ELECTRODYNAMIC COUPLING IN MAGNETICALLY CONFINED STELLAR X-RAY LOOPS

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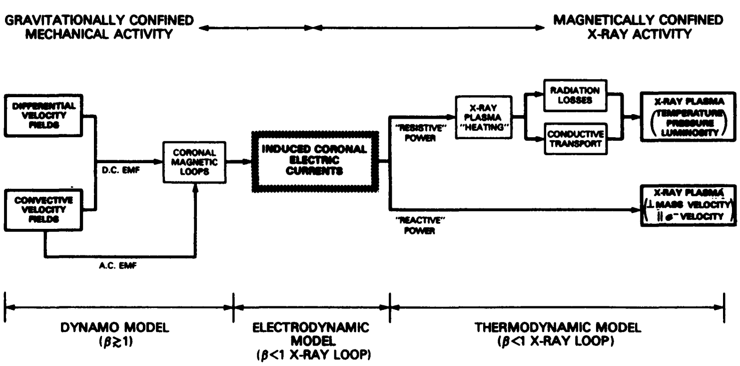
I. INTRODUCTION

The solar-coronal complex is the only astrophysical system whose X-ray structure has to some degree been spatially resolved. The most important lesson that we have learned from these relatively high-resolution observations is that the corona is highly structured, comprising a variety of closed, loop-like regions of enhanced radiative output. Furthermore, coronal radiation loops are now known to be spatially coincident with magnetic loops which confine the radiating plasma.

There is no reason to suspect that the basic X-ray morphology of the solar-coronal complex is unique, and it could in fact be fundamental in developing physical models of other as yet spatially unresolved X-ray emitting astrophysical systems. The general goals of this article are to identify and briefly discuss the primary sub-models that are involved in the global coupling between a $\beta \gtrsim 1$ mechnical energy reservoir and a contiguous site of $\beta < 1$ X-ray activity.

GLOBAL COUPLING SCENARIO



J. O. Stenflo (ed.), Solar and Magnetic Fields: Origins and Coronal Effects, 391–396.

https://doi.org/10.1017/S0074180900030047 Published online by Cambridge University Press

The "Dynamo Model" establishes a quantitative connection between properties of the mechanical driver (e.g., differential and convective velocity fields) and the dimensions, field strength and number density distribution of elemental magnetic loops. As pointed out by Golub et al. (1980), the mechanical energy reservoir comprises two regions that are differentiated in terms of the velocity field's convective time and size scales. Specifically, the "surface layer" velocity field is characterized by relatively small convective time and size scales compared to the underlying "subsurface layer." As pointed out by Ionson (1982) the overall potential magnetic field structure is established by large-scale subsurface velocity fields whose characteristc time scale exceeds the magnetic loop's Alfven transit time scale (i.e., D.C. emf's). In contrast, the relatively smaller scale surface convection, whose time scale is of the order of the magnetic loop's Alfven transit time, results in A.C. emfs which drive an elemental loop into a non-equilibrium electrodynamic state characterized by the flow of electrical currents along (i.e., force-free) and across (i.e., non-force free) the coronal B-field (i.e., "Electrodynamic Model"). These induced electrical currents couple to the magnetically confined plasma within a spatial resonance shell resulting in heating as well as a confined, cross-field coronal velocity field with radiation and conduction losses determining the X-ray emitting plasma's temperature, pressure and luminosity (i.e., the "Thermodynamic Model").

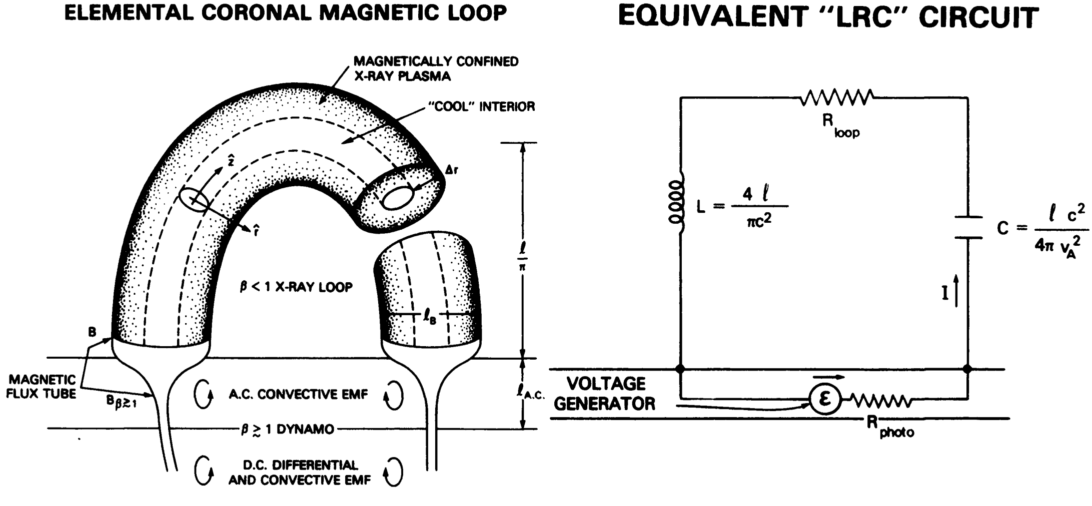
This article does not attempt to present a quantitative dynamo model. This extremely complicated problem has been the subject of articles too numerous to discuss here (c.f., review by Cowling 1981), many casting doubt upon various versions of the canonically accepted α-ω dynamo. Field amplification for an α-ω dynamo is accomplished by large scale differential motion (i.e., the ω-effect) with field reversal occuring due to the diffusive effects of helical convection (i.e., the α-effect). The result of this interaction is a temporal variation in magnetic flux generation along with a corresponding spatial propagation of this flux across the $\beta \gtrsim 1$ mechanical driving zone. A major observational problem with this model is that, at least for the sun, the total magnetic flux appears to be constant throughout the activity cycle (Golub et al., 1979). This is contrary to the predictions of various α-ω dynamo models. In addition, the hydrodynamically inferred solar differential rotation is directed in a sense that is opposite to that required by kinematic α-ω dynamos (Gilman 1981).

Unfortunately, today's conventional dynamo models are the weakest link in the global coupling scenario illustrated in Figure 1. Therefore, this article will build upon the observationally rationalized assumption that elemental magnetic loops are fundmental in the $\beta \gtrsim 1$ to $\beta < 1$ coupling process. The results of this analysis will thus be presented in a form that does not explicitly depend upon magnetic properties of a particular loop. There is, of course, a strong implicit dependence upon these magnetic properties.

II. ELECTRODYNAMIC COUPLING IN MAGNETIC LOOPS

Two classes of solar coronal radiation loops have been identified. Specifically, the so called "cool loops" with temperatures of the order of 10^4 - 10^5 °K and hot "X-ray loops with temperatures of about 2.5×10^6 K. Hot and cool loops typically have the same basic dimensions (i.e., lengths < 10^{10} cm and diameters ~ $10^{8.5}$ cm). In support of Foukal's (1975, 1976, 1978) original suggestion, Raymond and Foukal (1982) have recently presented evidence that some "hot" and "cool" loops are co-spatial within the resolution limits of the observing instruments (viz., ~ $10^{8.5}$ cm). A distinct possibility is that the currently observed loops actually represent an unresolved cluster of topologically distinct radiation loops whose diameter is significantly less than $10^{8.5}$ cm. This possiblity is logically consistent with the observed existence of small diameter (< $10^{7.5}$ cm) magnetic flux elements within the photosphere which extend into the corona, confining the radiating plasma. Raymond and Foukal's observations suggest that each of these unresolved radiation loops contains both "cool" and "hot" plasma which is consistent with many contemporary coronal heating theories -- the primary point of contention being the relative volumes of cool and hot plasma.

Ionson (1982 a,b) has demonstrated that the electrodynamic coupling between a $\beta < 1$ elemental magnetic loop and its underlying $\beta \gtrsim 1$ mechanical driver can be represented by a simple yet equivalent LRC circuit analog.



This derived analog points to the existence of global structure oscillations, such as Alfvenic surface waves, which resonantly excite internal field line oscillations within a spatial resonance shell of thickness Δr_{res}. These localized B-field oscillations result from induced currents that are driven by $\beta \gtrsim 1$, A.C., stressing emfs.

https://doi.org/10.1017/S0074180900030047 Published online by Cambridge University Press

Although the width of this spatial resonance as well as the magnitude of the induced currents explicitly depend upon irreversible processes (e.g., viscosity and resistivity), the resonant form for the heating rate (i.e., the "resistive power") is virtually independent of irreversibilities. This is a classic feature high "quality" resonant systems that are driven by a broad band source of spectral power. In this case the source of spectral power is the power spectrum of the A.C. stressing velocity, $\langle v^2_{\beta\gtrsim 1}\rangle_\nu$. The essential feature of a resonant heating mechanism is that magnetic loops with different lengths and field strengths, and hence different global resonance frequencies, are heated at a rate that critically depends upon the amount of a $\beta \gtrsim 1$ spectral power at the resonance frequency ν_0 as well as the value of B.

This analog has been a powerful tool in identifying relationships that quantitatively connect the thermodynamic state of the confined $\beta < 1$ X-ray plasma (e.g., temperature, T; thermal pressure, P; cross-field flow velocity, $v_{\beta<1}$) to the confining magnetic loop characteristics (viz., field strength, B; cross-field extent, ℓ_B; inverse aspect radio, ℓ/ℓ_B; magnetic expansion factor, $B_{\beta>1}/B$) and the $\beta \gtrsim 1$ stressing velocity, $v_{\beta>1}$. These relations fall into two broad categories. Namely, (1) diffuse heating resulting from efficient transport of energy throughout the magnetic loop volume and (2) isolated heating within the electrodynamic dissipation shell. For each of these cases Joule dissipation, shear viscous dissipation and compressional dissipation have been considered. Each of these models is characterized by three thermodynamic scalings that are parameterized by the magnetic loop properties and $v_{\beta>1}$. Eliminating the magnetic field intermediary from these relations and normalizing ℓ/ℓ_B and $B_{\beta>1}/B$ with respect to solar conditions results in a single, unique velocity scaling law for each model, viz.

Diffuse Heating (c.g.s. units)

$$v_{\beta<1} = \begin{cases} 7.5 \times 10^{-6}\, T^{0.33}\, P^{-0.16}\, v_{\beta\gtrsim 1}^{2.02} & \text{Joule dissipation} \\ 9.0 \times 10^{-5}\, T^{0.66}\, P^{-0.17}\, v_{\beta\gtrsim 1}^{1.34} & \text{shear viscous dissipation} \\ 1.6 \times 10^{3}\, T^{0.51} & \text{compressional viscous dissipation} \end{cases}$$

Isolated Heating

$$v_{\beta<1} = \begin{cases} 1.7 \times 10^{-7}\, T^{0.99}\, P^{-0.24}\, v_{\beta\gtrsim 1}^{1.47} & \text{Joule dissipation} \\ 3.8 \times 10^{-5}\, T^{0.88}\, P^{-0.18}\, v_{\beta\gtrsim 1}^{1.12} & \text{shear viscous dissipation} \\ 85.0\, T^{0.16}\, v_{\beta\gtrsim 1}^{0.75} & \text{compressional viscous dissipation} \end{cases}$$

Although other authors have recognized the significance of temperature and pressure scaling laws, the importance of $\beta < 1$ velocity scaling laws which complete our description of the electrodynamic coupling process have been overlooked until now.

https://doi.org/10.1017/S0074180900030047 Published online by Cambridge University Press

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DISCUSSION

KUPERUS: Your LRC circuit applies to coronal loops, where you have a well defined length scale (the loop length). Is it possible to extend this theory to open structures such as the coronal holes by the introduction of an equivalent length scale?

IONSON: This is an important question that we are attempting to answer.

SPRUIT: Let me respond to your statement about taking a step towards the observations. I think that even the observers would feel more comfortable in using theoretical results if these are based on solutions of equations rather than on the application of more simplified models.

IONSON: As discussed in Ionson (1982, 1983), these results are indeed based upon solutions of the equations of electrodynamics. The major point, reviewed by Dr. Chiuderi, is that these equations can be put into a *simple* form which still stresses the important physics.

UCHIDA: In your circuit model, is there any special device operating so that the energy is damped at places where the resistivity is not large, in other words, outside the photospheric level?

IONSON: As pointed out in Ionson (1982), the photospheric *resistance* is smaller than the coronal *resistance* unlike the case when one considers the resistivity.

FOING: (1) To what depths does your broad-band generator correspond in the photosphere, where the coupling is stronger? (2) How could you derive the spatial energy spectrum of subphotospheric convective motions, at the present state of velocity observations or convective theories?

IONSON: (1) The A.C. driver is found at the $\beta \approx 1$ level. (2) This model does not attempt to explain the subphotospheric energy spectrum. Rather, this spectrum is used as an observational input to the LRC coronal heating theory.

LOW: We should not think that one must regard a problem exclusively either from an MHD continuum or an LRC point of view. It would be useful if an MHD problem can be solved fully and its results be compared with the corresponding LRC model, to see to what extent the two approaches are similar and/or different. People who work with MHD cannot, with good reason, expect that a fluid system, with its impressive degrees of freedom, can be approximated by a linear circuit.

IONSON: I am surprised by this comment since the MHD-LRC connection has been demonstrated from first principles in Ionson (1982, 1983). In fact, Dr. Chiuderi has just finished reviewing this "impressive" connection during his invited review.

HEYVAERTS: Response to the comment by B.C. Low: In going from fluid picture to circuit model, an integration over loop cross section is made. The details of radial structure are lost. The oscillations are represented by a global oscillation period. In the work reported by Chiuderi (Heyvaerts and Priest, 1983), we took into account the fact that actually each magnetic surface has its own resonance frequency $\omega = \omega(x) = k_z c_A(x)$. Then, each shell of the loop resonates with the excitation at its own proper frequency and behaves individually much as described by Ionson. The net heating rate results from the integration of these individual heating rates over the loop cross section.