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The Flux Tube Tectonics model for coronal heating

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ABSTRACT

An account is presented of the Flux Tube Tectonics model for heating the solar corona, in which a multitude of current sheets are continually forming and dissipating. In addition, a model is summarised for the time-dependent response of the corona to the sudden dissipation of one such current sheet.

1. Introduction—the solar corona

Originally the solar corona was mainly observed at solar eclipses as a pearly white structure around a jet black Moon. Images such as Fig. 1a reveal closed coronal loops and open structures (later called coronal holes) along which the fast solar wind escapes. Later, the Skylab satellite followed up earlier rocket images of the corona in viewing the corona direct in soft X-rays (Fig. 1 b). These revealed the coronal holes as dark regions and also showed up the presence of hundreds of tiny X-ray bright points.

Then images from Yohkoh at much higher cadence showed the corona to be a dynamic magnetic world dominated by complex nonlinear interactions between the magnetic field and plasma. 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 most recent step has been taken by the Hinode satellite by revealing stunning detail on the structure and dynamics of the corona (Fig. 2), 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.

Many examples of low-frequency waves have been observed with TRACE and SoHO in the corona, but they are invariably too weak to be heating the corona. Furthermore, the UVCS instrument on SoHO has discovered preferential heating normal to the magnetic field in some ions, which suggests that high-frequency ion-cyclotron waves may be important for heating the large-scale diffuse corona. The most recent example from Hinode, studied by Hansteen et al. (2006), de Pontieu et al. (2008) and Suematsu et al. (2008), is of spicules at the limb swaying to and fro like straw in a prairy (Fig. 3). A gradient filter has been applied to enhance the spicules above the limb, since in reality the intensity scale-height is only 1–2 Mm.

The most natural explanation for heating the low corona, however, is still reconnection 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 two or three million degrees (Schmelz et al., 2009; Reale et al., 2009). This may be associated with a nanoflare component to the coronal heating (Fig. 4).

2. Coronal heating model by Tectonics

The classical model for heating the corona by nanoflares was proposed by Parker (1972), in which an initially uniform magnetic field is braided by complex photospheric motions to produce current sheets at the boundaries between braids.

A modern development of Parker's model is the Coronal Tectonics model (Priest et al., 2002), 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 eight other fragments on average (Close et al. 2004a, b). The statistical properties of the field lines show that 50% of the flux closes within 2.5 Mm of the photosphere and 90–95% within 25 Mm (Fig. 5). Furthermore, the time for all the field lines in the quiet corona to reconnect has been estimated to be only 1.5 h by

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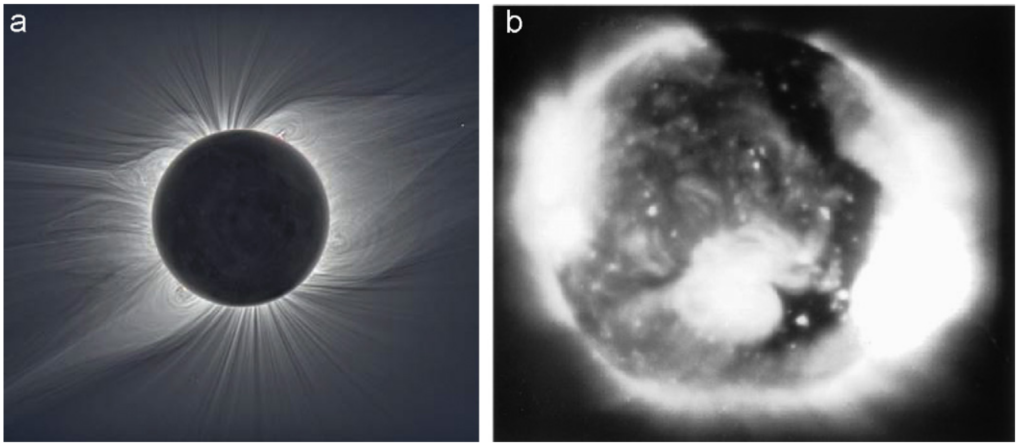

Fig. 1. The corona as viewed (a) from the eclipse of 1 August 2008 (courtesy M. Druckmüller, P. Aniol and V. Rusin) and (b) from Skylab (courtesy L. Golub).

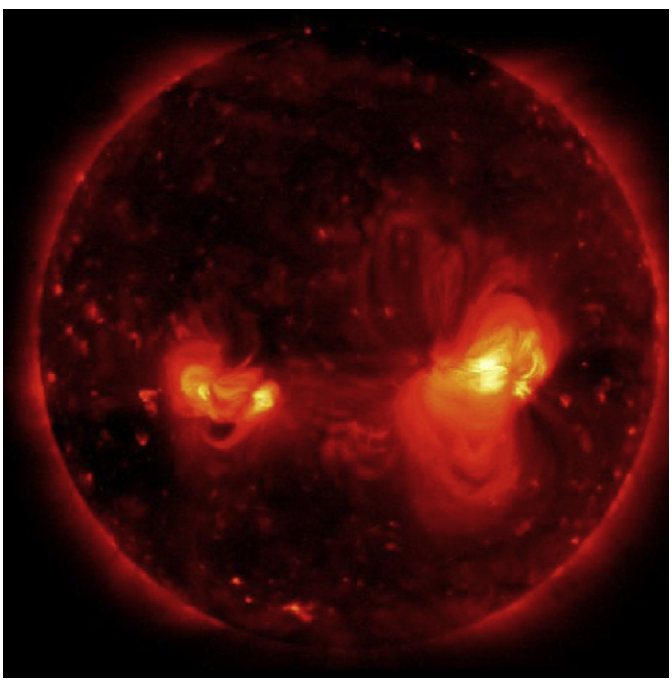

Fig. 2. An image of the corona from the X-ray telescope on Hinode (courtesy Leon Golub).

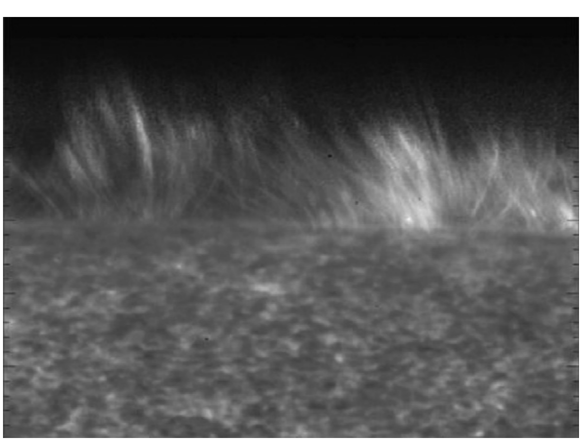

Fig. 3. A Hinode filter image in the CaII H line of spicules swaying to and fro (courtesy Mats Carlsson).

comparing extrapolations of a series of MDI magnetograms (Close et al., 2004a). In other words, there is an incredible amount of reconnection continually taking place and heating the corona.

Furthermore, the magnetic flux in the solar surface is continually moving around and injecting Poynting flux and magnetic helicity into the corona. As illustrated in Fig. 6, perhaps 50% of the flux in the quiet Sun emerges as ephemeral regions, at about one per 8 h per supergranule with a typical flux of 3×10^{19} Mx. Then each pole migrates to the boundary over about 4 h and fragments into 10 network elements (each carrying 3×10^{18} Mx). Finally, the network elements move along the boundary at about 0.1 km s^{-1} and either cancel or merge.

Using the *magnetic skeleton* is the way to describe this amazing coronal complexity. It consists of the web of separatrix surfaces that separate the coronal volume into topologically different regions (Fig. 7). Thus in two dimensions reconnection at the *X*-point transfers flux across two of the separatrix field lines from two of the regions into two of the others. In three dimensions, other the hand, reconnection at a separator can transfer flux across the separatrix surfaces from two volumes into two topologically distinct volumes.

Now, null points in three dimensions possess an isolated field line called a spine which approaches (or recedes from) the null point, as well as a surface of field lines called a fan, which do the opposite—i.e., they recede from (or approach) the null. One of the important aspects of a fan is that it spreads out into space as a separatrix surface, separating flux above the null from flux that is below the null.

So what is the effect on the corona of the relative motion of nearby magnetic fragments? Parnell and Galsgaard (2004) conducted a simple "fly-by" numerical experiment in order to model a "binary" interaction between two such opposite polarity photospheric fragments in an overlying uniform field (Fig. 8). 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. (2007) were able to answer this.

A vertical section through such a skeleton reveals a much more complex interaction than was expected, with six distinct steps (Fig. 9). Initially, two nonintersecting separatrix surfaces are present, 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