STRUCTURE OF THE SOLAR X-RAY CORONA

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ABSTRACT  Recent high resolution observations of the Solar X-ray corona, such as those from the NIXT sounding rocket payload, show that the emission is resolved into tightly-packed bundles of structures with very high aspect ratio (L/d > 100). Such structures appear to be inherently short-lived, in contrast to the post-Skylab view of relatively stationary loops as the fundamental constituents of the inner corona. We suggest that it is the overall magnetic configuration which is stable on long timescales, but that “coronal threads” are formed and destroyed rapidly in a continual process. The processes of energy input, plasma heating, disruption of the heated region, chromospheric evaporation, and radiative and conductive cooling of the plasma all take place on similar time scales, of order 10^3-10^4 seconds. On this view, coronal structures are fundamentally transient and only in quasi-equilibrium. One observes long-lived stable loops only when the spatial and/or temporal resolutions are inadequate.

Keywords: Solar corona; Coronal structure; Solar X-rays

INTRODUCTION

In the late 1960's and early 1970's high resolution imaging instruments functioning at UV and shorter wavelengths became available. Prior to this time, the commonly accepted view of the outer Solar atmosphere was that, to a first approximation this atmosphere was homogeneous with significant but only occasional structures present (the work of Billings being a notable exception). Coronal studies of that era were thus carried out in a manner similar to much of the stellar work being done at the present time, by subdividing the work into a portion focusing on the homogeneous aspects and a portion focusing on the additional complications due to some type of activity.

This view changed completely once it became possible to view the corona on the disk from sounding rockets (Vaiana, Krieger and Timothy 1973), and one can argue that the long duration observations carried out by the Solar telescopes flown on Skylab in 1973-74 did more to change our perception of the corona than any other instrument or collection of instruments. The key feature which was brought home by these observations is that essentially all of the emission seen in the corona comes from structures which we have called “loops” (Vaiana and Rosner 1978). There is no evidence for either open structure emission or for any diffuse emission – on the contrary, any emission which has at one time been thought to be diffuse has invariably been resolved into loops as better observations became available (Golub et al. 1990).

An example of the highly structured nature of the Solar corona is shown in Figure 1, an X-ray image taken from a recent flight of the NIXT sounding
rocket payload. This figure illustrates the basic point, that the hot corona is observed to consist entirely of closed structures, i.e., "loops".

Figure 1. NIXT X-ray image of Solar corona, 11 July 1991.

LOOP ATMOSPHERES

The first clear statement of the new view appeared in Rosner, Tucker and Vaiana (1978a) and in Craig, McClymont and Underwood (1978). These authors took the position that loops are the fundamental building block of the corona, and that each loop could be viewed as an independent "mini-atmosphere". From this position they calculated some general stability criteria for loops and the well-known thermodynamic scaling relation $T \sim (pL)^{1/3}$. In the same year Rosner et al. (1978b) proposed a model in which the magnetic field is directly involved in transferring mechanical energy directly from the photospheric convective motions up into the corona and depositing that energy for in situ heating of the coronal plasma. Numerical simulations of loop atmospheres (Peres et al. 1982) confirmed the RTV scaling law, extended it to loops larger than the pressure scale height (Serio et al. 1981), and are being used to examine the dynamic
behavior of loops in response to sudden changes in heating rate (Jakimiec et al. 1991).

Figure 2. a) NIXT X-ray image of active region structure, compared with b) photospheric magnetic field; 22 Feb. 91.

Thus, by the late 1970's the view that structure was only an intrusion into an otherwise quiescent and homogeneous atmosphere, was completely reversed. The loop structure and its heating were seen as the fundamental element, reflecting the emergence and diffusion of the magnetic field and the subsequent transfer of energy into the outer atmosphere via the field. An example of the close connection between the surface magnetic field and the coronal emission is shown in Figure 2, in which closed loops of X-ray emission, or in some cases the lower portions of large loop structure are seen to be intimately related to the locations of B. Within the context of this view, the discussion has come to
center around magnetic field structures which will provide stable loops, pressure, energy and mass balance within stable structures, and possible mechanisms for providing the energy required to balance radiative and conductive losses from coronal loops.

The critical role played by the magnetic field in the formation of coronae was made even more evident by the launch of the Einstein Observatory, which made possible for the first time the detection of X-ray emission from a large sample of ordinary solar-like stars (Vaiana et al. 1981). What was observed was completely contradictory to pre-launch expectations: rather than the Sun being near the upper end of the X-ray luminosity distribution because of its high acoustic flux level, the Sun turns out to be a rather weak X-ray emitter. Most other main sequence stars of spectral type F through M are stronger than the Sun and the determinant of X-ray level is rotation rate rather than spectral type (Pallavicini et al. 1981). The dramatic failure of standard acoustic heating theories and the availability of alternative magnetic field-related heating models marked a dramatic turning point in our view of coronal physics (cf. Rosner, Golub and Vaiana 1985).

Figure 3. NIXT image of coronal structure above a sunspot, 22 Feb 1991.
RECENT OBSERVATIONAL RESULTS

A. Sunspot Fields

Before discussing the new results related to the structure of the X-ray emitting corona, we briefly discuss a related but separate observation of the emission associated with sunspots. Figure 3 shows a portion of an X-ray image taken from the NIXT payload on 22 Feb. 1991. What is unusual about this flight is that we obtained perfectly coaligned and simultaneous X-ray and white light photos (for a detailed explanation see Sams, Golub and Weiss 1992), which show the X-ray coronal structures and the sunspot umbra/penumbra structure. We are thus able to trace the coronal fieldlines down into the spot without ambiguity.

When we carry out the comparison of coronal to surface fields, the following general rules become evident:

1. There are no hot loops seen coming out of the spot umbrae; this result has been known since the Skylab days, but it is now seen with much greater precision and clarity.

2. There is a class of loops which emanate from the spot penumbrae, apparently in association with the steeply inclined field lines coming from the bright (as opposed to dark) penumbral fibrils (see Title et al. 1991).

3. The brightest loops in active regions do not emanate from sunspots, but originate in enhanced network or plage, and connect to similar areas near but not in the sunspots.

Thus the correlation between brightness of X-ray emission and magnetic field strength is not monotonic: the weakest magnetic fields far away from active regions have weak X-ray emission as one would expect. However, the strongest magnetic fields also have little or no X-ray emission. Presumably, as argued in Rosner et al. (1978), what is needed to produce a hot corona is both a magnetic field and an input of mechanical energy into the field. The field lines ending in spot penumbrae are relatively strong, but show comparatively weak X-ray emission; this indicates that they form an intermediate class which emit less than they ought to for their field strength, possibly because they are anchored in a pattern of convection weaker than that of the enhanced network areas.

B. Dynamics of Coronal Loops

In the area of coronal heating, the past decade has seen the accumulation of several important new observational results which we consider directly relevant to the problem of constructing a viable coronal heating model. Briefly, these are:

- The observations by Martens et al. (1985) and Schadee et al. (1983) of hot $> 10^7$ K plasma in nonflaring coronal loops, with small filling factor ($< 10^{-3}$);

- Variability of “normal” loops on short times scales (Sheeley and Golub 1979; also see below) which suggest that static models are not appropriate;

- Vector magnetogram data extrapolated into the corona argue for the presence of large field-aligned currents flowing along the loops (Hagyard et al. 1984).
Observation of hard X-ray microflares associated with active regions (Lin et al. 1984) and microwave bursts with similar properties (Bastian 1991; note that these are not Type III bursts).

High resolution imaging results (Golub et al. 1990) which show that coronal "loops" are much narrower and tightly-packed than was previously thought.

If we attempt to assemble these recent results into a coherent picture, we are led to a model in which coronal structures are heated in very localized regions, with some disruptive process occurring to spread the heat throughout the larger loop volume. The heating is likely to be abrupt or at least rapid compared to the lifetime of the loop and the timescale for attaining equilibrium in response to the heat input; a series of related processes are all occurring more or less simultaneously, as indicated schematically in Figure 4.

![Schematic diagram](image)

**Figure 4.** Proposed series of events occurring within a coronal thread.
1. The high-T component occupying a small fraction of the volume indicates that the heating mechanism is strongly localized; it may be a separate physical process (see 3. below) which later disperses the energy throughout the remaining volume.

2. The transient nature of coronal structures is of fundamental importance, but unfortunately the published literature on this subject is inadequate. Based on available data and on examination of time-resolved coronal imaging data, we take the view that coronal variability in active regions is relatively rapid \((10^3 \text{ sec})\) and is embedded within an overall magnetic field configuration which typically evolves on much longer \((10^5 \text{ sec})\) timescales.

3. The hard X-ray and microwave bursts are seen to be a prevalent feature of active region, and may be argued to arise out of the dynamic processes occurring in the coronal structures. We will assume that they are in some way fundamentally linked to the formation and heating of coronal structures, either as cause or effect. Either case implies that the heating process is sporadic and intermittent.

Figure 5. NIXT coronal X-ray image, 11 July 1991, showing thread-like fine structure.
4. The presumed presence of strong currents in the corona leads to an examination of their effect. As argued in Beaufume, Golub and Coppi (1992), the result is strongly localized heating in short-lived structures.

5. The extremely high aspect ratio of coronal structures seen with the NIXT (Figure 5) leads to the conclusion that any current sheaths which form will disrupt very quickly (Beaufume et al. 1992). Thus the heating will proceed via brief bursts having a small duty cycle.

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