Twisted Flux Tubes Expel 'Wrong-Way' Ions

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Physicists seeking to tame plasma have figured out yet another of its wily ways. Knowing how plasma escapes the grip of magnetic fields may help researchers design better magnetic bottles to contain it. Magnetic confinement could be a crucial technology for electric power plants that harness nuclear fusion, the powerful process fueling the sun.

Metaphorically, it is hard to stop leaks when you haven't yet found them all, and three applied physicists at the California Institute of Technology identify a new leakage mechanism in the current issue of *Physical Review Letters*. Their model explains certain types of magnetic confinement degradation observed in the laboratory, and it may well be relevant to similar situations in the solar corona.

Nuclear fusion requires great energy to start, and it can release even more. At high energies, electrons are torn from atoms to make plasma, a gaseous mixture of electrons and ions. Although fusion-grade plasma is far too hot for solid walls to hold, a suitably arranged magnetic field can confine it, because electrons and ions are each subject to magnetic forces.

The solar corona provides a compelling example of plasma confinement by magnetic fields. Above the solar surface, magnetic fields sculpt plasma into vast glowing loops, which can last for weeks, only to burst in a violent spray of high-energy particles. Such sudden failures of magnetic confinement are not fully understood, but the Caltech physicists have modeled a process by which the magnetic fields presumed to confine plasmas may instead expel certain ions, under conditions they label "radially unstable motion" (RUM).

"My intuition wouldn't have predicted this effect," says Professor of Applied Physics Paul Bellan. "It's always been assumed that electrons and ions stay close to their magnetic field lines. The model wasn't easy because we had to change our thinking. You have to follow the mathematics and let that change your intuition."

The RUM model provides an explanation for mysterious phenomena previously observed in tokamaks. The tokamak is the configuration most likely to provide magnetic plasma confinement for industrial-scale fusion power generation. Like a twisted rope with ends spliced together, a tokamak is a plasma-filled, twisted magnetic flux tube that acts as a donut-shaped magnetic bottle. Through the plasma a very large electric current circles the donut hole, so that magnetohydrodynamic (MHD) forces confine the plasma within the flux tube.

One method for fueling tokamaks is to inject the plasma with energetic beams of neutral atoms, which quickly lose electrons to become energetic ions. Such ions escape much more quickly when they move against the direction of electric current than when they move along it. Because MHD does not distinguish between countermoving and comoving ions, MHD does not predict this behavior.

The RUM model shows that when an electric current flows along a flux tube, the associated magnetic field interacts with ion motion so that rapidly countermoving ions experience a significantly different energy landscape than other ions. Like flowing water, particles tend "downhill" toward regions of lower potential energy, remaining confined in energy valleys and flowing away from energy hills.

In a flux tube with a corkscrew-shaped magnetic field, the tube's center is an energy valley for comoving and slow countermoving ions, but seems uphill to fast countermoving ions, which accelerate outward and may be visible as an intense jet of plasma away from the tube. Such jets were observed experimentally before they were understood.

"We'd seen some hints of this right from the beginning," says Bellan. The effect is proportional to mass, so it is not as evident in hydrogen plasmas. "It was blatantly obvious in the argon experiment."

The researchers investigated this phenomenon in an experiment that simulated plasma-filled magnetic flux tubes looping through the solar corona. They applied high voltage between electrodes at opposite ends of a semicircular magnetic flux tube. This high voltage ionized argon gas to form plasma, which MHD forces concentrated into a bright arch about 20 centimeters long, like a solar coronal loop but a billion times smaller.

Doppler velocity measurements confirmed the existence of rapidly countermoving ions. The researchers varied the current, plasma density, and magnetic field to test the association between RUM and these fast "wrong-way" ions. They found their RUM onset prediction to be an excellent indicator for the loss of such ions from the magnetic flux loop through the resulting emission of plasma jets.

The authors of the paper, "Observation of Kinetic Plasma Jets in a Coronal-Loop Simulation Experiment," are Caltech postdoctoral fellow Shreekrishna Tripathi, who is now at UCLA, Paul Bellan, and Caltech graduate student in applied physics Gunsu Yun.

Source: Caltech