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FINAL TECHNICAL REPORT

Plasma Dynamics and Energetics in the Solar Atmosphere

NASA Solar Physics Grant NAGW-2449

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submitted by

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FINAL TECHNICAL REPORT

The NASA Solar Physics program "Plasma Dynamics and Energetics in the Solar Atmosphere" has been supported by Grant NAGW-2449 (for $50, 643) at the University of California, Irvine since 1 November 1990. During this year, the UCI group has produced two papers [listed in Appendix I], both effectively accepted for publication, acknowledging this grant, and has made further progress on prominence formation, loop dynamics and streamer evolution which will contribute to several planned papers.

Since the abstracts of our publications are provided in Appendix II, we will concentrate in this report on the main thrusts and significance of our research results.

A. Prominence Condensation and Support

One of the more complex and intriguing problems of solar plasma physics is the formation of prominences. One must adopt a physical model that couples together the energetics (radiation, compression and conduction) and the dynamics (flows and fields) in a nonuniform and anisotropic medium. In addition, the temporal and spatial derivatives increase by orders of magnitude, making computations difficult.

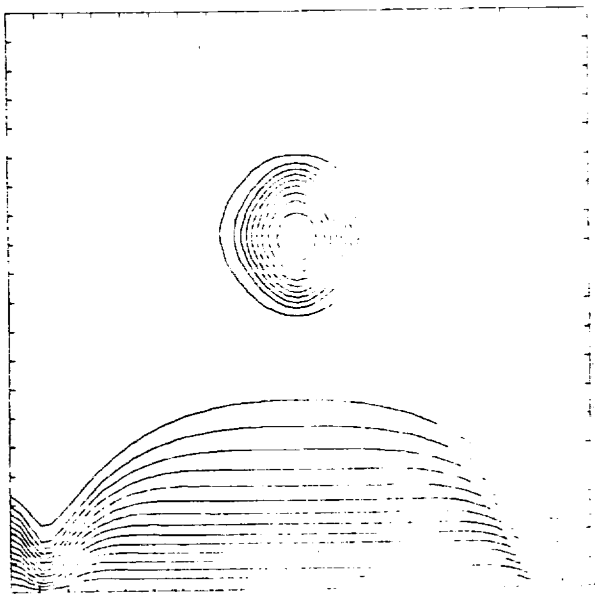
We have proceeded from 1-D to 2-D models, adding more pieces of the complete physics at each step. In 1D, we added the parallel (to **B**) component of solar gravity and deep chromospheres, and were able to initiate a prominence by interrupting the heat flow to the coronal portion of a magnetic loop or arcade. The resulting quasi-isobaric cooling (p changes by ~ 30%) provides to a reversal of the pressure gradient which then drives a growing siphon flow leading to a central condensation. In order to support the resulting cool prominence in the solar atmosphere, we then had to add global bending of the magnetic field as a result of mass loading. This required the addition of another half dimension to the model (*i.e.*, there are perpendicular (to **B**) flows and fields, but only one direction of spatial variation). With this change we were able to achieve the first *dynamic* simulation (Van Hoven et al. 1992, abstract attached) of the formation and support of a Kippenhahn-Schlüter (normal polarity) prominence in which all relevant physical effects are included.

We have since gone on to develop a full 2-D model with all of the dynamics and energetics involved. We start with a current-free arcade field, and then insert a realistic atmosphere that is structured by gravitation and heat flow. One thereby produces a magnetized corona bounded below by a chromosphere and a series of short and low cool loops (Klimchuk et al. 1987). Subsequent interruption of the heat flow into the corona leads to the dynamic condensation of an apex prominence and its self support by a Kippenhahn-Schlüter (1957) depression of the coronal magnetic field. A preliminary version of this structure is shown in Figure 1.

B. The Dynamics of Coronal Loops

The linear stability of coronal loops has been studied extensively using the ideal-MHD energy principle (Einaudi and Van Hoven 1983). In research under the present grant we have taken the next essential step and have applied 3-D MHD simulation to the study of the dynamics of loops. Our model can self-consistently represent the various phases of loop dynamics, from the quasi-static evolution through quasi-equilibrium states resulting from twisting photospheric-flow profiles, through the linear ideal and resistive MHD instability phase, and then into the nonlinear behavior after kink instabilities grow to large amplitudes and cause field-line reconnection. We have previously used this model (Mikic, Schnack, and Van Hoven 1990) to investigate the equilibrium magnetic structures of loops formed by realistic flow profiles, as well as the linear ideal-MHD stability of such loops to the kink mode.

We have now extended this study to investigate the nonlinear consequences of the line-tied kink instability. This problem has profound consequences in regard to the formation of current filaments and stored magnetic energy in the solar corona, and is intimately related to the coronal-heating problem (Parker 1972). Namely, suppose we start with a uniform magnetic field between

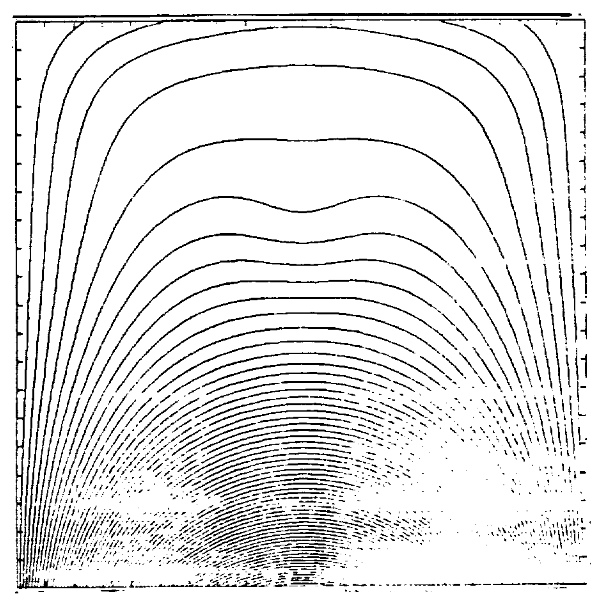


density contours

Fig. 1. The final state of a dynamically formed and magnetically supported arcade prominence.

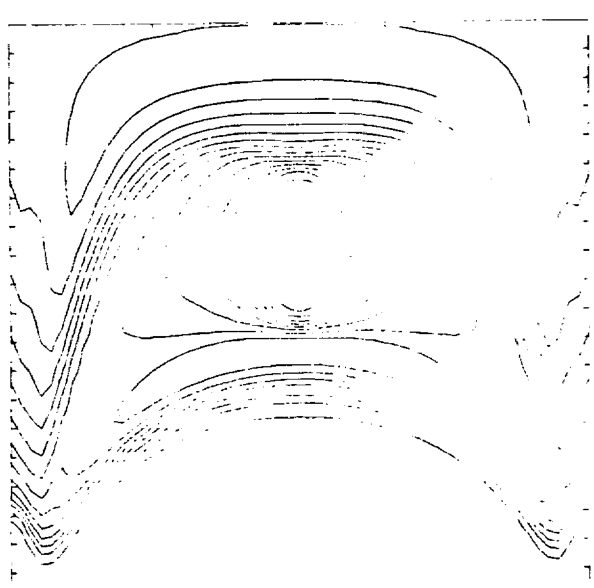
[Note the chromosphere at the bottom.]

gravity



magnetic-flux contours
(field lines)

temperature contours



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two plates which represents a straightened-out, large-aspect-ratio, coronal loop. A twisted flux tube can then be created by photospheric vortex convection. If the flux tube is twisted beyond a critical (threshold) angle, it can become unstable to an ideal kink mode (Einaudi and Van Hoven 1983).

The crucial question then becomes, does the development of the kink lead to the formation of a current sheet in ideal MHD, or does the flux tube tend to a new smooth equilibrium? In particular, we have explored the important questions as to whether finite-length line-tying effects in solar plasmas prevents current sheets from forming, and whether this regular-evolution model has a similar potential for coronal heating as the random drive treated by Mikic et al. (1989). This question has been explored directly by applying our cylindrical 3-D MHD code to the nonlinear evolution of the kink instability.

The influence of line-tying is expected to decrease as the loop length increases (since the line-tied ends of the loop will be removed further from the region of maximum instability displacement near the middle of the loop). We have studied the nonlinear consequences of the kink instability for loops of various lengths. To date we have determined the linear stability threshold for loops with aspect (length to radius) ratios of 4, 8, and 16. These cases have then been studied nonlinearly to determine the relationship between the loop length and the thickness of current layers generated by the nonlinear evolution of the kink. Preliminary results indicate that line tying seems to prevent current sheets from forming for the case when the aspect ratio is 4, although regions of concentrated current density do arise as shown in Figure 2.

C. Streamer Structure and Disconnection

In the past year, we have begun a study of coronal disconnection events. The lack of evidence for magnetic disconnection of coronal mass ejections (CMEs) from the sun is a puzzling problem, because it implies a monotonic build-up of the interplanetary magnetic field (IMF) magnitude over time. Such a build-up is ruled out by observations. McComas et al. (1989)

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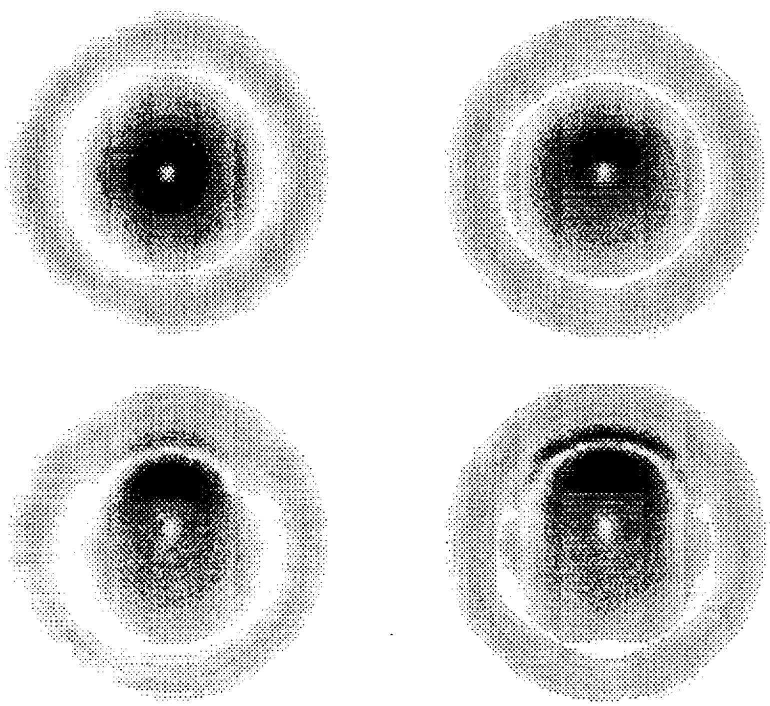
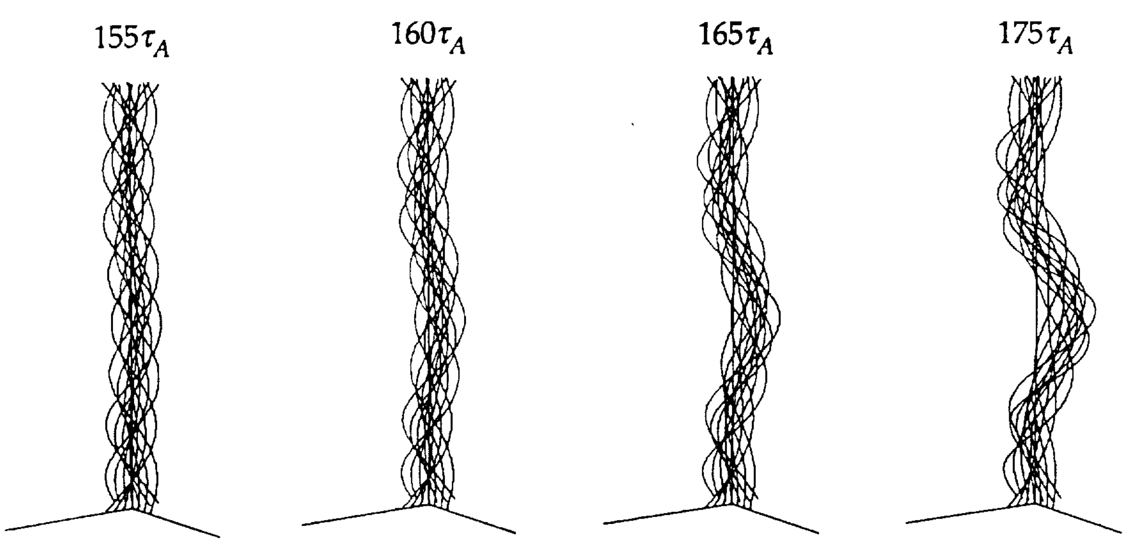


(a)



(b)

Figure 2. Nonlinear development of the kink instability in a line-tied flux tube. (a) Intensity of the transverse current density, and (b) traces of field lines during the linear-instability and nonlinear-saturation phases of the kink.

suggested that magnetic reconnection above helmet-streamer configurations could provide a mechanism for maintaining the observed relative constancy of the IMP, and later (McComas et al. 1991) showed observational evidence of reconnection above a streamer. We have used time-dependent MHD simulations to investigate the plausibility of this idea. We have modeled the opening of new magnetic flux on the sun (as might occur in a CME or other transient event) as an increase in magnetic flux at the poles of a simulated corona. We find that this perturbation can in fact cause reconnection above an equatorial helmet streamer, and the resultant density signature is similar to the observations (McComas et al. 1991). Our results are described by Linker et al. (1992, abstract attached).

We have also continued our study of the three-dimensional structure of helmet streamers. Previous simulation studies of streamers (e.g., Washimi et al. 1987) were axisymmetric. Although a two-dimensional description is useful, observations indicate that coronal streamers have a finite longitudinal extent, and are thus three-dimensional objects (e.g., Poland, 1978). Linker et al. (1990) performed the first three-dimensional MHD simulation of a coronal streamer. In the past year we have continued this study by performing similar simulations but at much higher spatial resolution (grid of 176 X 63 X 38). In addition to confirming the preliminary results described by Linker et al. (1990), we have also discovered new aspects of the 3-D structure. For example, because the magnetic field confines the plasma much more strongly in latitude than in longitude, small subsonic flows appear along the axis of the streamer, and these help to drive plasma into the weaker field regions. We have a manuscript on this study currently in preparation.

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APPENDIX I: UCI SOLAR PHYSICS PUBLICATIONS

Supported by NASA Grant NAGW-2449

1. Prominence Condensation and Magnetic Levitation in a Coronal Loop, appear in to Solar Phys. (1992); G. Van Hoven, Y. Mok and J.F. Drake.
2. Simulations of Coronal Disconnection Events, to appear in J. Geophys. Res. (1992); J.A.Linker, G. Van Hoven and D.J. McComas.

APPENDIX II: Abstracts of UCI Publications

Supported by NAGW-2449

(see following pages)

PROMINENCE CONDENSATION AND MAGNETIC LEVITATION IN A CORONAL LOOP

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Abstract. We describe the results of a model dynamic simulation of the formation and support of a narrow prominence at the apex of a coronal magnetic loop or arcade. The condensation process proceeds via an initial radiative cooling and pressure drop, and a secondary siphon flow from the dense chromospheric ends. The anti-buoyancy effect as the prominence forms causes a bending of the confining magnetic field, which propagates toward the semi-rigid ends of the magnetic loop. Thus, a wide magnetic "hammock" or well (of the normal-polarity Kippenhahn - Schlüter type) is formed, which supports the prominence at or near the field apex. The simplicity of this 1.5 - dimensional model, with its accompanying diagnostics, allows one to comprehend the various contributions to the nonlinear dynamics of prominence condensation and levitation.

1. Introduction

Filaments and prominences are cool and dense structures which form and levitate in the hot and diffuse, magnetized, solar atmosphere (*v.* Priest, 1989, for a review of their physical properties). It is believed that these condensations are initiated by a radiative instability (Parker, 1953; Field, 1965; Hildner, 1974; Sparks and Van Hoven, 1988) but their thermal and dynamical evolution is dominated by the anisotropic influence of the solar magnetic field (Chiuderi and Van Hoven, 1979; Van Hoven et al., 1986; Sparks et al., 1990). The

to appear in Solar Physics

Simulations of Coronal Disconnection Events

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Abstract. The lack of evidence for magnetic disconnection of coronal mass ejections (CMEs) from the sun has long been a puzzle, as it implies a build-up of the interplanetary magnetic field (IMF) magnitude over time. Such a build-up is ruled out by observations. Magnetic reconnection above helmet streamer configurations could provide a mechanism for maintaining the observed relative constancy of the IMF [*McComas et al.*, 1989]; *McComas et al.* [1991] showed observational evidence of reconnection above a streamer. We investigate this interpretation using time-dependent MHD simulations. We model the opening of new magnetic flux on the sun (as might occur in a CME or other transient event) as an increase in magnetic flux at the poles of a simulated corona. We find that this perturbation can in fact cause reconnection above an equatorial helmet streamer, and the resultant density signature is similar to the observations of *McComas et al.* [1991].

Introduction

Observations of the solar corona have been made with white light coronagraphs since the early 1970s. The coronagraph signal is predominantly produced by electron scattering in the coronal plasma, so measurements from these instruments reveal the line-of-sight integrated electron density of coronal structures. One of the more spectacular phenomena observed with coronagraphs are coronal mass ejections or CMEs [*Kahler*, 1987; and references therein].

CMEs often appear as bright, outward moving looplike structures. As significant

to appear in Journal of Geophysical Research