Observations and Modelings of the Solar Flux Emergence

Shin Toriumi (Univ. of Tokyo)

Supervisor: T. Yokoyama (U. Tokyo)

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1. Introduction
1. Introduction

- Numerical Simulation: Emergence from -20 Mm

Mag. field: \( \log \left( \frac{|B|}{B_0} \right) \)
Toriumi & Yokoyama (2012)
1. Introduction

- Importance of Flux Emergence
  
  - Transports the magnetic flux from the deep interior
  - Creates active regions
  - Sometimes causes eruptions such as flares and CMEs

Observational and Numerical studies
2. Emergence in the Deep Interior

- Importance of Flux Emergence
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Observational and Numerical studies
2. Emergence in the Deep Interior

- Numerical Simulations
  - Thin-flux-tube approximation (Spruit 1981)
    - $B_{eq}$ at the bottom of the CZ: at least $10^4$ G
    - Total flux of ARs: $10^{20}$-$10^{22}$ Mx
    - Cross-sectional size of the tube: $\sim1,000$ km
      - Pressure scale height: a few 10,000 km
  - Anelastic approximation (Gough 1969)
    - Equation of continuity is approximated by
      $$\nabla \cdot (\rho_0 \mathbf{V}) = 0$$

- Flux tube is “thin”
- Sound waves are filtered out
2. Emergence in the Deep Interior

* Numerical Simulations
  
  **Thin-flux-tube approximation** (Spruit 1981)
  
  - Field strength of $10^5$ G is required for the tubes to emerge at sunspot latitudes
  
  - *Colioris force* is responsible for various asymmetries between the leading and following polarities

  **Anelastic approximation** (Gough 1969)
  
  - Emergence in the rotating spherical shell
  
  - *Retrograde* flow along the flux tube
  
  - Emergence in the *convective* interior

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**Figure 2.** Snapshots of the 3D evolution resulting from the NT simulation. The images show the volume rendering of the absolute magnetic field strength $B$. [This figure is available as an mp4 animation in the electronic edition of the Journal.]
2. Emergence in the Deep Interior

++ Observational Studies
++ Probing by Local Helioseismology

Ilonidis et al. (2011)

- Time-distance helioseismology
- Detected seismic anomaly in the deep convection zone at ~-65 Mm
- Up to 2 days before the flux emergence attains its peak flux growth rate
- Rising velocity: 0.3-0.6 km s⁻¹
3. Birth of Active Regions

- Importance of Flux Emergence
  - Transports the magnetic flux from the deep interior
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Observational and Numerical studies
3. Birth of Active Regions

- 5-day Observation of AR 11130: Small-scale Features
3. Birth of Active Regions

Resistive Emergence Process

Suggestion of the Model (Pariat et al. 2004)

- Photospheric fields have **serpentine** structure (Strous & Zwaan 1999)
- Local **flux cancellations** of these fields $\rightarrow$ **Ellerman bombs**
- Later simulated by Isobe et al. (2007) and Archontis & Hood (2009)
3. Birth of Active Regions

- Resistive Emergence Process
  - Convective emergence (Cheung et al. 2010)
    - Cancellations coupled with convection remove mass from the surface layer
    - Key process for entire tube emergence

Cheung et al. (2010)
3. Birth of Active Regions

- Resistive Emergence Process
  - Spectroscopy (Matsumoto et al. 2008)
    - Observation of an Ellerman bomb
      - Upflow of 1-3 km s\(^{-1}\) in the chrom.
      - Downflow of 0.2 km s\(^{-1}\) in the photo.
    - Bi-directional jet due to reconnection

Matsumoto et al. (2010)
3. Birth of Active Regions

- Resistive Emergence Process
  - Future Observation → Hinode and Solar-C
  - Spectro-Polarimetry: SOT and SUVIT
  - Scan the emerging flux region at the photosphere and the chromosphere
  - To quantitatively investigate the contribution of each process to the entire flux tube emergence
1. Introduction

- Importance of Flux Emergence
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Observational and Numerical studies
4. Formation of a Flaring Active Region

- Flaring AR: NOAA 11158
  - Produced a series **strong flares** including X2.2-class event
  - **Highly sheared PIL** in the central δ-sunspots

Hinode/SOT: movie courtesy of T. Okamoto
4. Formation of a Flaring Active Region

- Previous Studies
  - Kusano et al. (2012)
    - Reconnection between the sheared coronal arcades
  - Sammis et al. (2000)
    - δ-sunpots produce many more large flares

![Graph showing relationship between spot group area and max. X-ray flux](image-url)
4. Formation of a Flaring Active Region

Previous Studies

- Kusano et al. (2012)
  - Sheared PIL, coronal arcade, and δ-sunspots
  - Important for production of intensive flares

- Sammis et al. (2000)
  - δ-sunspots produce many large flares

What creates such structures in an AR?

- Formation of AR from the flux emergence
- Target region: AR 11158
4. Formation of a Flaring Active Region

- Evolution of AR 11158
  - Composed of two emerging bipoles P1-N1 and P2-N2
  - Sheared PIL is created between N1 and P2, which forms δ-sunspots
4. Formation of a Flaring Active Region

Photospheric Evolution
1. P1-N1 / P2-N2 appear at the surface
4. Formation of a Flaring Active Region

Photospheric Evolution

1. P1-N1 / P2-N2 appear at the surface
2. P2 drifts along the southern edge of N1, forming a sheared PIL

Sheared PIL

δ-sunspots
4. Formation of a Flaring Active Region

Coronal Evolution

3. Coronal arcade connecting N1-P2 is then created above the PIL

4. A series of strong flares (including X and M events) occur at this PIL
4. Formation of a Flaring Active Region

- Formation of AR 11158
- Two possible scenarios for this AR

Case 1

Emergence of a single split tube

Case 2

Emergence of two independent tubes
4. Formation of a Flaring Active Region

- Formation of AR 11158
- 3D MHD simulation of magnetic flux tubes for Cases 1 and 2

Case 1

- Length: \( H_0 = 200 \text{ km} \)
- Time: \( \tau_0 = 25 \text{ s} \)
- Field strength: \( B_0 = 300 \text{ G} \)

Mimic the splitting by sinking the middle part
4. Formation of a Flaring Active Region

- Formation of AR 11158
- Results: Magnetogram

Case 1: single split tube

Case 2: two independent tubes
4. Formation of a Flaring Active Region

- Formation of AR 11158
- Results: Magnetogram

Case 1: single split tube

- \( \delta \)-sunspots
- Arrows: \( B_h \)
- Sheared PIL

\[ t/\tau_0 = 150.0 \]
4. Formation of a Flaring Active Region

↑ Formation of AR 11158

↑ Results: Coronal fields and reconnection

1. P1-N1 and P2-N2 come closer to the middle of the region.
2. Reconnection occurs in a current sheet.
3. Arcade field (N1-P2) is created, while post-reconnection field (P1-N2) is ejected upward.

Case 1 \((t/\tau_0 = 120)\)
4. Formation of a Flaring Active Region

Formation of AR 11158

Results: Coronal fields and reconnection

1. **P1-N1** and **P2-N2** come closer to the middle of the region.
2. **Reconnection** occurs in a current sheet.
3. **Arcade field** (N1-P2) is created, while post-reconnection field (P1-N2) is ejected upward.

**Case 1** \( (t/\tau_0 = 120) \)
4. Formation of a Flaring Active Region

- Comparison of the Observation and Simulations
- Creation of the sheared PIL
4. Formation of a Flaring Active Region

- Comparison of the Observation and Simulations
  - Creation of the sheared PIL

(a) AR 11158  
(b) Case 1   
(c) Case 2

- In AR 11158, N1→P2 vector rotates and the length becomes shorter.
- Only Case 1 shows a similar trend. In Case 2, N1 and P2 simply fly by.
4. Formation of a Flaring Active Region

- Formation of AR 11158
- Conclusion: **Case 1** is more likely the case

**Case 1**
Emergence of a single split tube

**Case 2**
Emergence of two independent tubes
4. Formation of a Flaring Active Region

 Formation of AR 11158

 Conclusion: Case 1 is more likely the case

- Two emerging fields of AR 11158 shared a common root below the surface.
- Emergence of single tube produced
  - Sheared PIL and coronal arcade
  - δ-sunspots
  which is responsible for the flares

- Large-scale flux emergence is greatly responsible for the flaring activities.
5. Summary

- Flux Emergence from the Interior to the Atmosphere
  - Emergence in the Deep Interior
    - Simulations
    - Helioseismology
  - Birth of Active Regions
    - Small-scale features
    - Resistive emergence model
      → Hinode / Solar-C
  - Formation of a Flaring Active Region
    - Sheared PIL, coronal arcade, and δ-sunspots
    - AR 11158: single split tube rather than two tubes
      → Large-scale emergence is responsible for the flare activities (Toriumi et al., submitted)
Thank you for your attention!