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CORONAL HEATING BY RECONNECTION

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ABSTRACT

The outermost atmosphere of the Sun, called the corona, is some 200 times hotter than the surface of the Sun. The main source of energy for heating the corona is believed to be the magnetic field which dominates the corona. Magnetic reconnection is probably the most important mechanism for releasing magnetic energy and may, therefore, be important for coronal heating or micro-flaring. The best observational examples of reconnection in the corona are thought to be X-ray bright points, which are small-scale brightenings seen randomly throughout the whole corona. Theoretical models can not only explain the key observations relating to bright points, but they can also explain the complex three-dimensional structures often seen in bright points. In these models magnetic neutral points play a significant role as the centres for reconnection both in two and three dimensions.

INTRODUCTION

The Sun's core is at a temperature of 15 million degrees Kelvin. As you move further from the its centre the temperature drops such that at the so-called "surface" of the Sun the temperature is just 6000 K. The Sun's "surface", known as the photosphere, is defined as the layer around the Sun in which the opacity reduces to such a level that photons, which, due to multiple collisions, have travelled for around 10 million years inside the Sun, are finally emitted. However, now as you move further from the solar surface the temperature increases dramatically to more than a million degrees Kelvin at about 3000 km above the photosphere. This region is known as the solar corona and the question of how it maintains such massive temperatures despite radiative and conductive losses is the coronal heating problem. It has been investigated by solar physicists for 50 years, but still remains a contentious issue.

At first it was believed that acoustic waves, generated by the convection motions of the plasma below the surface, heated the corona. However, observers studying the corona have never found evidence of these waves at sufficient amplitude and furthermore theories show that acoustic waves would be damped within 2000 km of the Sun's surface. A different heating source needed to be found. This source came in the form of the magnetic field, which dominates the corona. Order of magnitude calculations show that it contains ample energy to account for the radiative and conductive loses from the corona (Withbroe and Noyes, 1977). Also X-ray observations show that the magnetic loop structures of the corona are outlined by hot dense features. It is now generally accepted, therefore, that the corona is heated by magnetic effects, but the mechanism for the release of this energy is, however, still a hot topic. The main contenders are the various forms of magneto-acoustic wave heating mechanisms (e.g. phase mixing and resonant absorption) or magnetic reconnection. Here I will concentrate on the latter, in particular, on reconnection at magnetic neutral points.

I will show that both two- and three-dimensional magnetic neutral points are liable to collapse if their field lines are free to move: thus they can easily form current sheets and are ideal places for reconnection to occur. Then I will explain why reconnection is the most probable mechanism for heating small-scale coronal phenomena. The best known small-scale coronal events are X-ray bright points. A general two-dimensional model for bright points will be described and then two three-dimensional models for particular bright points will be discussed where neutral points play an important role.

RECONNECTION

Magnetic reconnection is a powerful mechanism for magnetic energy release. Its most notable features are that it not only efficiently converts magnetic energy to thermal, bulk kinetic and fast particle energy, but it also causes global changes in the magnetic field structure. These topological changes are crucial in the formation of structures such as plasmoids, which are often associated with the more dynamic heating events on both large scales (e.g. coronal mass ejections) and small scales (e.g. X-ray jets). Furthermore the simultaneous release of bulk kinetic energy accelerates these plasmoids to the observed high velocities. Magnetic reconnection also creates large electric currents, shock waves and filamentation.

Two-dimensional Collapse of a Null

$$\mathbf{B} = ([1 - \epsilon e^{\omega t}]y, [1 + \epsilon e^{\omega t}]x)$$

$$\epsilon = 10^{-3}$$

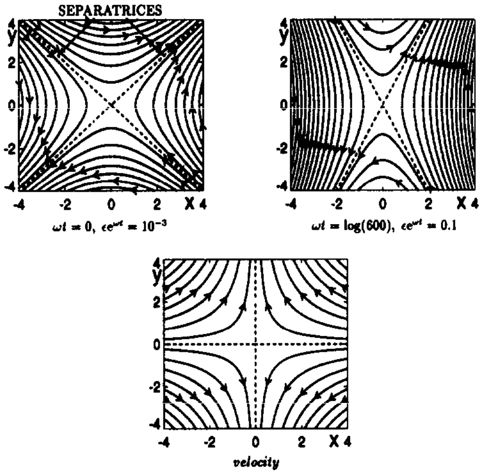


Figure 1: The collapse of a two-dimensional potential X-type neutral point where (a) is the initial equilibrium magnetic field, (b) is a snap shot of the field taken at a later time and (c) is the velocity field.

For reconnection to occur ideal magnetohydrodynamics (MHD) must break down locally such that diffusive effects become significant. This may happen, in two dimensions, in configurations such as neutral points and current sheets. If we consider the local structure of a potential magnetic neutral point in two dimensions it is not hard to show that, by assuming the magnetic field is not line-tied at the boundaries and that the field must evolve ideally, the null is unstable to small perturbations (Figure 1). First, consider the linearised form of the ideal MHD equations and assume that plasma pressure is much smaller than the magnetic pressure, so the plasma β is small. Then if the magnetic field, the velocity and the density are of the form $\mathbf{B} = \mathbf{B}_0 + \epsilon \mathbf{B}_1$, $\mathbf{v} = \epsilon \mathbf{v}_1$ and $\rho = \rho_0 + \epsilon \rho_1$, (where $\epsilon \ll 1$), the set of linearised equations may be written

$$\frac{\partial \mathbf{B}_1}{\partial t} = \nabla \times \mathbf{v}_1 \times \mathbf{B}_0\ , \tag{1}$$

$$\rho_0 \frac{\partial \mathbf{v}_1}{\partial t} = (\nabla \times \mathbf{B}_1) \times \mathbf{B}_0/\mu_0\ , \tag{2}$$

and

$$\frac{\partial \rho_1}{\partial t} = -\rho_0 (\nabla \cdot \mathbf{v}_1) \ . \tag{3}$$

Solutions to these equations are of the form

$$\mathbf{B} = B_0([1 - \epsilon e^{\omega t}]y,\ [1 + \epsilon e^{\omega t}]x)/l \,,$$

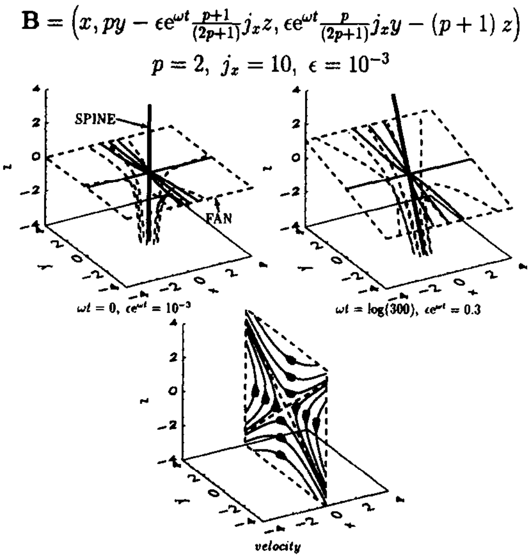
$$\mathbf{v} = \epsilon v_{\mathrm{A}} e^{\omega t}(-x,\ y)/l \,, \tag{4}$$

where B_0, ρ_0, $v_{\mathrm{A}} = B_0/(\mu_0\rho_0)^{1/2}$ and $\epsilon(\ll 1)$ are constants. The growth-rate is

$$\omega = 2v_{\mathrm{A}}/l \ ; \tag{5}$$

thus the system is unstable and as the field is perturbed the separatrices (the field lines that divide topologically distinct regions) begin to close up generating a current perpendicular to the plane of the null. This shows that in a given two-dimensional magnetic field containing neutral points it is possible for the field lines to move in such a way that the neutral points collapse to form a current sheets in which reconnection may occur.

Three-dimensional Collapse of a Null



$$\mathbf{B} = \left(x, py - \epsilon e^{\omega t}\tfrac{p+1}{(2p+1)}j_x z, \epsilon e^{\omega t}\tfrac{p}{(2p+1)}j_x y - (p+1)\,z\right)$$

$$p = 2,\ j_x = 10,\ \epsilon = 10^{-3}$$

Figure 2: The collapse of a three-dimensional potential neutral point where (a) is the initial equilibrium magnetic field, (b) is a snap shot of the field taken at a later time and (c) is the velocity field.

The collapse of a neutral point is not just a two-dimensional phenomenon, since three-dimensional neutral points are also unstable under similar conditions (Parnell *et al.*, 1996). For example, consider the initial equilibrium field of a three-dimensional potential null

$$\mathbf{B}_0 = B_0\,(x, py, -(p+1)z)\,/l \,, \tag{6}$$

where p, B_0 and l are constants (Figure 2a). This field may be perturbed such that a component of current is created in the x-direction (Figure 2b). In this case the linearised ideal MHD equations have solutions of the form

$$\mathbf{B} = B_0\left(x, py - \epsilon e^{\omega t}\frac{p+1}{2p+1}j_x z, \epsilon e^{\omega t}\frac{p}{2p+1}j_x y - (p+1)z\right)/l \,, \tag{7}$$

$$\mathbf{v} = \epsilon e^{\omega t} v_{\mathrm{A}}\left(0, \frac{p+1}{2p+1}j_x z, \frac{p}{2p+1}j_x y\right)/l \,, \tag{8}$$

where $p \neq -1/2$ and j_x, $\rho = \rho_0$, $v_A = B_0/(\mu_0\rho_0)^{1/2}$ and $\epsilon(\ll 1)$ are all constants. Here the growth-rate of the instability is

$$\omega = (2p+1)v_A/l \, , \tag{9}$$

and the current density (j), which is uniform throughout the region, equals

$$\mathbf{j} = \nabla \times \mathbf{B}/\mu_0 = B_0\epsilon e^{\omega t}\,(j_x, 0, 0)\,/l\mu_0 \, . \tag{10}$$

Thus, as in the two-dimensional case, three-dimensional neutral points are liable to collapse and are therefore one of the most likely places at which current sheets may form and reconnection will occur. However, in three dimensions, neutral points are not essential for reconnection. In fact, a general theory of magnetic reconnection in three dimensions (Schindler *et al.*, 1988; Hesse and Schindler, 1988) shows that the most important feature of reconnection is a localised component of the electric field parallel to the magnetic field.

X-RAY BRIGHT POINTS

Observations

X-ray bright points are the best studied of all the small-scale coronal events. They are small bright multiple-loop features that occur randomly throughout the whole corona (Golub *et al.*, 1974; 1976a and b; 1977). They are approximately 20000 km in diameter and have lifetimes between 2 and 48 hrs (with a mean of 8 hrs). Ten percent of bright points are observed to "flare". That is, their intensity increases by a factor of 10-100 for a period of up to 10 minutes (Golub *et al.*, 1974; Strong *et al.*, 1992). Long hot loops have also been observed extending out (normally in pairs) from bright points. These are known as X-ray jets (Shibata *et al.*, 1992a and b) and may also appear from small active regions (larger regions than bright points, but with similar characteristics). X-ray jet loops have lifetimes of the order of minutes and lengths of up to hundreds of megameters and velocities of 1100 km s^{-1}.

It is believed that X-ray bright points are heated by magnetic reconnection. The observational evidence supporting this is threefold. First, the structure of bright points outlines magnetic loops. Second, the fluctuations in intensity of bright points has no periodicity so they are less likely to be heated by a wave mechanism. Finally, the bright points appear above pairs of opposite polarity magnetic fragments (Golub *et al.*, 1974; Martin and Harvey, 1979; Harvey, 1984, 1985). Approximately two-thirds of these fragments converge and mutually lose flux, thus forming what is known as a *cancelling magnetic feature* (Martin *et al.*, 1984); whereas in the remaining one-third the fragments diverge and so are believed to be associated with emerging flux regions (Webb *et al.*, 1993; Harvey *et al.*, 1993).

I will concentrate only on the majority of bright points, i.e. those connected with cancelling magnetic features. First I will describe a general model for a bright point and its associated cancelling magnetic feature, called the Converging Flux Model which was proposed by Priest *et al.* in 1994; this model explains the key observations relating to bright points. Then I shall go on to discuss two models of particular bright points which explain their complex three-dimensional loop structure (Parnell *et al.*, 1994).

Converging Flux Model

The Converging Flux Model (Priest *et al.*, 1994) is a basic model for a bright point in which a pair of opposite-polarity magnetic fragments converge through three phases. The first stage is the *pre-interaction phase* (Figure 3a and 3b). Here a pair of opposite-polarity magnetic fragments are initially unconnected: thus, as observed, no chromospheric fibrils link them (Martin *et al.*, 1985). Then in the second phase, called the *interaction phase*, an X-point develops and rises in the corona; reconnection there releases energy in the form of a bright point (Figure 3c and 3d). Temperature fluctuations of bright points imply that the most likely regime of reconnection is an impulsive bursty one. It is also possible for long hot loops or jets to be

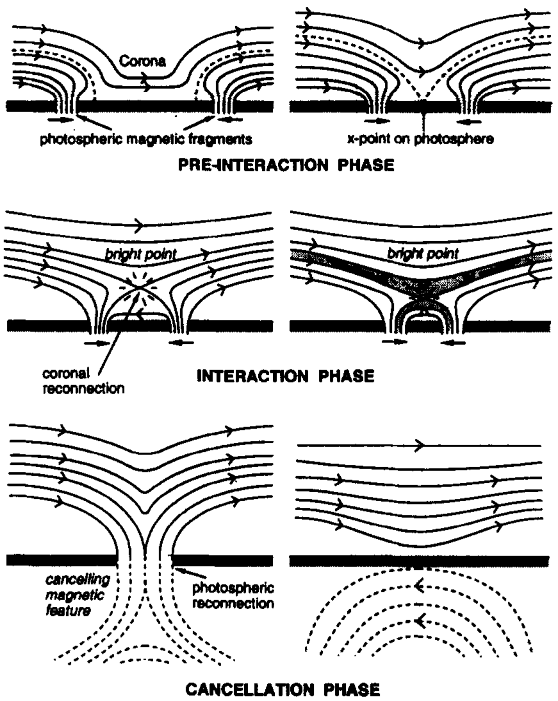


Figure 3: Converging Flux Model (qualitative). (a) and (b) The *pre-interaction phase* where the fragments are initially unconnected. (c) and (d) The *interaction phase* in which reconnection creates a bright point. (e) and (f) The *cancellation phase* where photospheric reconnection forms a cancelling magnetic feature.

created by the injection of heat and plasma along newly reconnected field lines (Shibata *et al.*, 1992a and b); these occur in pairs, as observed. Finally, in the *cancellation phase* the X-point descends to the photosphere and reconnection there creates a cancelling magnetic feature (Figure 3e and 3f).

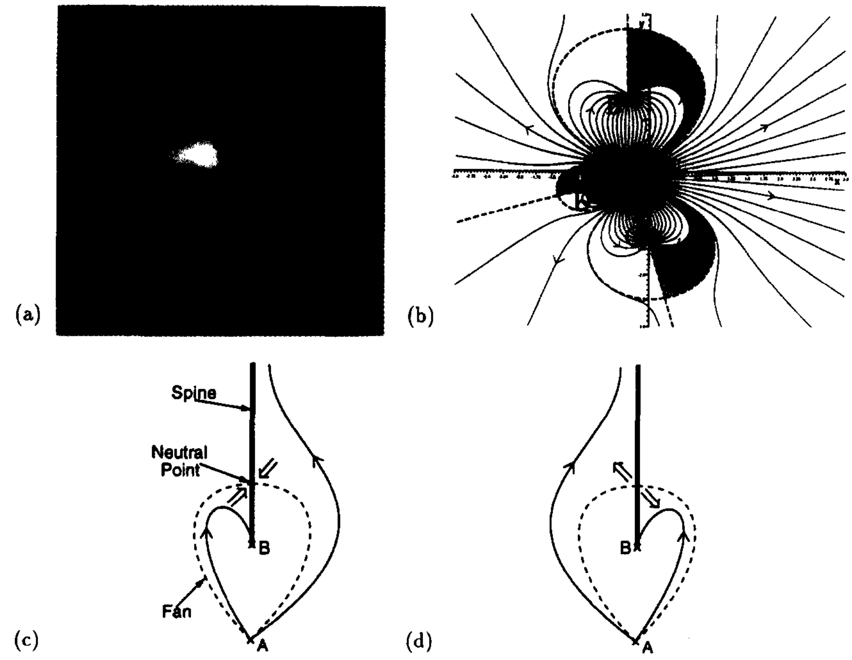


Figure 4: (a) Soft X-ray image of the bright point (courtesy of L. Golub). (b) The magnetic field due to the observed fragments in the underlying photosphere with the newly reconnected field lines shaded. (c) and (d) Simple sketches of "spine" reconnection where the field lines reconnect across the fan (dashed) and the spine (thick) becomes singular.

Three-dimensional Bright Point Models

The particular bright points studied were observed by NIXT on 11th July 1991 with magnetogram data supplied by Kitt Peak. The bright points were modelled using a similar philosophy to that of the Converging Flux Model. Magnetograms were used to identify the most important magnetic regions relating to the bright points; these regions were modelled as point sources. It was assumed that there were no regions of emerging flux and that the interaction of the existing flux alone caused the observed brightenings. As a working hypothesis it was assumed that, as the sources move, field lines reconnect and brighten due to the injection of heat and plasma along them.

Bird-like Bright Point – Spine Reconnection. The first bright point (Figure 4a) has a bird-like structure. It is modelled by one positive (A) and three negative (B, C and D) fragments. The positive pole is found to move towards D resulting in newly reconnected field lines, shaded in Figure 4b, which brighten to give a bird-like shape similar to that observed. Here the reconnection process is likely to be "spine" reconnection (Priest and Titov, 1996) in which the field lines in the fan reconnect and the spine becomes singular (Figure 4c and 4d).

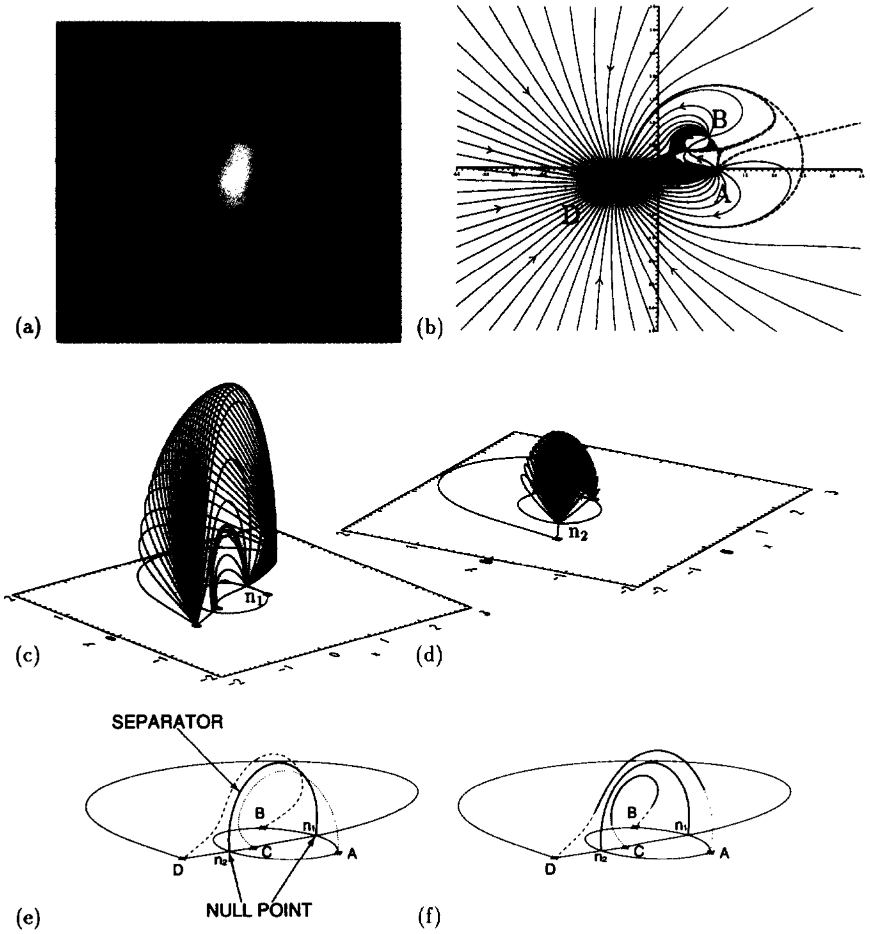


Figure 5: (a) Soft X-ray image of bright point (courtesy of L. Golub). (b) The magnetic field due to the observed fragments with the newly reconnected field lines shaded. (c) and (d) The field lines in the fan surfaces of the positive null (n_1) and negative null (n_2). (e) and (f) Three-dimensional reconnection near a separator. Field lines AC (dotted) and BD (dashed) reconnect along the separator (thick) to form new field lines AD and BC.

Second Bright Point - Separator Reconnection. The second bright point (Figure 5a) has a less distinctive structure, but is also associated with four fragments: this time two are positive (A and B) and two are negative (C and D). These fragments give rise to the shaded newly reconnected field lines, shown in Figure 5b, when the negative source C moved towards the positive source B. Again the field lines which are heated corresponded well with the observed brightening.

This time, however, the reconnection process is likely to be "separator" reconnection. The separator is the field line that connects the two null points n_1 and n_2; it lies in the intersection of the two separatrix surfaces which divide topologically distinct surfaces (Figure 5c and 5d). These surfaces are the fan planes of n_1 and n_2. Separator reconnection occurs in the manner shown in Figure 5e and 5f. Two field lines, one from A to C (dotted) and the other from B to D (dashed) are moved by the motion of the fragments such that they lie partially along the spine of each null and the separator (i.e. from A to n_1 along the separator to n_2 to C and from B to n_1 along the separator to n_2 to D). Reconnection takes place producing field lines from A to D and from B to C made up of parts from the original two field lines (AC-dotted and BD-dashed) and part of the separator (thick).

CONCLUSIONS

Magnetic reconnection is an important mechanism in the heating or micro-flaring of the solar corona: in particular, in the creation of the small-scale phenomena such as X-ray bright points and X-ray jets. It is also likely to be an essential part of other coronal events such as coronal mass ejections and solar flares because of its unique ability to change the global topology of the magnetic field, thus forming plasmoids or flux ropes.

Magnetic neutral points are important sites for reconnection because they allow a localised break-down of ideal MHD, thus allowing the plasma to diffuse through the magnetic field. They are locally unstable provided that the field lines are free to move and may collapse to form current sheets in which reconnection occurs. The collapse of both two and three-dimensional neutral points occurs in a similar manner: however, the types of reconnection that result are likely to be different, because of the more complex structure in three dimensions.

The Converging Flux Model for X-ray bright points gives plausible explanations to the key general observations relating to bright points. First, the opposite polarity fragments are unconnected, as observed. As they move together a bright point forms in the corona due to coronal reconnection. Finally, a cancelling magnetic feature is formed at the end of the bright point due to reconnection in the photosphere. The philosophy of this model gives rise to particular models that give good explanations for the complex structures that arise in bright points.

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