

The Role of Helicity in Magnetic Reconnection: 3D Numerical Simulations

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Abstract.

We demonstrate that conservation of global helicity plays only a minor role in determining the nature and consequences of magnetic reconnection in the solar atmosphere. First, we show that observations of the solar coronal magnetic field are in direct conflict with Taylor's theory. Next, we present results from three-dimensional MHD simulations of the shearing of bipolar and multi-polar coronal magnetic fields by photospheric footpoint motions, and discuss the implications of these results for Taylor's theory and for models of solar activity. The key conclusion of this work is that significant magnetic reconnection occurs only at very specific locations and, hence, the Sun's magnetic field cannot relax completely down to the minimum energy state predicted by conservation of global helicity.

1. INTRODUCTION

Magnetic reconnection has long been invoked as the physical mechanism underlying much of solar activity. For example, reconnection is believed to be the process driving many of the observed dynamic solar events ranging from spicules to the largest and most energetic manifestations of solar activity, coronal mass ejections (CME) and eruptive flares. In spite of the long and intensive study of reconnection in the solar atmosphere, the process is still not well understood, especially in three dimensions. One of the main difficulties in developing a comprehensive understanding is that reconnection may take on different forms depending on the details of the physical situation. Consequently, any theory that can provide some unifying insight into the nature of reconnection would be of great benefit to understanding many aspects of solar activity. This is the compelling motivation behind studies of magnetic helicity. Since magnetic helicity is believed to be conserved during reconnection in general, the hope is that helicity conservation may allow one to determine the final state of a reconnecting system without having to calculate the detailed dynamics of the evolution. Helicity conservation may also be able to provide some valuable information on the dynamics. In this paper we argue, however, that helicity plays a negligible role in determining the evolution of reconnecting magnetic fields in the Sun’s corona. It should be emphasized that by the term “helicity”, we refer in this paper solely to the global relative helicity [*e.g.*, *Berger*, 1985], which defines a single invariant. We are not referring to the helicity density which defines an infinite set of possible invariants. Only the global helicity is believed to be conserved during reconnection.

The basic theory for using helicity conservation to determine the evolution of magneto-plasmas has been developed by Taylor [1986]. For Taylor’s theory to be applicable to the solar corona, three key statements must be true. First, the helicity (global) is conserved during reconnection. Our numerical simulations agree well with this statement — the higher the magnetic Reynolds number of the simulation, the

better the agreement. Second, helicity is the only topological quantity that is generally conserved during reconnection. We believe that this assumption is also true, but our simulations cannot test it, because they all begin with a potential field in which a simple shear or twist flow is imposed on the photospheric boundary. There are no knots or disconnected flux in the coronal field, and no braiding motions or higher-order topologies produced by the boundary flows. Since the complete topology of our fields is contained in the helicity density, it is unlikely that there are any global topological invariants other than helicity available to be conserved.

It appears, therefore, that the first two requirements for Taylor’s theory are valid for our simulations, and probably for the corona as well. The final requirement is that *complete reconnection* occurs, *i.e.*, the reconnection continues until the magnetic energy achieves its lowest possible state. Note that this statement does not say anything about helicity, it is actually a model for reconnection. Unfortunately, this statement is completely wrong for our simulations and, we believe, also for the Sun.

The physical reason for the failure of complete reconnection in the corona is that it requires the formation of numerous current sheets, or sheet-like current structures. But we, and others, have found from both 2.5D and 3D simulations that due to photospheric line-tying, current sheets do not form easily in the corona [*e.g.*, *Mikic, Schnack, and Van Hoven*, 1989; *Dahlburg, Antiochos, and Zang*, 1991; *Karpen, Antiochos, and DeVore*, 1990]. It is instructive to note that the Taylor theory is closely related to Parker’s nonequilibrium theory for coronal heating [*Parker*, 1972; 1979]. The nonequilibrium theory also proposes that in a 3D system, current sheets will form spontaneously throughout the coronal volume. But, there have been numerous simulations testing nonequilibrium [*e.g.*, *Van Ballegooijen*, 1985; *Mikic, Schnack, and Van Hoven*, 1989; *Dahlburg, Antiochos, and Zang*, 1991], and to our knowledge, no simulation produces these current sheets. This does not mean that current sheets cannot form or that reconnection does not occur in the corona. Many simulations find that current

sheets readily form at magnetic separatrices [*e.g.*, *Karpen, Antiochos, and DeVore*, 1995; 1996; 1998], and intense current concentrations do form at those locations where the photospheric motions produce exponentially growing gradients in footpoint displacements, in particular, at stagnation points of the flow [*e.g.*, *Van Ballegooijen*, 1986; *Mikic, Schnack, and Van Hoven*, 1989; *Strauss*, 1993; *Antiochos and Dahlburg*, 1997]. But since reconnection occurs only at these very specific locations, it is far from complete, and Taylor’s theory cannot be used to determine either the final state of the field or its evolution. We assert, therefore, that while the global helicity is conserved, it plays little role in determining the corona’s dynamics and evolution.

This conclusion is also evident from observations. The Taylor theory would predict that the coronal field evolves towards a linear force-free field. For an infinite system like the corona, the only linear force-free field with finite energy is the field which is current-free in any finite volume [*Berger*, 1985]. Therefore if the theory held, the coronal field would evolve *via* reconnection to the potential field, in which case there would be no need for CMEs or eruptive flares. It may be argued that the Taylor theory should not be applied to the corona as a whole, since the helicity is not uniquely defined for an infinite system. But, in fact, the Taylor prediction for an infinite system is completely sensible. If reconnection could proceed freely, indeed it would be energetically favorable for the field to transfer all its shear and twist to the outermost field lines that extend toward infinity, such as the field lines at the poles. By transferring all the shear/twist to the longest field lines, the field conserves its helicity, but brings its energy down to the potential field value. The only problem with this type of evolution for the solar corona is that it is never observed.

One could argue, however, that a Taylor process may occur in some small portion of the corona, such as an active region, in which case the field should evolve to a linear force-free state inside this bounded domain. But this prediction also disagrees with observations. The canonical result from vector magnetograms and from H_α observations

is that the field is strongly sheared near photospheric polarity-reversal lines (“neutral” lines), and unsheared or weakly sheared far from these lines [*e.g.*, *Gary et al.*, 1987; *Falconer et al.*, 1997]. (By shear we mean that the field lines appear to be greatly stretched out along the reversal line.) We show below that such a shear distribution can explain the formation of prominences/filaments, which lends strong support to the observations. But this observed localization of the shear is *not* compatible with a linear force-free field.

In order to demonstrate this point, consider a simple analytic model for the field. Take the active region to consist of a 2.5D linear force-free field arcade:

$$\vec{B} = \nabla \times (A(y, z)\hat{x}) + B_x(y, z)\hat{x}. \quad (1)$$

Since this field must satisfy, $\nabla \times \vec{B} = \lambda \vec{B}$, where λ is a constant, we find that $B_x = \lambda A$, and the force-free equation reduces to the usual Helmholtz form, $\nabla^2 A + \lambda^2 A = 0$. One possible solution is:

$$A = \cos(ky) \exp(-\ell z), \quad (2)$$

where the wavenumbers k, ℓ , and λ are related by, $\lambda^2 = k^2 - \ell^2$. We have chosen the form of the flux function in Equation (2) so that it corresponds to a bipolar arcade with a photospheric polarity reversal line at $y = 0$, and a width $ky = \pi$ (this periodic solution actually corresponds to an infinite set of arcades.)

If the wavelengths in the vertical and horizontal direction are equal, $\ell = k$, then $\lambda = 0$, and the solution reduces to the potential field. However, if the vertical wavelength becomes larger than the horizontal one $\ell < k$ (we expect the force-free field to inflate upward), then the solution corresponds to a field with finite shear, $B_x \neq 0$. Assuming that our bipolar arcade is at disk center, then the observed shear of the field at the photosphere would be given by the angle, $\theta = \arctan(B_x/B_y)$. If the field is potential then $B_x = 0$, which implies that $\theta = 0$, and the field lines are perpendicular to the polarity reversal line (the x axis). For the nonpotential case we find from Equations (1)

and (2) that $B_y = dA/dz = -\ell A$. Hence, $\theta = -\arctan(\lambda/\ell)$. The shear is constant throughout the region rather than being localized near the polarity-reversal line. Although this result has been derived for only one family of solutions, it seems likely to hold true in general. A linear force-free field must have a constant ratio of electric current magnitude to magnetic field magnitude, and hence must have shear everywhere. But a broad shear distribution is in total disagreement with numerous observations of the solar field [*e.g.*, Gary *et al.*, 1987; Schmieder *et al.*, 1996].

We conclude, therefore, that complete reconnection does not occur even in small regions of the corona, and that helicity conservation is of limited usefulness for determining the structure and evolution of the coronal field. We verify this conclusion with large-scale 3D numerical simulations in the following sections. The goal of our simulations is to understand the formation and eruption of solar prominences and the accompanying CME, but as will be demonstrated below, the simulations also address the issues of the role of helicity conservation in magnetic reconnection and the applicability of the Taylor theory to the corona.

2. SIMULATIONS OF BIPOLAR FIELDS

The first simulation concerns the formation of prominences. Solar prominences or filaments consist of huge masses of cool ($\sim 10^4$ K), dense ($\sim 10^{11}$ cm $^{-3}$) material apparently floating high up in the hot ($\sim 10^6$ K), tenuous ($\sim 10^{-9}$ cm $^{-3}$) corona [*e.g.*, Priest, 1989]. Prominences reach heights of over 10^5 km, which is approximately three orders of magnitude greater than the gravitational scale height of the cool material. Hence, the most basic question concerning prominences is the origin of their gravitational support. It must be due to the magnetic field; the field lines in the corona must have hammock-like geometry so that high-density plasma can be supported stably in the hammock [Priest, 1989].

A characteristic feature of all prominences is that they form over photospheric

polarity-reversal lines which exhibit strong shear. Since many prominences are also observed to be very long compared to their width or height, 2.5D models for their magnetic structure (a magnetic arcade) have usually been considered. Both numerical simulations and analytic theory showed, however, that 2.5D models of a sheared bipolar arcade cannot produce field lines with the necessary dips to support prominence material [Klimchuk, 1990; Amari *et al.*, 1991]. This led many to consider more complicated topologies involving multi-polar systems or topologies with flux disconnected from the photosphere, the so-called flux ropes [*e.g.*, Priest and Forbes, 1990; van Ballegooijen and Martens, 1990].

We have shown, however, that the lack of dipped field lines is only an artifact of assuming translational symmetry, and that a sheared 3D bipolar field readily develops the correct geometry to support prominences [Antiochos, Dahlburg, and Klimchuk, 1994; Antiochos, 1995]. Our previous results were based on a 3D static equilibrium code that computed the force-free field in the corona given the connectivity of the field lines at the photosphere. Here we present results from recent fully time-dependent 3D simulations of photospheric shearing of a bipolar field. Since we include the dynamics, these simulations also address the issues of current-sheet formation, reconnection, and eruption.

The code uses a highly-optimized parallel version of our 3D flux-corrected transport algorithms to solve the ideal MHD equations in a finite-volume representation. The code is thoroughly documented and available on the WEB under the auspices of NASA's HPCC program (*see* <http://www.lcp.nrl.navy.mil/hpcc-ess/>). The computational domain consists of the rectangular box, $-20 \leq x \leq 20$, $-4 \leq y \leq 4$, $0 \leq z \leq 8$. We use a fixed, but very large non-uniform Cartesian mesh of $462 \times 150 \times 150$ points. The initial magnetic field is that due to a point dipole located at (0,0,-2) and oriented along the y -axis, so that the polarity reversal line at the photospheric plane ($z = 0$) corresponds to the x -axis. As boundary conditions, we impose line-tying with an assumed shear

flow and no flow-through conditions at the bottom, and zero gradient conditions on all quantities at the sides and top. The initial plasma density is uniform, and we neglect the effects of both plasma pressure and gravity in this simulation, corresponding to a zero beta approximation. Note, however, that the plasma is fully compressible and all Alfvén waves are included in the calculation,

We shear the field by imposing a flow at the photosphere that is localized near the polarity reversal line. The shear vanishes for $|y| > 1$, and for $|y| \leq 1$ it has the form:

$$V_x = (8\pi/\tau) \sin(\pi t/\tau) \sin(\pi y), \quad (3)$$

where the time scale for achieving the maximum shear $\tau = 100$. Even though we performed the simulations on the latest architecture massively-parallel machines, it is still not possible to use observed solar values for the shear properties. Our shear extends over roughly half the width of the strong field region on the photosphere, wider than is observed, and the average shearing velocity is approximately 10% the Alfvén speed in the strong field region, rather than the 1% typical of the Sun. But even with these limitations, dipped field lines form readily in the corona.

Plate 1 shows the magnetic configuration halfway through the shearing, at $t = \tau/2$. It is evident that the strongly sheared field lines have dipped central portions. The dips form as a result of the balance of forces between the increased magnetic pressure of the low-lying sheared field lines and the increased tension of the unsheared overlying field. Since the unsheared flux is strongest at the center of the system, the downward tension force is strongest there, producing a local minimum in the height of the sheared flux. Also shown in the Plate is the half-maximum iso-surface of electric current magnitude. As expected, the current is concentrated where the gradient of the shear is largest, in the boundary between the sheared and unsheared field.

The field of Plate 1 reproduces all the basic observed features of prominences; hence, we conclude that the magnetic structure of solar prominences and filaments is

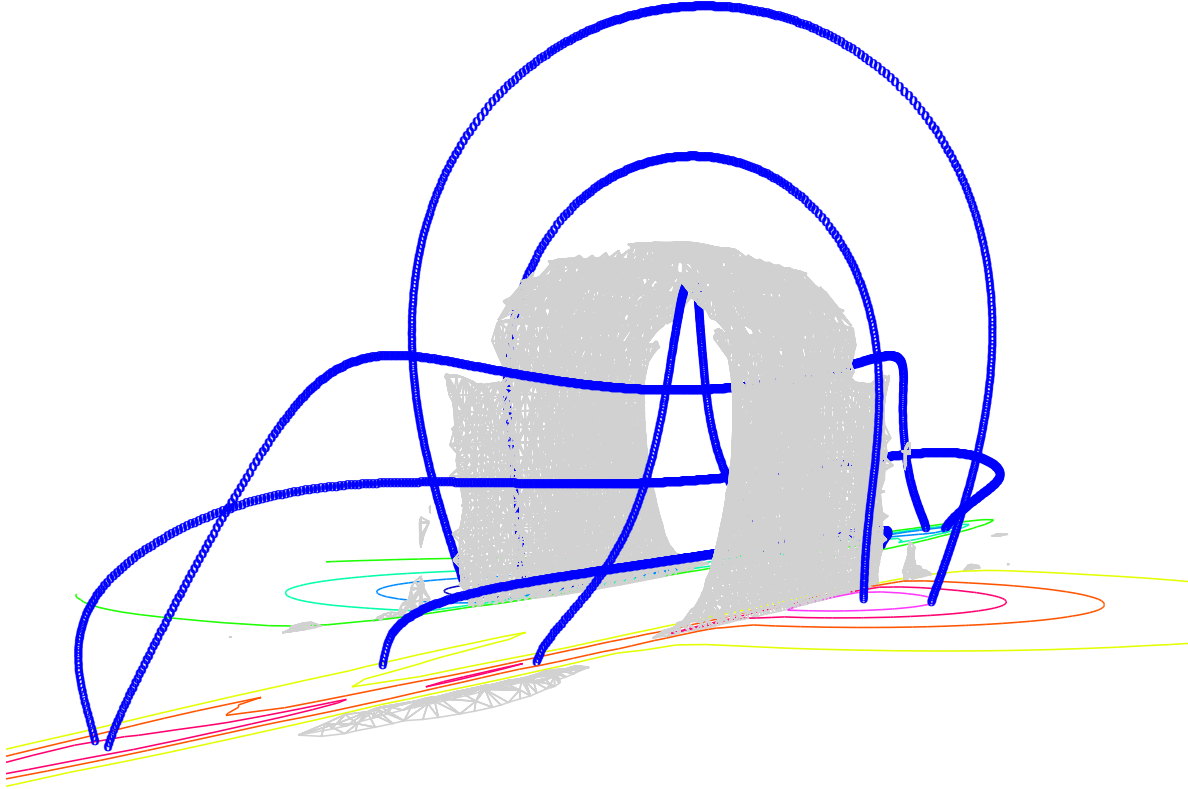


Plate 1. Structure of a bipolar magnetic field that has been sheared by footpoint motions at the photosphere, bottom plane in the Plate. Contours of normal-magnetic-field magnitude are plotted on the bottom plane. Four field lines with footpoints in the shear region and two field lines with footpoints outside this region are shown. Also plotted is the iso-surface of electric current magnitude at half-maximum.

simply that of a sheared 3D field. It is tempting to conjecture that continued shearing of this field eventually leads to eruption. This is the basic hypothesis of the tether-cutting model, which proposes that reconnection of the sheared field either with itself or with the unsheared flux destroys the force balance between sheared and unsheared flux, thereby allowing the field to erupt outward explosively [Sturrock, 1989; Moore and Roumeliotis, 1992]. Note that the tether-cutting model is physically similar to the Taylor theory since both hypothesize that reconnection transfers shear from inner to outer field lines.

Our simulation, however, shows no evidence for either tether-cutting or a Taylor process. We continued the shearing up to $t = 100$, twice as far as shown in Plate 1. We then set the photospheric velocity to zero, and let the system relax for another 100 Alfven times. The total magnetic energy and helicity are shown in Figure 1. The system

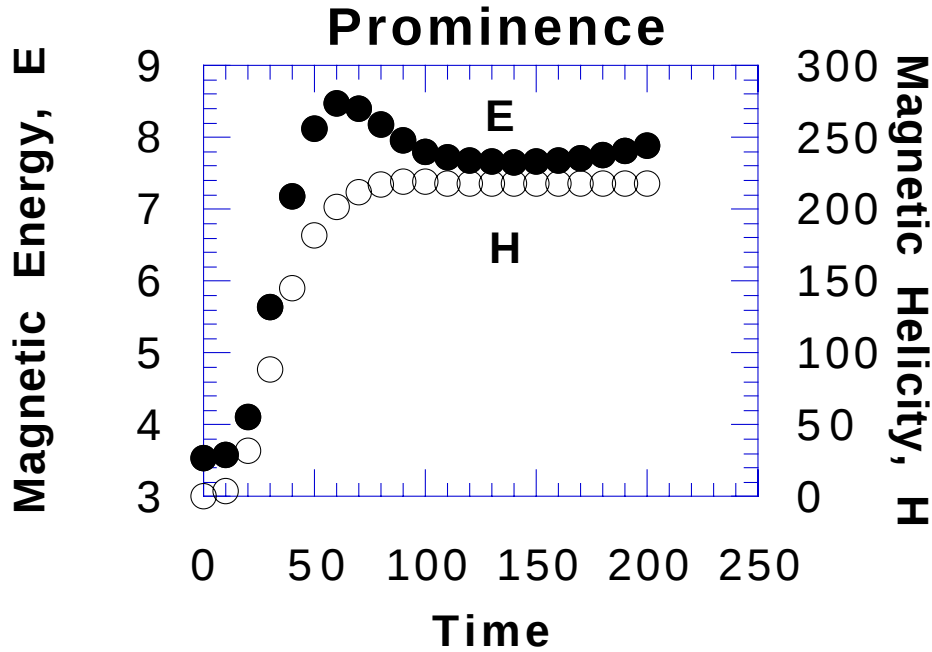


Figure 1. The total magnetic energy and magnetic helicity (relative) of a bipolar field that is sheared for 100 Alfven crossing times and then allowed to relax for another 100 Alfven times.

appears to achieve a stable equilibrium with negligible loss of either energy or helicity. A key point is that the system appears stable, even though some “reconnection” does occur. By $t = 80$ the imposed boundary shear is so extreme that even with our large grid we cannot resolve it numerically, which produces “current-sheets” in the corona, in particular, the current structure seen in Plate 1. As a result, reconnection (or perhaps more appropriately diffusion) occurs, and helical field lines begin to appear at this time. However, the appearance of helical lines is confined to the regions of strongest shear, and does not propagate outward as would be necessary for tether-cutting or for a Taylor process. We conclude, therefore, that our simulation rules out both tether-cutting and the Taylor theory as viable models for the corona.

3. SIMULATIONS OF MULTI-POLAR FIELDS

There are two fundamental reasons for the lack of eruption in the simulation described above. First, line-tying inhibits magnetic reconnection in a topologically smooth field such as a simple bipole. Second, eruption of the low-lying sheared flux requires the overlying unsheared field to open as well, but the Aly-Sturrock limit implies that no closed configuration can have sufficient energy to reach this open state [Aly, 1984; 1991; Sturrock, 1991].

We have argued that a multi-polar magnetic topology overcomes both these problems, and have proposed a “breakout” model for prominence eruptions and coronal mass ejections [Antiochos, 1998; Antiochos, DeVore, and Klimchuk, 1999]. Line-tying does not inhibit current-sheet formation at the separatrix surfaces between flux systems, and these current sheets can lead to sustained reconnection at separator lines [Karpen, Antiochos, and DeVore, 1995; 1996; 1998]. Furthermore, a multi-flux topology makes it possible to transfer the unsheared overlying flux to neighboring flux systems, thereby allowing the sheared field to erupt outward while keeping the unsheared flux closed. This allows the system to erupt explosively while still satisfying the Aly-Sturrock energy

limit [*Antiochos, DeVore, and Klimchuk, 1999*].

We show below results from our first 3D simulation of the breakout model. The simulation domain in this case consists of the region: $-3 \leq x \leq 3$, $-3 \leq y \leq 3$, $0 \leq z \leq 3$, with a fixed, non-uniform grid of $166 \times 166 \times 86$ points. The initial magnetic field is that due to three point dipoles: one located at $(0, 25, -50)$, with magnitude unity, and pointing in the $+y$ direction; another located at $(0, 1, -1)$, with magnitude 10, and pointing in the $-y$ direction; and the third at $(0, 0, -0.5)$, with magnitude 10 and pointing in the $-z$ direction. The initial density and pressure were chosen so that the average plasma beta near the base is less than 0.1. (This simulation did not use the zero-beta approximation.)

Plate 2a shows the initial potential field of the simulation. The magnetic topology consists of four flux systems due to four distinct polarity regions at the photosphere. There are two toroidal separatrix surfaces that define the boundaries of these flux systems, and their intersection in the corona defines a separator line, along which rapid reconnection can occur [*Antiochos, 1998*]. This configuration corresponds to a so-called delta-sunspot region. We impose similar boundary conditions as in the previous simulation, and apply a shearing motion localized near the circular polarity-reversal line of the delta-spot located at the center of the bottom plane. The shear is such that it produces a rotation of $\sim 2\pi$ over a time interval of 100 Alfvén times.

Plate 2b shows the effect of this shear. All field lines shown in Plates 2a and 2b are traced from exactly the same set of positions at the photosphere. It is evident that field lines with footpoints near the polarity reversal line have been twisted through almost a full rotation, (this sheared flux system corresponds to the sheared prominence bipole of Plate 1). A careful examination of the field lines in 2b reveals that some of the unsheared delta-spot flux overlying the sheared flux has become open, *i.e.*, it extends to the top boundary of the simulation box rather than closing down over the sheared field. This transfer occurs as a result of reconnection between the delta-spot flux and

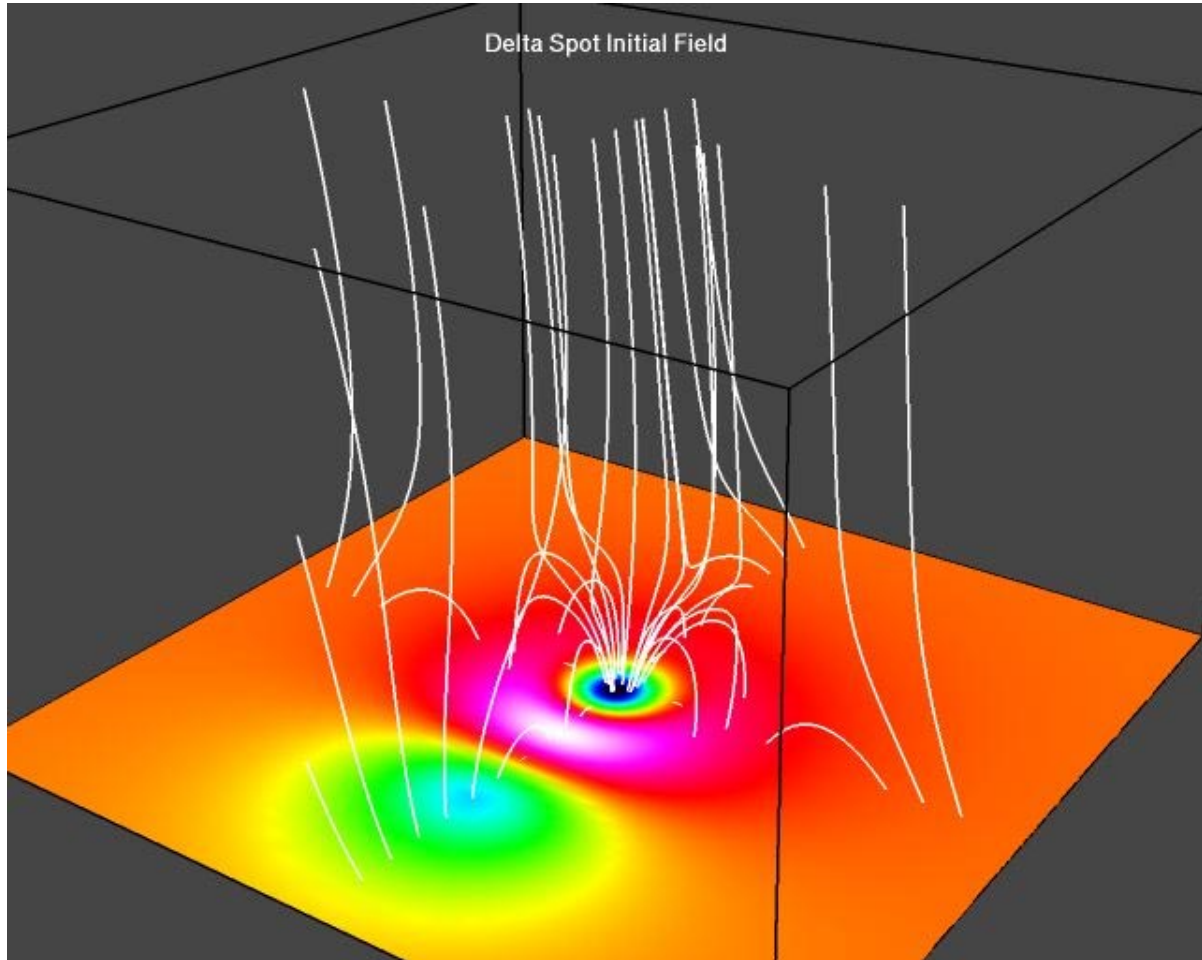


Plate 2a. Evolution of a delta-sunspot magnetic field that is sheared by footpoint motions. The initial current-free magnetic configuration.

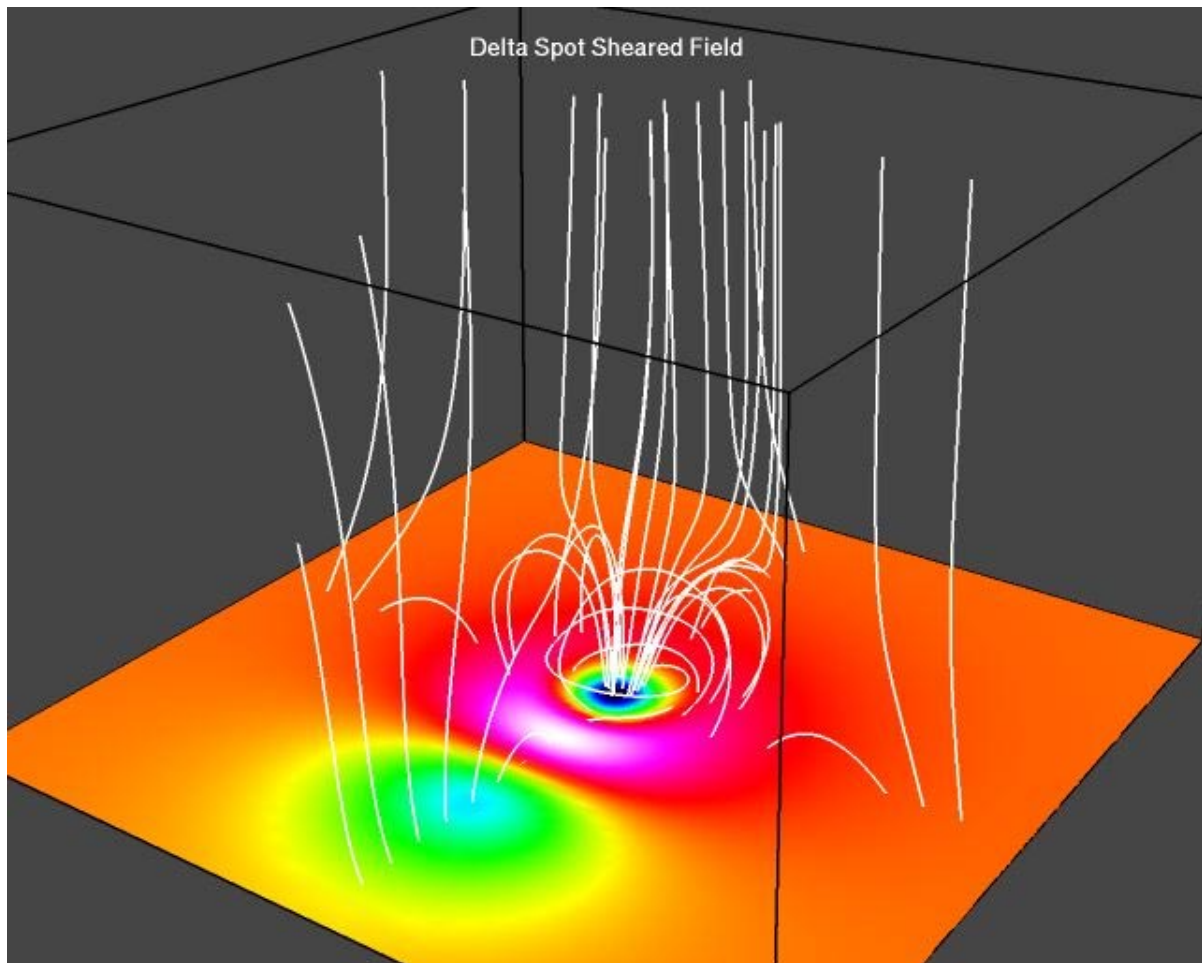


Plate 2b. The field lines after a shear of $\sim 2\pi$.

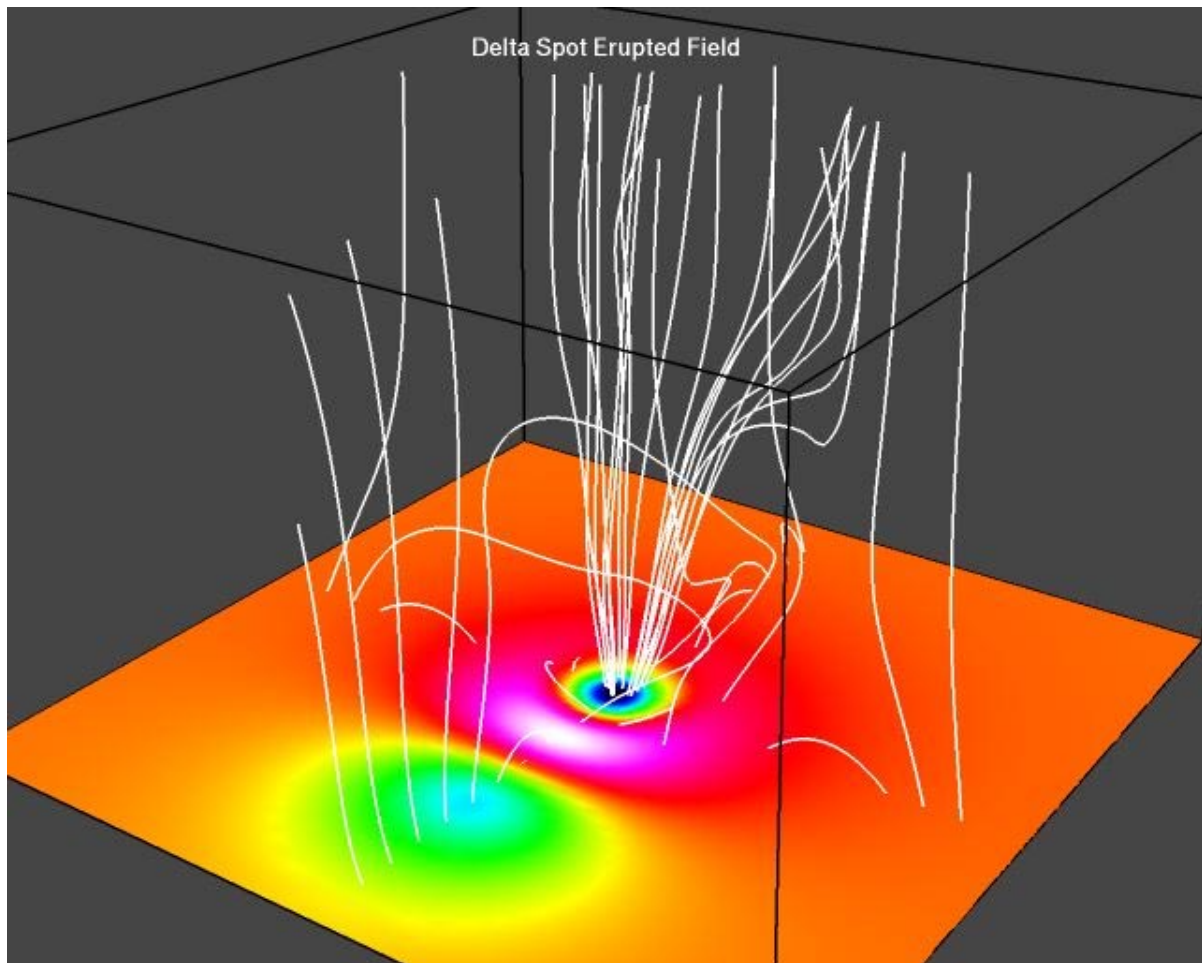


Plate 2c. The field lines after a shear of $\sim 4\pi$.

the neighboring open flux system.

The effect of another 2π rotation is shown in Plate 2c. Almost all the delta spot flux is now open. We show in Figure 2 the total magnetic energy and helicity of the system, equivalent to Figure 1. Near the end of the second shearing phase there is clearly a burst of impulsive energy release and helicity ejection through the top of the system. The helicity within the simulation volume decreases much faster than the energy, because of the eruption. Therefore, the evolution of our simulated corona is the exact opposite of a Taylor process!

Of course, this claim is somewhat overstated because we expect that, in fact, the helicity of the whole system (including the erupted field) stays constant, whereas the magnetic energy of the whole system decreases. It is interesting to note, however, that since solar telescopes observe only a finite coronal volume, eruptive opening of the magnetic field in that volume implies that the observed helicity decreases to zero, but

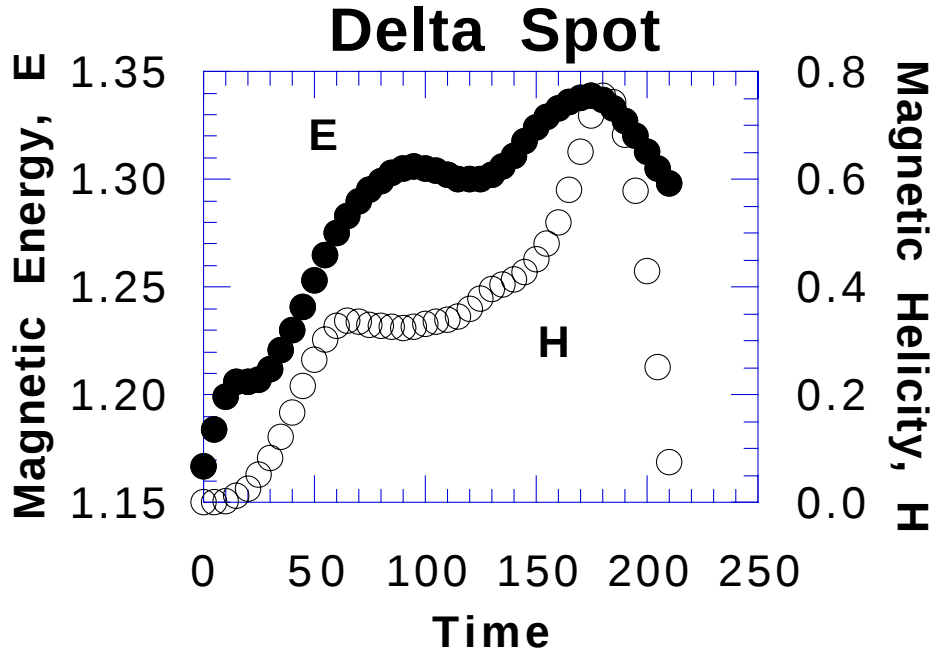


Figure 2. Total energy and helicity of a delta-sunspot field that undergoes 2 shearing phases, each of duration 100 Alfvén crossing times.

the observed magnetic energy asymptotes to the open field value, which is generally well above the potential field value. In this sense, an anti-Taylor process is an appropriate approximation for the evolution of coronal regions observed during an eruption.

A key result of our 3D delta-spot simulation is that even though a great deal of reconnection occurs, it is far from complete. The reconnection is confined to the separator line between the sheared and unsheared regions. Consequently, the field never approaches a linear force-free field. Instead it evolves toward an open state in which the currents are concentrated in a thin sheet. This also is opposite to what is expected for a Taylor process.

In summary, we conclude that while helicity is conserved and may well be the only topological quantity that is generally conserved during reconnection, the actual amount of reconnection in the Sun's corona is determined by the detailed magnetic topology of the particular region. Consequently, the global helicity by itself yields little information on coronal evolution.

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