

**LARGE-SCALE COMPUTER SIMULATION OF SOLAR ACTIVE PHENOMENA:  
SUMMARY OF A SESSION AT THE IAU GENERAL ASSEMBLY ON AUGUST  
2 - 11, 1988, BALTIMORE, MARYLAND, U. S. A.**

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**ABSTRACT.** The speakers at this session have demonstrated, by argument and example, that large-scale computer simulation represents a powerful method for understanding the nonlinear physics of solar active phenomena. The past decade, in particular, has seen the advent of ever more powerful large-scale computers and simulation algorithms, which have accelerated this trend. Thus, a number of complex problems concerning the nonlinear dynamics and energetics of astrophysical activity have now become solvable and have begun to reveal new and interesting observable phenomena. To illustrate this scenario we have organized this session to present current results which are obtained by computer simulation, along with their theoretical backgrounds. Some of the highlights are described in the following.

**1. ACTIVE REGION EVOLUTION AND FILAMENT CONDENSATION  
(D. D. SCHNACK)**

Among the important unsolved problems of coronal physics are the formation and evolution of prominences, the dynamics of active regions, and convective-input mechanisms for coronal heating. These long-wavelength, low-frequency, nonlinear, dynamical phenomena are, to an excellent approximation, well described by the equations of resistive magnetohydrodynamics (MHD), and are generally characterized by motions that occur on widely separated timescales. For example, dynamical events that evolve on an intermediate timescale may occur as a result of slow changes of the global configuration. Such a scenario may lead to an eruptive prominence or a solar flare, while also exciting Alfvén waves.

Historically, attempts at understanding these dynamical events have followed three courses: The conception of imaginative cartoons; the calculation of sequences of static equilibria; and the numerical solution of the time-dependent equations of motion as they evolve in response to driven boundary conditions. The limitations of the first approach are obvious. The second approach can describe adiabatic evolution, but is often restricted by the assumptions made for analytic simplification, and cannot address equations of stability or disruption. The third approach is potentially the most fruitful, but has been limited by insufficient computer resources and/or inefficient algorithms. Recently, however, advances in computational techniques and the general accessibility of supercomputers have made solutions by numerical simulation feasible. Three recent examples of such efforts are described briefly in the following.

Two-dimensional, nonlinear simulations have demonstrated for the first time the self-consistent formation of a cool, dense filament in a magnetized coronal plasma (Van Hoven et al., 1987). These filaments are thermally insulated from the rest of the corona by a sheared magnetic field,  $[\vec{B}(\vec{r})]$  which has been found to be crucial to their formation. The evolution proceeds dynamically in two steps with radiative cooling followed by parallel (to  $\vec{B}$ ) condensation, as described in Section 2. The dynamics of active regions have been studied by two- and three-dimensional simulations of

the evolution of a coronal arcade in response to an imposed photospheric shear flow (Wu et al., 1983; Mikic et al., 1988a). The evolution proceeds through a slow increase in coronal magnetic energy. The work of Mikic et al. shows that, when a critical value of magnetic shear is exceeded, the configuration becomes unstable and then evolves on a fast timescale, releasing a significant amount of the accumulated magnetic energy and ejecting a plasmoid. These calculations demonstrate that a significant amount of magnetic energy can be slowly stored in the corona and then quickly released; the resulting self-consistent dynamics have many features in common with two-ribbon flares.

Three-dimensional simulations are attempting to address questions concerning the heating of the corona by the dissipation of electric currents arising from small scale fields (Parker, 1983). Ideal MHD simulations have considered the dynamical response of the corona to sequences of long-wavelength braidings at the photosphere. It has been found that the quadratic nonlinearities in the MHD equations can lead to current structures in the corona whose steadily decreasing scale widths are much smaller than those imposed at the boundaries (Mikic et al., 1988b). Exact equilibria are obtained without distinct current sheets (i.e., true discontinuities). Further studies are required to determine the dissipation and heating rates in these growing current structures.

## 2. RADIATIVE CONDENSATION INSTABILITIES (L. SPARKS AND G. VAN HOVEN)

Prominences are relatively dense, gaseous structures which form in a few hours and extend thousands of kilometers into the sun's atmosphere. It is believed that prominences result from a radiative-cooling instability (Field, 1965) that occurs when heat flow is inhibited by solar magnetic fields (Chiuderi and Van Hoven, 1979). This instability is driven by optically-thin radiation, mainly from heavy-ion lines, which increases as the temperature falls from coronal values. The resulting local pressure drop drives mass inflow along the magnetic field, producing runaway cooling and condensation. The UCI (University of California, Irvine) group has been engaged in a long-term study of the condensation instability in the presence of magnetic shear. Linear studies (Van Hoven et al., 1986, and references cited therein) have discovered a new kinematic condensation mode in which energy balance (esp. anisotropic thermal conduction) is paramount in setting the characteristic scale of spatial variation. For such short-wavelength modes (Drake, Sparks and Van Hoven, 1988), which are of greatest interest in explaining prominence formation, plasma flow is primarily parallel to the magnetic field. Hence, the field does not impede plasma compression, and significant density enhancement can occur.

To study the nonlinear evolution of the condensation process, we have conducted numerical simulations using a two-dimensional sheared-field model, with the results shown in Figure 1. The process occurs in two stages, starting from a low-level noise excitation as shown in Figure 1.(a). First the temperature drops to a relative level of  $\sim 0.03$  in the central portion of the magnetic shear layer, where electron heat conduction is inhibited by the field-line tilt, as shown in Figure 1.(b). At this point, the density has only increased by a factor of  $\sim 2$ , as in Van Hoven, Sparks, and Schnack (1987), but significant parallel (to  $\vec{B}$ ) pressure gradients have arisen away from the center of the shear layer. In the second stage, the plasma flows along (off-center) field lines, further increasing the radiation, leading to the narrow (knife-blade-like) dense and cool filament shown in Figure 1.(c), which has  $n, T$  values agreeing with prominence observations.

## 3. MAGNETIC RECONNECTION: PARALLEL ELECTRIC FIELDS AND HELICITY (K. SCHINDLER)

Large-scale numerical studies in cosmic plasma dynamics profit from tools that allow one to optimize the choice of parameters and to provide a suitable and effective framework for analyzing the results.

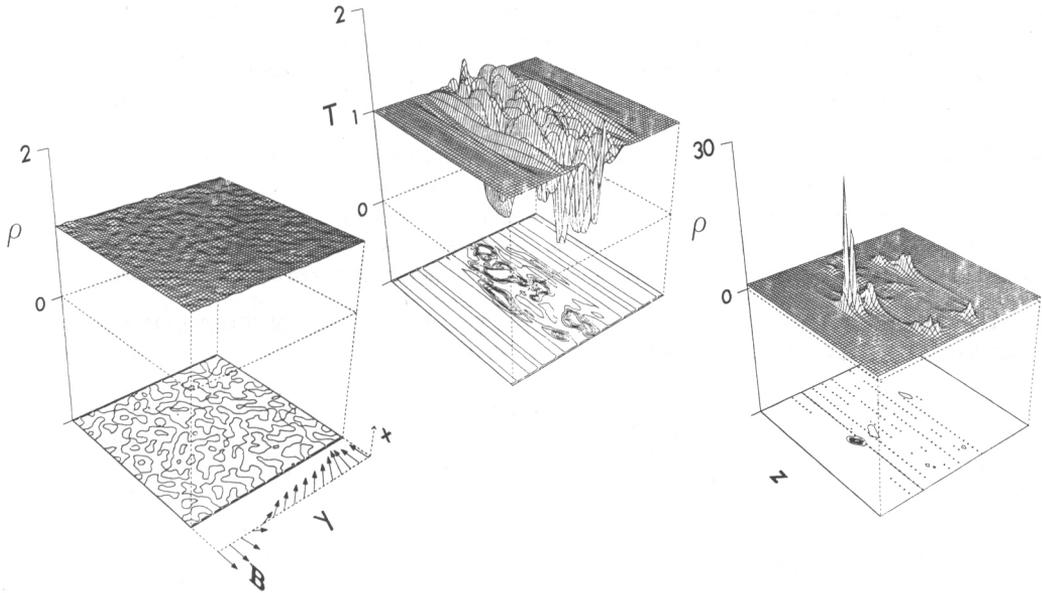


Figure 1. Filament condensation in a sheared magnetic field, as indicated in part (a). The left-hand figure shows the initial, random, density input, in a coordinate system in which the  $y$  axis is proportional to  $\sinh(y)$ , and the  $z$  axis is uniform. Part (b) displays the temperature profile (and contours) after the first nonlinear radiative-instability phase which is nearly isochoric. Part (c) shows the density profile late in the second, nearly isobaric phase, along with the parallel to (to  $\vec{B}$ ) flow vectors. The sharp prominence condensation has width (in  $y$ ) and height (in  $z$ ) of  $\sim 10^{-1}$  and 1 magnetic shear scales, respectively. The minimum temperature is  $\sim 10^{-2}T_c$  and maximum density  $\sim 10^{1.4}$ ,  $n_c$ , in agreement with filament/prominence observations.

For numerical stability studies, an investigation of the bifurcation properties of the underlying equilibrium problem proves particularly useful. Clearly, a linear instability associated with a forward bifurcation (with the control parameter increasing for decreasing stability) will not lead to dramatic dynamic effects such as required for solar flares. It is suggested that the evolution on branches that are stable with respect to dissipationless theory but unstable with respect to dissipative perturbations might play an important role in cosmic plasma activity. The onset point would be determined by mechanisms such as microinstabilities that rapidly enhance dissipation. An important example is the spontaneous formation and ejection of plasmoids. In particular, this process raises the question of whether collisional losses are sufficiently strong to provide the required dissipation (taking enhancement by current concentration into account) or whether collective loss mechanisms are required.

The majority of theoretical models of stellar and magnetospheric activity involve magnetic reconnection in one way or another. In fact, it seems reasonable to expect that progress in cosmic plasma activity depends on sufficient knowledge about reconnection. Up to now, mostly symmetric systems (e. g., those with translational invariance) have been modified by two-dimensional, analytical and computational techniques. The step to three-dimensional descriptions poses a number of conceptual problems, since the notion of magnetic reconnection in terms of separatrices and separators of the magnetic field seems to be inadequate in the general case. A concept that avoids such difficulties is based on the breakdown of magnetic-line conservation together with a localized

non-ideal plasma process. One finds that the electric-field component parallel to the magnetic field is the essential quantity in generic system which do not contain neutral lines. Furthermore, spontaneous reconnection processes must involve a change of magnetic helicity. Since this notion of magnetic reconnection is considerably broader than the earlier picture based on particular field topologies, it is important to identify those configurations where reconnection is particularly effective. This concept is being applied to a number of model situations relevant for active plasmas. One of the new features appearing in three-dimensional field configurations is stochastic reconnection. The new picture unifies all processes that one intuitively would classify as magnetic reconnection. Examples include the classical, two-dimensional, steady-state models, time-dependent processes such as the tearing instability, and the reconnection relaxation of sheared magnetic fields.

#### **4. TURBULENT EVOLUTION OF MAGNETIC ENERGY IN THE SOLAR ATMOSPHERE (R. B. DAHLBURG, J. P. DAHLBURG, AND J. T. MARISKA)**

Both observations and theoretical considerations suggest that the solar corona is heated by the dissipation of magnetic energy. Photospheric motions convect the footpoints of the coronal field structures; the resulting magnetic perturbations propagate into the corona and drive the plasma into a non-equilibrium state. As the plasma settles into a new quiescent state, magnetic energy is converted into heat. One step to understanding how this might take place is to study the viscosistive decay of a helically turbulent, three-dimensional magnetofluid.

We find that, when there is no background potential magnetic field, the perturbed field relaxes through a series of force-free (but non-constant  $\alpha = J/B$ ) states to a new equilibrium characterized by larger-scale structures. During this relaxation almost as much heat is released through viscous dissipation as through current sheets. When the same calculation is performed with a background potential field present, we find that heat production is inhibited and structure tends to develop parallel to the background field. We also see evidence for the generation of Alfvén waves, which might be observable in the solar corona. The detailed results are given by Dahlburg et al. (1988).

#### **5. NUMERICAL TECHNIQUES FOR THE MODELING OF MAGNETIC FIELDS (G. A. GARY AND S. T. WU)**

The upward extrapolation of photospheric fields employing the nonlinear force-free magnetic-fields equations is being pursued by a number of methods and investigators. The general process has been classified by Aly (1988) either as proceeding either by iterative methods or by the progressive extension method, which are generally variational or numerical-difference techniques respectively. The variational methods being investigated include those introduced by T. Sakurai (Univ. of Tokyo/Japan), D. Pridmore-Brown (Aerospace Corp./USA), P. A. Sturrock (Stanford Univ./USA), A. van Ballegooijen (Center for Astrophysics/ USA), M. Semel (Meudon Obs./France), and R. Kress (Univ. of Göttingen/FDR). The numerical-difference method is being investigated by S. T. Wu (UAH/USA).

As a result of the studies of J. J. Aly, H. Grad, M. M. Molodensky, B. C. Low and others, the important questions of convergence, stability, uniqueness, and existence are being answered. There are upper bounds to the strength of the possible electric currents in an active region for force-free fields. The existence of singularities remains an open question of analytic vs. discontinuous solutions. However the comparison of the two methods of extrapolation, in the near future, will provide a crucial test of our general ability to extrapolate the photospheric field into the corona. The iterative method insures that the force-free fields are stable against variations of the boundary conditions, while the progressive-extension method provides necessary-and-sufficient conditions for the unique determination of all the first derivatives, and the uniqueness of the solution in some domain.

Using the numerical-difference method, Wu et al. (1984) have shown the convergence of an algorithm both for analytic models and for data from the Marshall Space Flight Center vector

magnetograph. The analytic model shows that the numerical solution has errors less than a few percent at the present time. Further testing will provide the solar community with an additional procedure independent of T. Sakurai's code (1981), allowing for the verification of the extrapolated fields.

## 6. CONCLUDING REMARKS

Other interesting results were presented concerning the shocks produced by impulsively driven reconnection (Forbes, 1988), nonlinear reconnection in the solar corona (Steinolfson) and on coronal-loop thermal instability (Einaudi and Demoulin, 1988). In short, the presentations of this session showed the importance of large-scale numerical simulations and the role they will play in the understanding of the nonlinear dynamics and energetics of solar active phenomena.

## ACKNOWLEDGEMENT

The contributions of GVH to this report were supported by NSF and NASA; and those of STW by NASA grant NAGW-9 and Air Force grant AFSOR- 88-0013.

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