DOE Contract DE-AI02-00ER54591

The Plasma Panel met on March 5-6, 2001 at the National Science Foundation in Arlington, VA to review proposals before a panel of nine participating panelists. The contract costs were funded by DOE/Gaithersburg, MD and consisted of panelists airfare costs and catering services in support of the panel.

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DOE/ER/54591

Final Report: 0076065

Final Report for Period: 09/2000 - 08/2004

Principal Investigator: Stenzel, Reiner L.

Organization: U of Cal Los Angeles

Title:

Vortices, Reconnection and Turbulence in High Electron-Beta Plasmas

Submitted on: 11/05/2003

Award ID: 0076065

Project Participants

Senior Personnel

Name: Stenzel, Reiner

Worked for more than 160 Hours: Yes

Contribution to Project:

As Principal Investigator Prof. Stenzel produces the ideas for new research, writes research proposals, performs experiments, writes papers, delivers talks and presentations, guides students and research associates, and administers the grant.

Name: Urrutia, J. Manuel

Worked for more than 160 Hours: Yes

Contribution to Project:

As research physicist, Dr. Urrutia is responsible for the design and execution of experiments, in particular the digital data processing, the publishing and presenting of research findings, assistance to educate graduate students, and assistance in the research administration.

Post-doc

Graduate Student

Name: Griskey, Matthew

Worked for more than 160 Hours: Yes

Contribution to Project:

Matt participated in designing and constructing experiments on magnetic reconnection. He performed the experiments, evaluated the data, published part of his research findings and gave presentations at the 2001 APS-DPP meetings. He wrote a PhD dissertation and graduated in June 2002. He is presently performing post doctoral research.

Name: Strohmaier, Kyle

Worked for more than 160 Hours: Yes

Contribution to Project:

Kyle participates in our research on magnetic reconnection and field reversed configurations in EMHD plasmas. He has advanced to candidacy and defined his PhD thesis topic in the above area.

Undergraduate Student

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Pollock, Shawn

Worked for more than 160 Hours: Yes

Contribution to Project:

Shawn assisted in our research program by constructing magnetic probes, testing their properties and applying them to measure magnetic fields in plasmas.

DOE Patent Clearance Granted

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E-mail: mark.dvorscak@ch.doe.gov
Office of Intellectual Property Law
DOE Chicago Operations OfficeAug 31 2004
Date

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Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree
Fiscal year(s) REU Participant supported: 2001
REU Funding: REU supplement

Name: Choi, Brian

Worked for more than 160 Hours: Yes

Contribution to Project:

Brian helped with the our research program on magnetic turbulence in plasmas. He performed a variety of tasks involving construction of experiments, measurements and data analysis. He became a skilled experimentalist in physics.

Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Bachelor's Degree
Fiscal year(s) REU Participant supported: 2001
REU Funding: REU supplement

Name: Guevara, Gabriel

Worked for more than 160 Hours: No

Contribution to Project:

Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Associate's Degree
Fiscal year(s) REU Participant supported: 2003
REU Funding: No Info

Organizational Partners

Other Collaborators or Contacts

We have informal but fruitful dicussions on EMHD reconnection and turbulence in current sheets with the Princeton group headed by M. Yamada.

Activities and Findings

Research and Education Activities:

The goal of our research is to understand the nonlinear interaction of magnetic fields with dense plasmas in the parameter regime of electron magnetohydrodynamics (EMHD). Such processes are fundamental for explaining magnetic reconnection in space and laboratory plasmas. They also arise in strong whistler turbulence.

Our approach is to perform carefully diagnosed laboratory experiments.

We are working at the forefront of this field by studying three-dimensional(3D)magnetic field geometries, i.e., fields with three vector components that vary in three dimensions in space. These are formed by imposing a dipole field opposite to a weaker uniform magnetic field inside a dense laboratory plasma. It results in a field-reversed configuration (FRC) whose stability is also of great interest for fusion applications. The pulsed dipole field is rapidly switched off so as to observe the free relaxation of the FRC without stabilizing boundary currents. We have discovered a new precession motion of an EMHD FRC. During the relaxation magnetic field lines reconnect spontaneously until all closed field lines have been transferred to open field lines. Reconnection does not take place at the 3D magnetic null points but at the O-type null layer where field lines tear and annihilate. In this process magnetic energy is converted into kinetic energy of electrons. Electron heating facilitates the development of ion sound turbulence which produces anomalous resistivity and fast reconnection. The magnetic field topology of a tilted FRC exhibits four magnetic null points, two radial and two spiral nulles. All field lines are open. We started to investigate

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the mechanism of magnetic 'reconnection' in arbitrary 3D fields.

Two graduate student participated in this reasearch effort. One advanced student has completed his thesis work and graduated. The results are written up in six Physics of Plasmas papers and one Physical Review Letter. Both graduate students have made presentations at the last APS meeting. We also have trained two outstanding undergraduate students with the support of an NSF REU grant. Both of them persue graduate studies in physics. Another REU student is still working with us. Since his appointment extended beyond the original expiration date of the grant (8/31/2003) a one-year extension at no cost has been granted. However, most of the goals of the grant have been accomplished and are described at this time in the final report.

Findings:

A major result is the understanding how magnetic reconnection proceeds in three-dimensional EMHD plasmas: Field lines are NOT reconnected at the 3D radial magnetic null points but are annihilated in the toroidal quasi-2D null layer where most of the toroidal current flows. This current is driven by the inductive electric field associated with the decaying dipole field. The free energy source is the magnetic field produced by electron currents. Electron heating occurs due to Joule dissipation in regions where the electrons are essentially unmagnetized. No dissipation arises when the electrons are magnetized and support Hall currents that are perpendicular to electric fields. Strong ion acoustic turbulence is observed inside the current sheet. The theory of ion sound turbulence predicts anomalous resistivity which can explain why the observed reconnection rate greatly exceeds the value based on classical resistivity.

The experiment allows a careful analysis of the energy flow. Most of the free magnetic energy of the dipole field is converted into electron thermal energy, some of it is radiated away as whistlers and some goes into the unmagnetized ions via acceleration by space charge electric fields.

The self-consistently formed current sheets are usually broader than the electron inertial length. Thus, inertial EMHD effects are not observed. Turbulence may be the cause for current sheet broadening.

The stability of EMHD field reversed configurations has been investigated. They are less prone to tilting than MHD FRCs. The latter are unstable since in a single fluid subject only to magnetic forces a dipole likes to align itself with the external field; i.e., reverse its direction or tilt by up to 180 degrees. However, in EMHD fields the magnetic force which produces the tilting is balanced by the electric force, i.e., the fields are force free and do not rotate the electron fluid. However, the null regions in an FRC are not subject to EMHD physics and some tilting does occur. Most interesting is the discovery that a tilted EMHD FRC precesses around an axis defined by the uniform external field. The reason is that the perpendicular field components are frozen into the electron fluid which rotates in the toroidal direction. The observed precession velocity is that of the toroidal electron fluid flow.

Further novel results are that in a tilted FRC the toroidal null line degenerates into two spiral magnetic null points. There is no separatrix surface which distinguishes between closed and open field lines. All field lines are open. Nevertheless, magnetic energy conversion does occur near the spiral magnetic null points. Understanding these phenomena is at the forefront of research in 3D reconnection physics. 3D field topologies are the essence of strong EMHD turbulence which may produce 'anomalous' dissipation and fast reconnection on the MHD scales.

We also have studied EMHD turbulence driven by pressure gradients in a high-beta plasma. In this work a dense nonuniform discharge plasma is created in a weak external magnetic field. The electron pressure exceeds the magnetic pressure and the magnetic field is expelled from the plasma interior. First, it was observed that the standard MHD pressure-balance equation does not hold. The reason is that with unmagnetized ions the electron pressure is balanced by both magnetic and electric forces, i.e., a combination of magnetic and Boltzmann equilibrium. Second, a strong instability was observed which arises from the electron diamagnetic drift through the unmagnetized ions. It produces large density and magnetic field fluctuations ($\sim 48\%$; $\sim 40\%$) in the range of the lower hybrid frequency. Using the technique of on-line conditional averaging the space-time dependence of the fluctuations has been mapped. The density perturbations consist of field-aligned flutes which propagate close to the ion sound speed in the direction of the average cross-field electron drift. The magnetic perturbations form flux ropes embedded in the density flutes. The self-helicity of magnetic field and current density is negative irrespective of the sign of the perturbation. Superimposing the fluctuations on the average quantities, the instantaneous density, magnetic field, and current density are obtained in 3D space. The field lines are compressed in density depressions, rarefied in density enhancements with an opposite twist, i.e., alternating net magnetic helicity. In large density enhancements, the magnetic field is so weak that the electrons become effectively unmagnetized. Large Larmor radius effects reduce the electron drift, which saturates the instability. In density depressions, where the magnetic field is large, the instability propagates at the sound speed in the electron drift direction, and with >1 twists, compresses, and expands the initially uniform magnetic field lines. The magnetic turbulence is measured with probes, analyzed by correlation techniques, 3D hodograms, and conditional averaging. Instantaneous magnetic field lines and current density lines in 3D space have been resolved. The magnetic fluctuations consist of flux ropes embedded in density flutes. With fluctuations on the order of the mean field, the electrons become locally demagnetized which also saturates the instability. Anomalous transport, nonlinear wave steepening, formation of current sheets, and non-adiabatic electron orbits have been observed in this turbulent high- β plasma. The observed mode, having properties of sound waves and oblique whistlers, has been called an electron magnetosonic mode in a high beta plasma.

Our earlier research was focussed on the properties of linear whistler vortices. The observation of whistler vortices and flux ropes was a major contribution to plasma physics. These propagating magnetic structures are excited by pulsed currents, pulsed magnetic fields, and electron pressure pulses in a large uniform magnetoplasma in the parameter regime of EMHD. The magnetic field perturbation, $\delta B(r,t)$,

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measured with magnetic probes and resolved in three-dimensional space and time resembles that of three-dimensional vortices or flux ropes. The structures propagate predominantly along the stronger background magnetic field. When Fourier transformed in space and time, the eigenmodes are shown to fall on the dispersion surface of low-frequency, plane, oblique whistlers. In weakly collisional plasmas, energy and magnetic helicity are well conserved quantities and the magnetic field can be shown to be frozen into the electron fluid.

EMHD vortices have the unique property that their helicity depends on the direction of propagation along. Helicity conservation implies that the injection of helicity produces unidirectional emission of vortices. Helicity injection has been accomplished with knotted or linked antenna currents. A magnetic antenna, consisting of a loop linked through a torus, exhibits vacuum fields similar to plasma fields of EMHD vortices. Experiments show that for positive antenna helicity only a vortex propagating along B_0 is excited, for negative antenna helicity only a vortex opposite to B_0 is produced with typically 20dB directivity (forward/backward energy ratio 100:1). The sign of the antenna helicity is determined by the relative direction of the current flow in the loop and torus. The antenna directionality based on helicity matching also holds for the detection of vortices. Transmission between two identical loop-torus antennas is unidirectional and non-reciprocal. Helicity receiving antennas have also been used to measure the degree of helicity of natural whistler wave noise in the discharge plasma. Observations showed that the magnetic fluctuations in the low frequency whistler branch exhibit more negative than positive helicity, implying preferential propagation against B_0 ; or along the beam of primary electrons emitted by the cathode. The latter excites oblique whistlers by a Cherenkov instability.

Theoretically, magnetic helicity is an invariant in an ideal fluid. However, a dilemma arises when a vortex reflects from a conducting boundary: Its helicity must change sign since the direction of wave propagation changes. This is indeed observed. The violation of helicity conservation is explained by a breakdown of the frozen-in condition near the plasma-boundary interface. Field-line tying is not observed.

Helicity conservation also breaks down when an EMHD vortex propagates through a magnetic null point where the direction of B_0 reverses sign. At the null point the frozen-in condition breaks down and allows the violation of helicity conservation.

The collision of electromagnetic vortices is of general interest as a nonlinear wave phenomenon and of particular importance to the formation of turbulence through wave-wave interactions. Using two identical exciters, small amplitude vortices of opposite helicity are excited and propagate through each other. The vortices do not change their individual propagation, do not deflect in glancing collisions, i.e., exchange no momentum or energy. The observed interaction is identical to a linear superposition of the fields of individual vortices, even when the wave fields approach a significant fraction of the ambient field. These unusual properties are explained by the force-free nature of EMHD fields. Parallel currents cause no attraction since in uniform plasmas magnetic and electric forces are balanced.

However, when the magnetic field of a whistler vortex exceeds the background magnetic field the vortices produce many nonlinear effects. These arise from the $J \times B$ force and from magnetic null points where EMHD breaks down. For example, the penetration and propagation depends both on the direction and strength of the vortex fields. When the vortex field adds to the ambient field, the vortex can propagate in the whistler mode. In the opposite case, when a magnetic null point is formed, whistler propagation is not possible. When an oscillating magnetic field of a loop antenna excites vortices of opposite polarity the nonlinear plasma response produces locally dc and harmonic magnetic fields. When two nonlinear vortices propagate against each other they merge into a single vortex. Nonlinear vortex collisions are inelastic while linear vortices collide elastically. When a large amplitude vortex relaxes it can become unstable to tilting.

Training and Development:

Students were trained in designing and performing laboratory experiments, in writing data acquisition programs, evaluating and displaying digital data, and presenting their original research findings in written and oral forms.

Three undergraduate students were involved in our research program. They were sponsored by REU grants. Their early exposure to research stimulated them to pursue graduate studies in physics.

Outreach Activities:

Our research group has included a diverse group of students which included a woman of color, members of under-represented groups, and many undergraduate students. We are offering the possibility of apprenticeships in our laboratory to motivated community college students who are seeking a career in science. We are advising high school students with science projects. We have received support for three undergraduates from the NSF REU program (Research Experience for Undergraduates). The REU students became excited about experimental physics and, after two of them graduated, they entered graduate school in physics at UCLA.

Dr. Manuel Urrutia, an established scientist from an underrepresented community, is very active in various outreach programs with the Los Angeles Unified School District. He advises the UCLA chapter of Society of Mexican American Engineers and Scientists, and mentors high school students. He is active in symposia designed to increase minority participation in science. He plays a key role in the NSF sponsored outreach effort aimed at attracting Hispanic students to math and science. He is also currently serving as a mentor in the UC-sponsored Puente Project, which is designed 'to help educationally underserved students succeed academically, enroll in college, and return to the community as mentors and leaders' (<http://www.puente.net/>).

Journal Publications

R. L. Stenzel, J. M. Urrutia, M. C. Griskey, and K. D. Strohmaier, "3D EMHD Reconnection in a Laboratory Plasma", *Earth, Planets and Space* (EPS), Terra Scientific Publ. Co., p. 553, vol. 53(6), (2001). Published

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M. C. Griskey and R. L. Stenzel, "Magnetic helicity reversal of a whistler vortex transmitted through a three-dimensional magnetic null point", *Physics of Plasmas*, p. 4810, vol. 8, (2001). Published

R. L. Stenzel, J. M. Urrutia, M. C. Griskey, and K. D. Strohmaier, "3D EMHD reconnection in a laboratory plasma", *Earth, Planets and Space* (Terra Scientific Publishing), p. 553, vol. 53 (6), (2001). Published

R. L. Stenzel, J. M. Urrutia, M. Griskey, and K. Strohmaier, "A new laboratory experiment on magnetic reconnection", *Physics of Plasmas*, p. 1925, vol. 9 (5), (2002). Published

R. L. Stenzel, M. C. Griskey, J. M. Urrutia, and K. D. Strohmaier, "Precession of an Electron-Magnetohydrodynamic Field-Reversed Configuration", *Physical Review Letters*, p. 185004, vol. 88, (2002). Published

R. L. Stenzel, M. C. Griskey, J. M. Urrutia, and K. D. Strohmaier, "Three dimensional electron magnetohydrodynamic reconnection. I. Fields, currents, and flows.", *Physics of Plasmas*, p. 2780, vol. 10, (2003). Published

M. C. Griskey, R. L. Stenzel, J. M. Urrutia, and K. D. Strohmaier, "Three-dimensional electron magnetohydrodynamic reconnection. II. Tilt and precession of a field-reversed configuration", *Physics of Plasmas*, p. 2794, vol. 10, (2003). Published

M. C. Griskey, R. L. Stenzel, J. M. Urrutia, and K. D. Strohmaier, "Three dimensional electron magnetohydrodynamic reconnection. III. Energy conversion and electron heating", *Physics of Plasmas*, p. 2801, vol. 10, (2003). Published

R. L. Stenzel, M. C. Griskey, J. M. Urrutia, and K. D. Strohmaier, "Three dimensional electron magnetohydrodynamic reconnection. IV. Instabilities, fluctuations, and emissions", *Physics of Plasmas*, p. 2810, vol. 10, (2003). Published

J. M. Urrutia, R. L. Stenzel, and M. C. Griskey, "Laboratory studies of magnetic vortices. III. Collisions of EMHD Vortices", *Physics of Plasmas*, p. 519-28, vol. 7, (2000). Published

R. L. Stenzel, J. M. Urrutia, and M. C. Griskey, "Vortices and Flux Ropes in Electron MHD Plasmas I", *Physica Scripta*, p. 112-116, vol. T84, (2000). Published

J. M. Urrutia, R. L. Stenzel, and M. C. Griskey, "Vortices and Flux Ropes in Electron MHD Plasmas II", *Physica Scripta*, p. 117-121, vol. T84, (2000). Published

R. L. Stenzel and J. M. Urrutia, "EMHD Turbulence in a High-Beta Plasma. I. Plasma Parameters and Instability Conditions", *Physics of Plasmas*, p. 4450-4456, vol. 7, (2000). Published

J. M. Urrutia and R. L. Stenzel, "EMHD Turbulence in a High-Beta Plasma. II. Single Point Fluctuation Measurements", *Physics of Plasmas*, p. 4457, vol. 7, (2000). Published

R. L. Stenzel and J. M. Urrutia, "EMHD Turbulence in a High-Beta Plasma. III. Conditionally averaged multipoint fluctuation measurements", *Physics of Plasmas*, p. 4466, vol. 7, (2000). Published

Books or Other One-time Publications

M. Hoshino, Reiner L. Stenzel, K. Shibata, "Magnetic Reconnection in Space and Laboratory Plasmas", (2001). Book, Published
 Editor(s): M. Hoshino, Reiner L. Stenzel, K. Shibata
 Bibliography: *Earth, Planets and Space* 53, No.6, 2001
 Terra Scientific Publishing Company, Tokyo, Japan

Matthew Charles Griskey, "Laboratory Studies of the Transition Region from a Magnetized to an Unmagnetized Plasma"

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", (2002). Thesis, Published
 Bibliography: PhD Dissertation
 March 22, 2002
 Department of Physics and Astronomy,
 University of California, Los Angeles, CA 90095-1547

Web/Internet Site

URL(s):

<http://www.physics.ucla.edu/plasma-exp/> or
<http://www.physics.ucla.edu/people/index.html>

Description:

Site describes experimental program, devices, research findings, publications and conference presentations, all supported by past and present NSF grants.

In addition there is a link to an undergraduate laboratory course in plasma physics with excellent pictures of electron beams which have frequently been asked to be referenced.

Other Specific Products

Product Type: Data or databases

Product Description:

A new computerized data acquisition system has been developed. It serves to collect large data sets semi-automatically for measuring multi-dimensional functions such as three-dimensional vector fields in space and time. Future applications will include six-dimensional phase space measurements of electron distribution functions. Another application includes the remote supervision and control of our large plasma device during continuous operation.

Sharing Information:

Design and operation will be described in an article in the Review of Scientific Instruments.

Contributions

Contributions within Discipline:

Basic physics predicts that the electromagnetic energy is a highly conserved quantity in a medium of high electrical conductivity. A hot ionized gas, such as the plasma around the sun, can be considered a nearly perfect conductor. However, observations of solar flares demonstrate that magnetic energy is NOT conserved in these events but rapidly converted into thermal energy. After half a century of research, no satisfactory explanation has been found on this puzzle, called magnetic reconnection.

Laboratory experiments modelling the basic interaction of time-varying magnetic fields with plasmas have been performed. Most have modelled two-dimensional fields with null points since this is what early theories by Sweet-Parker and Petschek described. In nature fields are usually three dimensional. Our experiment deals with reconnection of magnetic fields with three-dimensional null points. Furthermore, we address a parameter regime called electron magnetohydrodynamics (EMHD) which applies to the conditions near a magnetic null point. There the ions are unmagnetized while the electrons are still magnetized. This parameter regime has not been studied by other researchers in the field. Our experiment provides for fully three-dimensional time and space resolved field measurements which cannot be done in space plasmas. The laboratory plasma is large enough to neglect boundary effects so that our results are applicable to space plasmas. With this unique experiment we have discovered many new features of reconnection:

- (i) Magnetic fields do not reconnect at a 3D radial null point but only at null lines.
- (ii) Magnetic fields are annihilated in an O-type null line.
- (iii) In EMHD magnetic energy is converted into electron thermal energy. When the electron temperature exceeds the ion temperature, current-driven ion sound turbulence is generated in the current sheet which enhances the resistivity, hence rate of dissipation or reconnection. Our experiment clearly demonstrates the important role of microturbulence in reconnection.
- (iv) We have demonstrated the frozen-in concept in EMHD plasmas. Electron fluid motion causes magnetic field line twisting, stretching, and compressing. The 'out-of-plane' field component in 2D EMHD reconnection is a simple manifestation of the frozen-in concept. It is readily observed in our experiments in toroidal geometry.
- (v) We have discovered violations in the concept of conservation of magnetic helicity. Helicity is not conserved when a magnetic vortex propagates through a magnetic null point or when it reflects from a conducting boundary. The observations have been explained by a breakdown of the frozen-in condition in magnetic null regions and boundary layers.
- (vi) We have shown that a tilted EMHD FRC precesses. Its topology is fundamentally different from that of an untilted FRC: There is no

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closed separatrix; all field lines are open. The toroidal null line degenerates into two spiral null points. The two original radial null points move off-axis and, with increasing tilt, lie close to the new spiral nulls.

Thus, our laboratory experiments have produced new findings in the basic physics of conservation laws in electromagnetism, 3D reconnection physics, and field topologies in plasmas.

Contributions to Other Disciplines:

Magnetic reconnection and magnetic topologies play an important role in space science. Examples are magnetospheric plasmas, solar and astrophysics. Our laboratory experiments on magnetic field topologies and reconnection are closely related to these fields. We have made the following contributions to those disciplines:

(i) We resolve plasma phenomena on the electron inertial scale. This is seven orders of magnitude better than the best spatial resolution in solar physics. Thus, our laboratory experiments allow us to study small scale electron phenomena present in space plasmas but unknown to solar physicists. We expect to find on such small scales new dissipation processes that are unknown in classical MHD models. EMHD turbulence may provide 'anomalous' dissipation in MHD fields just like Debye-scale microturbulence provides 'anomalous' resistivity in large scale current systems.

(ii) We have made the first observations of spiral magnetic null points in plasmas. These have been predicted theoretically but cannot be directly measured in space plasmas. In the laboratory we perform multipoint measurements at up to 10,000 points whereas four points in space is the best resolution obtained by cluster satellites in the magnetosphere. From the highly resolved field measurements we obtain the plasma currents. We stress the importance of current closure which is often neglected in unrealistic two-dimensional theories.

(iii) Many reconnection models in space science invoke thin current sheets. Our measurements show that current sheets always exceed the expected electron inertial length due to the formation of turbulence and the presence of Hall currents.

(iv) We have studied magnetic turbulence with an advanced measurement technique called conditional averaging. This technique allows us to observe the average properties of random magnetic structures with a single pair of probes. We have studied the formation of flux ropes in high beta plasmas which are of interest in the solar wind. We measure their helicity. We have discovered a new whistler-sound mode in a high beta plasma. It steepens into a whistler-sound shock wave. These phenomena are unknown in space yet likely to occur.

Thus, our laboratory experiments have revealed new physical processes that are of interest in other disciplines such as space science and we developed new measurement techniques useful for electromagnetic turbulence studies in many fields.

Contributions to Human Resource Development:

The NSF support has enabled one graduate student to obtain his Ph. D. degree in Physics (M. C. Giskey, 2002), another student to advance to candidacy for the Ph. D. (K. D. Strohmaier), one student to earn her M. S. degree (Tsitsi Madziwa, 1998), and several undergraduates to obtain research experience in the laboratory. The Co-PI (Dr. J. M. Urrutia) is a professional scientist from an underrepresented group; T. Madziwa is a female student of color.

Contributions to Resources for Research and Education:

Our research stimulated ideas for new experiments in undergraduate teaching laboratories. For example, the Physics Department provided the P.I. with \$55,000 to upgrade a large lower division laboratory course in electromagnetism. He designed many new experiments and digital measurement techniques which were based on the experience gained from our laboratory research program.

Our research program in EMHD physics stimulated other groups to enter this field of research (see G. Ravi et al, Phys. Plasmas 10, 2194, 2003; <http://link.aip.org/link/?php/10/2194/>).

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Organizational Partners

Contributions: To Any Beyond Science and Engineering