the instability grows even when the seed magnetic field is infinitesimal. Inclusion of the resistivity, however, leads to the appearance of an instability threshold. When the resistivity $\eta$ depends on the instability-induced turbulent magnetic fields $\delta \mathbf{B}$ as $\eta(\langle \delta B^2 \rangle)$, the marginal stability condition self-consistently determines the $\alpha$ parameter of the angular momentum transport due to the magnetic stress. For fully ionized disks, the magnetic viscosity parameter $\alpha_B$ is between 0.001 and 1. Our three-dimensional MHD simulation confirms these unstable eigenmodes. It also shows that the $\alpha$ parameter observed in simulation is between 0.01 and 1, in agreement with theory. The observationally required smaller $\alpha$ in the quiescent phase of accretion disks in dwarf novae may be explained by the decreased ionization due to the temperature drop.

IFSR #685

# On inertial-range scaling laws

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Inertial-range scaling laws for two- and three-dimensional turbulence are reexamined within a unified framework. A new correction to Kolmogorov's $k^{-5/3}$ scaling is derived for the energy inertial range. A related modification is found to Kraichnan's logarithmically corrected two-dimensional enstrophy-range law that removes its unexpected divergence at the injection wavenumber. The significance of these corrections is illustrated with steady-state energy spectra from recent high-resolution closure computations. Implications for conventional numerical simulations are discussed. These results underscore the asymptotic nature of inertial-range scaling laws.

IFSR #686

# Normal modes and continuous spectra*

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## Abstract

We consider stability problems arising in fluids, plasmas and stellar systems that contain singularities resulting from wave-mean flow or wave-particle resonances. Such resonances lead to singularities in the differential equations determining the normal modes at the so-called critical points or layers. The locations of the singularities are determined by the eigenvalue of the problem, and as a result, the spectrum of eigenvalues forms a continuum. We outline a method to construct the singular eigenfunctions comprising the continuum for a variety of problems.

# LIE GROUP ANALYSIS OF PLASMA-FLUID EQUATIONS

Publication No. ________

Raul Acevedo, Ph.D.

The University of Texas at Austin, 1995

Supervisor: Philip J. Morrison

Lie group methods for nonlinear partial differential equations are implemented to study, analytically, a subset of the full solution space of a family of plasma-fluid models. The solutions obtained by this method are known as group invariant solutions. The basic set of equations considered comprise the three-field fluid model due to Hazeltine (HTFM), which was obtained to describe nonlinear large aspect ratio tokamak physics. This model contains as particular limits the physics of the Charney-Hasegawa-Mima equation (CHM) and reduced magnetohydrodynamics (RMHD), which are two other models known to describe some features of nonlinear behavior of tokamak plasmas.

Lie's method requires a large number of systematic calculations to determine the Lie point symmetries of the system of differential equations. These symmetries form a Lie group and describe the geometrical invariance of the equations. The Lie symmetries have been calculated for the systems mentioned above by using a symbolic manipulation program. A detailed analysis of the physical meaning of these symmetries is given. Using the Lie algebraic properties of the generators of the symmetries, a reduction of the number of independent variables for the full nonlinear systems of equations is calculated, which in turn yields simplified equations that sometimes can be solved analytically. A discussion of some of the reductions and solutions generated by this technique is presented. The results show the feasibility of using Lie methods to obtain analytical results for complicated nonlinear systems of partial differential equations that describe physically interesting situations.

IFSR #688

# Neoclassical and anomalous transport in axisymmetric toroidal plasmas with electrostatic turbulence

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## Abstract

Neoclassical and anomalous transport fluxes are determined for axisymmetric toroidal plasmas with weak electrostatic fluctuations. The neoclassical and anomalous fluxes are defined based on the ensemble-averaged kinetic equation with the statistically averaged nonlinear term. The anomalous forces derived from that quasilinear term induce the anomalous particle and heat fluxes. The neoclassical banana-plateau particle and heat fluxes and the bootstrap current are also affected by the fluctuations through the parallel anomalous forces and the modified parallel viscosities. The fluctuating part of the drift kinetic equation gives the response of the distribution function to the potential fluctuation, from which the quasilinear term, the anomalous forces, and the anomalous particle and heat fluxes are evaluated. The averaged drift kinetic equation with the quasilinear term is solved for the plateau regime to derive the parallel viscosities modified by the fluctuations. The entropy production rate due to the anomalous transport processes is formulated and used to identify conjugate pairs of the anomalous fluxes and forces, which are connected by the matrix with the Onsager symmetry. Estimates are given from the dispersion relation for the ion temperature gradient driven mode for the anomalous fluxes and viscosity.

IFSR #689

# Exactly Conservative Integrators

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July 13, 1995

**Abstract**

Traditional numerical discretizations of conservative systems generically yield an artificial secular drift of any nonlinear invariants. In this work we present an *explicit* nontraditional algorithm that exactly conserves invariants. We illustrate the general method by applying it to the three-wave truncation of the Euler equations, the Volterra–Lotka predator–prey model, and the Kepler problem. We discuss our method in the context of general symplectic (phase space conserving) integration methods as well as non-symplectic conservative methods. We comment on the application of our method to general conservative systems.

**Key words**: conservative, integration, numerical, symplectic

**AMS subject classifications**: 65L05, 34-04, 34A50

IFSR #690

## Numerical simulation of bump-on-tail instability with source and sink

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A numerical procedure has been developed for the self-consistent simulation of the nonlinear interaction of energetic particles with discrete collective modes in the presence of a particle source and dissipation. A bump-on-tail instability model is chosen for these simulations. The model presents a kinetic nonlinear treatment of the wave-particle interaction within a Hamiltonian formalism. A mapping technique has been used in this model in order to assess the long time behavior of the system. Depending on the parameter range, the model shows either a steady-state mode saturation or quasiperiodic nonlinear bursts of the wave energy. We demonstrate that the mode saturation level as well as the burst parameters scale with the drive in accordance with the analytical predictions. We also quantify the threshold for the resonance overlap condition and particle global diffusion in the phase space. For the pulsating regime, we show that when $\gamma_L > 0.16\Delta\Omega$, where $\gamma_L$ is the linear growth rate for the unperturbed system and $\Delta\Omega$ is the frequency separation of neighboring resonances, overlap occurs together with an amplification of the free energy release compared to what is expected with the saturation of nonoverlapping modes. The effect of particle losses on the wave excitation is included in our model, which illustrates in a qualitative way the bursting collective losses of fast ions/alpha particles due to Alfvén instabilities.

IFSR #691

## Reynolds Stress of Localized Toroidal Modes

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### Abstract

An investigation of the 2D toroidal eigenmode problem reveals the possibility of a new consistent 2D structure, the dissipative BM-II mode. In contrast to the conventional ballooning mode, the new mode is poloidally localized at $\pi/2$ (or $-\pi/2$), and possesses significant radial asymmetry. The radial asymmetry, in turn, allows the dissipative BM-II to generate considerably larger Reynolds stress as compared to the standard slab drift type modes. It is also shown that a wide class of localized dissipative toroidal modes are likely to be of the dissipative BM-II nature, suggesting that at the tokamak edge, the fluctuation generated Reynolds stress (a possible source of poloidal flow) can be significant.

IFSR #692

## Singular eigenfunctions for shearing fluids I

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### Abstract

We construct singular eigenfunctions corresponding to the continuous spectrum of eigenvalues for shear flow in a channel. These modes are irregular as a result of a singularity in the eigenvalue problem at the *critical layer* of each mode. We consider flows with monotonic shear, so there is only a single critical layer for each mode. We then solve the initial-value problem to establish that these continuum modes, together with any discrete, growing/decaying pairs of modes, comprise a complete basis. We also view the problem within the framework of Hamiltonian theory. In that context, the singular solutions can be viewed as the kernel of an integral, canonical transformation that allows us to write the fluid system, an infinite-dimensional Hamiltonian system, in action-angle form. This yields an expression for the energy in terms of the continuum modes and provides a means for attaching a characteristic signature (sign) to the energy associated with each eigenfunction. We follow on to consider shear-flow stability within the Hamiltonian framework. Next, we show the equivalence of integral superpositions of the singular eigenfunctions with the solution derived with Laplace transform techniques. In the long-time limit, such superpositions have decaying integral averages across the channel, revealing phase mixing or *continuum damping*. Under some conditions, this decay is exponential and is then the fluid analogue of Landau damping. Finally, we discuss the energetics of continuum damping.

IFSR #693

## Quantitative Predictions of Tokamak Energy Confinement from First-Principles Simulations with Kinetic Effects

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### Abstract

A first-principles model of anomalous thermal transport based on numerical simulations is presented, with stringent comparisons to experimental data from the Tokamak Fusion Test Reactor (TFTR) [Fusion Technol. 21, 1324 (1992)]. This model is based on nonlinear gyrofluid simulations, which predict the fluctuation and thermal transport characteristics of toroidal ion-temperature-gradient-driven (ITG) turbulence, and on comprehensive linear gyrokinetic ballooning calculations, which provide very accurate growth rates, critical temperature gradients, and a quasilinear estimate of $\chi_e/\chi_i$. The model is derived solely from the simulation results. More than 70 TFTR low confinement (L-mode) discharges have been simulated with quantitative success. Typically, the ion and electron temperature profiles are predicted within the error bars, and the global energy confinement time within ±10%. The measured temperatures at $r/a \simeq 0.8$ are used as a boundary condition to predict the temperature profiles in the main confinement zone. The dramatic transition to the improved confinement in the supershot regime is also qualitatively explained. Further work is needed to extend this model of core heat transport to include particle and momentum transport, the edge region, and other operating regimes besides the ITG-dominated L-mode. Nevertheless, the present model is very successful in predicting thermal transport in the main plasma over a wide range of parameters.

IFSR #694

# Stabilization of the Resistive Shell Mode in Tokamaks

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**Abstract**

The stability of current-driven external-kink modes is investigated in a tokamak plasma surrounded by an external shell of finite electrical conductivity. According to conventional theory, the ideal mode can be stabilized by placing the shell sufficiently close to the plasma, but the non-rotating "resistive shell mode," which grows on the characteristic L/R time of the shell, always persists. It is demonstrated, using both analytic and numerical techniques, that a combination of strong edge plasma rotation and dissipation somewhere inside the plasma is capable of stabilizing the resistive shell mode. This stabilization mechanism does not necessarily depend on toroidicity or the presence of resonant surfaces inside the plasma.

IFSR #695

# More on core-localized toroidal Alfvén eigenmodes

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## Abstract

A novel type of ideal toroidal Alfvén eigenmode, localized in the low-shear core region of a tokamak plasma, is shown to exist, whose frequency is near the upper continuum of the toroidal Alfvén gap. This mode converts to a kinetic-type toroidal Alfvén eigenmode above a critical threshold that depends on aspect ratio, pressure gradient, and shear. Opposite to the usual ideal toroidal Alfvén eigenmode, this new mode is peaked in amplitude on the small-major-radius side of the plasma.

IFSR #696

# "Heavy Light Bullets" in Electron-Positron Plasma

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**Abstract**

The nonlinear propagation of circularly polarized electromagnetic waves with relativistically strong amplitudes in an unmagnetized hot electron-positron plasma with a small fraction of ions is investigated. The possibility of finding localized solutions in such a plasma is explored. It is shown that these plasmas support the propagation of "heavy light bullets"; nondiffracting and nondispersive electromagnetic (EM) pulses with large density bunching.

IFSR #697

# Shear flow effects on ion thermal transport in tokamaks

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## Abstract

From various laboratory and numerical experiments, there is clear evidence that under certain conditions the presence of sheared flows in a tokamak plasma can significantly reduce the ion thermal transport. In the presence of plasma fluctuations driven by the ion temperature gradient, the flows of energy and momentum parallel and perpendicular to the magnetic field are coupled with each other. This coupling manifests itself as significant off-diagonal coupling coefficients that give rise to new terms for anomalous transport. We derive from the gyrokinetic equation a set of velocity moment equations that describe the interaction among plasma turbulent fluctuations, the temperature gradient, the toroidal velocity shear, and the poloidal flow in a tokamak plasma. Four coupled equations for the amplitudes of the state variables radially extended over the transport region by toroidicity induced coupling are derived. The equations show bifurcations from the low confinement mode without sheared flows to high confinement mode with substantially reduced transport due to strong shear flows. Also discussed is the reduced version with three state variables. In the presence of sheared flows, the radially extended coupled toroidal modes driven by the ion temperature gradient disintegrate into smaller, less elongated vortices. Such a transition to smaller spatial correlation lengths changes the transport from Bohm-like to gyroBohm-like.

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IFSR #698

## On the quasihydrostatic flows of radiatively cooling self-gravitating gas clouds

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### Abstract

Two model problems are considered, illustrating the dynamics of quasihydrostatic flows of radiatively cooling, optically thin self-gravitating gas clouds. In the first problem, spherically symmetric flows in an unmagnetized plasma are considered. For a power-law dependence of the radiative loss function on the temperature, a one-parameter family of self-similar solutions is found. We concentrate on a constant-mass cloud, one of the cases, when the self-similarity indices are uniquely selected. In this case, the self-similar flow problem can be formally reduced to the classical Lane-Emden equation and therefore solved analytically. The cloud is shown to undergo radiative condensation, if the gas specific heat ratio $\gamma > 4/3$. The condensation proceeds either gradually, or in the form of (quasihydrostatic) collapse. For $\gamma < 4/3$, the cloud is shown to expand. The second problem addresses a magnetized plasma slab that undergoes quasihydrostatic radiative cooling and condensation. The problem is solved analytically, employing the Lagrangian mass coordinate.

IFSR #699

## Area Preserving Nontwist Maps: Periodic Orbits and Transition to Chaos

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March 1, 1995

### Abstract

Area preserving nontwist maps, i.e. maps that violate the twist condition, are considered. A representative example, the *standard nontwist map* that violates the twist condition along a curve called the shearless curve, is studied in detail. Using symmetry lines and involutions, periodic orbits are computed and two bifurcations analyzed: periodic orbit collision and separatrix reconnection. The transition to chaos due to the destruction of the shearless curve is studied. This problem is outside the applicability of the KAM (Kolmogorov-Arnold-Moser) theorem. Using the residue criterion we compute the critical parameter values for the destruction of the shearless curve with rotation number equal to the inverse golden mean. The results indicate that the destruction of this curve is fundamentally different from the destruction of the inverse golden mean curve in twist maps. It is shown that the residues converge to a six-cycle at criticality.

IFSR #700

## Ion Temperature Gradient Driven Transport

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### Abstract

The steep ion temperature gradients produced in the large tokamaks are analyzed in terms of the anomalous transport of ion energy and momentum. The transport equations take into account that for low viscosities and high effective Rayleigh numbers both neutral fluids and plasma show the spontaneous generation of sheared mass flows. The self-generated flows are driven by the ion temperature gradient through the turbulence and are one method for creating the transport barrier. In addition, the external control parameter from the direct injection of perpendicular ion (angular) momentum gives a second method for creating a transport barrier. The threshold conditions are derived for the bifurcations from the three confinement regimes of L-mode, H-mode, and a super-suppressed transport (SST) confinement regime.

IFSR #701

## Revisit to Self-Organization of Solitons for Dissipative Korteweg-de Vries Equation

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### Abstract

The process by which self-organization occurs for solitons described by the Korteweg-de Vries (KdV) equation with a viscous dissipation term is reinvestigated theoretically, with the use of numerical simulations in a periodic system. It is shown that, during nonlinear interactions, two basic processes for the self-organization of solitons are energy transfer and selective dissipation among the eigenmodes of the dissipative operator. It is also clarified that an important process during nonlinear self-organization is an interchange between the dominant operators, which has hitherto been overlooked in conventional self-organization theories and which leads to a final self-similar coherent structure determined uniquely by the dissipative operator.

# THE LONGITUDINAL COLLECTIVE INSTABILITIES OF NONLINEAR HAMILTONIAN SYSTEMS IN A CIRCULAR ACCELERATOR

Publication No. __________

Bo Chen, Ph.D.
The University of Texas at Austin, 1995

Supervisors: Alexander Wu Chao
Toshiki Tajima

The understanding of collective instabilities of high intensity beams is essential to modern accelerators. In this dissertation, the subject of longitudinal collective instabilities of a single bunched beam in a circular accelerator, for which the Hamiltonian used to describe particle motion is nonlinear, is systematically studied. The analysis described in this work is applied to study the newly discovered instability, the longitudinal head-tail instability, and to substantially improve upon the study of the well known longitudinal mode-coupling instability.

It is necessary to adopt a nonlinear Hamiltonian to precisely describe the motion of a particle in an accelerator. Traditionally, the perturbation theory is used to study the instabilities. However, the conventional formalism is based on the linear model and cannot be directly applied to nonlinear systems. In this work, a technique is developed to treat the instabilities of nonlinear systems. This technique involves a canonical transformation from the conventional variables to a new set of generalized variables. The new set of variables consist of the Hamiltonian itself, which serves as the new action variable, and another conjugate variable. This technique is applied to a system with a nonlinear momentum compaction factor to study the newly discovered longitudinal head-tail instability. The growth rate of the instability seems to agree quantitatively with experimental observations.

In a linear system, the particles in a bunched beam move in a parabolic potential well. A distortion of the potential well, due to the electromagnetic fields of the beam, also contributes nonlinear terms to the otherwise linear Hamiltonian. This so-called potential well distortion effect is studied, and given as a possible cause of an apparent discrepancy between experimental observations and conventional calculations of the longitudinal mode-coupling instability. The results from the perturbation theory in this work, which includes the potential well distortion, are comparable with the experimental observations.

One of the key inputs to study of the collective instabilities is a detailed knowledge of the impedance, a function describing the conductive environment quantitatively. The algorithm commonly used to calculate the impedance is studied in this work. An intrinsic numerical error, which leads to a fictitious high frequency impedance, is discovered by applying the algorithm to an intuitive case. This study is also include in this dissertation.

IFSR #703

## Studies of impurity mode and ITG mode in toroidal plasmas

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### Abstract

The impurity mode and $\eta_i$ mode driven by impurity ions with outwardly peaked density profiles, just as it is at the boundary of tokamak plasmas, and the ion temperature gradient, respectively, are studied in high temperature toroidal plasmas. The gyrokinetic theory is applied and finite Larmor radius effects of both hydrogenic and impurity ions are included. It is found that the impurity mode is enhanced by the ion temperature gradient. In addition, the impurity ions with outwardly peaked density profiles are demonstrated to have destabilizing effects on the $\eta_i$ mode. These two modes are strongly coupled to each other so that it is impossible to distinguish between them when both the driving mechanisms are strong enough to drive the corresponding mode unstable independently. The correlation of the results with nonlinear simulations and the experimental observations are discussed.

IFSR #704

## Connection formula near a singular "tip"

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When MHD eigenvalue equations break down near a singular tip, the nonideal solutions are likely to have a response that is not the same as the one predicted by analytic continuation. A boundary layer analysis is described here that can be implemented in large MHD computer codes even without an aspect ratio expansion. The nonideal boundary layer equation reduces to a fourth order differential equation whose asymptotic properties are analytically calculated. Large MHD shooting codes can be systematically corrected to give the proper nonideal response at frequencies close to the one corresponding to a singular tip.

# Sinuous oscillations and steady warps of polytropic disks[a)]

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## I. INTRODUCTION

In an asymptotic development of the equations governing the equilibria and linear stability of rapidly rotating polytropes (papers I[1] and II[2]) we employed the slender aspect of these objects to reduce the three-dimensional partial differential equations to a somewhat simpler, ordinary integro-differential form. Specifically, the polytrope is characterized by an equatorial radius $a$ and a characteristic thickness $\epsilon a$. The dimensionless parameter $\epsilon = k_J a$, where $k_J$ is the Jeans wavenumber[3] based on conditions at the center of the disk. The equations are then asymptotically solved in the limit $\epsilon \to 0$ and, once this solution is in hand, $\epsilon$ may be expressed in terms of known global parameters of the disk, such as density, entropy, mass and angular momentum.

The earlier calculations dealt with isolated objects that were in centrifugal balance, that is, the centrifugal acceleration of the configuration was balanced largely by self gravity with small contributions from the pressure gradient. Another interesting situation is that in which the polytrope rotates subject to externally imposed gravitational fields. In astrophysics, this

a) To be published in the *Proceedings of the 10th Florida Workshop in Nonlinear Astronomy: Waves in Astrophysics*, eds. J. Hunter and R. Wilson, New York Academy of Sciences (1994).

IFSR #706

is common in the theory of galactic dynamics because disks are unlikely to be isolated objects.[4]

The dark halos associated with disks also provide one possible explanation of the apparent warping of many galaxies. If the axis of the highly flattened disk is not aligned with that of the much less flattened halo, then the resultant torque of the halo gravity on the disk might provide a nonaxisymmetric distortion or disk warp.[4]

Motivated by these possibilities we shall here build models of polytropic disks of small but finite thickness which are subjected to prescribed, external gravitational fields. First we estimate how a symmetrical potential distorts the structure of the disk (Sec. II), then we examine its sinuous ocillations to confirm that they freely decay, hence suggesting that a warp must be externally forced (Sec. III). Finally (in Sec. IV), we consider steady warps of the disk plane when the axis of the disk does not coincide with that of the halo.

# IFSR #705

# Lyapunov Exponents of Many Body Systems

Publication No. ________

David Mallory Barnett, Ph.D
The University of Texas at Austin, 1995

Supervisor: Toshiki Tajima

For many body systems, we show that the separation rate between two adjacent trajectories in phase space tends to an asymptotic level with relatively small fluctuations about that level. We define an instantaneous phase space expansion rate to be the separation rate in this asymptotic regime. The long time average of the instantaneous expansion rate is the largest Lyapunov exponent familiar in the literature. Gross changes in the instantaneous expansion rate are shown to be a microscopic correlative of macroscopic changes in the system. Instantaneous expansion rates may be definable in circumstances when statistical quantities such as temperature and pressure are hard to calculate or have no meaning.

This work advances the computational technique and theory for Lyapunov expansion rates. We also show that the size of the transient separation rate depends on the choice of metric for defining distance on phase space.

An ab initio theoretical expression for the Lyapunov exponent of a dilute gas is derived. It shows the Lyapunov exponent to be a function of the time integral of the two time auto-correlation function for the second derivative of the interparticle potential (approximately a power $\frac{1}{3}$ law). Such auto-correlations are related to the system's response functions via the fluctuation-dissipation theorem, establishing a link between the Lyapunov exponent and the transport coefficients. We apply the theory to a one component plasma and compare it with numerical simulations. The Lyapunov exponent is proportional to the diffusion coefficient to the power $\frac{1}{3}$, as predicted. The theoretical plasma parameter dependence also corresponds well.

# IFSR #707

# Nonlinear Instability and Chaos in Plasma Wave-Wave Interactions. II. Numerical Methods and Results

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## Abstract

In Part I of this work [IFSR #682 (Ref. 1) and Physics of Plasmas, June 1995], the behavior of linearly stable, integrable systems of waves in a simple plasma model was described using a Hamiltonian formulation. It was shown that explosive instability arises from nonlinear coupling between modes of positive and negative energy, with well-defined threshold amplitudes depending on the physical parameters. In this concluding paper, the nonintegrable case is treated numerically. Several sets of waves are considered, comprising systems of two and three degrees of freedom. The time evolution is modelled with an explicit symplectic integration algorithm derived using Lie algebraic methods. When initial wave amplitudes are large enough to support two-wave decay interactions, strongly chaotic motion destroys the separatrix bounding the stable region for explosive triplets. Phase space orbits then experience diffusive growth to amplitudes that are sufficient for explosive instability, thus effectively reducing the threshold amplitude. For initial amplitudes too small to drive decay instability, small perturbations might still grow to arbitrary size via Arnold diffusion. Numerical experiments do not show diffusion in this case, although the actual diffusion rate is probably underestimated due to the simplicity of the model.

# IFSR #708

## Pulse dynamics in an unstable medium[a)]

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### Abstract

A study is presented of a one-dimensional, nonlinear partial differential equation that describes evolution of dispersive, long-wave instability. The solutions, under certain specific conditions, take the form of trains of well-separated pulses. The dynamics of such patterns of pulses is investigated using singular perturbation theory and with numerical simulation. These tools permit the formulation of a theory of pulse interaction, and enable the mapping out of the range of behavior in parameter space. There are regimes in which steady trains form; such states can be studied with the asymptotic, pulse-interaction theory. In other regimes, pulse trains are unstable to global, wave-like modes or *its radiation*. This can precipitate more violent phenomena involving pulse creation, or generate periodic states which may follow Shil'nikov's route to temporal chaos. The asymptotic theory is generalized to take some account of radiative dynamics. In the limit of small dispersion, steady trains largely cease to exist; the system follows various pathways to temporal complexity and typical bifurcation sequences are sketched out. The investigation guides us to a critical appraisal of the asymptotic theory and uncovers the wealth of different types of behavior present in the system.

**Key words.** Partial differential equations, chaos, nonlinear dynamics, singular perturbation theory, solitary waves

**AMS(MOS) subject classifications.** 34C35, 34C37, 35B25, 35A35.

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# IFSR #709

## On the Hamiltonian Structure of the Linearized Maxwell–Vlasov System

Publication No. ________

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The University of Texas at Austin, 1995

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A detailed analysis of the noncanonical structure of the linearized Maxwell–Vlasov equations is presented. The full Maxwell–Vlasov bracket is linearized about a stable, homogeneous and isotropic equilibrium. Velocity space moments are taken leading to a natural decomposition of the system into longitudinal and transverse parts. This bracket together with the linearized energy is shown to give the usual linearized moment equations. A family of integral transforms whose kernels are closely related to singular eigenfunctions are introduced. It is shown that, by means of these transformations, both the bracket and energy can be brought into diagonal form. The diagonalizing transformation is essentially a transformation to linear action-angle variables for this infinite-dimensional Hamiltonian system. The resulting energy expression, which depends on the Fourier transform of the electric field, has physical meaning as the energy of the perturbations and in general is *not* equal to the usual expression for the wave energy in a dielectric. Equilibria that support discrete modes are also studied. It is shown that the eigenfunctions corresponding to the discrete modes enter as a natural result of regularizing the (now singular) inverse transform. It is seen that in the case of neutral modes, the transformed variables must be interpreted as generalized functions. Lastly, quadrature rules for Cauchy integrals are discussed and an efficient, high accuracy algorithm for computing Hilbert transforms is developed. This algorithm is used to evaluate the exact solution of the longitudinal equations for different initial conditions.

IFSR #710

## Elliptical vortices in shear: Hamiltonian moment formulation and Melnikov analysis

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### Abstract

The equations of motion for interacting, elliptical vortices in a background shear flow are derived using a Hamiltonian moment formulation. The equations reduce to the 6th order system of Melander *et al.* [J. Fluid Mech. **167**, 95 (1986)] when a pair of vortices is considered and shear is neglected. The equations for a pair of identical vortices are analyzed with a number of methods, with particular emphasis on the basic interactions and on the implications for vortex merger. The splitting distance between the stable and unstable manifolds connecting the hyperbolic fixed points of the intercentroidal motion—the separatrix splitting—is estimated with a Melnikov analysis. This analysis differs from the standard time-periodic Melnikov analysis on two counts: (a) the "periodic" perturbation arises from a second degree of freedom in the system which is not wholly independent of the first degree of freedom, the intercentroidal motion; (b) this perturbation has a faster time scale than the intercentroidal motion. The resulting Melnikov integral appears to be exponentially small in the perturbation as the latter goes to zero. Numerical simulations, notably Poincaré sections, provide a global view of the dynamics and indicate that there are two modes of merger. The effect of the shear on chaotic motion and on chaotic scattering is also discussed.

IFSR #711

## Theory of Self-Organized Critical Transport in Tokamak Plasmas

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### Abstract

A theoretical and computational study of the ion temperature gradient and $\eta_i$ instabilities in tokamak plasmas has been carried out. In toroidal geometry the modes have a radially extended structure and their eigenfrequencies are constant over many rational surfaces that are coupled through toroidicity. These nonlocal properties of the ITG modes impose strong constraint on the drift mode fluctuations and the associated transport, showing a self-organized characteristic. As any significant deviation away from marginal stability causes rapid temperature relaxation and intermittent bursts, the modes hover near marginality and exhibit strong kinetic characteristics. As a result, the temperature relaxation is self-similar and nonlocal, leading to a radially increasing heat diffusivity. The nonlocal transport leads to the Bohm-like diffusion scaling. The heat input regulates the deviation of the temperature gradient away from marginality. The obtained transport scalings and properties are globally consistent with experimental observations of L-mode discharges.

IFSR #712

## Line-broadened quasilinear burst model

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### Abstract

A quasilinear model is developed to produce realistic self-consistent saturation levels when modes do not overlap, and give self-consistent diffusion and wave evolution when modes do overlap. Both regimes give steady or pulsating behavior in weakly driven systems with classical relaxation and background dissipation present. An avalanche response is demonstrated: wave momentum release caused by the overlap of closely spaced modes can produce mode overlap of more widely spaced modes (a domino effect) or the growth of modes which would be stable in systems unaffected by the closely-spaced modes' diffusion. Detailed analysis and calculations are performed for the bump-on-tail instability, and extension of the method to more general problems is briefly discussed.

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IFSR #713

## Simulation of Alfvén wave-resonant particle interaction

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### Abstract

New numerical simulations are presented on the self-consistent dynamics of energetic particles and a set of unstable discrete shear Alfvén modes in a tokamak. Our code developed for these simulations has been previously tested in the simulations of the bump-on-tail instability model. The code has a Hamiltonian structure for the mode-particle coupling, with the superimposed wave damping, particle source and classical relaxation processes. In the alpha particle-Alfvén wave problem, we observe a transition from a single mode saturation to the mode overlap and global quasilinear diffusion, which is qualitatively similar to that observed in the bump-on-tail model. We demonstrate a considerable enhancement in the wave energy due to the resonance overlap. We also demonstrate the effect of global diffusion on the energetic particle losses.