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Also submitted to electronic portal at: www.osti.gov/elink-2413

SUBJECT: Final technical report DE-FG02-06ER54853

Grant Title: Experimental Studies of Self Organization with Electron Plasmas

PI: W. H. Matthaeus, Department of Physics and Astronomy, University of Delaware

Date: 10 April 2011

Overview: This is a final technical report on the subject grant DE-FG02-06ER54853 to the University of Delaware. The period of the grant was from 12/1/2005 to 11/30/2008, and was extended formally for another year, with a cost extension that ended 11/30/2009. The total budget was $163,396. The original PI was Prof. Travis Mitchell. A PI change was approved on 1/29/2008 that changed the PI to Prof. W H Matthaeus. The local UD designation of the grant was PHYS37213206000. I apologize that this report is so late – some of the reasons are given in a later section on "Other factors".

Research Progress and Scientific Findings:

The findings in this project are best summarized in the context of the goals of the research program, to study the nonlinear, self-organizing and turbulent behavior observed in the University of Delaware Penning Trap Experiment constructed and operated by Prof. Travis Mitchell. Following the departure of Prof. Mitchell from the Department of Physics and Astronomy, Prof. W. H. Matthaeus supervised the project; until last year this was under support of a re-search grant from the US Department of Energy. Prof. Mitchell was an experimental, and built the Penning trap, and Prof. Matthaeus is a theorist. So when the PI-ship changed hands and Prof. Mitchell was no longer at UD, the emphasis changed from primary experimental work and analysis to a more theoretical emphasis, but still in close contact with the Penning Trap experiment. A planned continuation of the experimental data acquisition, employing customized plasma initialization to study issues emerging in the theoretical studies, has not materialized, due to events beyond control of the students and researchers involved in the project. See Other Factors section. Therefore the project has focused on theoretical interpretation of the existing datasets. Given these restrictions, the group has been able to make very good scientific progress, outlined below.

- One very important accomplishment is that two PhD students have finished their degrees, with their theses directly relating to this project. These are:

1) Dr. Doug Rodgers, thesis defense August 2010, graduated December 2010, thesis title ”Turbulent Relaxation and Meta-stable Equilibrium of an Electron Plasma.”

2) Dr. Md. Tareque Aziz, thesis defense February 2011, will graduate May 2011, thesis title “Spectral and Statistical Study of Relaxation Processes in Two-Dimensional Guiding Center Plasma Using Penning Trap Data.”

- A good measure of the scientific activities and progress we have made in this project is given by a review of the papers we submitted to journals and conferences. Here is a description with citations:

We completed several systematic studies of several related aspects of the nonlinear and frequently turbulent character of the 2D electron fluid plasma dynamics observed in the Delaware Penning Trap [1–7]. This progress can be summarized in four related projects:

1. Relaxation to a meta-stable state. For more than a decade there has been a discrepancy between predicted final states of a 2D periodic hydrodynamic or guiding center fluid, and the observations made in a Penning trap. The UD group clarified this situation through experimental, numerical and theoretical modeling of the single vorticity (charge sign) species fluid in a circular free slip (conducting) boundary. The conclusion is that more turbulent systems relax toward a metastable state that is better described by maximum entropy theory than by selective decay theory [1, 2, 4]. This topic was a major component of the thesis of D. Rodgers.

2. Similarity Decay of the Enstrophy. The self preservation hypothesis of von Karman and Howarth provides a familiar basis for understanding the decay of energy in hydrodynamic turbulence. The UD Penning trap group extended this theory to the case of a single species system, taking into account relaxation to a final metastable state. In the Penning trap data, the free enstrophy was found to decay with reasonable accuracy according to a similarity law [3, 5, 7].

3. Vortex census and its evolution. We know that vortices become isolated and then orbit each other and merge, Therefore, along with enstrophy decay we must have a decrease in the number of vortices. As we discussed above, one needs to define a “vortex” carefully and quantitatively for these statements to acquire a definite interpretation. Here a method was described for counting vortices in the Penning trap data. Using more than a dozen experimental datasets, we showed that the decrease in the number of vortices vs. time follows a range of behavior. Almost all cases are bounded by the strong turbulence scaling ($1/t^{0.7}$) and the two body collision limit ($1/t$) as described previously based on two signed vorticity hydrodynamics simulations . This greatly expands on the single Penning trap case described previously by Fine.

4. Turbulent suppression of nonlinearity in electron plasma. Besides the global decay of quantities like enstrophy, and the decrease in the number of large structures, such as vortices, the decay of turbulence is characterized by the suppression of nonlinear interaction strengths due to the appearance of special correlations. In 3D hydrodynamics these are Beltrami flows, Alfv´enic correlations and force free states. Here we showed for the first time that such nonlinearity suppressing correlations also appear in the dynamics if the 2D electron fluid in the Penning trap. The correlation appears very early in the experimental runs, and at later times it is seen to slowly become enhanced.

The first two accomplishments above were principally the content of the PhD thesis of Doug Rodgers. The third and fourth research accomplishments above are the main results of the PhD thesis of Tareque Aziz.

- Prospects and directions for future research.

The most obvious direction for improvements and extensions of the present results would be to carry out and analyze experiments employing finer scale initial conditions. This would give rise to larger enstrophy (mean square charge density) and increased enstrophy to energy ratios. Both of these would produce a more turbulent system, which would allow better representation of the conditions that are expected to lead to similarity decay of enstrophy and the number of vortices. In addition large number of vortices may allow a more complex evolution of the local correlations that suppress nonlinear couplings. Furthermore the technology exists both to produce such complex initial electron distributions, using programmable photocathoodes, and to produce the associated high resolution datasets using improved CCD cameras. Unfortunately the UD Penning trap was disassembled and scrapped, so these advances will not occur in our laboratory in the near future. Another interesting future line of research would be to construct accurate and high resolution numerical simulation codes in Penning trap geometry and with varying boundary conditions. This would enable study of high Reynolds number flows, and also varying dissipation functions, to complement the experimental results. It also will be very important eventually to understand better how principles such as similarity decay, suppression of nonlinearity and other aspects of turbulent dynamics can be placed into a general framework that enables us to understand on equal footing how these principles apply to hydrodynamics, magnetohydrodynamics, electron fluids, and plasma dynamics in general.

- Bibliography

[1] W. H. Matthaeus, S. Servidio, D. Rodgers, D. C. Montgomery, T. Mitchell, and T. Aziz, AGU Fall Meeting Abstracts pp. B1203+ (2008).

[2] D. J. Rodgers, S. Servidio, W. H. Matthaeus, D. C. Montgomery, T. B. Mitchell, and T. Aziz, Physical Review Letters 102, 244501 (2009).

[3] D. Rodgers, S. Servidio, W. Matthaeus, and T. Mitchell, APS Meeting Abstracts pp. 8061P–+ (2009).

[4] D. Rodgers, S. Servidio, W. Matthaeus, D. Montgomery, and T. Mitchell, APS Meeting Abstracts pp. 8062P–+(2009).

[5] D. Rodgers, S. Servidio, W. H. Matthaeus, D. Montgomery, T. Mitchell, and T. Aziz, AGU Fall Meeting Abstracts pp. B1760+ (2009).

[6] T. Aziz, M. Wan, K. Osman, D. J. Rodgers, S. Servidio, T. Mitchell, and W. H. Matthaeus, AGU Fall Meeting Abstracts pp. B1215+ (2010).

[7] D. J. Rodgers, W. H. Matthaeus, T. B. Mitchell, and D. C Montgomery, Physical Review Letters 105, 234501 (2010).

Papers 2 and 7 in PDF format are attached to this Report.

- Summary

During the period of this grant we had a very active research effort in our group on the topic of 2D electron plasmas, relaxation, 2D Navier Stokes turbulence, and related issues. This led to two PhD theses, and several high profile publications (so far). We are currently working on two additional draft publications based on the thesis work of Dr. Aziz. The project was also influential in motivated other studies we carried out such as a study of 2D turbulence with two-species vorticity, reported in

> S. Servidio, M. Wan, W. Matthaeus and V. Carbone, Local relaxation and maximum entropy in two-dimensional turbulence, Phys. Fluids. 22. 125107 (2010),

which was supported by other grants. In addition to existing and planned manuscripts and papers at meetings, we also still have nearly 1 Terabyte of data from the Penning trap, much of which has yet to be fully analyzed. Prof. Mitchell's data remains very valuable and we suspect that it will be employed in future research projects as well. Overall we view this as a very successful DOE project.