Storage of magnetic flux tubes in the solar overshoot region
MPS Solar Group Seminar

Emre Işık

in cooperation with
Volkmar Holzwarth, Manfred Schüssler

Max-Planck-Institut für Sonnensystemforschung
Katlenburg-Lindau

June 10th, 2008
Azimuthal $B$ in the solar interior

- Indicated by photospheric observations
- Numerical simulations of rising flux tubes suggest $B \sim 10^5$ G

Problem

- Can toroidal flux tubes be stored for sufficiently long?

- Effects of finite perturbations and external flows
Magnetic buoyancy (Parker) instability

- Magnetic flux tube in lateral pressure balance:

\[ p_i + \frac{B^2}{8\pi} = p_e \]

- Cause: growing density deficit in rising/expanding portion of a flux tube

- Critical quantities: \(|B|, \delta \equiv \nabla - \nabla_{ad}\)

- Probably an important cause of flux loss in the dynamo layer
Magnetic buoyancy instability
Linear stability analysis (Ferriz Mas & Schüssler 1995)

Stability diagram for middle-overshoot region

▶ Solar overshoot region: $B_{\text{crit}} \sim 10^5$ G
When friction is included..
Friction-induced instability

Stokes-type acceleration
\[ \mathbf{a}_S = -\alpha (\mathbf{u}_{\text{rel}} \cdot \mathbf{e}_n) \mathbf{e}_{n0} \]

Instability criterion:
\[ u_e > -u_{ph} \] (flux tube frame)

Holzwarth et al. 2007
Numerical simulation of friction-induced instability

\[ B = 7 \cdot 10^4 \text{ G, latitude} = 30^\circ, R_{\text{tube}} = 1000 \text{ km, rad.perturbation} = 550 \text{ km (}10^{-2}H_p)\]
Numerical simulations of friction-induced instability
Effect of radial flows
Azimuthally periodic flows – linear analysis

- Linearised eqs. of motion for nonaxisymmetric perturbations of a thin toroidal flux tube
- ⇒ Dynamical equilibria for a toroidal flux tube subject to external flows
Effect of finite perturbations on flux tubes

- Growth time of the nonlinear buoyancy instability $\sim 1000$ d for a tube with $R=1000$ km, $B=7 \cdot 10^4$ G
- Corresponding flow: $m=5$, $v\sim 10$ m s$^{-1}$ at mid-overshoot
Effect of radial flows
Localised downflow – nonlinear simulation

- $v_{\text{max}} = -20 \text{ m s}^{-1}$ at mid-overshoot; $\sigma_\phi = 5^\circ$
- Flow duration: 60 days. $B = 7 \cdot 10^4$ G, lat.$= 0^\circ$
- Eruption time $\approx 10$ years
Effect of radial flows
Localised downflow – nonlinear simulation

- $v_{\text{max}} = -20 \text{ m s}^{-1}$ at mid-overshoot; $\sigma_\phi = 5^\circ$
- Flow duration: **200 days**. $B = 7 \cdot 10^4 \text{ G}$, lat.$= 0^\circ$
- Eruption time $\approx 3.3 \text{ years}$
Conclusion

- Frictional coupling ⇒ instability for $B \gtrsim 4 \cdot 10^4$ G
  - Frictional instability: linear growth times consistent with nonlinear simulations

- Nonlinear simulations: up to $\sim 3$ yr,
  - finite perturbations: stable
  - external radial flows: stable for $v \lesssim 20$ m/s in the mid-overshoot region

- Dependence on flow parameters:
  - Time variation (e.g., duration $\lesssim 200$ d)
  - Maximum speed ($\lesssim 20$ m s$^{-1}$)
  - Azimuthal extent ($\lesssim 10^\circ$)