Cover:
This image shows Perspective view of potential well for ions moving in a model Field-Reversed Configuration.

Source image provided by Jim Howard, modified by Genevieve Taylor.
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About CIPS

The Center for Integrated Plasma Studies (CIPS) is a research center at University of Colorado at Boulder, CO. Situated in the Duane Physics Complex (see maps and photos on pp. 5-6), its main office is on the 8th floor of the Gamow Tower.

The center first came into being in 1993, in order to consolidate plasma research on campus and in the Boulder scientific community at large. Since the first days of its existence it has hosted scholars from all over the world. In 2003, its 10th year, CIPS was home to 10 Fellows, 14 Members, 19 Scientist Associates, 23 graduate and undergraduate students, as well as other staff, which altogether made 43 regular and temporary employees.

CIPS’s scholars constitute a number of research groups, each responsible for its own projects. Our scholars make use of a number of highly specialised laboratories across the Physics Department.

CIPS is funded by research grants received from NASA (National Aeronautics and Space Administration), NSF (National Science Foundation), DOE (Department of Energy), and other agencies.
Directions and Contact Information

CIPS is located on Colorado Avenue, in the middle of the main campus of the University of Colorado at Boulder, CO. The closest parking lot is on Euclid Avenue (numbered 15 on the map on p. 6) and comprises a short-term, pay parking garage.

Our mailing address is:
Center for Integrated Plasma Studies
390 UCB
Boulder, CO 80309-0390
USA

Email us at:
info@cips.colorado.edu

Or phone or fax us at:
tel. (303) 492 8760
fax. (303) 492 0642

Carolyn James, Administrative Officer.

The Duane Physics Complex building (view from NW).

Scott Knappmiller, a student researcher, in the plasma laboratory.
Mission Statement

The mission of the Center for Integrated Plasma Studies is to foster plasma and beam related science and research. In particular, CIPS provides a home for interdisciplinary plasma related activities. This includes coordination of high-performance scientific and networking capability. The Center for Integrated Plasma Studies has the additional mission of scientific outreach, including making plasma physics, general physics and astrophysics highly accessible to the general public.
General Outline of Research

The focus of research carried out at CIPS is the study of plasma, hot ionized gas, such as found in the stars, in space, and in lightning storms. It is used for applications as diverse as fluorescent lighting and microchip fabrication.

Plasma physics has broadened considerably from its original domain. It includes not only the study of ionized gases, but also the study of strongly coupled systems, non-neutral plasmas, dusty plasmas, and charged particle beams. Plasma research has long been applied to space, astrophysical, and fusion plasmas, but in addition is now applied to semiconductor processing, intense particle beams, and high-definition video display. Plasma physics is important in both naturally occurring systems as well as in the laboratory.

Because of the broad scope of plasma physics, members have links to many other units at University of Colorado. These units include the Departments of Physics, Astrophysical and Planetary Science, Applied Mathematics, Mechanical Engineering, Aerospace Engineering, and Electrical Engineering. Other institutes, such as the Laboratory for Atmospheric and Space Physics (LASP) and JILA, are represented as well. In addition, CIPS reaches outside the University with affiliates from government labs, such as the National Institute of Standards and Technology (NIST), the High Altitude Observatory of the National Center for Atmospheric Research (NCAR), and the Space Environment Labs of the National Oceanic and Atmospheric Administration (NOAA), and from several local research companies, such as Lodestar Corporation, Tech-X Corporation and Science Applications International Corporation.

The Center for Integrated Plasma Studies supports communication and exchange of ideas in plasma physics. It does so through its seminar series, which covers all aspects of plasma physics. In addition, CIPS provides research opportunities for students and all others interested in this field.
Note from the Director

This past year was our 10th year of existence and we celebrated with a retreat, a barbecue, and an overnight stay at the University’s Mountain Research Station. We thank Alan Kiplinger and Carolyn James for the arrangements that made the retreat go smoothly. Many of us had our first chance to use the observatory that Alan assembled at the Research Station for his research on coronal mass ejections. The clear dark skies provided excellent views of Mars icy polar cap, the Ring Nebula and a number of star clusters in the Milky Way.

The highest point of the year, however, was our beginning a search for a new faculty member in experimental plasma physics. The retirement of Prof. Raul Stern had reduced the breadth of our experimental program. We appreciate the strong support from the College of Arts and Sciences and from the Physics Department that made the search possible, and look forward to interacting with a new experimentalist next year.

Scott Robertson
CIPS 10th Anniversary Retreat

CIPS members, friends, and their families celebrated the 10th Anniversary of the Center on August 26, 2003, star gazing at the University of Colorado Alpine Observatory at the Mountain Research Center. This star party coincided with the closest approach of Mars in 60,000 years. There was a new moon, so we also observed for Uranus, Neptune, star clusters, galaxies, nebulae, iridum flares, and other satellites and meteors.

Captured image of Mars as viewed from the Mountain Research Station.

Marty Goldman, Steve Seibold (MRS), and Alan Kiplinger pose for a shot.

CIPS members conversing on the lodge deck.
Personnel

Director:  Scott Robertson
Associate Director:  Scott Parker

CIPS Fellows
John R. Cary, Professor
Isidoros Doxas, Senior Research Associate
Martin V. Goldman, Professor
Alan Kiplinger, Senior Research Associate
James D. Meiss, Professor
David L. Newman, Senior Research Associate
Scott E. Parker, Associate Professor
Scott H. Robertson, Professor
Theodore Speiser, Professor Emeritus
Raul A. Stern, Professor Emeritus

CIPS Members
Daniel Barnes, Senior Research Associate
Yang Chen, Research Associate
Kathy Garvin-Doxas, Research Associate
Rodolfo E. Giacone, Research Associate
Amanda A. S. Gulbis, Research Associate
James E. Howard, Research Associate
Marie J. Jensen, Research Associate
Chet P. Nieter, Research Associate
Zoltan Sternovsky, Research Associate

CIPS Research Support Staff
Carolyn M. James, Professional Research Assistant
Graduate Students
Brent Goode  Jonathan Regele
Samuel Jones  Naresh Sen
Charlson Kim  Kiran Sonnad
Jinhyung Lee  Ireneusz Szczesniak
Jim Peoble  Srinath Vadlamani
Viktor Przebinda  Weigang Wan

Undergraduate Students
Marina Bondarenko  Candace Nichols
Russell Harding  Christopher Omland
Amanda Heaton  Kelsi Singer
Scott Knappmiller  Amber Westcott
Jason Kohut  Patrick Wheeler
Arthur Michalak

Volunteer
Arlena Szczesniak, volunteer

Members from other Institutes
Frances Bagenal, Professor of APS
Daniel Baker, Professor, Director of LASP
Timothy Fuller-Rowell, Senior Research Associate with CIRES
Alan Gallagher, JILA
Mihály Horányi, Associate Professor of Physics/LASP

CIPS Scientist Associates
HAO/NCAR: Paul Charbonneau, Tom Holzer, Art Hundhausen, BC Low, Gang Lu,
Art Richmond and Ray Roble.
Lodestar Corporation: Dick Aamodt, Dan D’Ippolito, and Jim Myra
Space Science Inst: Paul Dusenbery
SEC/NOAA: Ernie Hildner, Terry Onsager, Vic Pizzo, Howard Singer and Ron Zwickel
NIST: John Bollinger
Tech-X Corporation: Svetlana Shasharina, David Bruhwiler and Peter Stoltz
University of Northern Colorado, Greeley: Robert Walch
## Research Grants

### active during calendar year 2003

<table>
<thead>
<tr>
<th>Agency</th>
<th>Funding Period</th>
<th>Primary Investigator; Co-Investigators</th>
<th>Amount</th>
<th>Title</th>
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<tbody>
<tr>
<td>DOE</td>
<td>1995-2004</td>
<td>John R. Cary</td>
<td>1,649,000</td>
<td>Chaotic Dynamics in Accelerator Physics</td>
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<td>DOE</td>
<td>1997-2003</td>
<td>Scott Robertson; Mihály Horányi</td>
<td>1,005,000</td>
<td>Fundamentals of Dusty Plasma</td>
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<td>DOE</td>
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<td>Scott Parker</td>
<td>290,000</td>
<td>Electromagnetic Gyrokinetic Turbulence Simulations</td>
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<td>DOE</td>
<td>2002-2005</td>
<td>Scott Parker</td>
<td>755,000</td>
<td>Plasma Microturbulence Project</td>
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<td>HHS</td>
<td>2002-2005</td>
<td>Ronald Cole; Lecia Barker, Lynn Snyder, Barbara Wise, Scott Schwartz (Kathy Garvin-Doxas)</td>
<td>888,189</td>
<td>IERI: Scaling Up Reading Tutors</td>
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<tr>
<td>NASA</td>
<td>2001-2004</td>
<td>Alan Kiplinger</td>
<td>255,228</td>
<td>Hard X-Ray Spectroscopic Microwave and H-Alpha Linear Polarization Studies with Hard X-Ray Observations From HESSI</td>
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<td>Agency</td>
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<td>Amount</td>
<td>Title</td>
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<tr>
<td>NASA</td>
<td>2002-2005</td>
<td>Yi-Jiun Su; Scott Parker, Robert Ergun</td>
<td>97,001</td>
<td>CUSP Dynamics-Particle Acceleration by Alfven Waves</td>
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<td>NASA</td>
<td>2002-2005</td>
<td>Joshua Colwell; Scott Robertson, Mihály Horányi</td>
<td>383,979</td>
<td>Dynamics of Charged Dust Near Surfaces in Space</td>
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<td>NASA</td>
<td>2003-2006</td>
<td>Scott Robertson, Mihaly Horanyi</td>
<td>209,858</td>
<td>Mesospheric Aerosol Particle Spectrometer.</td>
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<td>NIST</td>
<td>2001-2005</td>
<td>Scott Robertson</td>
<td>211,493</td>
<td>Study of Laser-Cooled Ions in Penning Traps for Quantum Information Processing</td>
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<td>NSF</td>
<td>2001-2005</td>
<td>John R. Cary; Isidoros Doxas</td>
<td>350,000</td>
<td>ITR/AP: Application of Modern Computing Methods of Plasma Simulation</td>
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<tr>
<td>Agency</td>
<td>Funding Period</td>
<td>Primary Investigator; Co-Investigators</td>
<td>Amount</td>
<td>Title</td>
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<td>NSF</td>
<td>2002-2003</td>
<td>Isidoros Doxas</td>
<td>8,345</td>
<td>SGER: Using Branch Prediction and Speculative Execution to Predict Space Weather with a Cluster of Inexpensive PCs</td>
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<td>NSF</td>
<td>2002-2005</td>
<td>Lecia Barker; Kathy Garvin-Doxas</td>
<td>400,000</td>
<td>ITR: Research on Recruiting Middle School Minority and Majority Girls into a High School IT Magnet</td>
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<td>NSF</td>
<td>2002-2005</td>
<td>James Howard</td>
<td>94,000</td>
<td>Nearly Axisymmetric Systems</td>
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<td>NSF</td>
<td>2003-2006</td>
<td>Walter Kintsch; Isidoros Doxas</td>
<td>99,992</td>
<td>Scalable and Sustainable Technologies for Reading Instruction and Assessment</td>
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<td>University of Texas, Austin</td>
<td>2001-2005</td>
<td>Isidoros Doxas</td>
<td>104,604</td>
<td>Low-Dimensional Models for the Solar Wind Driven Magnetosphere-Ionosphere System</td>
</tr>
</tbody>
</table>

* italicized names signify CIPS non-members
Seminar Series
coordinated by Zoltan Sternovsky, David L. Newman

<table>
<thead>
<tr>
<th>Date</th>
<th>Speaker</th>
<th>Title</th>
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<tbody>
<tr>
<td>January 24</td>
<td>Peter Stoltz, Tech-X Corporation</td>
<td>Secondary electron emission related to heavy-ion fusion</td>
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<tr>
<td>January 31</td>
<td>Christopher Watts, NM Tech</td>
<td>Alfvén wave studies in a helicon plasma</td>
</tr>
<tr>
<td>February 7</td>
<td>Charlson C. Kim, CIPS</td>
<td>Hybrid kinetic-MHD simulations in general geometry</td>
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<tr>
<td>February 28</td>
<td>Kiran Sonnad, CIPS</td>
<td>Finding a near integrable Hamiltonian using Lie Transformation</td>
</tr>
<tr>
<td>March 21</td>
<td>Alexey Burov, FNAL</td>
<td>Circular modes and beam adapters</td>
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<tr>
<td>April 4</td>
<td>Tom Crowley, NIST</td>
<td>Fluctuation and electric potential measurements in the Madison symmetric torus</td>
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<td>April 11</td>
<td>Charlson C. Kim, CIPS</td>
<td>Hybrid kinetic-MHD simulations in general geometry</td>
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<tr>
<td>April 18</td>
<td>Yang Chen, CIPS</td>
<td>Simulations of turbulence transport with kinetic electrons and electromagnetic effects</td>
</tr>
<tr>
<td>April 25</td>
<td>Srinath Vadlamani, CIPS</td>
<td>The &quot;Continuum-particle method&quot;: an algorithmic unification of Vlasov and particle-in-cell methods</td>
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<td>May 2</td>
<td>Yi-Jiun Su, LASP</td>
<td>Electron accelerations by Alfvén Waves in the dayside Auroral region</td>
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<td>May 8</td>
<td>Viktor Przebinda, CIPS</td>
<td>Implementing dynamic load balancing for VORPAL</td>
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<td>May 9</td>
<td>Marie Jensen, NIST</td>
<td>Temperature measurements of laser-cooled ions in a Penning Trap</td>
</tr>
<tr>
<td>Date</td>
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<tr>
<td>August 4</td>
<td>Carl R. Sovinec, Univ. Wisconsin</td>
<td>Analyzing pulsed poloidal current drive and single helicity in the reversed-field pitch</td>
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<tr>
<td>September 5</td>
<td>David L. Newman, CIPS</td>
<td>Hybrid Vlasov/fluid simulations of coherent phase-space structures: low-cost approaches to studying 2-D plasma dynamics</td>
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<td>September 12</td>
<td>Peter Stoltz, Tech-X Corp.</td>
<td>Numerical modeling of electron emission from the walls of high-power waveguides</td>
</tr>
<tr>
<td>September 19</td>
<td>Scott H. Robertson, CIPS</td>
<td>Teaching plasma physics to undergraduates with Mathcad®</td>
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<td>October 17</td>
<td>Dan D’Ippolito, Lodestar Corp.</td>
<td>Blob transport in the Tokamak scrape-off-layer (SOL)</td>
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<tr>
<td>October 24</td>
<td>Scott E. Parker, CIPS</td>
<td>Gyrokinetic simulations of electromagnetic turbulence</td>
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<tr>
<td>November 7</td>
<td>Robert Ergun, APS</td>
<td>Auroral particle acceleration by strong double layers</td>
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<td>November 14</td>
<td>Fatima Ebrahimi, Univ. of Wisconsin</td>
<td>Nonlinear magnetohydrodynamics of AC helicity injection</td>
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<td>November 21</td>
<td>Peter Messmer, Tech-X Corp.</td>
<td>Generation of teraHerz radiation by laser-solid interaction</td>
</tr>
<tr>
<td>December 5</td>
<td>James E. Howard, CIPS</td>
<td>The Discrete Virial Theorem</td>
</tr>
</tbody>
</table>
Professional Interests

Yang Chen
My research is on the numerical modeling and prediction of turbulence and transport in toroidal fusion plasmas. In order for the fusion reaction to take place in a self-sustained manner, the plasma must be heated and maintained at a certain level of density and temperature. However, instabilities tend to develop in such plasmas which either terminate the plasma or lead to saturated turbulence and enhances particle and energy transport.

John R. Cary
My interests are concentrated in plasma physics, beam/accelerator physics, nonlinear dynamics, and computational physics. My plasma physics interests include studies of space plasma physics as well as fusion plasma physics. My beam physics interests are in understanding collective instabilities, the nonlinear dynamics of two-degree-of-freedom symplectic maps, and the use of laser plasma interactions to generate large electric fields for particle acceleration. My computational interests are in massively parallel computing and in scientific Object Oriented Programming.

Dan Barnes
Dr. Barnes develops and applies advanced computational methods for the study of magnetically confined plasmas. He is especially interested in the coupling and interplay between fluid and particle methods, both by extending fluid methods to include kinetic effects, and by extending particle methods to the long time step and large spatial scale regime required for the study of macroscopic phenomena. He is currently a member of the NIMROD team which develops advanced fluid modeling codes and the VORPAL team which develops advanced electromagnetic particle codes.

Dr. Barnes also has been and continues to be a principal in the Innovative Concepts program of the national fusion program. He contributes to the theory of field-reversed configurations and also has a continuing interest in electrostatic confinement systems.
Kathy Garvin-Doxas

My research focus is on education and technology particularly in the sciences. I evaluate a variety of new learning tools as they are being designed using a combination of quantitative and qualitative methods (pre- and postsurveys, video-taped and direct observations and analysis, individual and focus group interviews) to determine student learning gains, how well the learning tool works, and recommendations for improvements. This work has lead to my involvement with national efforts to employ evaluation as an agent for change in teaching and learning at the classroom, discipline, and institutional levels. I also work on gender issues related to science and technology, as well as effective collaboration in classrooms—particularly in science lab settings.

Rodolfo Giacone

My research activities are in the area of plasma physics, with emphasis on laser plasma interactions as related to plasma based accelerators. I am also interested in the use of modern computing methods with applications to laser-plasma physics. Our research in the area of plasma based accelerators was focused on laser wake field accelerator schemes. In particular, we studied some proposed all-optical injections schemes to inject electrons into a plasma wake field for acceleration. We performed numerical simulations using VORPAL, particle-in-cell code developed in our group. We showed the previous proposed all-optical injection schemes failed to produce single particle beams. We proposed an alternative scheme which generated a high quality, single particle beamlet.

Isidoros Doxas

The main subject of my research is plasma turbulence in laboratory and space plasmas, especially as analyzed by the methods of nonlinear dynamics and large-scale particle simulations. I have worked on stochastic transport in fusion devices, and on the limits of quasilinear theory. For the past ten years I have participated in and directed research projects in magnetospheric physics.
Amanda Gulbis

Since I received my degree in December of 2002, I spent the spring and summer of 2003 wrapping up my thesis work. We presented the work in one paper and at three different conferences, and have submitted an additional paper for publication. I conducted follow-up experiments on dust transport in plasma sheaths and created documentation for my work to allow continuation of the project with future students.

Martin Goldman

I continue to develop nonlinear theoretical models to interpret measurements in Earth’s auroral ionosphere of localized unipolar fields (double layers), associated localized bipolar electric field structures and highly nonthermal particle distributions. This year I have developed a theory of associated shear-driven instabilities.

James Howard

My research interests lie mainly in applications of Hamiltonian dynamics to a wide variety of physical problems, including dust dynamics in planetary magnetospheres, asteroidal satellites, microwave ionization of Rydberg atoms, plasma confinement, and RF ion traps. In addition I collaborate with Applied Math faculty on dynamics problems, particularly Hamiltonian systems and symplectic maps. I also enjoy collaborations with colleagues in Vienna, Potsdam and Budapest on a variety of astrophysical problems.
Alan Kiplinger
My research revolves around several areas of observing solar activity. In particular, solar activity that has direct effects on the Earth and its space environment. These phenomena include solar flares and their associated interplanetary particle events and coronal mass ejections. Efforts involve the use of solar hard and soft X-ray, microwave, optical and EUV data.

Marie Jensen
My recent work has been focused on measuring the temperature of laser-cooled ions in a Penning trap, primarily motivated by the possibility of creating many-particle entangled states. Such states would have applications in the fields of both quantum information and frequency standards. A Penning trap is a device used to trap charged particles. The confinement is due to a combination of static electric and magnetic fields.

James Meiss
My research is in the area of dynamical systems, in particular the study of the onset and characterization of chaos. Current research has focused on the geometry of three and four dimensional dynamical systems.
Scott Parker
My research areas include theory and simulation of plasma turbulence and transport, kinetic particle effects and kinetic closure of macroscopic magnetohydrodynamic fluid models, magnetosphere and auroral ionosphere Alfven waves, and new numerical methods for kinetic plasma simulation.

Chet Nieter
My research is in the area of radio frequency heating of fusion plasmas, in particular the numerical modeling of mode conversion and resonant absorption with the plasma physics code VORPAL. I have used VORPAL to model the generation and absorption of Electron-Berstein waves in magnetically confined, over-dense plasmas.

David L. Newman
My primary research activities are in the field of nonlinear plasma physics, with emphasis on theoretical modeling and nonlinear simulation of wave and particle phenomena in a variety of near-Earth space plasma and laboratory environments.
Scott Robertson
My research interests are in experimental plasma physics including the ionosphere and space, as well as the development of rocket-borne probes for ionospheric aerosols (NASA-funded). A second NASA grant (with Josh Colwell) supports laboratory studies of the electrostatic transport of lunar and martian dusts. A DOE grant (with Mihály Horányi) supports fundamental studies of dusts in plasmas. I also involve undergraduates in research on confinement of plasma in Penning traps and interact with a NIST group using Penning traps. In 2002, although I was officially on sabbatical leave, I continued to advise Engineering Physics students and to advise graduate students.

Zoltan Sternovsky
My research interest is currently in plasma probes, in the physics of dusty plasmas and in the electric properties of cosmic dust particles. I perform experiments in this area and I am also involved in the development of probe theories and dust charging in plasmas. I build experimental set-ups, develop instrumentations and perform numerical calculations.
Publications

**Celestial Mechanics**


**Dusty plasmas**


**Education**


**Ionospheric Physics**


**Laboratory Plasmas**


**Laser Plasma**


**Magnetic fusion**


Nonlinear dynamics and chaos


Non-neutral plasma


Particle accelerators


Space Physics

Presentations

papers presented at professional conferences but not published and invited talks

Celestial Mechanics


Dusty plasmas


Education


**Ionospheric Physics**


**Laboratory Plasmas**


**Magnetic fusion**


Non-linear dynamics


Non-neutral plasma


Particle accelerators


Plasma diagnostics

Space physics


Current Research Programs

The following abstracts are brief summaries of various research projects currently carried out by CIPS scientists.

Dan Barnes

Extended MHD modeling with NIMROD

Describing high temperature plasmas in terms of fluid variables presents a challenging numerical problem because of the importance of widely varying time and space scales. CIPS is playing a central role in extending the NIMROD community code (http://www.nimrodteam.org) to include important effects which are omitted from previous treatments of the plasma as a single electrically conducting fluid (magnetohydrodynamics or MHD model). Recently, a time-implicit method has been developed and applied to describe plasmas as two independent fluids (electrons and ions).

While a single-fluid plasma has only non-dispersive waves which have a frequency increasing linearly with wavenumber, a two-fluid plasma supports dispersive waves, for which the frequency increases quadratically with wavenumber. If a time-explicit method is applied to a two-fluid plasma description with realistic spatial resolution, the maximum numerically stable time step becomes extremely small. Figure 1 shows how the frequency depends on wavenumber for a case in which the variation is primarily perpendicular to the magnetic field, and also shows excellent agreement of the numerical results with theoretically predicted modes.

Only the two lowest frequency modes are shown in the Figure. There is a higher frequency branch which has a frequency about $10^6$ times the highest frequency shown. Thus, if an explicit time advance requiring $t < 1$ were used, about one trillion time steps would be required to represent a single period of the lowest frequency mode. As a practical matter then, the time advance must be made implicit.

![Figure 1: Mode frequency $\omega$ vs. wavenumber $k_{||}$ times ion collisionless skin depth $d_i$. The open symbols show the theoretical frequencies, while the solid symbols show the numerical results. There are two modes for two different values of plasma pressure ($\beta = 10^{-2}$ and $\beta = 10^{-8}$) shown. The green (red) dashed lines show the behavior of a nondispersive (dispersive) mode.](image-url)
The time advance used to obtain the results of the Figurez reduce to about 60 the number of time steps required to represent a single period of the low frequency modes of interest here. The method uses a predictor-corrector method with a direct solve based on the SuperLU (http://acts.nersc.gov/superlu) software package and is implemented in the NIMROD finite element framework so that it may be applied to any plasma geometry.

John R. Cary, Brent Goode

RF heating of plasmas

There are many applications of of Radio Frequency (RF) power in plasma, from heating and current drive, to profile control and instability suppression. The accurate prediction of the propagation and absorption of RF waves in plasmas is a crucial element in the design of a working fusion reactor. We are working in collaboration with Lee Berry of Oak Ridge National Lab. We have calculated an improved plasma response theory with additional terms to describe new physical effects, which were not included in previous calculations. These new terms allow us to add the effects of magnetic field gradients in arbitrary directions and magnetic field curvature to the calculation of the plasma’s response to RF fields. When previous calculations left these effects out they made assumptions about the size of these effects relative to other physical phenomena, such a thermal motions of particles.

We are using our new theory to examine the effect that these approximations had on the accuracy of previous results. Our new theory also has a more complete incorporation of collisional effects than other RF absorption theories used for fusion physics. We have incorporated the effects of collisions from the start. This allows us to derive an expression for the plasma response which is valid at all temperatures, unlike previous theories which assumed high temperatures in their treatment of collisions. When we take the high temperature limit of our theory, we find that the coefficient of the collisional term in one previous theory needed a correction. There are cases in existing fusion experiments where this correction would make a difference in the propagation and absorption of a wave.
John R. Cary, Rodolfo Giacone

Production of high quality, single electron beams by optical injection

Our research efforts have recently been concentrated on a promising, novel concept to generate high quality particle beams in the laser wake field accelerator (LWFA) scheme called optical injection. Through the use of a new computer code (VORPAL) developed in our group, we demonstrated that most proposed all-optical injection schemes failed to produce a single electron beamlet. We showed that multiple particle beams are generated instead, which is very undesirable for most applications. We have developed and tested new alternatives for injection schemes by performing computer simulations using VORPAL. In one proposed scheme, we made use of a cleanup pulse to effectively eliminate all but the first accelerating bucket. The absence of trailing accelerating buckets then eliminates the production of trailing beamlets. We were able to obtain single, short (< 10 fs.) beams with normalized emittance less than 0.5 pi-mm-mrad and energy spread of a few percent. We also showed that a similar effect can be achieved by propagating a laser pulse in a plasma channel. One advantage of this method is that it uses only two laser pulses instead of three as in the cleanup pulse scheme.

John R. Cary, Jinhyung Lee

Microwave cooling of a strongly magnetized electron plasma

For a strongly magnetized electron plasma whose transverse temperature is below the Landau temperature of the plasma, the gyromotion separates from the other dynamics, and the motion is quantized. From results of molecular-dynamics simulations for the strongly magnetized electron plasma, we concluded that crystallization can be achieved below a longitudinal critical temperature irrespective of transverse temperature. In order to get such a cold electron plasma whose longitudinal temperature is low enough for the plasma to be a crystalline phase, we introduce microwave cooling to the electron plasma. A microwave tuned to a frequency below the gyrofrequency forces electrons moving towards the microwave to absorb a microwave photon. Simultaneously the electrons move up one in Landau state and then lose their longitudinal momentum. In this process, the longitudinal temperature of the electron plasma can be decreased. On the basis of a small ratio
between the ground and the first excited state, we set up two level transition equations and then derive a Fokker-Planck equation from the two level equations. With an aid of a finite element method (FEM) code for the equation, the cooling times are calculated for several values of the magnetic field, the microwave cavity, and the relative detuning frequency from the gyrofrequency. Consequently, the optimal values of microwave cavity and detuning frequency from the gyrofrequency, for longitudinal cooling of a strongly magnetized electron plasma with microwave bath, have been found. Also, the microwave intensities to keep a constant ratio between two transverse Landau levels has been calculated. By applying the optimal values with an appropriate microwave intensity, the best cooling can be obtained. For the electron plasma magnetized with 10T, the cooling time to the solid state is approximately 2 hours.

Isidoros Doxas with Wendell Horton, Manish Mithaiwala

Low-dimensional dynamical models for the solar wind driven magnetosphere-ionosphere system

A new, spatially-resolved nonlinear dynamics model of the coupled solar wind driven magnetosphere-ionosphere system is developed for the purpose of determining the energy flows from the nightside magnetosphere into the ionosphere. The model is derived from Maxwell’s equations and nonlinear plasma dynamics and focuses on the key conservation laws of mass, charge and energy in the power transfer elements in this complex dynamical system. In contrast to neural networks, the model delineates the physically realizable, time ordered sequence of events in substorm dynamics initiated by changes in the solar wind and interplanetary magnetic field (IMF). The spatially resolved model predicts a different causal order and different signatures for the consequences of the different energetic events associated with magnetic reconnection in the geotail and the onset of near geosynchronous orbit flux tube convection. The conservation laws constrain the numerous energy transfer coupling mechanisms leading to various, and sometimes chaotic, dynamical events in the transfer of electrical power to the inner magnetosphere and to the ionosphere.

Figure 4: A plot of the chaotic attractor of the coupled magnetosphere-ionosphere in the I-V (current-voltage) space. The model exhibits chaotic behavior for certain parameter ranges, with unpredictable onset times.
Isidoros Doxas with Robert Weigel, Daniel Baker, Michael Wilberger, John Lyon, Wendell Horton

Using branch prediction and speculative execution to forecast Space Weather

Recent advances in the development of integrated models of the Sun-Earth environment are placing increasing emphasis on data assimilation schemes that can maximize the information extracted from our sparse sampling of upwind conditions. Standard Kalman Filter techniques, widely used in tropospheric weather modeling, require significantly better coverage than is available upwind.

Branch Prediction and Speculative Execution consists of making probabilistic estimates of current upstream conditions, and distributing among available machines simulations that assume each of the probabilistically estimated states as initial conditions. As the near-Earth space evolves and near-Earth satellite data are compared with the models, some of the speculatively executed simulations will be proved wrong. At that point the machines that were executing them will be reassigned either to new lines of speculative simulation, or to increase the processing power devoted to more promising simulations already executing. The scheme is particularly suited to Space Weather since our upwind early warning sentries can provide only sparse sampling of the incoming solar wind, while the bulk of our monitors, which can provide significantly better coverage, are located close to Earth and provide much shorter lead times. By the time the data comes in from the near-Earth monitors, the forecasts of the speculative simulations are already in hand, reducing the lead time computational penalty (the portion of the lead time devoted to advancing the model) to almost zero. The scheme is similar to Ensemble Kalman Filters but is less reliant on dense data coverage, allows numerical models easier adherence to conservation laws, and can be used with empirical models without modification.

Isidoros Doxas, Delores Knipp, Courtney Willis

Using Space Weather to motivate the standard Electricity and Magnetism curriculum

A computer module is being developed that uses the real-life effects of Space Weather as a motivation for studying the basic concepts of Electricity and Magnetism at the level of a typical introductory physics course for non-majors. The module is designed to enable instructors to engage students in exploring problems that are complex enough...
to be of practical interest, while still allowing them to concentrate on the simple concepts and equations they need to learn. The design of the module is based on studies carried out over the past six years at three different Universities, and the evaluation shows an improvement both in student attitudes towards science, and in content assimilation.

Isidoros Doxas, Walter Kintsch, Michael Klymkowsky, Kathy Garvin-Doxas, Noah Finkelstein, Courtney Willis

Using Latent Semantic Analysis to classify student concepts in science

Misconceptions are deep-seated models that students hold about the way the physical world works. They are an impediment to learning, and they can best addressed with specifically designed instructional tools and methods. Mapping the dominant misconceptions in a field is also critical for the development of research-based assessment tools in that field, because they make the most reliable distracters in multiple-choice instruments. This project uses Latent Semantic Analysis (LSA) to identify and classify misconceptions in Physics, Astronomy, and Biology. LSA is a vector-based model that uses Singular Value Decomposition to identify the most important eigenvectors in a multidimensional space derived from texts on a given subject, affording a wide number of semantically meaningful vector operations, like dot products. Results so far indicate that LSA is comparable to human experts in classifying student essays according to science concepts present in them.
Kathy Garvin-Doxas, Isidoros Doxas

The Use of technology to enhance student learning

Kathy Garvin-Doxas works in research and evaluation of STEM (Science, Technology, Engineering and Mathematics) education initiatives, particularly those that involve the use of technology to enhance student learning. With STEM Colorado, she coordinates assessment and evaluation efforts among participating departments as well as basic organization for the project. Her research focuses on misconceptions about classroom collaboration and cooperative learning; issues of gender and diversity among those who study and work in information technology fields; articulating the communication process necessary for eliciting student misconceptions about STEM subjects as a model for computer-student interactions; and the development of research-based learning assessment instruments as well as protocols and instruments for use in evaluating course transformation and the success of innovations. Additionally, she provides workshops on institutional change and course transformation for many national organizations in STEM education, and on improving teaching and learning in STEM classrooms.

Kathy Garvin-Doxas, Lecia Barker

Recruiting middle school girls into a high school Information Technology Magnet program

The project examines the recruiting message and methods for recruiting middle school girls into the Denver Public Schools Computer Magnet (DPSCM), a three-track program that recruits from all 22 middle schools in the Denver Public School District (DPS). The objective is to identify recruiting methods that IT magnet programs across the nation can use to have more effective and sustainable means of attracting girls from different socio-cultural groups. The project builds upon previous research, which shows that middle school is a critical juncture for girls since it is at that stage when girls begin to make choices that are more influenced by stereotypical career choices and other culture-based beliefs than personal preference. The project identifies barriers to entry and retention as well as positive messages that increase participation. Both approaches are needed because simply removing the barriers does not necessarily increase girls’ participation.
Martin Goldman, David L. Newman, Naresh Sen

Kinetic Simulation of nonlinear electrostatic field structures in Earth’s Auroral zone and analogous laboratory environments

Recent in situ observations by satellites such as FAST (Fast Auroral SnapshoT) reveal the key role played by electrostatic structures, such as double layers and electron phase-space holes (Figure 10), in Earth’s auroral current system. Our research — performed in collaboration with Prof. Robert Ergun and Dr. Laila Andersson of CU’s Laboratory for Atmospheric and Space Physics (LASP) — is focused on understanding the origin and evolution of such structures through the use of numerical simulations. In addition to their role in the near-Earth space environment, we are interested in how analogous phenomena can be studied in a laboratory setting. Our simulations are based on the numerical integration of the Vlasov equations, which describe the evolution of the phase-space distribution of particles in a collisionless plasma.

Effect of hot electron “halo” populations on the formation and evolution of strong auroral double layers

Double layers are characterized by intense localized electric fields that can accelerate electrons and ions to high energies. Electron holes are long-lived nonlinear structures that are formed by the electrons accelerated through the double layer. New observations suggest that the characteristics of auroral double layers can be influenced by the presence or absence of a hot background population of halo electrons. Figure 11 compares the electric field histories from two Vlasov simulations, which differ only in the density and temperature of the halo electrons. Note how the presence of a cool and dense halo results in a more stable and less turbulent double layer.
Two-dimensional structure of auroral double layers and electron holes in the opposite limits of strong and weak ion magnetization

Our Vlasov simulations of auroral double layers and electron holes have been extended to a second spatial dimension using different reduced treatments to model the perpendicular particle dynamics. Figure 12 contrasts two simulation runs in which the ions were treated alternatively in the limits of strong and weak magnetization. Note in particular how the structure of the double layer (bounded by dashed purple lines) differs in the two runs.

Theory and simulation of electron-shear-modified two-stream instabilities

Our 2-D double-layer simulations reveal the presence of gradients (perpendicular to \(B\)) in the electron current (parallel to \(B\)). This electron shear can play a potentially important role in the subsequent evolution of the plasma. We have begun a study of the role of electron shear on the linear and nonlinear evolution of streaming instabilities. Figures 13 and 14 show electrostatic potentials and fields at three times during the evolution of periodic 2-D Vlasov simulations for initial states of symmetric counterstreaming electron beams with and without velocity shear. The linear stages of evolution are in good agreement with theoretical predictions from a model based on the eigenvalues and eigenfunctions of the Mathieu equation. The nonlinear stages are quite different, with larger electron holes in the sheared run.

Unsheared Electron Distribution

Figure 13: Electrostatic potential and electric-field intensity from a periodic Vlasov simulation with strongly magnetized unsheared electrons. The top, middle, and bottom rows are from the linear, early nonlinear, and late nonlinear stages of evolution.

Sheared Electron Distribution

Figure 14: Same as Fig. 13, but for electrons that are initially sheared so that the electron beam velocities are maximum at the center (in y) and minimum at the edges.
New “reduced” kinetic algorithms for efficient simulation of multidimensional plasmas

We are engaged in an ongoing effort to develop new simulation techniques that take advantage of the essentially noiseless character of the Vlasov method while simultaneously reducing computational demand that a full-Vlasov approach would require in higher dimensions.

“Dissipative moment closures” for unmagnetized particles

We have implemented a method in which the perpendicular dynamics of an unmagnetized plasma species is evolved using dissipative moment closures, which reproduce the linear kinetic response while evolving only a limited number of moments of the distribution. The parallel dynamics continue to evolve using a fully kinetic (Vlasov) algorithm. This approach greatly reduces the size of the computational grid needed. As an illustration, Figure 15 shows three times during the evolution of an initially symmetric ion-acoustic pulse using the reduced Vlasov simulation method for both electrons and ions. The symmetry of the pulse at subsequent times is an indication of how the moment method matches the full kinetic behavior.

Reduced algorithms for weakly magnetized particles

Treating a weakly magnetized species with a full Vlasov simulation is particularly costly because it requires at least five phase-space dimensions. Several reduced methods are under consideration to ease the computational demand. In one such method, the two perpendicular velocity dimensions are reduced to a single ring in the perpendicular velocity plane. Despite the great reduction in computational complexity, this reduced algorithm can be shown to yield linear dispersion curves (Fig. 16) that agree rather well with those derived from full kinetic theory.

Figure 15: Electron and ion density at three stages during the evolution of an initially symmetric ion-acoustic pulse using the reduced Vlasov simulation method for both electrons and ions.

Figure 16: Comparison of dispersion relation from reduced model (red) and full kinetic theory (black).
James Howard

Nearly Axisymmetric Systems

Nearly axisymmetric systems occur in many physical problems, including dust dynamics in planetary magnetospheres, ion motion in a Paul trap, microwave ionization of Rydberg atoms, field errors in plasma fusion devices, or any axisymmetric device where imperfections introduce small azimuthal variations. In a truly axisymmetric system, all dynamical quantities, including the canonical momentum $p$, are independent of the azimuthal angle $\phi$, allowing a two-dimensional description of single particle motion in terms of an effective potential, $\Phi^e$. In the presence of small azimuthal variations it often happens that $\Phi^e$ merely oscillates about an average value, $\Phi^e_0$, which may be used to define an average effective potential, $U^e$. The motion may then be described as quasi-two dimensional, with orbits confined within a topological torus much smaller than the exact zero velocity surface.

Ion Traps

Another important and very actively studied axisymmetric system is the RF Paul trap, which offers myriad physical and technological applications. While the pioneering experiments were conducted in purely axisymmetric geometry, current experiments are almost invariably performed using slightly nonaxisymmetric electrodes, in order to establish an “axis of crystallization,” along which ions can line up. In addition, easily fabricated elliptic traps are widely used in quantum computation research. In all these applications it is essential to avoid unstable combinations of parameters, which can lead to “crystal melting” and rapid loss of trapped ions. Perhaps the most thoroughly studied configuration is the relative two-ion motion, which is conveniently split into a rapid “Zitterbewegung” and a slow time-averaged “secular” motion.

Elliptic traps are also of current interest for quantum computation applications. In contrast to the dust problem, where the perturbation strength is small and dictated by planetary parameters, the asymmetry of the Paul trap has no such limitations and can in fact be quite large. Preliminary results indicate that two-ion motion in an elliptic trap with an asymmetry smaller than about 10 percent remains quasi-two-dimensional. At large asymmetry particle confinement is limited only by the topology of zero-velocity surfaces, which involves some interesting applications of singularity theory, where the familiar two-dimensional
dimensional critical points are generalized to Morse saddles with normal forms \( u = x_1^2 \pm x_2^2 \pm x_3^2 \), where the \( x_i \) are local rectangular coordinates. Figure 17 is a three-dimensional contour plot of the zero-velocity surfaces for two-ion motion in an elliptic trap.

**Plasma Physics**

*Field-Reversed Configurations*

Field-Reversed Configurations (FRC) offer several attractive features for a fusion reactor: high \( \beta \) (and therefore high power density) operation, negligible toroidal magnetic field, structural simplicity (no internal coils), and the potential for environmentally desirable advanced fuels. In addition, FRCs provide insight into other fusion devices (e.g. Tokomaks, Mirror Machines, and other Compact Tori), as well as the opportunity to study basic plasma physics problems. For these reasons several major FRC experimental programs are underway worldwide (particularly in Russia and Japan) with a scattering of small-scale theoretical programs. These include equilibrium and stability studies utilizing various combinations of fluid and kinetic models, as well as numerical code development. In the USA significant programs exist at Princeton, Cornell, U. Washington, and Los Alamos National Laboratory, in both prolate and oblate geometry. Of these the prolate case has been more thoroughly studied as more suitable for extrapolation to a fusion reactor, although oblate configurations offer their own set of advantages. The magnetic field is purely poloidal with a field null within the plasma, resulting in typically chaotic ion dynamics. For small gyroradius, the FRC is theoretically unstable to three \( n = 1 \) MHD modes; the radial shift, tilt, and interchange modes. However, several experiments demonstrate stability to the most important of these modes, the tilt mode. The reasons for this anomalous stability may lie in neglected finite gyroradius effects or perhaps are rooted in kinetic effects not present in a fluid model.

We have shown that while classical guiding center motion only exists for very low particle energy in such a well, ions are nevertheless well confined by energy conservation, and may circulate, as shown in Figure 19 or suffer reflections between high-field regions, making transitions between these two modes. In general the motion is a mixture of a chaotic sea, with regular (non-chaotic regions) embedded as phase...
space islands centered on periodic orbits.

**Dust Dynamics**

*Saturn*

We have continued our investigations of charged dust dynamics in planetary magnetospheres, with new excursions to Jupiter and Mars. A more complete treatment of orbital equilibrium and stability has been carried out for dust grains near Saturn, with emphasis on the subtle synergism between the topology of zero velocity surfaces and orbital chaos and ergodicity. New classes of orbits have been discovered and paths for their possible loss to the planet or outer space. Two-dimensional Lyapunov exponents have also been calculated in order to quantitatively measure the degree of orbital chaos. Calculation of 3D Lyapunov exponents is under way to measure the nonaxisymmetric effects of radiation pressure. Surprisingly, we have found significant populations of orbits which are confined in open potential wells by virtue of an underlying invariant action. This intriguing synergism between topology and ergodicity may have profound implications for particle confinement and loss.

*Jupiter*

We have verified our conjecture that the tilt of the jovian magnetic axis induces strongly chaotic behavior for dust grains smaller than about 750 nm, an interesting application of nearly axisymmetric theory. The predictions of a simplified model have been confirmed by more complete orbital simulation. It remains to implement a perturbative expansion of the single particle Hamiltonian to demonstrate that an invariant averaged canonical momentum exists for regular orbits.
Asteroidal Satellites

*Transverse Orbits*

We are continuing our work on the equilibrium and stability of asteroidal moons about extended asteroids. Our principal results demonstrate that initially circular orbits remain so under gradual increase in asteroid rotation rate. Remarkably, periodic orbits appear to remain *exactly* periodic, now recognized as an instance of “adiabatic switching.” In a new paper for *Celestial Mechanics*, in collaboration with Prof. Dan Scheeres (U. Mich.), we extend our repertory of gravitational models and employ second order perturbation theory to improve our semi-analytic description of orbital tilt into a successful quantitative theory.

Microwave Ionization of Rydberg Atoms

Classical models have enjoyed considerable success in describing the ionization of Rydberg atoms by microwave radiation. In particular, this approach, a wedding of celestial mechanics and atomic physics, yields useful ionization thresholds, which shed light on both classical dynamics and “quantum chaology.”

Circular Polarization

Experiments are currently being planned using elliptically and circularly polarized (CP) microwaves, which are usually studied in the case where the orbital plane coincides with the plane of polarization. At very low scaled RF frequencies $\omega/\omega_K < 0.1$ ionization is well described by a static Stark model. Here we consider the range $0.1 < \omega/\omega_K < 0.8$ but allow out-of-the-plane motion. For small electric field strength we again have a nearly axisymmetric system, with the spherically symmetric Kepler Hamiltonian as unperturbed system. We are currently investigating the structure of the zero velocity surface which turns out to be isomorphic to the ZVS for the radiation pressure model for a nonmagnetic planet.

Two-Frequency Excitation

Our previous theoretical work on two-frequency excitation resulted in successful experiments carried out at SUNY Stony Brook. These experiments, originally at high microwave frequency, i.e. well above the orbital frequency of the participating electron, are now being extended to much lower microwave frequencies, where new resonances come into play. A new theory for this interesting frequency regime has been developed, featuring a new “island interspersal” condition on the two frequencies. The theory is complicated by the presence of new island chains corresponding to sums and differences of the driving frequencies and their harmonics.
Nonlinear Dynamics

Virial Theorem

The virial theorem is one of the keystones of classical mechanics, with a myriad applications in statistical mechanics (kinetic theory of gases), astrophysics (galactic dynamics), plasma physics (fluid and kinetic models), and practically every branch of the physical sciences. There are in fact many virial theorems, taking specialized forms for magnetic systems, special and general relativity, quantum mechanics, etc., etc. For natural Hamiltonian systems it yields a simple connection between the time averaged kinetic and potential energies of bounded orbits.

Recently we proved that a virial theorem also holds for discrete symplectic maps of a particular form analogous to natural Hamiltonian flows, for which kinetic and potential "energies" may be constructed. We also proved strong and weak forms of the classical virial theorem for both continuous and discrete Hamiltonian systems. Whilst applying these results to specific well-known examples, such as the Hénon-Heiles system (Fig.23) and the standard map (Fig. 24), we noticed pronounced differences in the rate of convergence of the virial for chaotic and regular orbits. Subsequent investigation revealed that this difference could be quantified and employed to provide a simple new measure of chaos, which we dubbed "meander." We are presently applying these results to other physical examples, including the Paul trap and dust dynamics in planetary magnetospheres. Figure 25 illustrates a new discrete "power map" which illustrates bounded chaos.

Figure 23: Poincare section for the Hénon-Heiles system. Chaotic regions are represented in red, regular regions in green.

Figure 24: Standard Map (k=0.95)

Figure 25: Power Map
Marie Jensen
Measuring the temperature of laser-cooled ions in a Penning trap is primarily motivated by the possibility of creating many-particle entangled states. A Penning trap is a device used to trap charged particles. The confinement is due to a combination of static electric and magnetic fields. There is a strong magnetic field (in our case produced by a superconducting magnet) along the z-axis, also called the trap axis. This field provides the radial confinement, i.e., charged particles cannot escape from the trap along a direction perpendicular to the trap axis. The axial confinement is due to electric fields (appropriate voltages are applied to the electrodes to create the needed fields).

Experiments on trapped ions are carried out at NIST by Marie Jensen, Taro Hasegawa and John Bollinger. In this experiment, ions of beryllium are confined in a 4.5 T field. The ions are laser-cooled to a temperature of ~1 milliKelvin resulting in a crystalline state. When the laser-cooling is turned off, the ion plasma heats up from collisions with residual gas. At the phase transition, which occurs at a temperature of 10 mK corresponding to a coupling parameter of $\Gamma=170$, a sudden, large temperature increase is observed. This increase is caused by the onset of a coupling to ion motion, which is not cooled by the laser-cooling and therefore is excited to higher temperatures prior to turning off the laser-cooling. A method has been found, by which this abnormal excitation can be avoided. In this case, the heating rate remains low and is sufficiently low that ion-entanglement experiments will be pursued.

Alan Kiplinger
Dr. Kiplinger has been pursuing a three year grant under NASA’s Sun-Earth Connection Guest Investigator Program in support of the Ramaty High Energy Solar Spectroscopic Imager (RHESSI). Rhessi was launched in February of 2002 has recorded over 10,000 solar flares in its first two years – including the largest solar flare ever recorded from space. An objective of these efforts is to study X-ray and other data on solar events, including flares, coronal mass ejections and interplanetary particle events, into order to obtain a more comprehensive view of our Sun-Earth connections regarding interplanetary proton events. Part of these efforts are to better predict occurrences of interplanetary proton events that can be dangerous to astronauts and spacecraft.
In late October and early November 2003 the Sun provided one of the most active periods of solar activity since spacecraft have been in space. On the same hemisphere of the sun there were three sunspot groups (known as active regions) that produced more than 100 major solar flares, the largest recorded flare as seen in X-rays and very large interplanetary particle events and geomagnetic storms. One of the active regions is known as region 486 and can be proclaimed as the most powerful of regions during this solar cycle.

Figure 28: A full disk h-alpha image of the sun taken on Oct. 28, 2003 at Big Bear Solar Observatory. All 3 great active regions responsible for the solar activity seen in Oct. and Nov. are clearly visible. The region below center (active region 486) is the largest and most energetic region seen during this solar cycle.
Two of its solar flares saturated NOAA’s soft X-ray detectors that are used to classify solar flares. Kiplinger has carefully reconstructed the soft X-ray light curves of these giant flares by matching curves of similar but smaller flares from region 486. Images taken after the peak of the flare taken by NASA’s Transition Region and Coronal Explorer (TRACE) satellite are shown below in the light of Fe XII in the extreme ultraviolet. The temperature of the plasma loops is approximately 500,000 K to 2,000,000 K. The reconstructed data however shows that the effective temperature of the soft X-ray emitting plasma is far hotter at ~ 38 million K. Moreover, the flare saturated the detectors at a level of ~X18.4 but the corrected data indicates fluxes 66% larger at X30.6 – easily making this the largest ever seen since X-ray observations began in the mid-1960’s.

Almost simultaneously with the great flare, a Coronal Mass Ejection (CME) erupted from the vicinity of region 486 at a speed that appears to be the fastest on record. The speed measured from these and other images is approximately 5 million miles per hour or ~ 2240 km/s. Images of this eruption as recorded by the coronagraph on the Solar Heliospheric Observatory (SOHO) are shown on the following page.

Figures 29 and 30: The most powerful solar flare ever observed in X-rays as imaged by the TRACE satellite in the light of ionized Fe XII. The image to the left was taken just at the end of the energy releasing eruptive stage. The image below right shows the graceful post flare loop system that formed two hours later.
This was indeed a most remarkable period of activity when the Sun – Earth Connection and Plasma Physics really hit home. One Japanese spacecraft was lost completely and more than 25 other research satellites had to placed in safe hold conditions or suffered instrument losses. Astronauts on the International Space station were ordered into aft sections five times in order to receive more protection from proton storms. Power grid operators modified routing operations and reduced output of nuclear power plants in order to avoid damage from the numerous geomagnetic storms. Global positioning systems (GPS) had problems including a deep ocean drilling ship. We were fortunate that the great flare and CME pictured above occurred when it did and not five days earlier. Had that occurred, Earth would have taken the full blast of the CME and interplanetary particle storms – we would have had some real problems. In a paper being prepared, Kiplinger has found that intrinsic characteristics of these great flares are not fundamentally different from previous large events, but rather, they are just bigger.

Kiplinger has also continued work and support from two solar optical telescope systems operated by the U.S. Air Force. They are known as the Improved Solar Optical Observing Network (ISOON) and the Solar Optical Observing Network Solar Patrol on Tape (SOONSPOT). The ISOON is a vast improvement over the older SOON world wide
network and was intended to replace it. However, only one ISOON telescope is yet in operation. ISOON does support full disk imaging and it records precise images in the light of Hydrogen – alpha every minute. H-alpha is a most sensitive spectral line in which to see solar flares. Dr. Kiplinger recognized the patrol potential of this remarkable telescope in detecting the elusive phenomena of “flare waves” which accompany either major solar flares or CME’s. Accordingly he developed a means to observe not only the brightness of the hydrogen on the Sun, but to also measure its motion via sensitive Doppler measurements and to fold that data into the massive datastream. Several wave events of differing types have been seen. One such event is shown below that is associated with an X11 flare from region 486 on October 29. In the image, one sees not only the flare itself in the lower right hand corner, but also a series of large diffuse light and dark bands. The light bands show the Sun’s chromosphere moving upward and the dark bands show it moving downward. Although this flare is less powerful than the X30.6 flare described above, it was a very powerful gamma ray line flare that allowed the RHESSI satellite to obtain some of its best gamma ray imaging to date. (RHESSI missed the peak of the X30 flare).

Progress was also made with respect to the older SOON system and Dr. Kiplinger’s data archival system SOONSPOT. In 2003, the SOONSPOT system employed 3 U.S. Air Force SOON observatories located around the world. Each site records full disk Ha images every 30 minutes, and large scale H-alpha images of active regions or other features every five minutes (or 30s during flares). As described below, student support is being utilized to catalog and make available all SOONSPOT data of important flares observed by RHESSI. In 2003, SOONSPOT data for flares was saved to hard disk for more convenient access than tapes provide. Other recent advances are that new data is slated to be recorded on DVD’s instead of tapes. This makes data retrieval and searching far more convenient due to the random access of the DVD medium. Finally, a new Memorandum of Understanding has been written approved and signed by the U.S. Air Force, the NOAA Space Environment Center and the University of Colorado to continue the SOONSPOT archival program.
James Meiss

Transport and Mixing in Three Dimensional Fluid Flows

Fluid mixing corresponds to the transport of passive scalars by kinematic advection and their subsequent diffusive homogenization. Such phenomena are fundamentally important in many physical systems and engineering applications and occur at a variety of scales ranging from the very small (micrometer scale) to the very large (planetary scales and beyond). For instance mixing in microchannels can be used to efficiently homogenize reagents in chemical reactions even when the flow is laminar. Understanding transport for planetary scale flows is critical for climate modeling and pollution dispersion in atmospheric science and eddy dynamics in oceanography. Transport and mixing are also important in granular flows, population biology, and reaction-diffusion systems.

Figure 34: Lyapunov exponents and invariant tori for a three-dimensional flow corresponding to hexagonal convection cells.

Fold and Cusp Singularities of the Frequency Map for Hamiltonian Systems

In an integrable Hamiltonian system almost all motion takes place on invariant tori. The motion on these tori is conjugate to linear motion with frequencies that vary with the torus. The map that assigns to each torus its frequency is called the frequency map. Now consider an integrable symplectic

Figure 35: Frequency map with a cusp singularity.
map with a fold in the frequency map. The torus corresponding to the actions that map onto the fold has vanishing twist. The fold of the frequency map (the caustic) consists of singular values. The fold is a stable singularity for Lagrangian mappings, and therefore a one parameter family of such maps will not destroy the fold, but move it around in the frequency plane. Therefore the caustic will cross rational frequencies. When the map is perturbed by a small periodic perturbation interesting dynamics are expected when the fold is near a resonant frequency such that the resonance is in the image of the frequency map. This is the situation we study first. In a second step the existence of a special point on the fold line is assumed, which is another stable singularity, the cusp.

Scott Parker, Yang Chen

Our research is on the numerical modeling and prediction of turbulence and transport in toroidal fusion plasmas. In order for the fusion reaction to take place in a self-sustained manner, the plasma must be heated and maintained at a certain level of density and temperature. However, instabilities tend to develop in such plasmas which either terminate the plasma or lead to saturated turbulence and enhances particle and energy transport. Over the past years we have developed a Monte-Carlo simulation code, GEM (Journal of Computational Physics 189 (2003) 463-475), which can be used to study turbulence and transport in toroidal plasmas. GEM achieves large time steps and finite-beta capability by using three key algorithmic elements.

It uses the parallel canonical formulation to eliminate the difficulty with the inductive electric field, it uses the split-weight scheme to increase the time step, and it uses a novel algorithm for the Ampere’s equation. Extensive benchmarks with continuum codes, which do
not use a Monte-Carlo approach, have been carried out. Recently the code has been extended to treat general equilibrium profiles, including equilibrium sheared ExB flow and sheared parallel flow. We have also improved the parallelization scheme so that more than 512 processors can be used on the NERSC SEABORG supercomputer. Recent GEM simulation indicates that electromagnetic turbulence is more robust to shear-flow suppression. In particular, turbulence can self-sustain by nonlinear effects in the presence of sheared flow, even if the plasma is linearly stable.

Scott Parker, Weigang Wan

Tearing mode instabilities play an important roll in tokamak discharges. The basic process is the anti-parallel magnetic field lines break and reconnect in the plasma to form magnetic islands. The perturbed vector potential is symmetric with respect to the central layer. Using an electromagnetic gyrokinetic \( \delta \) particle-in-cell simulation model [Y. Chen and S. Parker, J. Comp. Phys. 189, 463 (2003)], we studied the evolution of collisionless and semi-collisional tearing mode instabilities. Drift-kinetic electrons are used. Linear eigenmode analysis is presented for the case of fixed ions and there is excellent agreement with simulation. A double peaked eigenmode structure is seen indicative of a positive \( \Delta' \). Nonlinear evolution of a magnetic island is studied and the results compare well with existing theory in terms of saturation level and electron bounce oscillations. Electron-ion collisions are included to study the semi-collisional regime. The algebraic growth stage is observed and compares favorably with theory. Nonlinear saturation following the algebraic stage is observed. In simulations with larger box sizes (64 ion gyroradii radially) we found that the ion gyrokinetic response is important and cannot be neglected. Furthermore, in these larger box simulations, the instability exhibits an odd parity, different than the even tearing parity.
Scott Robertson and Zoltan Sternovsky

Charged Aerosol Particles in the Ionosphere

In the northern summer, ice particles form in the polar ionosphere at about 83 km altitude. When these particles grow sufficiently large they are observed near the Arctic Circle as noctilucent clouds. The distribution of these particles, their relationship to climate, and their effect on charge balance is just beginning to be understood. We have developed a series of rocket-borne probes to detect charged aerosol layers. These probes have flown in rocket campaigns from the Andoya rocket range in Norway and from Esrange in Sweden. We are developing more sophisticated probes to determine the charge-to-mass ratio of the aerosol particles so that particle sizes can be determined. In conditions too warm for clouds, the probes may observe the predicted global layer of aerosol particles containing metals ablated from meteors. These particles may serve as the condensation nuclei for the cloud particles.

Figure 39: Rocket-borne probe for charged aerosols

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Nonneutral plasma in Penning traps

Nonneutral plasmas are plasmas consisting of electrons or ions alone. The Penning trap is a device in which a magnetic field prevents loss of the particles in the radial direction and biased conductors at the ends prevent loss in the axial direction. In the absence of collisions with gas molecules, there should be no plasma losses. We used our Penning trap this past year to investigate the loss of electrons arising from “collisions” with stray electric fields. This loss mechanism has been termed asymmetry transport and limits...
confinement times. We find that this transport is greatly reduced when the inside surfaces of the vacuum chamber are spray-painted with colloidal graphite. Probe data show that the potentials above these surfaces are spatially very uniform, with variations of order 15 millivolts, which is near to the resolution of the diagnostic probe. Without the coating, potential variations are ~250 millivolts although the surfaces are carefully cleaned with acids and solvents. Electron confinement times are increased by about an order of magnitude. Improved confinement times are particularly important for plasmas that are difficult to create, such as positron and antiproton plasmas.

*Dusty plasmas*

Surfaces of airless moons and asteroids are covered with a dusty regolith that is charged by the electrons and ions of the solar wind and by the photoelectric effect. There is observational evidence from satellites that the regolith particles are levitated and transported by electric fields and deposited in low-lying regions. The smaller particles may be accelerated to escape velocity. We have investigated these effects in the laboratory by placing dusty surfaces beneath plasma and in UV radiation. Simulated lunar and Mars dusts have been used as well as lunar dust returned by the Apollo 17 mission. CCD images have been made of levitated particles and of the spreading of dust layers. Modeling of dust charging and of the forces on the dust particles predict the sizes of particles that can be transported. Experiments have also been done with simulated Mars regolith. These experiments provide a basis for interpretation of data from robotic space missions and will help in planning future missions to the moon, Mars, a comet or an asteroid. Instruments are being developed for a return mission to the moon that will probe the plasma and dust environment at the lunar surface.
Laboratory plasmas
In order to understand our dusty plasmas, we have needed to develop better diagnostic tools for low-temperature laboratory plasmas. The standard diagnostic tool is the wire probe developed by Langmuir. Careful analysis of the plots of current versus voltage shows two significant deviations of the data from the standard theoretical models. The first of these is an excess ion current arising from ion collisions near the probe. In collaboration with scientists at the Naval Research Laboratory, we developed a theoretical model for the ion current and showed that it explained a large discrepancy between theory and experiment for the ion part of the probe current. Another discrepancy is caused by a population of electrons created by secondary emission from the wall. A theory with two electron populations and with ion collisions fits the data to within a few percent, gives densities and temperatures for the two electron populations, and allows electron and ion densities to be compared as a check for consistency. With the improved data analysis, it is possible to being modeling the flow of energy between the two electrons populations and to make a predictive model for electron temperature.
Extra Activities
additional tasks and positions

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CEO, Tech-X Corporation
Member, American Geophysical Union
Member, organizing and program committee, Advanced Accelerator Concepts Workshop.
Member, Organizing Committee of the Particle Accelerator Conference (2004)
Member, Plasma Science Committee, National Research Council, National Academy of Sciences
Member, Program Committee of the Particle Accelerator Conference (2004)
Member, Sherwood Fusion Theory Conference Executive Committee
Member of thesis committee of Sam Jones and Charlson Kim
Postdoctoral advisor of Rodolfo Giacone and Chet Nieter
Principal dissertation advisor for Kiran Sonnad, Brent Goode, and Jinhyung Lee
Supervisor of Kathy Garvin-Doxas and Isidoros Doxas

Yang Chen
Advisor for Weigang Wan, a graduate research assistant
Member, American Physical Society

Isidoros Doxas
Chair, Space Science and Astronomy Committee, American Association of Physics Teachers.
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Kathy Garvin-Doxas
Chair, Distance Education and Educational Technologies Topical Interest Group, American Evaluation Association.
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Evaluator, Digital Library for Earth Science Education (DLESE)
Evaluator, Field Tested Learning Assessment Guide (FLAG)

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Martin Goldman
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Member, American Physical Society Anti-terrorism Task Force
Member, American Geophysical Union,
Member, American Physical Society, Division of Plasma Physics Publication Committee
Member, American Physical Society Panel on Public Affairs
Member, American Institute of Physics, Committee on Journals
Member, International Advisory Board of European Center for Nonlinear Sciences
Member, Physics Dept. Chair Election Committee
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Associate Editor, Physics of Plasmas.
Peer Reviewer for various Adjudications and Letters.
Principal Dissertation/Thesis Advisor for Naresh Sen (with David Newman)
Member of Dissertation/Thesis Committee for Daniel Main, APS Dept
Member of Masters or Ph.D. Qualifying Examination Committee for Colin Mitchel and David Foster

James Howard
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Member, American Astronomical Society
Member, Committee on Space Research (COSPAR)
Helped teach graduate class in classical mechanics.
Marie Jensen
Member, American Physical Society

James Meiss
Principal Dissertation/Thesis Advisor for multiple Graduate Students. Member of Dissertation/Thesis Committee for Masoud Asadi-Aeydabadi, Member of PhD Qualifying Examination Committee, APWM. Supervisor, Dynamical Systems Tetrahedron Supervisor, Fall 2003, Independent study for Karl Obermeyer, APPM Major Professor, Spring 2003 APPM 8100, Seminar in dynamical systems Professor, Fall 2003, APPM 7100 Dynamical Systems and Chaos APPM 7100, 10 students Professor, Spring 2003, APPM 2360 Diff Eq, 100 students Course Coordinator for APPM 2360, Spring 03 Co-Organizer for a symposium, ‘Transport and Mixing in Three-Dimensions’ for the May 2003 SIAM Dynamical Systems Meeting with I. Mezic Associate Chair for Graduate Studies, Advisor for our 1st and 2nd year students Graduate Committee. Departmental Technology Liaison to the FTEP program Departmental Technology Liaison to the FTEP program Fellow, Colorado Center for Chaos and Complexity. Associate Editor for SIAM Journal on Applied Dynamical Systems Peer Reviewer for various papers and proposals.

David L. Newman

Chet Nieter
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Scott Parker
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