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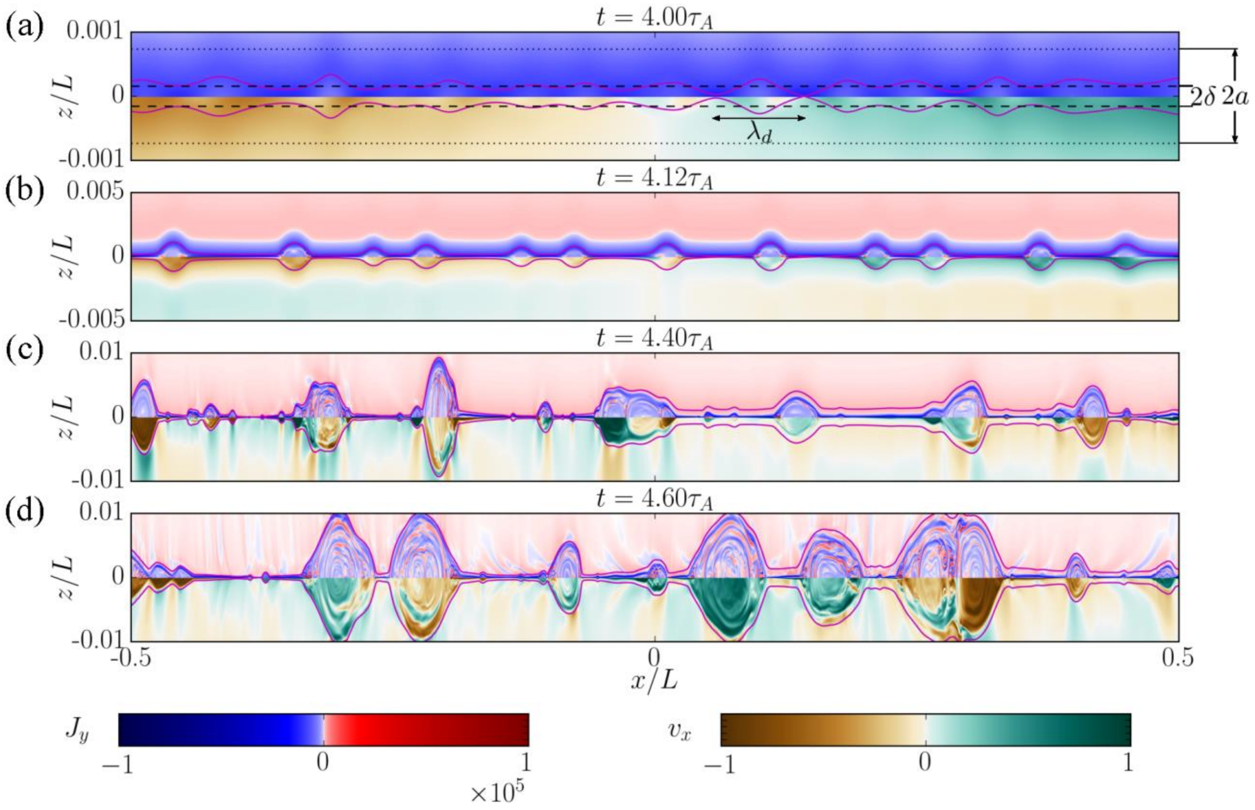
Predicting Magnetic Explosions: From Plasma Current Sheet Disruption to Fast Magnetic Reconnection

Many of the most explosive events in the universe are associated with magnetic reconnection, in which magnetic energy is suddenly converted to kinetic energy. Supercomputer simulations and theoretical analysis shed new insight on when, and how, fast reconnection occurs.



Caption: From current sheet disruption to fully developed plasmoid-mediated fast reconnection. In each panel, the upper half shows the current density, and the lower half shows the plasma outflow velocity along the horizontal direction. **Panel (a)** shows the moment of the disruption of the primary reconnecting current sheet when the typical size of the plasmoids (marked in magenta lines) exceeds the inner layer width (marked by the two dashed lines) of the sheet. After the disruption, secondary current sheets between plasmoids again become extended and thin, as shown in **panel (b)**. These extended secondary current sheets become unstable to the plasmoid instability, triggering the next level of disruption, as shown in **panel (c)**. This self-similar, fractal-like process of current sheet disruption leads to a hierarchy of plasmoids of different sizes, **panel (d)**.

The Science

Magnetic reconnection “breaks” magnetic fieldlines, and converts magnetic *potential* energy to *kinetic* energy of the charged particles in the ionized gas called plasma. Reconnection can have many impacts.

In magnetic fusion devices for electricity generation, such as “tokamaks,” magnetic reconnection causes so-called “sawtooth crashes” that degrade plasma confinement and can lead to disruptions that severely damage the device. Magnetic reconnection is a key driver of solar flares and coronal mass ejections that produce highly energetic particles that impact the Earth’s magnetosphere, presenting radiation hazards to astronauts and spacecraft, and possibly disrupting cell phone service and knocking out electric power grids. Magnetic reconnection may be behind gamma-ray bursts associated with supernova explosions and formation of neutron stars and blackholes. A gamma-ray burst in the Milky Way, if pointing towards Earth, could potentially cause a mass extinction event. Clearly, it is important to know when, how, and why, magnetic reconnection takes place.

Magnetic reconnection events are often preceded by an extended quiescent period, during which the magnetic energy gradually accumulates, followed by an impulsive “onset” phase, when the magnetic energy is suddenly released. The reconnection *rate* (which measures the number of fieldlines that are broken and reconnected per unit time) increases abruptly, and reconnection proceeds rapidly thereafter.

Although reconnection has been extensively studied, exactly what causes the rapid onset remains poorly understood. Using supercomputer simulations and theoretical analysis, our study suggests that disruption of the current sheet caused by plasmoid instability in the sheet may provide such a trigger.

The Impact

Magnetic reconnection starts from the formation of a current sheet, a sheet-like structure of concentrated electric current in plasma. Global forces acting on the system cause the current sheet to become thinner as it evolves in time. When the sheet becomes thin enough, the magnetic force and the resistive friction between electrons and ions give rise to the “plasmoid” instability. Plasmoids are plasma “bubbles” that are isolated from their surroundings by the magnetic field, just as the air in bubbles of soap is isolated from the external atmosphere. When the magnetic field “breaks” more plasmoids can form. The plasmoids, when they are large enough, disrupt the current sheet when the sheet becomes too thin and unstable. The disrupted sheet fragments into a cascading hierarchy of self-similar plasmoids at different length scales, reminiscent of fractals in mathematics. This fractal-like fragmentation is what was missing in traditional theories, and it is this that triggers the transition from “slow” to “fast” reconnection.

The theory we have developed predicts at what time, and under what conditions, the current-sheet disruption will occur. Our general theoretical framework can be applied to understand a broad range of energetic events driven by magnetic reconnection.

Summary

The corroboration between the computer simulations and theoretical analyses that we used puts our conclusions on a solid foundation. A key question is how the current sheet width, the instability growth rate, and the number of plasmoids depends on certain plasma parameters. Reconnection theories emphasize various timescales. They focus on how quickly the magnetic energy “spreads” or “diffuses” through space as measured by the resistive diffusion time, compared to the travel time of “vibrations” or “oscillations” in the magnetic field — the so-called Alfvén time. (Perturbations in the magnetic field rapidly travel along the magnetic fieldlines, just like vibrations in a guitar string.) However, previous theories could not account for the current sheet disruption and the onset of fast reconnection when the ratio of these timescales, called the Lundquist number, was as large as it is in the solar corona, for example. Our study demonstrated that the previous theoretical prediction was accurate only when the Lundquist number was moderate. At high Lundquist numbers, the current sheet disruption takes place before traditional theories predict. Moreover, the Lundquist number is not the only parameter that affects the current sheet disruption. The level of random fluctuations in magnetic field, plasma density, and so on, also influences the formation of plasmoids.

Our phenomenological theory correctly predicts the dependence on the Lundquist number and the random fluctuations obtained in state-of-the-art supercomputer simulations. Our theory incorporates (i) the time evolution of the current sheet, (ii) the time rate-of-changes of the sizes of plasmoids, and (iii) the amount of plasma "ejected" by the reconnection outflow jets. The theory also determines the critical Lundquist number, below which the instability cannot grow large enough to disrupt the current sheet before it is transported away by the reconnection outflow jets. These results provide a fundamentally insightful understanding of the onset of fast magnetic reconnection.

Contact

Yi-Min Huang
Department of Astrophysical Sciences, Princeton University
yiminh@princeton.edu

Participating Institutions

Department of Astrophysical Sciences, Princeton University
Princeton, NJ 08544

Princeton Plasma Physics Laboratory
Princeton, NJ 08543

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Publications

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