# The hidden mechanics of magnetic field reconnection, a key factor in solar storms and fusion energy reactors

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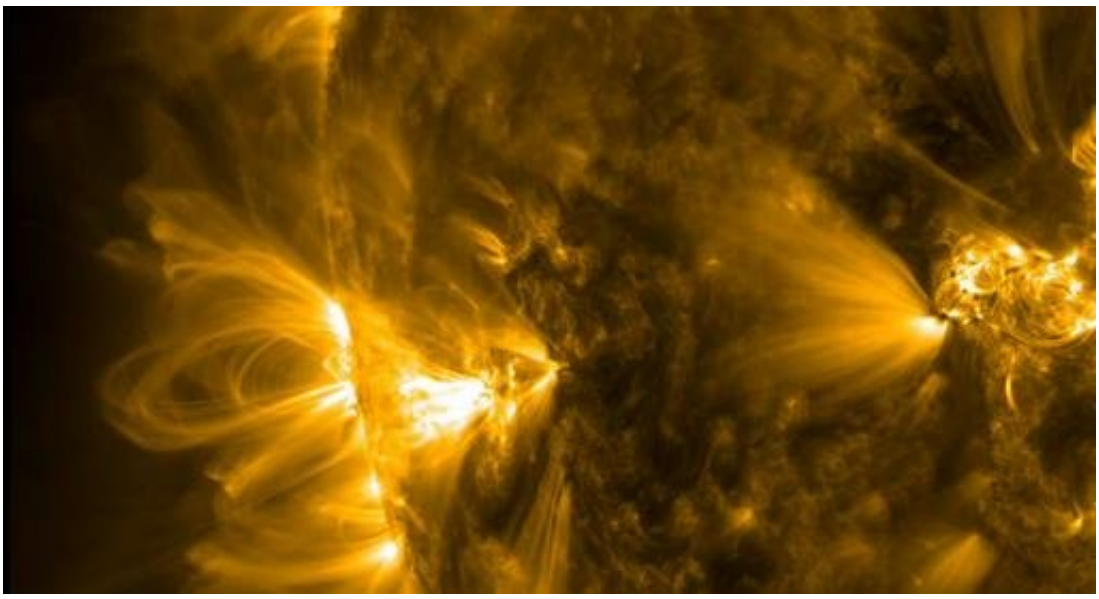

Coronal loops on the sun are linked to magnetic fields. Princeton Plasma Physics Laboratory experiments are combining with Oak Ridge National Laboratory supercomputer simulations to illuminate how the fields break apart and reconnect. Credit: NASA/Solar Dynamics Observatory.

In July 2012, a powerful solar storm almost struck Earth. Scientists estimate that had the storm, called a coronal mass ejection (CME), hit the planet, the impact would have crippled power grids worldwide, burning out transformers and instruments.

A NASA probe that happened to lie in the CME's path detected some of the charged particles it contained. Data the satellite collected showed the storm was twice as powerful as a 1989 event that knocked out Quebec's entire power grid, disrupted power delivery across the United States and made the northern lights visible as far south as Cuba. In fact, the recent storm might have been stronger than the first and most powerful CME known to hit the planet, the Carrington event. That 1859 storm sprayed sparks from telegraph lines, setting fire to telegraph stations. Researchers put the odds of a Carrington-size CME occurring by 2024 – and possibly hitting Earth – at 12 percent.

Such events occur when field lines in the sun's massive magnetic system snap and reconnect. "Magnetic fields are a reservoir of an enormous amount of energy, and major eruptive events occur in which this energy is liberated," says Amitava Bhattacharjee, a plasma physicist at the Princeton Plasma Physics Laboratory (PPPL), a Department of Energy facility in Princeton, New Jersey. "Charged particles tend to get tied to magnetic field lines like beads on a wire – when the wire breaks, the beads get thrown off at enormous speeds."

The phenomenon, known as fast magnetic reconnection, remains a mystery. No one knows how field lines break and rejoin fast enough to expel the billions of tons of material unleashed in a CME, or even in the smaller eruptions of common solar flares. In laboratory experiments and simulations, Bhattacharjee and his colleagues have revealed new mechanisms that help explain fast magnetic reconnection.

Bhattacharjee has been in pursuit of such mechanisms since graduate school, when he realized that plasma physics is "a beautiful, classical field with wonderful equations that were good things to analyze and do computer simulations with," he says. At the same time, he saw that plasmas – which constitute 99.5 percent of the visible universe – are also the key to "a very practical and important problem for humanity, namely

magnetic fusion energy."

For decades, nuclear fusion machines, such as doughnut-shaped tokamaks, have promised a virtually limitless supply of relatively clean energy. But a working fusion device is still out of reach, partly because of fast magnetic reconnection. "Magnetic fusion reactors have magnetic fields in them, and these magnetic fields can also reconnect and cause disruptive instabilities within a tokamak fusion plasma," says Bhattacharjee, professor of astrophysical sciences at Princeton University and head of PPPL's Theory and Computation Division.

In the present model of reconnection, opposing magnetic fields are pushed together by some external force, such as plasma currents. A thin, flat contact area forms between the two fields, building tension in the field lines. In this thin region, called a current sheet, plasma particles – ions and electrons – collide with one another, breaking field lines and allowing them to form new, lower-energy connections with partners from the opposing magnetic field. But under this model, the lines reconnect only as fast as they are pushed into the current sheet – not nearly fast enough to explain the tremendous outpouring of energy and particles in a fast-reconnection event.

Since this slow reconnection model depends on plasma particle collisions, many research groups have searched for collisionless effects that might account for fast reconnection. Promising explanations focus on the behavior of charged particles in the current sheet, where field strength is close to zero. There, the charged properties of the massive, sluggish ions are suppressed, and the nimble electrons are free to carry the current and whip field lines into new configurations.

For laboratory experiments on hidden mechanisms, Bhattacharjee's team uses powerful lasers at the University of Rochester's Omega facility. To develop computer models, the group uses Titan, a Cray XK7

supercomputer at the Oak Ridge Leadership Computing Facility, a DOE Office of Science user facility, through the Office of Science's Innovative and Novel Computational Impact on Theory and Experiment (INCITE) program. The Office of Science's Fusion Energy Sciences program and the DOE National Nuclear Security Administration sponsor the experiments.

In an early experiment led by PPPL research physicist Will Fox, the team pointed two intense Omega lasers at materials that yield plasma bubbles under the beams. Each bubble spontaneously generated its own magnetic field through an effect known as the Biermann battery. As happens in the sun and nuclear fusion devices, charged plasma particles lined up on the magnetic field lines. The bubbles plowed into each other, and a current sheet formed between them. The reconnection rate between the fields was fast – too fast for classical theory.

"That's where we were first establishing the underlying mechanism for reconnection happening in this machine," Bhattacharjee says. The team now had a model for fast magnetic reconnection, one applicable to earlier pioneering experiments conducted by groups in the United Kingdom and the United States. A simulation on Titan showed that more field lines were crammed together in the current sheet than anyone had realized, a phenomenon called flux pileup. The study showed that, in addition to previously suggested collisionless effects, flux pileup plays a role in fast reconnection.

In later experiments led by Gennady Fiksel, now at the University of Michigan, the team didn't want to rely solely on spontaneously generated magnetic fields. "We felt we needed greater control on the magnetic fields we were using for the reconnection process," Bhattacharjee says. "And so we used an external generator called MIFEDS (magneto-inertial fusion electrical discharge system), which produced external magnetic fields we could control."

To capture changes in this field, the team filled the space with a thin background plasma, generated by a third laser, and imaged it using a beam of protons, which magnetic fields deflect. When two plasma bubbles impinged on the external magnetic field, the team created the clearest image so far of events taking place in the region where field lines reconnect. The new configuration also showed flux pileup, followed by a reconnection event that included small plasma bubbles forming in the region between the bubbles and, finally, abrupt annihilation of the magnetic field.

"The mechanism that we found is that you form this thin current sheet that can then be unstable, in what we call a plasmoid instability that breaks up this thin current sheet into little magnetic bubbles," Bhattacharjee says. "The plasmoid instability is a novel mechanism for the onset of fast reconnection, which happens on a time scale that is independent of the resistance of the plasma."

Bhattacharjee and his colleagues are working to understand how their discovery fits into the big picture of solar activity, solar storms and nuclear fusion devices. Once they and the broader community of plasma physicists fully understand reconnection, the ability to predict CMEs and tame some of the plasma instabilities inside tokamak reactors, for example, may be within reach.

Provided by US Department of Energy

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