Nonlinear Plasma Physics of the Solar Corona

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Abstract. As a tribute to Dennis Papadopoulos, we present a review of some recent ideas in solar coronal plasma physics. In particular we discuss some models of coronal heating, notably the coronal tectonics model, as well as some ideas on the nature of reconnection in three dimensions. In addition, we summarise a model for the time-dependent response of the corona to the sudden dissipation of a current sheet.

Keywords: Solar physics, Stars, Magnetohydrodynamics, Solar magnetic fields
PACS: 96.60.-j, 97.10.-q, 95.30.Qd, 96.60.Hv

INTRODUCTION

Dennis Papadopoulos

Dennis Papadopoulos gained his PhD in Maryland in 1968 and worked at NRL for 10 years before returning to Maryland. I myself completed a PhD in 1969 and my first couple of papers were on collisionless shocks, but since collisionless plasma physics seemed so complex, I decided to focus on the simpler area of MHD. Dennis on the other hand was fearless in tackling many of the hardest problems in plasma astrophysics and as a result came up with many revolutionary ideas. The ones that I particularly appreciate are:

*strong turbulence in beam-plasma interactions which led to a basic understanding of type III radio bursts;

*anomalous transport and resistivity in the ionosphere;

*and key work on the nature of collisionless shock waves, such as ion heating in the Earth's bow shock and electron heating in supernova shocks at high Alfvén Mach number, when particle reflection leads to two stream instability in the upstream region.

Throughout, his approach has been to use state-of-the-art computing coupled with highly creative ideas.

At an IAU Symposium in Maryland in 1979 Dennis reviewed type III radio bursts and can be seen in the conference picture, with a beardless Loukas Vlahos and a bearded Costas Alissandrakis behind him (Figure 1). Four years later at a similar symposium, the conference photo reveals Denis again, and a little group including myself on the front row with a now bearded Loukas Vlahos behind and also Kanaris Tsinganos (Figure 2).

Loukas Vlahos gained his PhD with Dennis and Mukhul Kundu in Maryland in 1979 and after a spell in the army returned to Maryland before moving to Thessaloniki in 1985. At the Annecy SMY Workshop in 1981, I and my student Peter Cargill met Loukas, who persuaded Peter after a couple of years in Boulder as a postdoc to move to Maryland (1984-1992). Those of you who are parents will share the hope that your children fall in with good company, and the same is true of academic children – in this case Peter fell in with the best company of all in the form of Dennis Papadopoulos, who taught him all the microscopic plasma physics he knows – he is very sorry not to be here today to share in this joyous celebration of a great man and his work.

THE SOLAR CORONA

Yohkoh revealed the corona to be a dynamic magnetic world dominated by complex nonlinear interactions between the magnetic field and plasma. Fundamental aspects of astrophysical plasma physics on which Dennis and his students have been making ground-breaking contributions, are revealed there, including particle acceleration, shock waves, instabilities, wave and magnetic reconnection. There is in the corona a subtle coupling between the macroscopics (described by MHD) and the microscopics (in the realm of kinetic plasma physics). The MHD determines the global environment, but the microscopics is responsible for the transport coefficients and particle acceleration.

The Hinode satellite is revealing stunning detail on the structure and dynamics of the corona (Figure 3), but the key question remains: how is the corona heated to several million degrees by the magnetic field. The traditional answer has been: waves or magnetic reconnection. With Trace and SoHO, many examples of waves have now been observed in the corona, but they are invariably too weak to be heating the corona. The most recent example from Hinode, studied by Hansteen et al. [1], de Pontieu et al. [2] and Suematsu et al. [3], is of spicules at the limb

FIGURE 1. Close-up of conference photo in Maryland in 1979

swaying to and fro like straw in a prairy.

Reconnection remains, however, the most natural explanation for heating the low corona, especially since x-ray brightenings invariably occur above opposite-polarity fragments that are emerging or cancelling. Recent observations from Hinode of a quiescent active region reveal the presence of substantial amounts of plasma at 10 MK or hotter in addition to the normal emission at 2 or 3 million degrees [4, 5].

CORONAL HEATING MODELS

Parker proposed a classical model for heating the corona by nanoflares in which an initially uniform magnetic field is braided by complex photospheric motions to produce current sheets at the boundaries between braids.

In contrast, Vlahos [6] has proposed that an active region is a nonlinear driven dissipative system. He notes that flux elements in the photosphere are likely to form a power-law distribution: indeed, Parnell et al. [7] has resolved a previous controversy by using Hinode and SoHO observations to extend the observations downwards in scale by a factor of a hundred to much smaller fluxes (Figure 4). The results imply such a power-law distribution with an exponent of -1.8. In the corona the observed microflares and nanoflares also have a power-law distribution (although the errors are not insignificant [8]).

Thus the physics appears to be scale-free, but what is that physics in a way that is consistent with MHD? Vlahos suggests that an active region is in a self-organised critical state, as current sheets form at all scales and reconnect. Furthermore, stochastic acceleration of particles is likely in the fractal electric fields associated with such current sheets [see also 9, 10, 11, 12, 13].

The Coronal Tectonics Model [14] is a development of Parker's model which takes account of the fact that the coronal field comes up from many small sources in the photosphere so that there are many more current sheets and they form much more easily. Observed magnetograms from SoHO imply that each magnetic fragment is connected to 8 other fragments on average [15, 16] and that the time for all the field lines in the quiet corona to reconnect is only 1.5 hours. In other words, there is an incredible amount of reconnection continually taking place and heating the corona.

The way to describe this amazing coronal complexity is in terms of the *magnetic skeleton*, which is the web of separatrix surfaces that separate the coronal volume into topologically different regions (Figure 5).

The idea of the coronal tectonics model is that the magnetic flux in each observed coronal loop will go down through the solar surface in many magnetic fragments – and the flux from each such fragment is separated from its neighbour by a separatrix surface . Thus, as the magnetic sources move, current sheets will be produced on the separatrices and separators. The corona is therefore filled with myriads of current sheets heating impulsively. The estimate is that a single x-ray bright point is likely to have at least 800 separators and each of the finest Trace loops is likely to have 80 separators.

THREE-DIMENSIONAL RECONNECTION

In three dimensions reconnection has many new surprising features that make it quite different from two-dimensional reconnection. In 2D, reconnection can occur

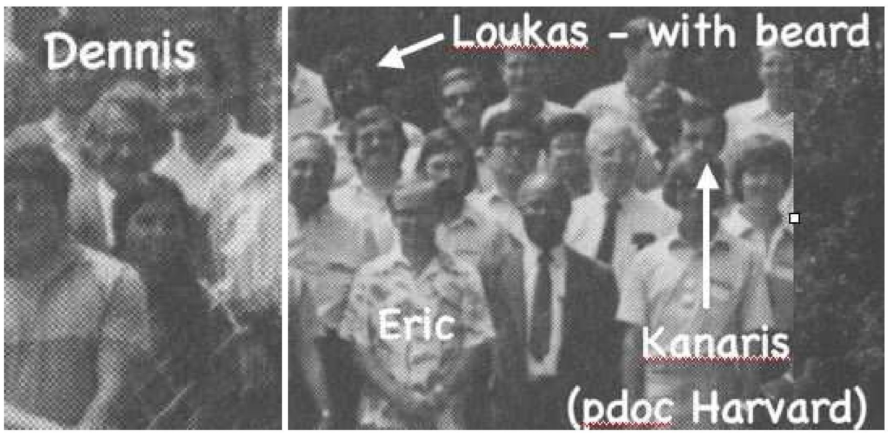

FIGURE 2. Close-ups of conference photo in Maryland in 1983

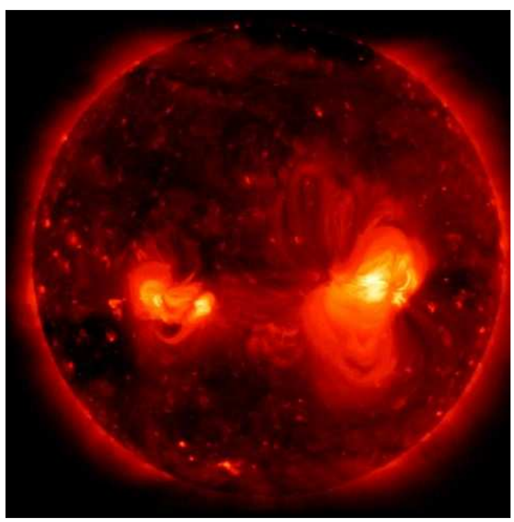

FIGURE 3. The corona as viewed by the XRT telescope on Hinode (courtesy Leon Golub)

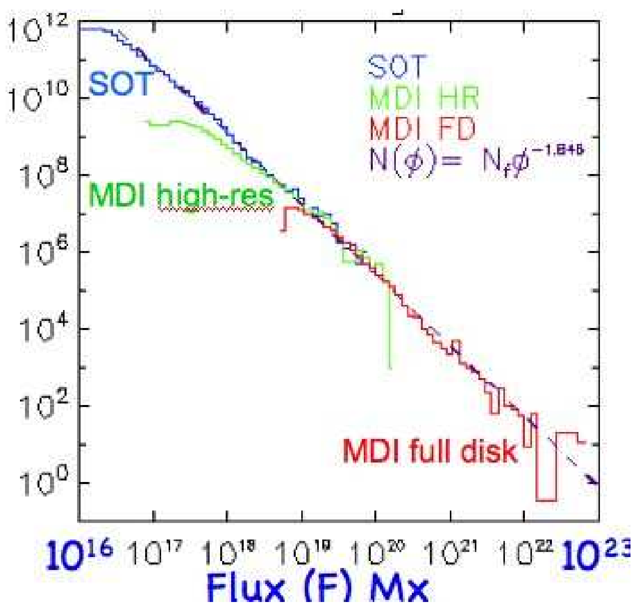

FIGURE 4. The distribution of magnetic flux elements with flux in Maxwells, as observed with Hinode and SoHO (After [8]).

only at an X-type null point: the magnetic field lines slip through the plasma, but change their connections only at the X-point. In 3D, however, the field lines continually change their connections as they pass through the diffusion region. In 3D too, the structure of a null point is quite different: the simplest such null has magnetic field $B_x = x$, $B_y = y$, $B_z = -2z$, and the particular isolated field line that approaches the null along the z-axis is called the *spine* of the null, while the surface of field lines that recedes in the xy-plane is called the *fan* of the null (Figure 6).

In three dimensions reconnection can occur at a null point by spine reconnection, fan reconnection or separator reconnection, depending on whether the current becomes concentrated along the spine, fan or separator. But reconnection can also occur in the absence of a null, at so-called *quasi-separatrix surfaces* where the mapping gradient is large.

A simple "fly-by" numerical experiment was conducted by Parnell and Galsgaard [17] on a "binary" interaction between two opposite polarity photospheric fragments in an overlying uniform field. Initially, the two fragments were not joined, but as they approached they became joined by reconnection, but the question arose: what type of reconnection was occurring. It was only by constructing the magnetic skeleton that Haynes et al. [18] were able to answer this. It revealed a much more complex interaction than was expected. A vertical section through such a skeleton, shows what is happening in 6 steps (Figure 7). First of all, there are two separatrix surfaces below which the flux from each source is open in the sense that it goes to the nearby boundary. Then they touch and intersect in two separators at which reconnection transfers flux from the "open" regions into a "closed" region that represents flux joining one source to the other. In the third step, the lower separator moves down through the lower boundary, while reconnection at the upper separator increases the amount of closed flux. Then the two sides of the closed separatrix move outwards and touch the other separatrices and proceed to intersect them in two new separators each, making five in all. Next, two of those separators descend through the lower boundary and finally we are left with just one separator and most of the flux reopened.

THE TIME-DEPENDENT CURRENT SHEETS IN CORONAL TECTONICS

If reconnection is heating the corona at many current sheets by coronal tectonics, how does the energy spread out, by conduction along the magnetic field, by reconnection jets, by waves across the magnetic field or by fast particles? Furthermore, if reconnection is time-dependent, how much energy is liberated locally and how much globally?

Longcope and Priest [19] attempted to answer these questions by setting up a simple model problem. Consider initially the magnetic field of a current sheet in the form

$$B_y + iB_x = B' \sqrt{(w^2 - z^2)}. \qquad (1)$$

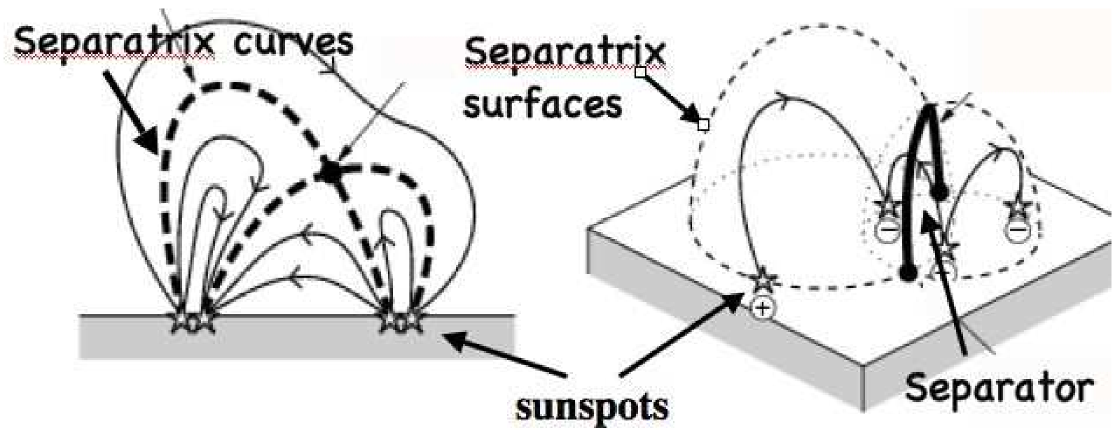

FIGURE 5. The skeleton of a field: (a) in 2D separatrix curves coming from X-points; (b) in 3D separatrix surfaces.

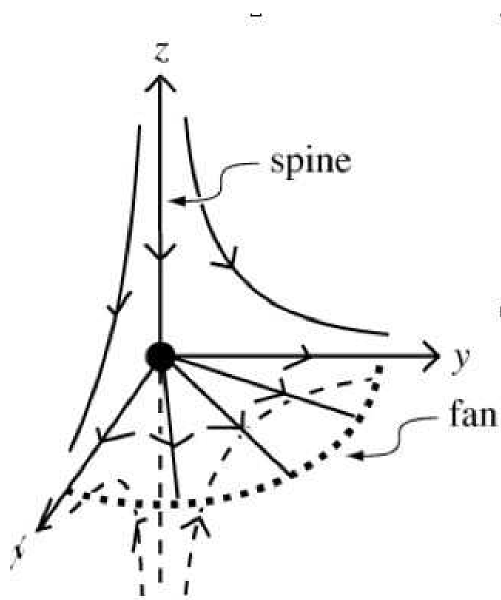

FIGURE 6. The structure of the simplest 3D null point.

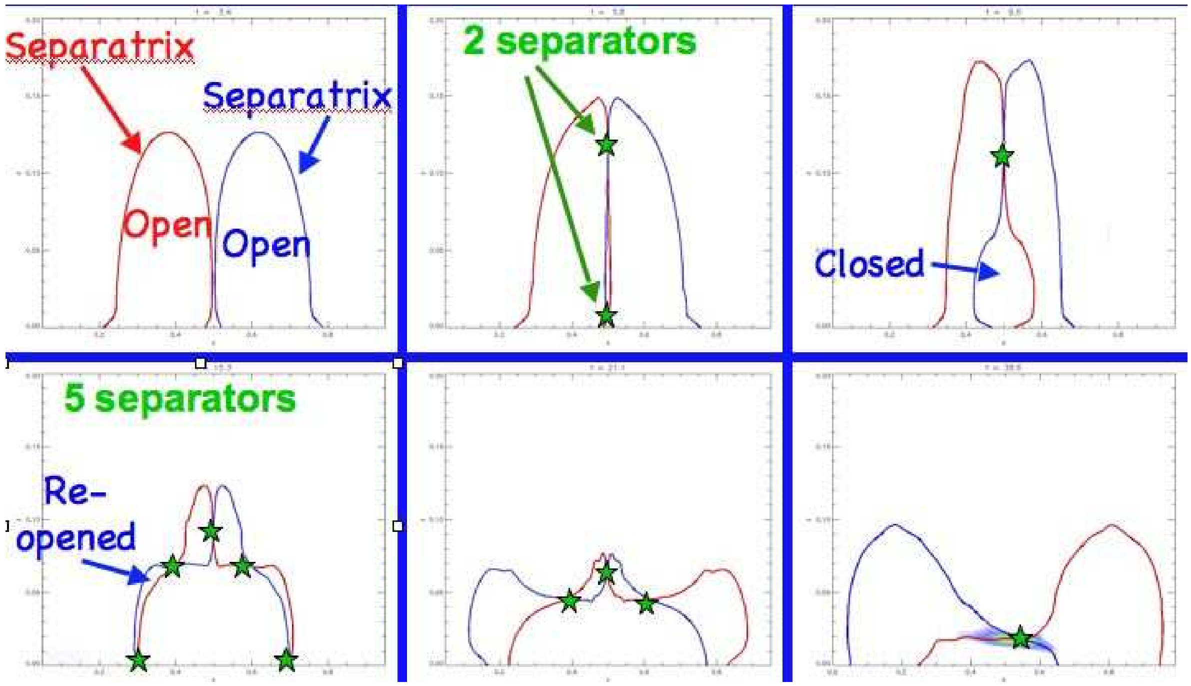

FIGURE 7. A series of vertical cross-sections through the skeleton [After 18].

At large distances (r) we may expand $\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1$, where

$$\mathbf{B}_0 = -B'[y\hat{x} + x\hat{y}], \qquad B_{1\phi} = \frac{I_0}{2\pi R}, \qquad (2)$$

where the latter term is the field of a line current I_0. There is thus lots of energy in the magnetic field that lies at large distances from the origin, and we may define a natural Alfvén frequency as $\omega_A = B'/\sqrt{4\pi\rho}$.

Now, suppose the current (I) in the sheet dissipates. This is a local process, but it has global consequenceses. The decrease in current implies that the magnetic field must change at large distances, but how? We set up a model for the effect of reconnection by linearising about the X-point field ($\mathbf{B}_0$) in the low-beta limit, so that the induction equation and equation of motion become

$$\frac{\partial \mathbf{B}_1}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v}_1 \times \mathbf{B}_0) = \eta \nabla^2 \mathbf{B}_1, \qquad (3)$$

$$\rho_0 \frac{\partial \mathbf{v}_1}{\partial t} = \mathbf{j}_1 \times \mathbf{B}_0. \qquad (4)$$

We assume that $\mathbf{B}_1$ at $t = 0$ is due to the current sheet, and that then the diffusion is turned on and the current diffuses with reconnection.

The natural variable in these equations is $rB_{1\phi} \equiv I(r,t)$, which is twice the current enclosed in a circle of radius r. The equations may be combined to give

$$\frac{\partial^2 I}{\partial t} = \omega_A^2 r \frac{\partial}{\partial r}\left(r\frac{\partial I}{\partial r}\right) + \eta r \frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial^2 I}{\partial r \partial t}\right), \qquad (5)$$

where the first term on the right represents wave behaviour and the second represent magnetic diffusion. We expect that both terms will cause and initially uniform I to spread out from the origin in time.

In the large r limit when $R = \ln(r/l_\eta) \gg 1$, where $l_\eta = \sqrt{(\eta/\omega_A)}$, the diffusion term is negligible and 5 becomes a normal wave equation in R and t with solution

$$I(R,t) = I_0 - F(t-R). \qquad (6)$$

On the other hand, in the small r diffusive limit, the wave term is negligible and we obtain

$$I)r,t) = I_0 - I_0 \exp\left(-\frac{r^2}{4\eta t}\right), \qquad (7)$$

so that the electric current density $j \equiv (1/r)\partial I/\partial r$ tends to zero at the origin as time increases.

A numerical solution of Equation (5) does indeed show a transition from diffusive to wave-like behaviour, with a sheath of current propagating outwards. However, in the wake of the sheath there is a flow and an associated convective electric field $E_v(r,t)\hat{z} \equiv -\mathbf{v}_1 \times \mathbf{B}_0$ with a surprising behaviour (Figure 8). Instead of the flow, electric field and current at the origin diminishing in time, it slowly increases.

The resolution to the paradox is that a third regime exists at large time ($t > 1/\omega_A$) when the left-hand side of (5) is negligible and the two terms on the right balance to

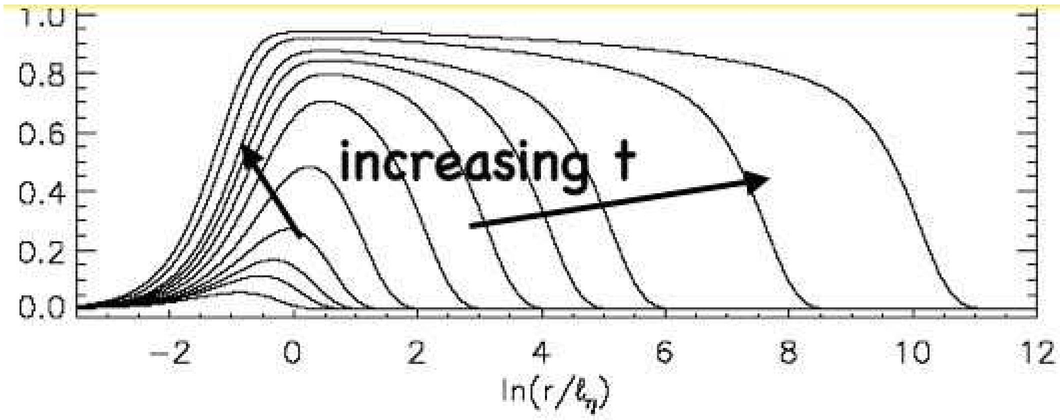

FIGURE 8. The convective electric field (E_v) as a function of dimensionless radius $R = \ln(r/l_\eta)$ at several times [From 19].

give

$$I(r,t) = \frac{I_0}{2\omega_A t}\left[1 - \exp\left(-\frac{\omega_A^2 r^2 t}{\eta}\right)\right]. \qquad (8)$$

The resulting current density is

$$j = \frac{1}{r}\frac{\partial I}{\partial r} = \frac{I_0 \omega_A}{\eta}\exp\left(-\frac{\omega_A^2 r^2 t}{\eta}\right), \qquad (9)$$

which equals $I_0\omega_A/\eta$ at the origin. Thus the peak in current remains at the X-point and the outwards propagating wave continues to drive a steady electric field ($I_0\omega_A$) there that is independent of η – i.e., fast reconnection.

CONCLUDING COMMENT

One important conclusion is that three-dimensional reconnection is completely different from two-dimensional reconnection. Another is that coronal heating may be modelled in promising complementary ways, including as a self-organised critical state or by the coronal tectonics model as an updated version of Parker's nanoflare idea. Furthermore, an enhanced resistivity in a current sheet converts much of the free magnetic energy into wave energy which is later dissipated.

However, Dennis has been very much a prophet of plasma physics, far ahead of his time in many respects. What is needed is a revolution based on his ideas to fully understand the corona, with a coupling between microscopic and macroscopic plasma physics.

ACKNOWLEDGMENTS

I am grateful to all my colleagues in the St Andrews Solar Group for help and stimulation and to the EU SOLAIRE network and UK Particle Physics and Astronomy Research Council for financial support.

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FIGURE 9. A benevolent Dennis, hopefully looking down in an encouraging way on our attempts to understand the solar corona.

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