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VIII. Theory of Solar Flares

(E.R. Priest)

A. INTRODUCTION

By far the most significant event for Solar Flares as a whole over the past 3 years has been the operation of the Solar Maximum Mission Satellite, together with the accompanying data analysis, ground-based support and theoretical modelling. This has culminated in the series of SMM Flare Workshops, whose proceedings have now appeared (Kundu and Woodgate 1986 (I)), with chapters on a wide variety of topics which indicate the enormity and complexity of the flare problem.

Here we shall review only one aspect, namely the MHD theory of a flare (Priest 1986a), focussing on two topics. These are the instability or nonequilibrium process which initiates a large flare and the magnetic reconnection process whereby the stored magnetic energy is released. However, one should bear in mind the subtle interaction between the MHD and the microscopic plasma physics of the flare : the MHD provides the environment (the current sheets, shock waves and turbulent medium) where particles can be accelerated, whereas microscopic processes will determine the turbulent transport coefficients. Furthermore, the MHD coupling between a plasma and a magnetic field is much more complex and represents quite different physics from simply the electromagnetism of circuits, so it can often be misleading and dangerous to use circuit theory analogues.

A large solar flare has three phases : a preflare phase, during which a flux-tube (a prominence) starts to rise slowly ; a rise phase, when the prominence suddenly erupts rapidly and reconnection is initiated ; a main phase, when the reconnection continues and produces separating Hα ribbons and rising "post"-flare loops.

The role of reconnection is : to create small flares by emerging flux (Park et al. 1984) or by lateral motion or by reconnection submergence in cancelling magnetic features (Martin et al. 1985, Priest 1986a,b) ; to initiate the energy release at the rise phase of a large flare (below the rising prominence) and to continue the energy release through the main phase ; it may even trigger the eruption.

B. BASIC RECONNECTION THEORY

Reconnection is important for heating the plasma as well as producing the intense and localised electric fields to accelerate fast particles. The basic theory is split into two parts (Priest 1984, Dubois et al. 1985, Hones 1984, Pudovkin and Semenov 1985) : the tearing mode instability of a current sheet or sheared magnetic field, whereby an equilibrium goes linearly unstable to the breaking and reconnecting of field lines; the fast nonlinear state of steady reconnection. Tearing theory has been extended in many ways : e.g. by including viscosity (Park et al. 1984) ; by studying its non linear evolution at very large magnetic Reynolds number (Steinolfson and Van Hoven 1984a), which shows that the islands can become much wider than previously thought and that secondary islands can be generated ; and by coupling with optically thin radiation (Steinolfson and Van Hoven 1984b, see also references in Section IV A-1). The latter shows that radiative tearing can operate much faster than ordinary tearing and that perpendicular conduction produces thermal ripples (Steinolfson 1984).

Detailed numerical experiments have shown that, in its nonlinear development, tearing can evolve into a fast steady regime, but often such regimes are rather different from the classical modes. Analytically, a new unified theory for fast steady reconnection has been discovered (Priest and Forbes 1986) which includes the distinct classical models due to Sweet-Parker, Petschek and Sonnerup as special cases; it also possesses many new regimes, such as flux pile-up with a reconnection rate much faster than Petschek, up to the Alfven speed. The new regimes explain many previously puzzling features of numerical experiments (Forbes and Priest 1987).

The most detailed numerical experiments (Biskamp 1986) show three new features;the new inflow regimes of Priest and Forbes (1986) ; jets of plasma expelled along the separatrices, for which a theory exists (Soward and Priest 1986); and reversed current spikes or fast shocks at or near the ends of the central diffusion region (see also Forbes and Priest 1984, Forbes 1986). In addition, reconnection may sometimes have a filamentary and turbulent structure (Mattheus and Lamkin 1986), and a series of simulations of reconnection in the geomagnetic tail are also of importance for flares (Birn 1984, Birn and Schindler 1986, Birn et al.1987, Lee et al. 1985, Lee and Fu 1986, Sholer and Roth 1987) .

C. CAUSE OF ERUPTION

Theoretical proposals for the onset of a prominence eruption include : an eruptive MHD instability (of kink type) of the preflare magnetic configuration, modelled either as a flux tube or as a coronal arcade (Priest 1986) ; a lack of magnetic equilibrium reached after a slow evolution through a series of force free or magnetostatic equilibria (Priest 1986). Substantial progress has been made recently on the analysis of such instability and nonequilibrium thresholds, as follows. Nonequilibrium of a flux tube acted on by magnetic tension and magnetic buoyancy may occur if the tube becomes twisted too much or its footpoints become too widely separated (typically a few times the coronal scale height) (Browning and Priest 1984, Browning and Priest 1986). A most important analysis of arcade equilibria has also been completed with the footpoint positions and base pressure imposed (Moreno-Insertis 1986) ; it shows how magnetic catastrophes can occur with certain combinations of base conditions. Earlier work on the ideal stability of magnetic arcades has been greatly extended. A crucial stabilising effect that is now included is that of photospheric line-tying, and it has been shown by that it is best simulated by assuming "rigid wall" conditions so that all components of a coronal disturbance vanish at the photospheric boundary (Hood

1986b). New separable magnetohydrostatic solutions have been discovered (Melville et al. 1984), and sufficient conditions produced for their stability, which also become necessary when the axial field vanishes (Hood 1984a, Hood 1984b, Melville et al. 1986). Ideal ballooning instabilities which are driven by pressure gradients have been analysed (Hood 1986a) and resistive ballooning modes are found always to be unstable when the plasma pressure has a maximum on the arcade axis - this demonstrates that line-tying is not sufficient to stabilise resistive modes (Velli and Hood 1986). Both ballooning and thermal condensation modes are likely to be important in creating small-scale filamentation in the corona and in enhancing the global transport coefficients (Van Hoven et al 1987, Bodo et al 1985, Bodo et al 1987, see also references in section IV A-1). A study of a simple sheared arcade demonstrates how a pressure gradient can destabilise the arcade, but three force-free arcades were found to be stable to all the perturbations that were tried (Cargill et al 1986). The conclusion therefore is that eruptions may result when either the pressure build-up or the size of the magnetic island associated with the presence of a prominence are too great.

A new method for calculating force-free fields numerically has been set up (Yang et al 1986) which suggests that a closed field always has less energy than a completely open field, in agreement with Aly's conjecture(Aly 1984), but an example of a catastrophic opening to partly open field has been discovered (Low 1986). Global magnetostatic fields may also be buoyantly unstable (Low 1984).

D. MAIN PHASE OF ENERGY RELEASE

Much more detailed models have been developed of the main phase reconnection process as the field lines close down and create the hot "post"-flare loops and Ha ribbons. The kinematic model for deducing the electric field in the reconnection region from observed ribbon or loop motions has been greatly extended and applied to particular flares (Kopp and Poletto 1984, Kopp and Poletto 1985, Poletto and Kopp 1986). Furthermore, the fully MHD numerical model has several new interesting features (Forbes 1986, Forbes and Malherbe 1986, see also references in section IV A-1) : reconnection develops into an impulsive bursty regime, which explains the sudden observed jumps in loop height ; the presence of a fast-mode shock standing in the downflow from the reconnection site reduces the flow speed by a factor of four - it may be a source of fast particles and triggers a radiative condensation for the cool loops ; a reversed deflection current deflects the flow around the stagnation region ; most of the energy released at the slow shocks is conducted down to the chromosphere where it drives plasma upwards by evaporation.

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