Numerical Simulation of Reconnection Associated with Magnetic Flux Emergence

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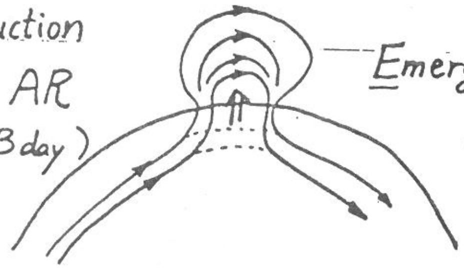
Introduction

new AR
($\lesssim$ 3day)



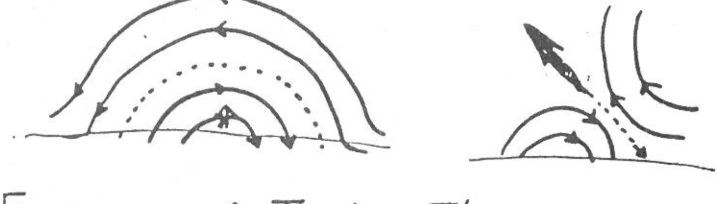
Emerging Flux Region
(EFR)

EFRs are very active
plages, arch filaments,
surges, XBP, flares ...

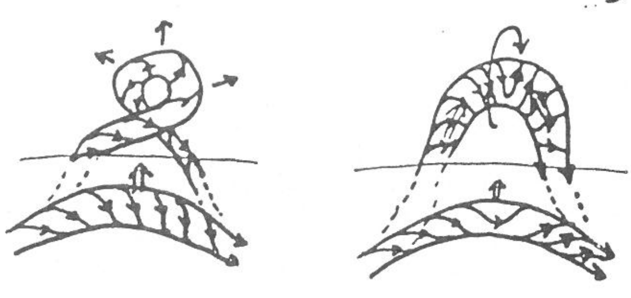
Why ?
How ?

Emerging Flux Models of Flares

- Current Sheet Formation and Reconnection
  (Heyvaerts et al. 1977,
  Uchida and Sakurai 1977, ...)



- Emergence of Twisted Flux Tube
  (Piddington 1975, Parker 1974,
  Tanaka, 1987, Kurokawa 1988,
  Uchida and Shibata 1988)



Schematic Picture of Emerging Flux Region (EFR)

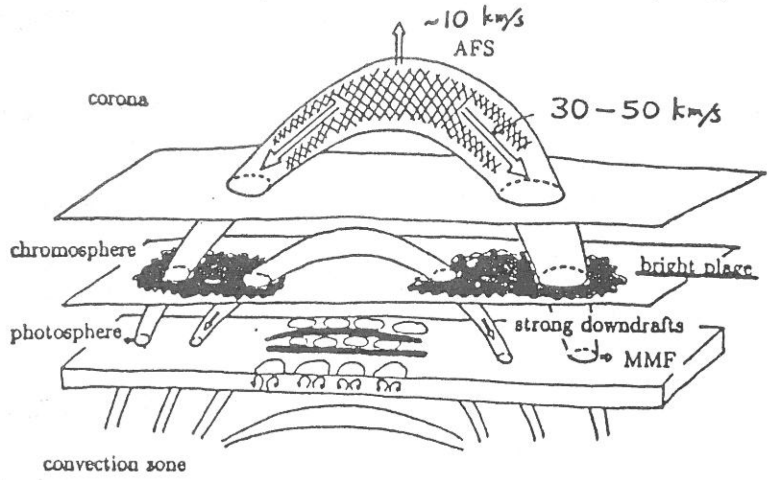


Fig. 9

2D-MHD simulations of reconnection between coronal field and "emerging flux"

Forbes and Priest (1984) Solar Phys. 94, 315

$g = 0$!

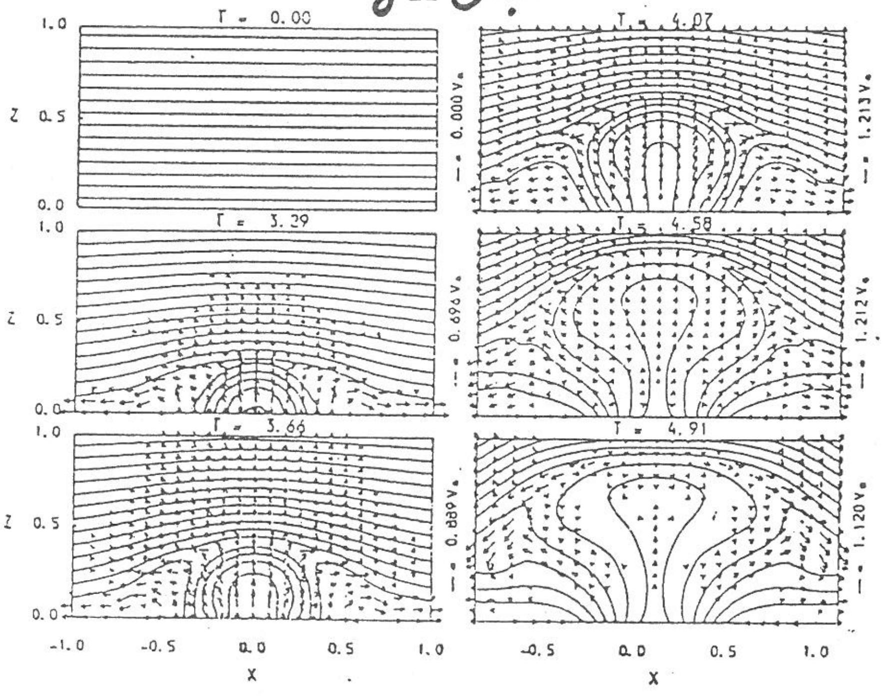


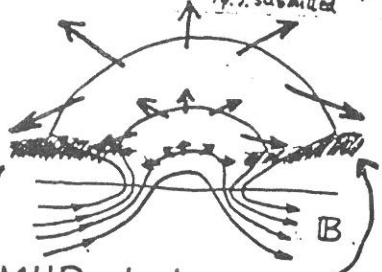
Fig. 1. Time sequence of magnetic field lines and flow vectors showing reconnection between a pre-existing, horizontal magnetic field and an emerging region of closed magnetic field lines which are antiparallel to the pre-existing ones. The times are in units of the time initially required for an Alfvén wave to travel from the bottom to the top of the numerical box. The magnitudes of the flow vectors are in units of the initial Alfvén velocity, V_o, and are rescaled in each panel with the scaling of the fastest flow speed indicated to the right of each panel. Each flow vector represents 24 grid points in the numerical mesh. Emergence of new flux at the base occurs in the region $|X| < 0.5$ from $t = 0.0$ to $t = 4.0$ at an input speed of about $0.12 V_o$.

Today's talk

(1) 2D-MHD Model of Emerging Flux

- self-similar expansion of magnetic loop
  (Shibata et al. 1989a, 1990, Nozawa et al. 1990) Ap. J. 338, 471. / Ap. J. 351, L25. / Ap. J. submitted

$g \neq 0$



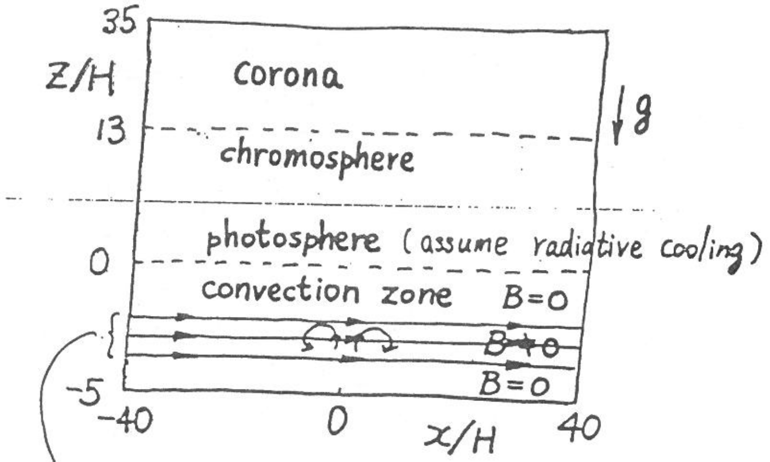
- strong MHD shocks
  (Shibata et al. 1989b) Ap. J 345, 584.

(2) Reconnection between Emerging Flux and Overlying Coronal Field

- formation of magnetic islands, their coalescence, and associated heating (Shibata and Nozawa 1990) in preparation

Two-Dimensional MHD Numerical Simulation.

Initial Condition

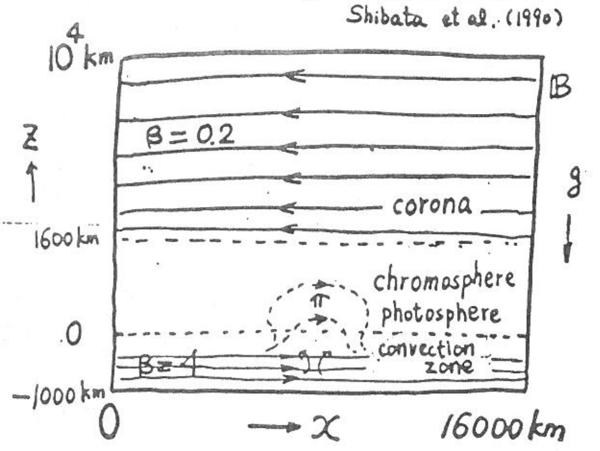


isolated flux sheet with $\beta = 4$

unstable for undular mode ($\mathbb{k} \parallel \mathbb{B}$) of magnetic buoyancy instability (i.e., Parker instability)

simulation model

cf. Nozawa et al. (1990)
Shibata et al. (1990)



resistivity model

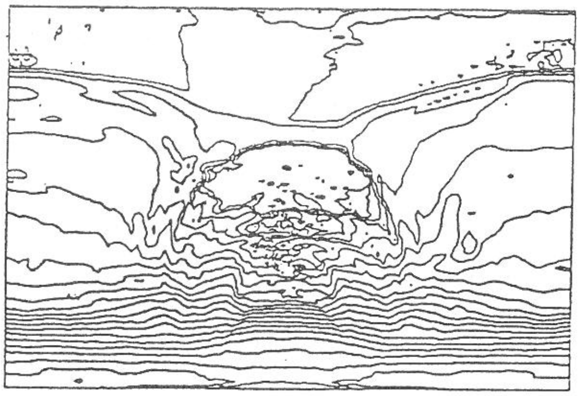
$$\eta = \begin{cases} \eta_0 (v_d - v_c)^2 / v_c^2 & \text{if } v_d \equiv j/\rho > v_c \\ 0 & \text{if } v_d < v_c \end{cases}$$

magnetic Reynolds number

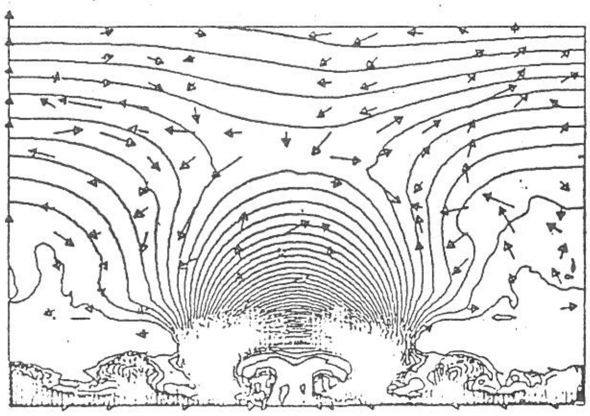
$$R_m \equiv C_s H / \eta \sim 10$$

$$\left[\ \widetilde{R_m} \equiv V_A L / \eta \sim 10^3\ \right]$$

log ρ



B + V

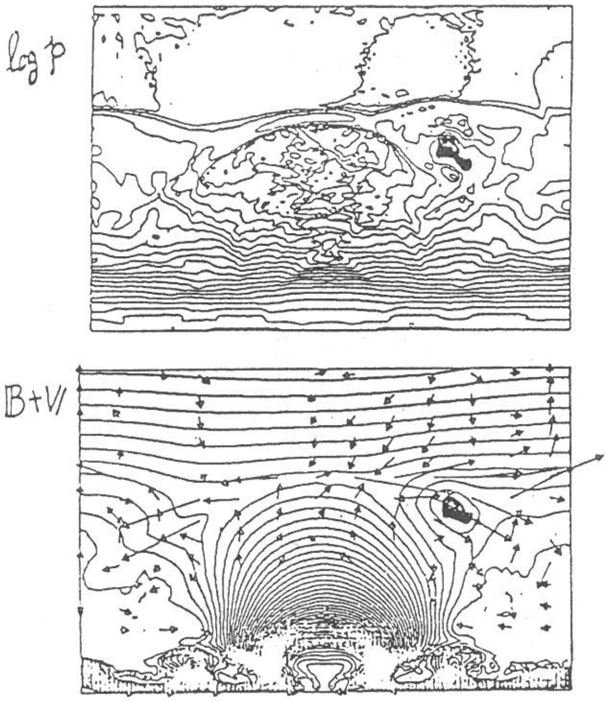


106.9 32000

XNM = 9.0

—— VNM = 5.0

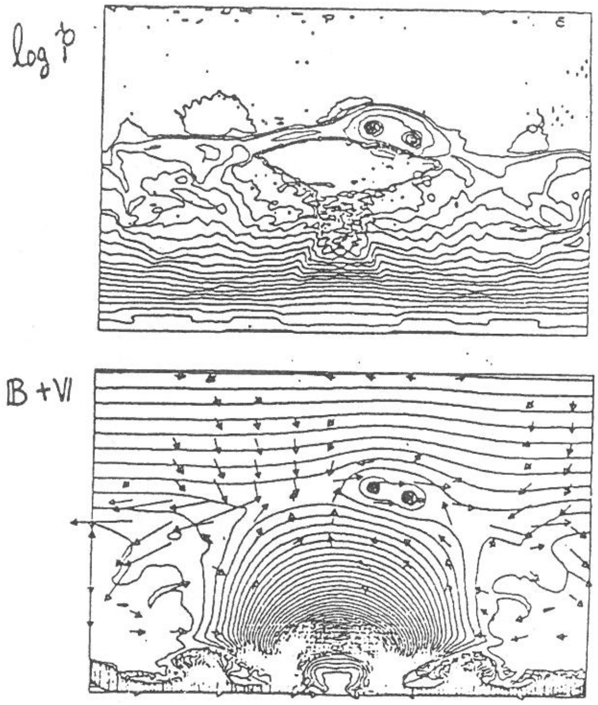
MREH02A



96.3 28000

XNM= 9.0
VNM= 5.0

MREHO2A (XMAX, ZMAX)= 80.0 54.0

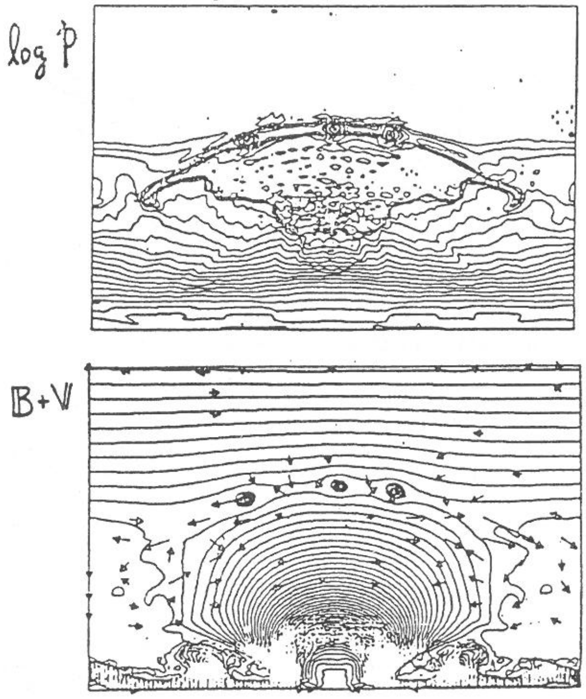


91.7 26000

XNM= 9.0
VNM= 5.0

MREHO2A (XMAX, ZMAX)= 80.0 54.0

high resolution model



88.2 24000

XNM= 9.0
VNM= 5.0

MREHO2A (XMAX, ZMAX)= 80.0 54.0

Summary

(1) self-similar expansion of magnetic loop

rise velocity of loop

$v_z \simeq 0.05\, C_s\, z/H$ → AFS

$\simeq 15$ km/s at $z \simeq 6000$ km

$\lesssim 1$ km/s at $z \lesssim 400$ km → photospheric emerging flux

$\rho \propto z^{-4}$

$B_x \propto z^{-1}$

(2) MHD shocks at the footpoints of loops

→ heating of plage chromosphere

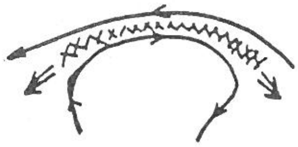
$v_{df} \simeq 30\text{–}50$ km/s $\simeq 3\text{–}5\, C_s$

$F \sim \frac{1}{2} \rho_{df} v_{df}^3 \sim 10^7$ erg cm^{-2} s^{-1}

$\left(\frac{dE}{dt} \sim 10^{25} \text{ erg s}^{-1}\right)$

(3) reconnection between emerging flux and overlying coronal field

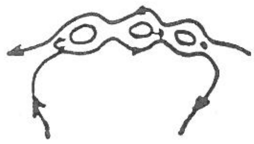
arch filament disappear due to gravity



$v_d = j/\rho$ ↗

↓

magnetic island formation



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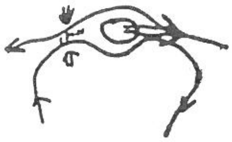
island coalescence



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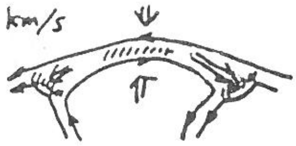
~3 min

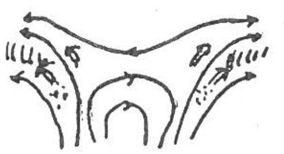
supermagnetosonic jet

for $\beta_{cor} \simeq 0.2$ ↓ $v \sim V_A \sim 50\text{–}100$ km/s

fast shock



$T \approx 5\times10^5 \sim 10^6$ K



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boundary filament

hot loop

Discussion: Why are EFRs so active?

- Origin of kinetic energy of downflow

  $\Rightarrow$ magnetic energy stored in convection zone flux tube

- Most of magnetic energy is converted into heat in the photosphere and chromosphere (by compressional and shock heating)

- Magnetic energy transferred into corona

$$F_{mag} \sim \frac{B_x^2}{4\pi} v_z \sim 4\times10^7 \left(\frac{Z}{2\times10^4\,\mathrm{km}}\right)^{-1} \mathrm{erg\ cm^{-2}\ s^{-1}}$$

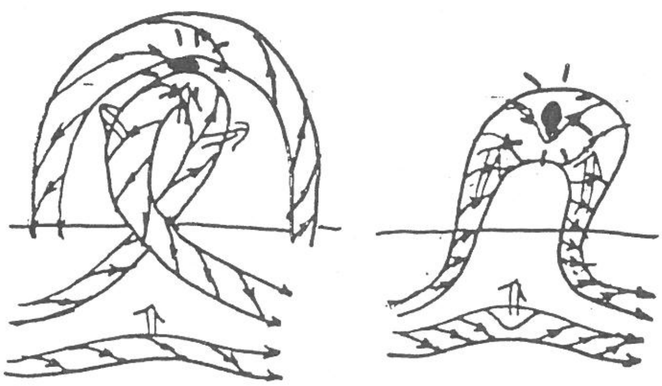
$\Downarrow$

released by magnetic reconnection

($\rightarrow$ surges, XBP, flares ?)

Future Plans

3D simulation of emergence of twisted flux tubes



$$F_{mag} \sim \frac{1}{4\pi}(B_x^2 + \underline{\underline{B_\varphi^2}}) V_z \quad > \frac{B_x^2}{4\pi} V_z$$