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Solar magnetic reconnection seen in detail

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Solar flares can heat plasma in the Sun's atmosphere, normally around one million kelvin, to tens of millions of kelvin. They're often accompanied by coronal mass ejections (CMEs), which spew billions of tons of plasma into interplanetary space. CMEs that reach Earth's magnetosphere can disrupt the power grid, communications networks, and other infrastructure, and they may endanger astronauts and passengers on high-altitude polar flights.

In the 1960s, a picture emerged in which solar flares are driven by magnetic reconnection, the interaction of oppositely directed field lines in the Sun's twisted, tangled magnetic field. The field lines change their topology to adopt a lower-energy configuration, as shown in figure 1, and thereby rapidly convert some of their magnetic energy into thermal and kinetic energy. Flare observations have largely supported that theory (see the article by Gordon Holman in PHYSICS TODAY, April 2012, page 56). But the evidence has been spotty and indirect, in part because the existing solar observatories lacked the spatial and temporal resolution to capture the key aspects of magnetic reconnection, which occur on time scales as short as seconds.

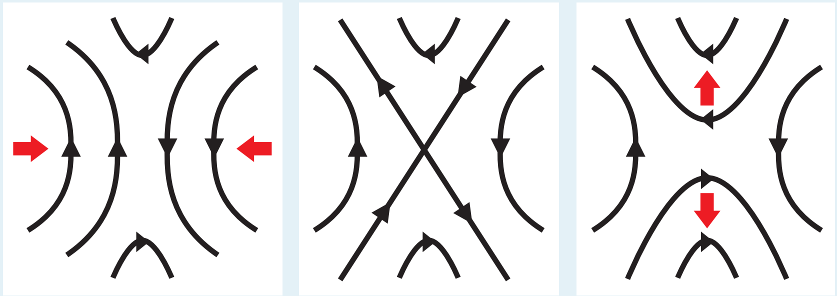

Figure 1. A simple picture of magnetic reconnection in two dimensions. When oppositely directed field components are pushed together, they can change their topology and convert some magnetic energy into kinetic energy. Note that at the so-called X point at the center of the reconnection region, field lines point in four different directions. The field in the plane of the page at the X point itself must therefore be zero.

In 2010 NASA launched its *Solar Dynamics Observatory* (*SDO*), whose Atmospheric Imaging Assembly (AIA) images the Sun with greater speed and detail than ever before. And now, using AIA data, Yang Su (University of Graz, Austria) and an international team of collaborators, including Holman, have presented the most complete observational evidence yet for magnetic reconnection in a solar flare.[1] Says Eric Priest of the University of St. Andrews in the UK, "This is exactly the type of event many of us have been eagerly awaiting for many years."

Rapid energy release

Magnetic field lines are theoretical constructs, but in the Sun's corona they can be considered to have a physical reality. The plasma in the corona is an excellent conductor of electricity. In such an environment, an electric field would immediately be neutralized by electric currents. That means the magnetic field lines cannot move with respect to the underlying plasma—if they did, the changing magnetic field would generate an electric field.

The coronal plasma and magnetic field lines are thus pinned together, with the charged plasma particles orbiting their respective field lines. As the Sun rotates and its plasma convects, the field lines are contorted into an ever-more complicated tangle of loops whose topology, under ideal plasma conditions, cannot change.

Magnetic reconnection, therefore, requires the solar plasma to temporarily deviate from the infinitely conducting ideal. When oppositely directed field regions get pushed together, the changing magnetic flux generates a sheet of electric current. (In the configuration in figure 1, that current flows perpendicular to the plane of the page.) A strong enough current taxes the plasma's ability to conduct electricity, which allows an electric field to build up and the magnetic field lines to move through the plasma and reconnect. At the same time, it produces heat by ohmic dissipation. The newly reconnected field lines are then free to lower their energy by snapping back from the reconnection region, converting magnetic energy into heat and bulk kinetic energy. The hot plasma that results is best observed in the extreme UV (EUV) and x-ray regimes. Because photons at those energies don't penetrate Earth's atmosphere, the observation must be done by satellite.

A modest flare

Using four telescopes, the AIA images the Sun in 10 channels: 7 in the EUV (ranging in wavelength from 94 Å to 335 Å), 2 in the UV, and 1 in the visible. It collects one complete image of the Sun in each channel every 12 seconds with a spatial resolution of 0.6 arcseconds. (The Sun viewed from Earth is 1900 arcseconds across.) Compared with its predecessors, that's a fourfold increase in spatial resolution and a 10- to 700-fold increase in time resolution.[2]

It's possible for the AIA to collect images even faster, by restricting its field of view to just part of the Sun, to observe some phenomenon of interest in real time. But the flare reported by Su and company, which occurred on 17 August 2011 just after 4:00 universal time, wasn't noticed until long after the fact. Su discovered it serendipitously: "I was searching the *SDO* database for a different study," he explains, "on the propagation of high-energy electrons in flaring loops."

Many solar flares have erupted in the three years since *SDO*'s launch, but none show the features of magnetic reconnection as well as the 17 August flare, for two reasons. First, the flare was located on the solar limb, the visible edge of the solar disk, so it could be seen from the side rather than the top, and its orientation gave Earth-orbiting telescopes an almost ideal viewing angle. Second, it was a relatively small flare, so it didn't saturate the sensitive AIA detectors and

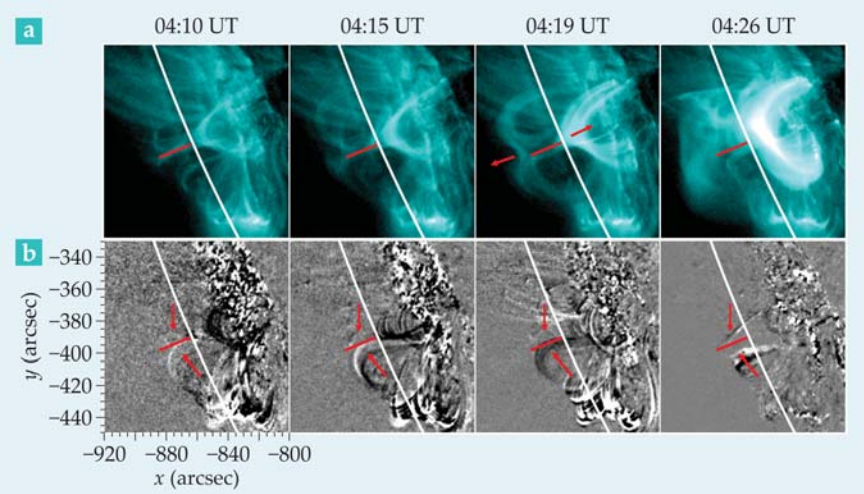

Figure 2. Images of a flare captured by the Atmospheric Imaging Assembly (AIA) on the *Solar Dynamics Observatory*. The flare erupted on 17 August 2011 near the visible edge of the solar disk, shown by the white curve. **(a)** The AIA's 131-Å channel imaged the loops of hot plasma flowing outward from the reconnection region (red line). **(b)** Difference images derived from the lower-energy extreme UV channels show loops of relatively cool plasma flowing inward toward the reconnection region. (Adapted from ref. 1.)

obscure the flaring region, as larger flares tend to do.

A more complete picture

Figure 2 shows images of the flare, taken over a span of 16 minutes. (Movies of the entire flare at the full 12-second resolution accompany the online version of reference 1.) The images in figure 2a are from the AIA's 131-Å channel, which is most sensitive to plasma heated to about 10 MK. They show hot plasma pinned to the magnetic field loops flowing away from the reconnection region, as shown by the red arrows, and getting brighter as the flare progresses.

Figure 2b shows difference images derived from some of the AIA's longer-wavelength EUV channels, sensitive to the relatively cool plasma between 50 000 K and 2 MK. White indicates an increased intensity compared to the image taken one minute earlier; black indicates a decreased intensity. The sequence shows relatively cool plasma loops moving laterally inward, along the solar surface, toward the reconnection region.

Another NASA instrument, the *Reuven Ramaty High-Energy Solar Spectroscopic Imager*, helped to complete the picture. *RHESSI*, which collects spectrally resolved hard x-ray data (see PHYSICS TODAY, September 2003, page 22), found bright x-ray sources moving outward from the reconnection region along with the 131-Å loops observed by the AIA. The hard x-ray sources indicate the location of the hottest flare plasma and the presence of particles accelerated to superthermal energies by the reconnection.

Taken together, the AIA and *RHESSI* data support the basic mechanism of magnetic reconnection. But they also show new features that aren't a part of most theoretical models of solar flares. For example, the inflowing loops had a wide range of temperatures, and some of them were seen to originate tens of thousands of kilometers away from the reconnection site. In contrast, in the standard solar-flare model, reconnection takes place in a uniform linear arcade of magnetic loops. Furthermore, a quantitative analysis of the inflows and outflows revealed that the rate of reconnection was nonuniform, with loops intermittently piling up at one side of the reconnection region or the other. "That had not been noted before," says Su, "and it should be considered in future models."

The necessary revisions to the models go beyond mere tweaking. Some of the features of the 17 August flare are inherently three-dimensional and therefore impossible to account for in a simple 2D picture of magnetic reconnection. Theorists have been working on 3D reconnection, but because complicated and varied field topologies become possible in three dimensions, it remains a topic of ongoing research.[3]

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