Magnetic explosions in space

James F. Drake

The magnetic field that surrounds the Earth is rarely quiet. An explanation for the explosive nature of magnetic storms is gathering support from satellite data.

Violent magnetic storms at the fringes of the Earth's atmosphere are the consequence of explosions driven by an unusual source of energy — the magnetic field produced by electric currents streaming through the tenuous ionized gases (plasma), which form the Earth's magnetosphere. These storms can last from half an hour to several days, producing bright auroral displays and sometimes disrupting satellite communications (Fig. 1). Understanding how magnetic energy can be released so quickly in these storms — and in similar explosions in the Sun's atmosphere called solar flares — has perplexed scientists for nearly four decades. In the past few years a new theory has been developed to explain the explosive release of this magnetic energy. Now, on page 557 of this issue, Deng and Matsumoto[1] provide evidence for the smoking gun of the new theory — the 'whistler waves' that play a central role in the energy release[2].

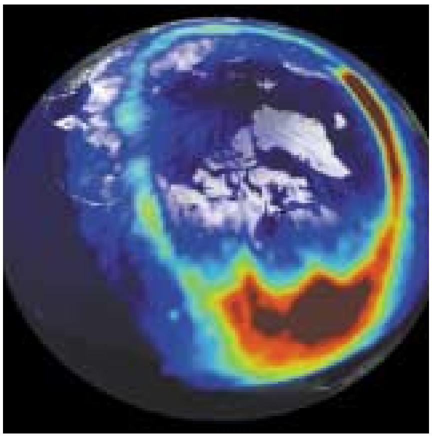

Figure 1 **Magnetic storm in the Northern Hemisphere imaged by the Visible Imaging System on the Polar spacecraft in July 2000. The aurorae are represented in false colours with red indicating areas where activity is highest.**

Magnetic energy is generated throughout the Universe by the swirling motion of ionized gases in a process known as a dynamo — the twisting and folding of the magnetic field by the plasma motion amplifies the magnetic field. Similar dynamo processes are active in the core of most planets, including the Earth. Understanding the reverse process — the conversion of magnetic energy into the kinetic energy of the plasma flow — is crucial to both fundamental and practical science issues. For example, why are the atmospheres (coronae) of stars hotter than their surfaces? And why do plasmas in fusion experiments sometimes blow apart?

A major mystery is why the release of magnetic energy occurs so quickly. It was recognized long ago that solar flares are driven by the magnetic energy in the Sun's corona — the only available energy source that is large enough. But it takes electric currents in the corona around 10,000 years to release their energy, which is hopelessly slow compared with a flare growth time of 30 minutes or less. Similar processes with fast energy release have been documented in laboratory fusion experiments.

It is widely believed[3–6] that the critical explosive events occur in regions where the magnetic field reverses, resulting in a magnetic 'x-line' configuration — Fig. 2 shows two examples of x-lines. Magnetic field lines act like rubber bands — when they are strongly bent they release their tension by springing outwards (Fig. 2a; black arrows). Essentially all of the magnetic energy is released from the field as this happens. Moreover, the outward-flowing magnetic field and plasma, which are tied together, cause the plasma pressure near the magnetic x-line to drop, pulling the plasma above and below towards the x-line (white arrows). So the whole process is self-driven and explosive. But it differs from a conventional explosion in that the energy is not released equally in all directions. Instead, the plasma flows in from one direction and flows out in another.

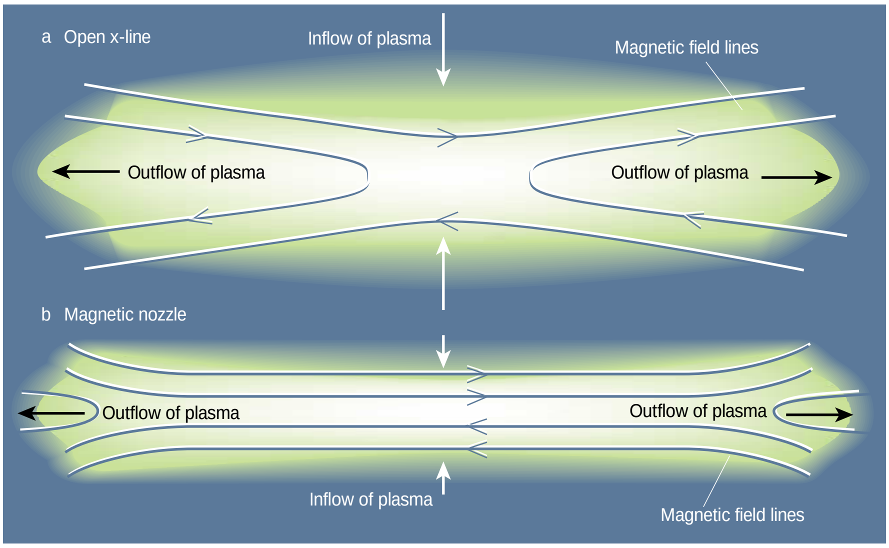

Figure 2 **What happens to magnetic field lines and plasma flows during magnetic explosions.** a, **Open x-line configuration. In regions where the magnetic field reverses, the magnetic field lines can break and cross-link (magnetic reconnection). In this situation, the highly bent field lines appear to behave like a slingshot, first stretching then rebounding, and releasing their stored-up energy.** b, **Magnetic nozzle configuration. In the simple magnetized fluid picture of reconnection, the plasma forms a magnetic nozzle, and the rate of energy release is limited by the speed at which the plasma can flow out of the nozzle. This theory falls short of explaining the short timescales associated with explosive magnetic storms. Deng and Matsumoto[1] now provide evidence for a class of plasma waves called whistler waves that can accelerate electrons to much higher velocities. The presence of whistler waves means that the size of the nozzle no longer throttles the total plasma flow — the outflow velocity can increase, so the inflow rate remains high.**

This theory, known as magnetic reconnection, is strongly supported by observation. Satellites in the Earth's magnetosphere have measured the outflow velocity of plasma on the reconnected field lines in Fig. 2a. The measurements agree with the expected Alfvèn speed, c_A, which is the velocity resulting from the conversion of magnetic energy into kinetic energy. Simultaneous measurements from two satellites also confirm the geometry of the outflow — in two opposite directions[7] (Fig. 2a).

A fundamental problem with magnetic

reconnection, however, is that the theoretical details don't add up. Instead of the open x-line configuration of Fig. 2a, the theory of simple magnetized fluids predicts a macroscopic magnetic 'nozzle' as shown in Fig. 2b. In this picture, the rate of energy release is limited by the speed at which plasma, and the magnetic field associated with it, can flow into the x-line region. Like water in a hose, the flow of plasma into the nozzle is limited by how fast the plasma flows out of the nozzle. But the maximum velocity that the outflowing plasma can reach is the Alfvèn velocity. Because the outflow velocity is fixed, if the length of the nozzle in Fig. 2b is doubled, the inflow velocity is halved. So because the magnetic nozzle is very long and narrow, the inflow of plasma is severely limited and the rate of magnetic energy release is very slow. Sweet[4] and Parker[5] first proposed the theory behind this magnetic nozzle in the 1950s, and modern computer simulations confirm the basic finding. The problem is that the slow rates of energy release predicted by this theory are inconsistent with the explosive events seen in nature and in the laboratory.

This dilemma has been resolved in recent years as theorists re-examined the assumptions behind the simple magnetized fluid, or 'magnetohydrodynamic', picture of reconnection. The breaking of the magnetic field lines actually takes place in a narrow region around the x-line of Fig. 2a. In this narrow region the magnetohydrodynamic description fails: instead of the electrons and protons moving together, as predicted by the magnetohydrodynamic model, the two species move independently. As a result, a new class of plasma waves called whistlers is generated, which can accelerate electrons to much higher velocities in a localized region near the x-line. As the name implies, these waves were first heard by radio operators as a falling tone — the wave velocity varies inversely with the wavelength, so short-wavelength, high-frequency waves reach the operators first. The acceleration of outflowing electrons to very high velocities by the whistler wave bypasses the bottleneck created by the magnetic nozzle in Fig. 2b and restores the open x-line of Fig. 2a, with its explosive rates of magnetic energy release.

The characteristic signature of a whistler wave is the generation of magnetic field components in and out of the plane shown in Fig. 2a. Confirming the existence of these field components around the x-line is a key test of the whistler theory. In earlier laboratory experiments on magnetic reconnection, Stenzel and Gekelmann[8] measured the out-of-plane magnetic fields. But Deng and Matsumoto[1] report the first measurements of these fields in a natural environment — from data taken by the Geotail satellite at the magnetopause, the boundary between the incoming solar wind and the Earth's magnetosphere. The data are tantalizing because the character of the magnetic field components seems to match exactly the theoretical predictions. More detailed measurements, especially of electron and ion flows, are required to make a compelling case that the theory is valid. The proposed NASA Magnetospheric Multiscale Mission is being designed to tackle these issues by using a cluster of satellites to obtain a complete picture of magnetic reconnection.

The emerging theory of magnetic reconnection seems to offer an explanation for the fast release of magnetic energy, but leaves many mysteries unsolved. Why do the magnetic fields remain apparently quiescent for long periods of time and then suddenly explode for no apparent reason? This behaviour is seen in the solar corona, the magnetosphere and laboratory plasmas. The spark that ignites the release process is still poorly understood. So, despite the large steps taken to unravel one of the biggest puzzles in plasma physics, the drama in our skies will demand further investigations.

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