PLASMA PHYSICS

Connecting Again with Magnetic Reconnection

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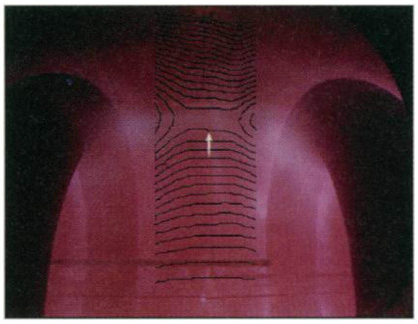
Magnetic reconnection—the breaking, and topological rearrangement of field lines—is an important manifestation of the interplay between plasma and magnetic fields. In recent soft x-ray imaging of solar flares by the Yohkoh (*1*) and SOHO satellites, many large solar flares were observed to be strongly interacting and rapidly changing their topology. The observed time scale of a few minutes is much faster than the value predicted by classical theory, and magnetic reconnection is the primary candidate for explaining these striking observations. More generally, the recent availability of new information from laboratory plasma experiments, satellite observations, theoretical studies, and computer simulations has raised interest in magnetic reconnection among communities in solar physics, magnetospheric physics, and general plasma physics. A recent international workshop held at the Princeton Plasma Physics Laboratory (*2*) this year was a reflection of the growing interest and the desire to better understand this key physical process through cross-disciplinary interactions. Questions regarding magnetic reconnection were recast and re-evaluated by more than 70 frontline scientists, including the two principal originators of this field of study, E. N. Parker and H. Petschek.



Crossed lines. Plasma discharge in the MRX device. The two dark rings are coils that generate the reconnection layer, which is marked by the arrow on the the measured magnetic field lines superimposed on the figure.

The concept of magnetic reconnection and the associated release of magnetic energy is not new in solar physics. It was first suggested more than 50 years ago in order to explain some of the properties of solar flares. For instance, long and quiet periods (days to months) exist before a sudden (minutes to hours) explosion of a solar flare. Rapid changes in macroscopic structures associated with strong magnetic fields have been a mystery since they were first observed more than 40 years ago. Sweet (*3*) and Parker (*4*) separately proposed a magnetic reconnection model to solve this mystery. This model was rather revolutionary in the sense that it was shown for the first time how localized "reconnection" of field lines can cause the observed macroscopic changes. Soon after it was proposed, however, it was realized that the Sweet-Parker model gives a characteristic time of weeks to months for such macroscopic changes to take place. This predicted time scale is too long to be consistent with observations. A key element of the model is the existence of a "diffusion region"—essentially a rectangular box where the magnetic field diffuses and reconnects. The dimensions of such a "box" is of crucial importance since the geometry controls the rate of magnetic reconnection by balancing incoming and outgoing plasma and flux flow and thus the time scale for reconnection. The length of this box is of macroscopic scale but its width is determined by the local plasma resistivity which causes magnetic diffusion; that is, faster reconnection occurs with larger resistivity. With resistivities estimated by classical theories, the Sweet-Parker model gives a reconnection rate too slow to explain solar flares. A decade later, in an attempt to explain this time discrepancy, Petschek proposed an alternative model (*5*) which consists of a much smaller diffusion region and standing wave structures (shocks). The much smaller size of the diffusion region allows a much faster reconnection rate which can be consistent with observations. The Petschek model has since been favored from an observational perspective over the Sweet-Parker model—especially because of its faster predicted reconnection rates. However, computer simulations of magnetic reconnection are generally in better agreement with the Sweet-Parker than the Petschek model.

The debate over the Petschek and Sweet-Parker models has continued over the years because neither has been verified or disproved in real plasmas. However, results from a recent laboratory experiment called MRX (Magnetic Reconnection Experiment, headed by M. Yamada at Princeton University) (*6*) have shed some new light on this key issue (see figure). As pointed out by Ji (*7*), the reconnection rates observed in MRX can be explained by a generalized Sweet-Parker model with the normal Spitzer resistivity replaced by the measured effective resistivity and other minor corrections. Basically, the geometry of the measured diffusion region is consistent with the Sweet-Parker model. One can measure the reconnection rate from the speed of the moving poloidal flux contours. The experimental support for the Sweet-Parker type of model noted here could represent a first step toward a comprehensive understanding of the nature of magnetic reconnection. A key observation is that the measured width of the current layer is much larger than that associated with the familiar resistive diffusion due to Coulomb collisions. One plausible interpretation is that the resistivity is "anomalous"; namely, that enhanced electric field fluctuations in the diffusion region scatter the current and cause the associated profile to broaden to the measured widths. Kulsrud (*8*) has suggested that this interpretation could help resolve the discrepancy between the two models. New evidence emerged during the meeting that ion dynamics (rather than the electron dynamics as previously believed) can control the reconnection rates. Without introducing anomalous resistivity, Drake (*9*) reported that the width of the diffusion region is decided by ion dynamics, in particular the so-called ion skin depth (rather than by local resistivity as in the Sweet-Parker model). This physical picture, which resulted from two-fluid (electrons and ions) simulations, is in agreement with 2D full particle simulations, where both ions and electrons are treated as particles (*10*), and with measured widths in MRX, which are on the order of the ion skin depth (*6*). More definitive results on this issue are expected in the near future from detailed fluctuation measurements planned for MRX and from the emergence of more realistic fully-kinetic 3D simulations.

Understanding magnetic reconnection is the key to resolving a number of critical questions in solar and magnetospheric physics. For example, magnetic reconnection is believed to play an important role in producing both the day-side and night-side observations of the magnetosphere. Whatever the underlying dynamics might be, they are unlikely to be clarified by the conventional magnetohydrodynamic description of reconnection as a

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steady, laminar process. This is because reconnection could well be a very turbulent process—both in time (intermittent) and space (patchy). Moreover, the effects of boundary conditions need to be more realistically taken into account. The desired resolution to these issues will be driven by more advanced diagnostic and computational approaches which will enable progress in uncovering the interrelationship between local plasma dynamics in the reconnection layer and global boundary conditions.

Even as the debates continue on the Sweet-Parker model versus the Petschek model, on the nature and cause of anomalous resistivity, and on the relationship between magnetic reconnection and dynamo mechanisms, the emergence of ways to study these issues provides hope for substantive breakthroughs. After the workshop, Petschek commented that "I found the meeting very stimulating. In particular, I had not been aware of the number of ways people have found to calculate reconnection rates. The new experiments are very nice. If one has been looking at interpretations based on single satellite measurements, the rakes of magnetometers (the internal probes on MRX) seem to generate huge amounts of correlated data which makes interpretation so much easier."

References and Notes

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11. This commentary was prepared with the help of information provided by M. Yamada, R. Kulsrud, J. Drake, and H. Ji.

MATERIALS SCIENCE

A Dislocation Crash Test

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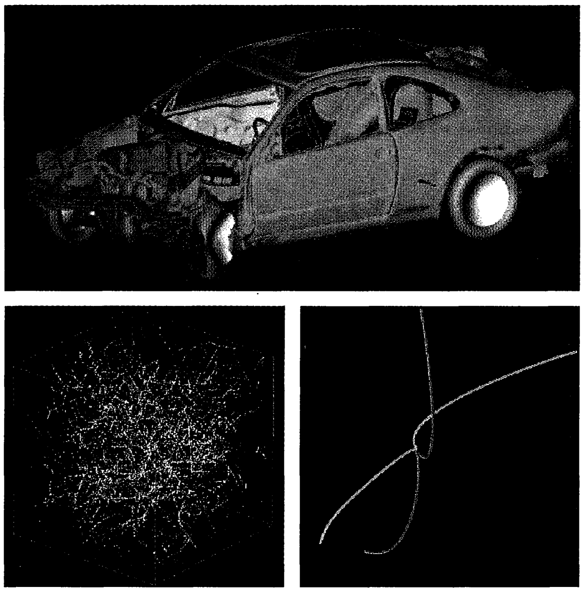
What makes an atomic-level simulation of lattice defects in pure copper crashing into each other interesting? Not the detailed results of the multimillion-atom calculation reported by Zhou *et al.* on page 1525 of this issue (*1*), but rather the idea that such simulations can contribute one important missing part of a big puzzle: the physical basis for the engineering description of the deformation of materials.

For engineering simulations of a car crash (see figure, top) or of metal-forming processes such as deep drawing or rolling, continuum mechanical techniques like the finite element method are exclusively used. Any such continuum description requires the specification of the governing constitutive equations, that is, equations that relate the response of a material to an applied force. Currently, the necessary parameters are empirically adjusted to experiments, but simulations could in the near future allow these constitutive equations to be determined from physically based simulations.

Materials deformation consists of a well understood elastic contribution and a permanent plastic contribution. The plastic deformation is mainly carried by dislocations, line-defects of the regular crystal lattice. When a dislocation moves through the crystal, it shears the crystal along its plane of motion (slip) by a well-defined displacement vector. Different dislocations strongly interact with each other (*2*). The long-range interaction can be well described by linear elasticity theory, which is sufficient for many applications of dislocation mechanics. The short-range interaction, however, is crucial when one dislocation intersects another or changes its slip plane (cross-slip). In order to simulate large macroscopic deformations, it is necessary to consider many dislocations and all of their interactions and their dynamics.



Smashing simulations. Modeling of large-scale deformation, such as in a car crash (**top**, courtesy of Daimler-Benz AG), requires equations that describe the response of a material to an applied load. In the near future, one may be able to obtain such equations from discrete dislocation simulations (**bottom, left**, courtesy of B. Devincre CNRS/ONERA); these, in turn, require atomistic input on dislocation core structure, cross slip, and dislocation intersection (**bottom, right**).

Six years ago, a French research group (*3*) first simulated such dislocation motion on the basis of interacting discrete, straight dislocation segments in its full three-dimensional complexity (see lower part of figure) and has since led the field. These discrete dislocation dynamic (DDD) simulations serve two main purposes: First, they help us understand the processes that lead to self-organization and structuring of the dislocation fields, and second, they have the potential to give a physically based description of the materials' response during deformation, which can then be used for continuum modeling (*4*).

The DDD simulations need to be given mobility laws, which describe how a dislocation responds to a stress acting on it. Although one generally has to consider the whole dislocation structure, in some metals and in certain temperature regimes, this response critically depends only on one individual dislocation type. An example is the low-temperature deformation of body-centered cubic metals like iron or molybdenum, where the screw dislocation is known to control the plastic response (*5*). Its properties can reasonably well be understood in qualitative terms by analyzing the core of the dislocation atomistically (*6*). Such atomistic studies of the core structure

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