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Institution: University of New Hampshire (in partnership with Dartmouth College)

Project Title: Center for Integrated Computation and Analysis of Reconnection and Turbulence (CICART)

Principal Investigator: Professor Amitava Bhattacharjee

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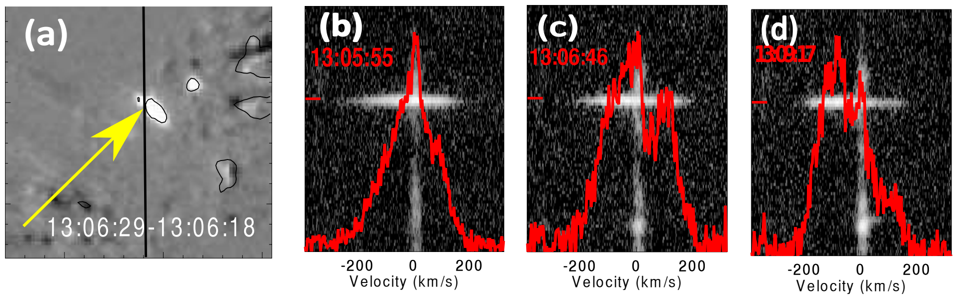
Abstract of Project Goal and Objective:
CICART is a partnership between the University of New Hampshire (UNH) and Dartmouth College. CICART addresses two important science needs of the DoE: the basic understanding of magnetic reconnection and turbulence that strongly impacts the performance of fusion plasmas, and the development of new mathematical and computational tools that enable the modeling and control of these phenomena. The principal participants of CICART constitute an interdisciplinary group, drawn from the communities of applied mathematics, astrophysics, computational physics, fluid dynamics, and fusion physics. It is a main premise of CICART that fundamental aspects of magnetic reconnection and turbulence in fusion devices, smaller-scale laboratory experiments, and space and astrophysical plasmas can be viewed from a common perspective, and that progress in understanding in any of these interconnected fields is likely to lead to progress in others. The establishment of CICART has strongly impacted the education and research mission of a new Program in Integrated Applied Mathematics in the College of Engineering and Applied Sciences at UNH by enabling the recruitment of a tenure-track faculty member, supported equally by UNH and CICART, and the establishment of an IBM-UNH Computing Alliance. The proposed areas of research in magnetic reconnection and turbulence in astrophysical, space, and laboratory plasmas include the following topics: (A) Reconnection and secondary instabilities in large high-Lundquist-number plasmas, (B) Particle acceleration in the presence of multiple magnetic islands, (C) Gyrokinetic reconnection: comparison with fluid and particle-in-cell models, (D) Imbalanced turbulence, (E) Ion heating, and (F) Turbulence in laboratory (including fusion-relevant) experiments. These theoretical studies make active use of three high-performance computer simulation codes: (1) The Magnetic Reconnection Code, based on extended two-fluid (or Hall MHD) equations, in an Adaptive Mesh Refinement (AMR) framework, (2) the Particle Simulation Code, a fully electromagnetic 3D *P*article-*I*n-*C*ell (PIC) code that includes a collision operator, and (3) GS2, an Eulerian, electromagnetic, kinetic code that is widely used in the fusion program, and simulates the nonlinear gyrokinetic equations, together with a self-consistent set of Maxwell's equations.

Principal Accomplishments

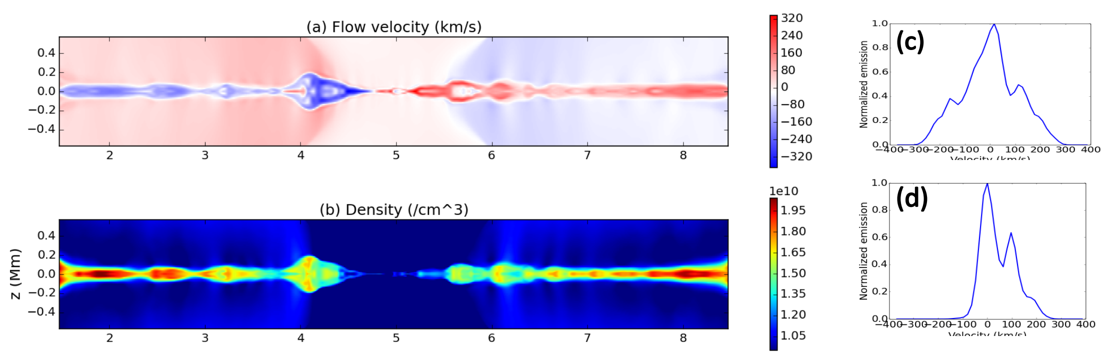
Magnetic Reconnection

We have made fundamental breakthroughs on the problem of onset of fast reconnection in high-Lundquist-number plasmas mediated by the plasmoid instability. The main challenge is to explain why reconnection in nature or laboratory devices (including fusion devices) can proceed rapidly from a relatively quiescent state in weakly collisional plasma characterized by high values of the Lundquist number (S). The classical Sweet-Parker theory, based on resistive MHD, predicts a reconnection rate that scales as $S^{-1/2}$ For many systems of interest, the Sweet-Parker reconnection rates are much slower than those observed. Recent work has demonstrated that there is a fundamental flaw in the Sweet-Parker argument, even within the framework of resistive MHD. When the Lundquist number exceeds a critical value, the Sweet-Parker layer is unstable to a super-Alfvenic tearing instability, hereafter referred to as the plasmoid instability, with a growth rate that *increases* with increasing S. Thus, the original Sweet-Parker current sheet breaks down into a chain of plasmoids and progressively thinner current sheets. Numerical simulations, supported by heuristic scaling arguments, strongly suggest that within the framework of resistive MHD, the nonlinear reconnection rate mediated by the plasmoid instability becomes insensitive to the value of S Because the plasmoid instability can initiate a cascade to current sheets that are much thinner than the original Sweet-Parker sheet, the so-called Hall terms in the generalized Ohm's law become important, triggering the onset of Hall reconnection, which lead to higher reconnection rates. We have carried out the largest 2D Hall MHD simulations to date that demonstrate the rich dynamics enabled by the interplay between the plasmoid instability and the Hall current. It is shown that the topology of Hall reconnection is not inevitably a single stable X-point. There exists an intermediate regime where the single X-point topology itself exhibits instability, causing the system to alternate between a single X-point and an extended current sheet with multiple X-points produced by the plasmoid instability. Examples of applications have been drawn from magnetically confined laboratory plasmas, high-energy density plasmas, and space plasmas.

Thus, our understanding of the process of fast reconnection has undergone a dramatic change driven, in part, by the availability of high-resolution numerical simulations that have consistently demonstrated the break-up of current sheets into magnetic islands, with reconnection rates that become independent of Lundquist number, challenging the belief that fast magnetic reconnection in flares proceeds via the Petschek mechanism that invokes pairs of slow-mode shocks connected to a compact diffusion region. The reconnection sites are too small to be resolved with images but these reconnection mechanisms, Petschek and the plasmoid instability, have reconnection sites with very different density and velocity structures and so can be distinguished by high-resolution line-profile observations. Using IRIS spectroscopic observations, the CICART and MPI (Germany) groups have obtained a survey of typical line profiles produced by small-scale events thought to be reconnection sites on the Sun. The profiles can be reproduced with the multiple magnetic islands and acceleration sites that characterize the plasmoid instability but not by bi-directional jets that characterize the Petschek mechanism. This result suggests that if these small-scale events are reconnection sites, then fast reconnection proceeds via the plasmoid instability, rather than the Petschek mechanism during small-scale reconnection on the Sun.



IRIS observations of short-lived, small-scale brightening on the Sun: (a) Slit-jaw difference image; (b-d) Si IV spectral images along the vertical black line and line profiles (red) at the site of the yellow arrow in (a). The profiles have multiple components often showing a bright core and broad wings.



High Lundquist number MHD simulations (a, b) of the plasmoid instability show low- velocity, high-density plasmoids within Alfvénic outflow jets. This characteristic current layer is used to synthesize line profiles (c, d), which reproduce the observed bright line core and broad wings seen in the IRIS spectra.

Recently, magnetic reconnection has been observed in high-energy-density, laser-produced plasmas, in the presence of extremely high magnetic fields self-generated by the Biermann effect. In the experiments, which open up a new experimental regime for reconnection study, bubbles of high-energy-density plasma are created by focusing lasers down to sub-millimeter-scale spots on a plastic or metal foil. The bubbles, created at small separation, expand into one another, and their self-generated magnetic fields are squeezed together and reconnect. The CICART group has carried out experiments (on the Omega facility at the University of Rochester) as well as fully electromagnetic, particle-in-cell simulations that account for salient features of these experiments. These laser-driven experiments are in many ways complementary to traditional experiments with magnetized discharge plasmas. Some notable features include the high plasma beta of these experiments and the laser-driven plasma expansion, which drives the bubbles together at approximately the sound speed, leading to much stronger inflows than have traditionally been studied in reconnection experiments. The PIC simulations suggest that these laboratory experiments are the first to produce magnetic flux pile-up at the reconnection layer, which is a regime of great interest for a number of astrophysical applications where supersonic, magnetized flows collide, such as the interactions of planetary magnetospheres with the solar wind, the heliopause, accretion disks, and supernova remnants.

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Astrophysical Turbulence

Our most important accomplishment in the area of astrophysical turbulence has been the development of a quantitative theory for determining the stochastic heating rate in low-frequency turbulence. This effort was a truly collaborative endeavor involving Barrett Rogers and Bo Li at Dartmouth College and Ben Chandran and Kai Germaschewski at UNH, as well as colleague Eliot Quataert (not part of CICART) at UC Berkeley. This work resulted in a paper in the Astrophysical Journal in 2010 that has already been cited 77 times, attesting to the impact that CICART has had in the astrophysics community. This paper also served as the basis for several follow-up papers that generalized our original theory to account for minor ions and differential flow between ion species and that tested our original theory using numerical simulations and solar-wind observations. In related work, we also published two papers on the stochastic acceleration of electrons in solar flares.

The second main area of progress was non-compressive Alfven-wave turbulence in the solar wind and solar corona. We carried out direct numerical simulations of this type of turbulence, accounting for the radial inhomogeneity in the solar-wind outflow velocity, density, and magnetic field strength. These inhomogeneities reflect outward-propagating waves back towards the Sun, providing the necessary mix of counter-propagating waves needed to generate Alfven-wave turbulence. Our simulations were the first of their kind. We showed that even if only large-scale Alfven waves are launched from the Sun, reflection-driven turbulence is sufficiently vigorous that the Alfven-wave energy can cascade to small scales and dissipate in the solar corona and near-Sun solar wind, providing the turbulent heating that is needed in order to heat and accelerate the solar wind. We published our work in the Astrophysical Journal.

Our third main accomplishment in the area of astrophysical turbulence was on the topic of kinetic plasma instabilities in the solar wind, which are a source of small-scale turbulence in the solar wind. We considered instabilities driven by several different mechanisms, including differential flow between alpha particles and protons and the temperature anisotropy of alpha particles or protons. Two hallmarks of our work were the derivation of analytic expressions for the instability thresholds and the derivation of self-consistent, non-Maxwellian, marginally stable distribution functions for protons in the presence of parallel-propagating Alfven/ion-cyclotron waves. We published our work in several papers in the Astrophysical Journal.

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Gyrokinetic reconnection and turbulence

The Dartmouth group has been remarkably successful in applying gyrokinetic theory and simulations to (i) turbulent transport in fusion plasmas (core as well as edge) as well as laboratory plasmas (ii) coherent structures such as zonal flows that emerge spontaneously from turbulence, and (ii) studies and numerical implementation of sophisticated collision operators that enable studies of plasmas at various levels of collisionality

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Qian Xia, PhD

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Other Support

CICART personnel have benefitted greatly from synergistic support from DOE, NASA, and NSF, both during the period of the grant, as well as after. In other words, CICART research has benefitted UNH and Dartmouth College in particular, and more broadly, the state of New Hampshire in expanding the scope of research in laboratory, space, and astrophysical plasmas.