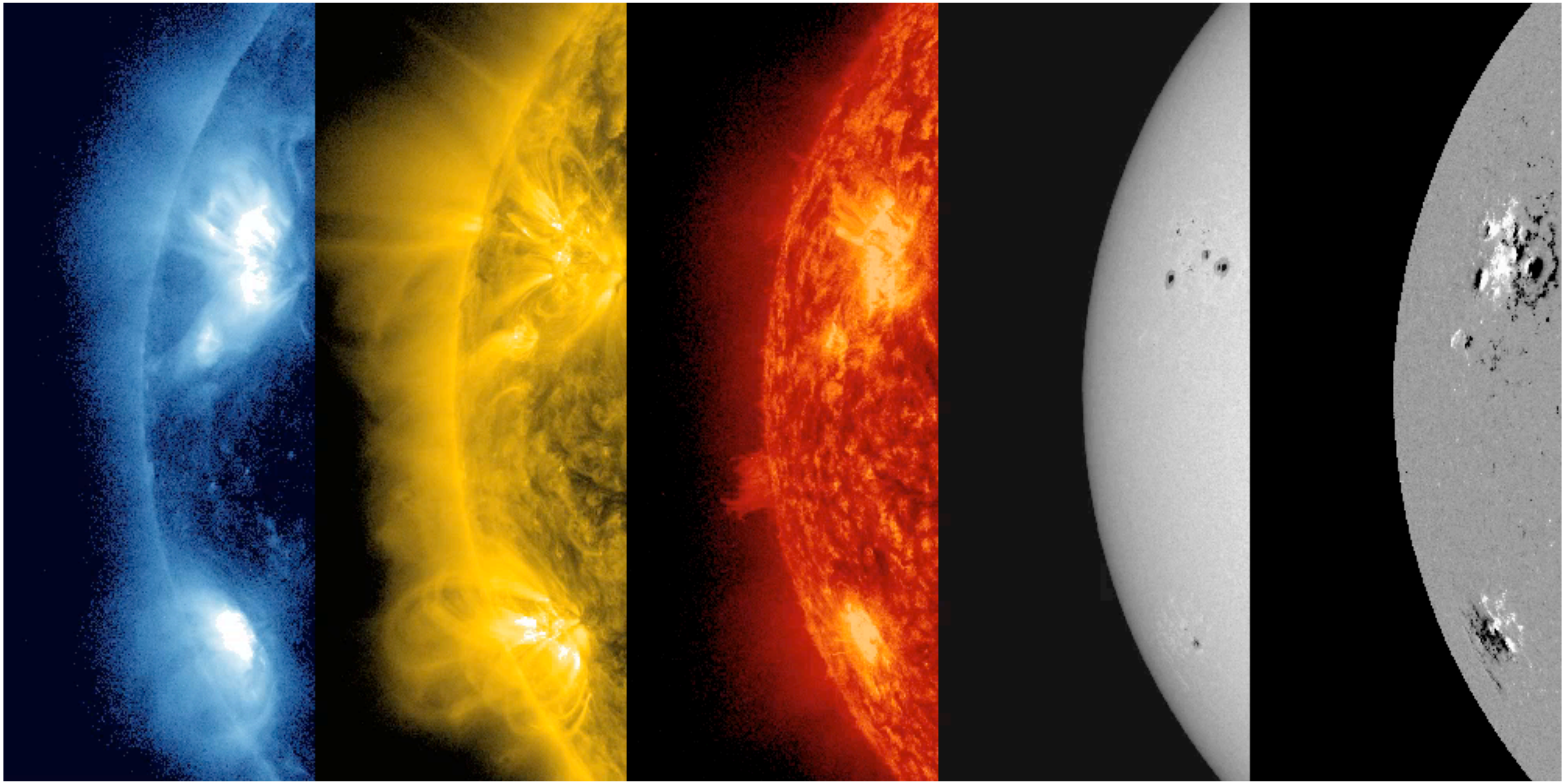
Observations and Modelings of the Solar Flux Emergence

Shin Toriumi (Univ. of Tokyo)

Supervisor: T. Yokoyama (U. Tokyo)

Hinode-7 (2013 Nov. 13)

1. Introduction

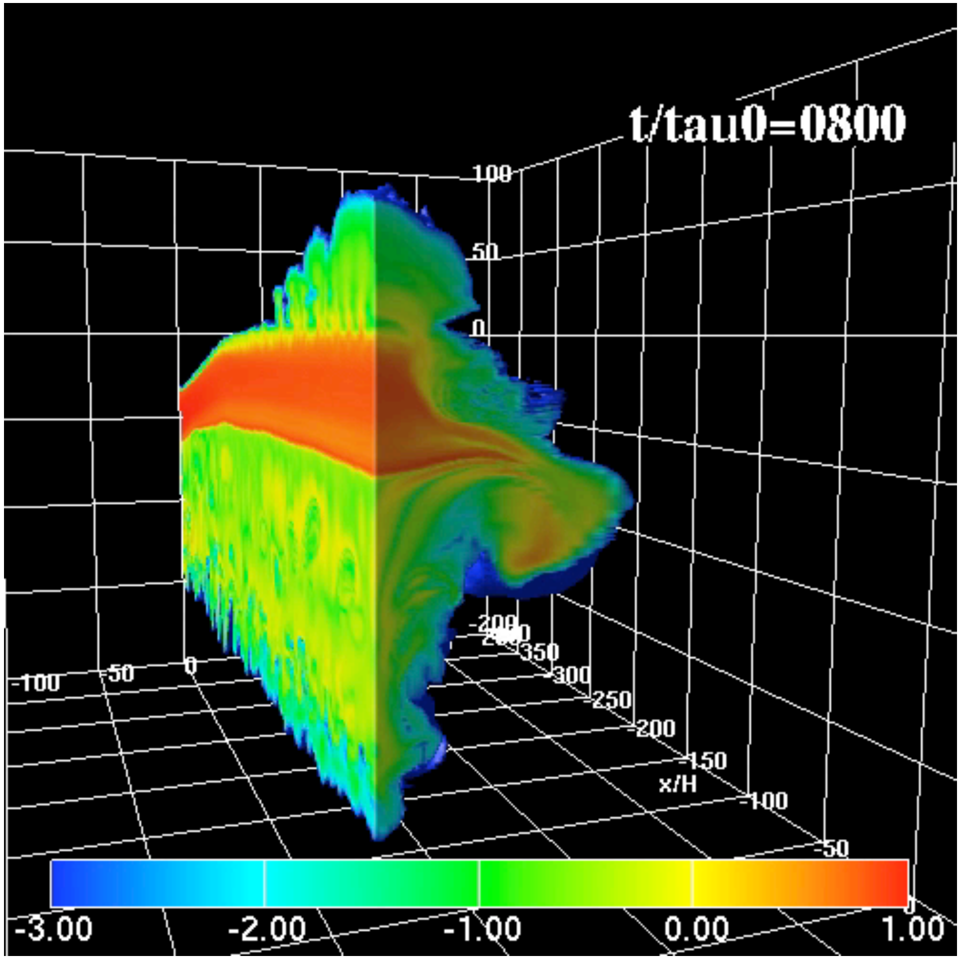


AIA 335 Å　AIA 171 Å　AIA 304 Å　HMI Cont.　HMI Mag.

NASA/SDO

1. Introduction

- Numerical Simulation: Emergence from -20 Mm

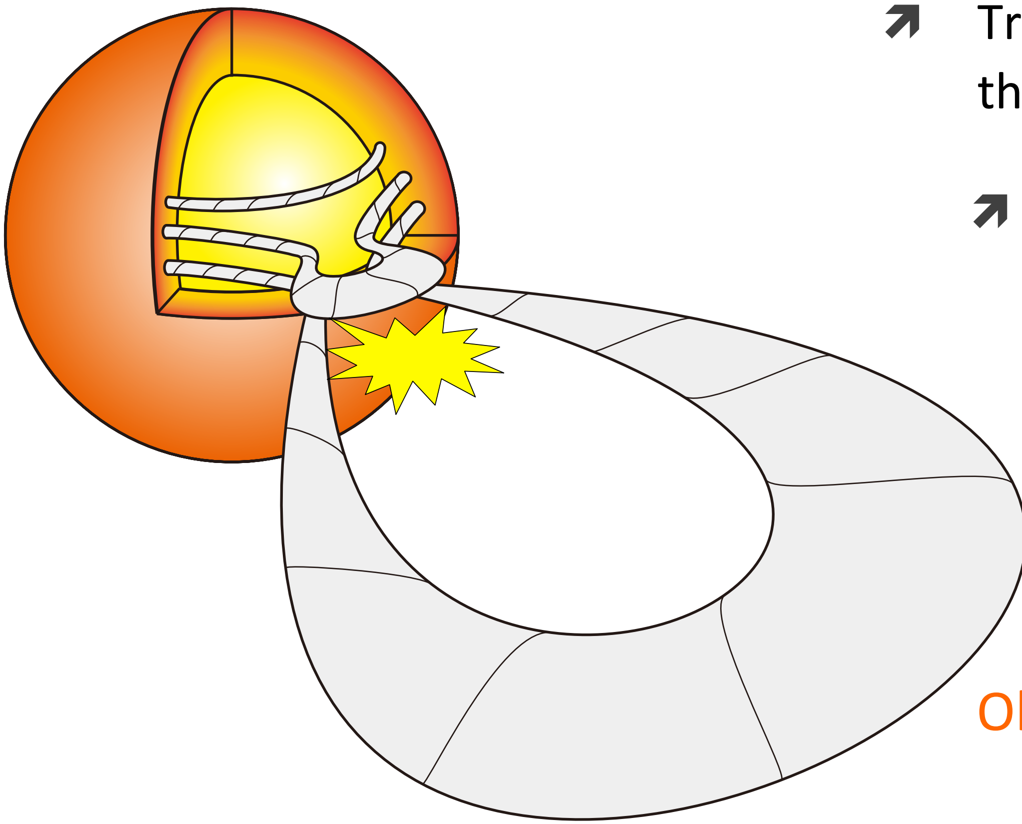


Mag. field: $\log(|B|/B_0)$

Toriumi & Yokoyama (2012)

1. Introduction

- Importance of Flux Emergence

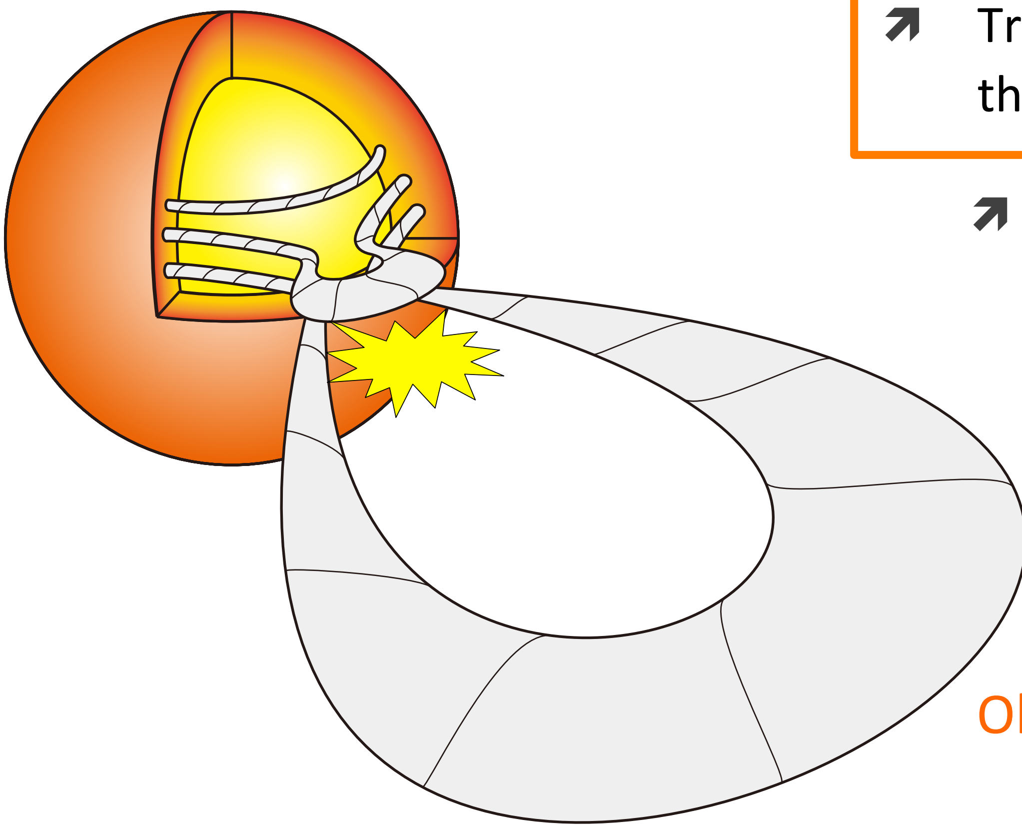


- Transports the magnetic flux from the deep interior
  - Creates active regions
    - Sometimes causes eruptions such as flares and CMEs

Observational and Numerical studies

2. Emergence in the Deep Interior

- Importance of Flux Emergence



- 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

- Numerical Simulations
  - Thin-flux-tube appoximation (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: ~1,000 km

      Pressure scale height: a few 10,000 km

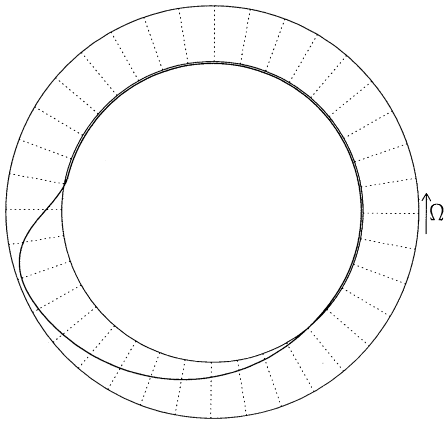
    ⇒ ✓ Flux tube is "thin"
  - Anelastic approximation (Gough 1969)
    - ✓ Equation of continuity is approximated by

$$\nabla \cdot \left(\rho_0 \mathbf{V} \right) = 0$$

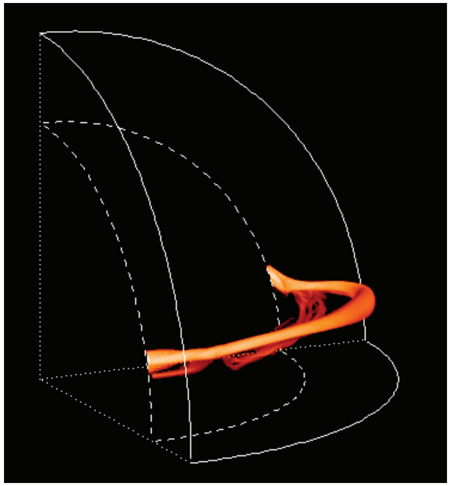
    ⇒ ✓ Sound waves are filtered out

2. Emergence in the Deep Interior

- Numerical Simulations
  - Thin-flux-tube appoximation (Spruit 1981)
    - ✓ Field strength of <u>10^5 G</u> is required for the tubes to emerge at sunspot latitudes
    - ✓ <u>Colioris force</u> is responsible for various asymmetries between the leading and following polarities
  - Anelastic approximation (Gough 1969)
    - ✓ Emergence in the rotating spherical shell
    - ✓ <u>Retrograde</u> flow along the flux tube
    - ✓ Emergence in the <u>convective</u> interior

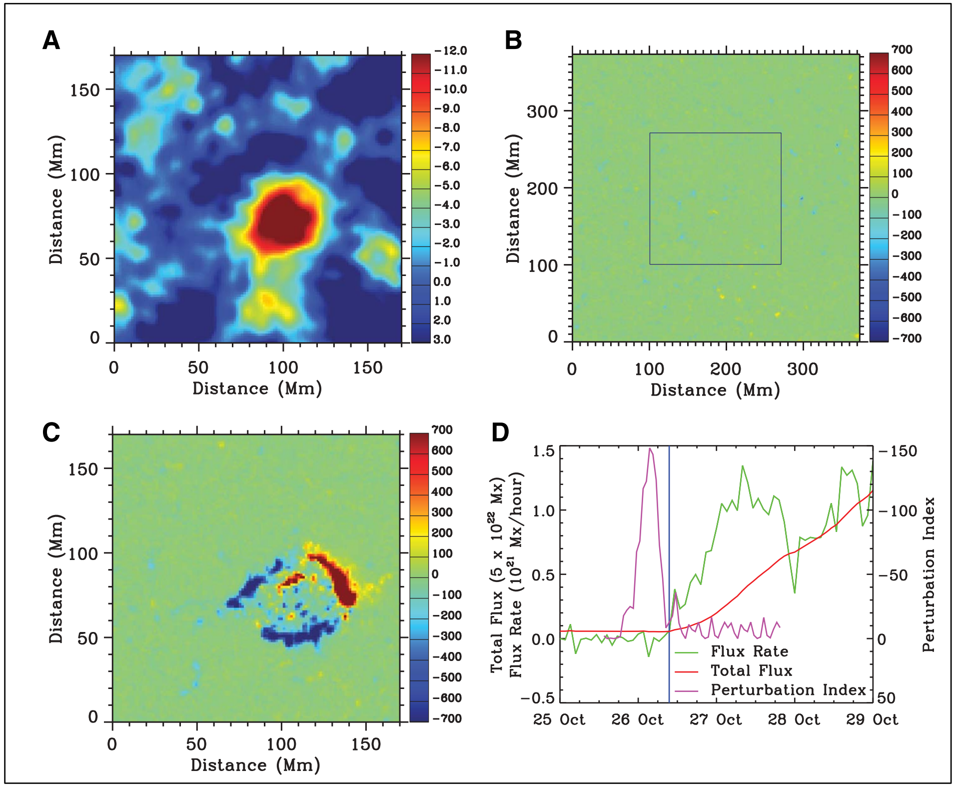


Caligari et al. (1995)


Fan (2008)

2. Emergence in the Deep Interior

- Observational Studies
  - Probing by Local Helioseismology



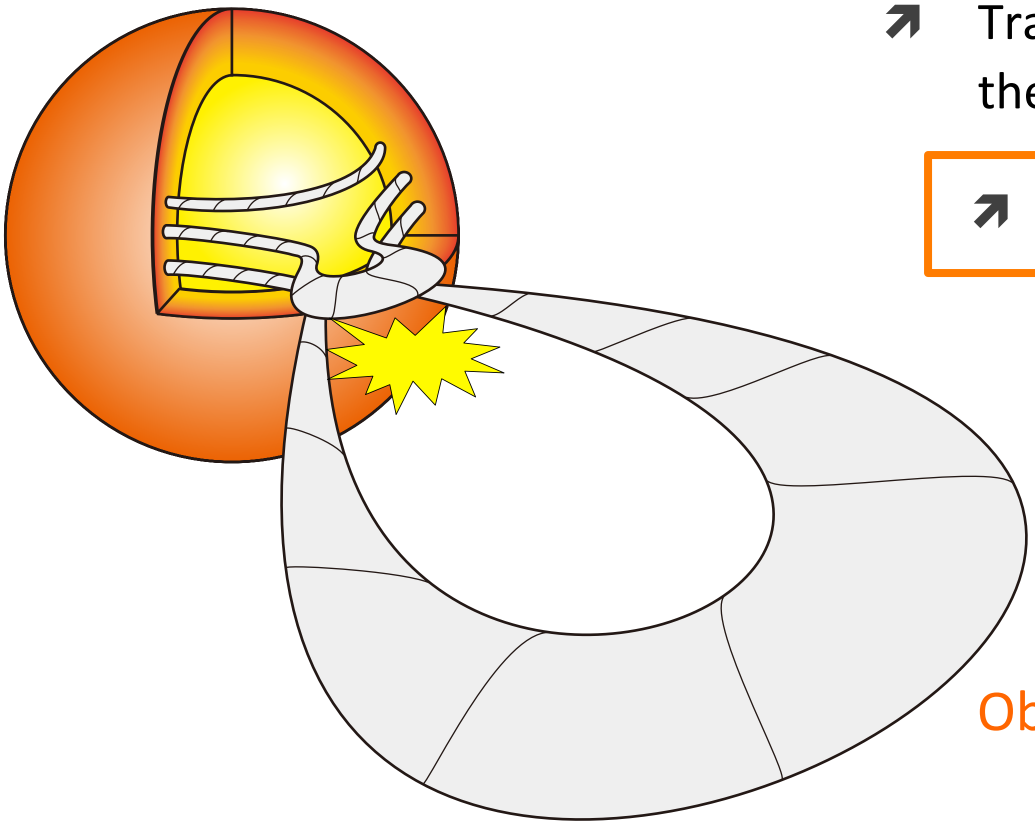
Ilonidis et al. (2011)

✓ 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

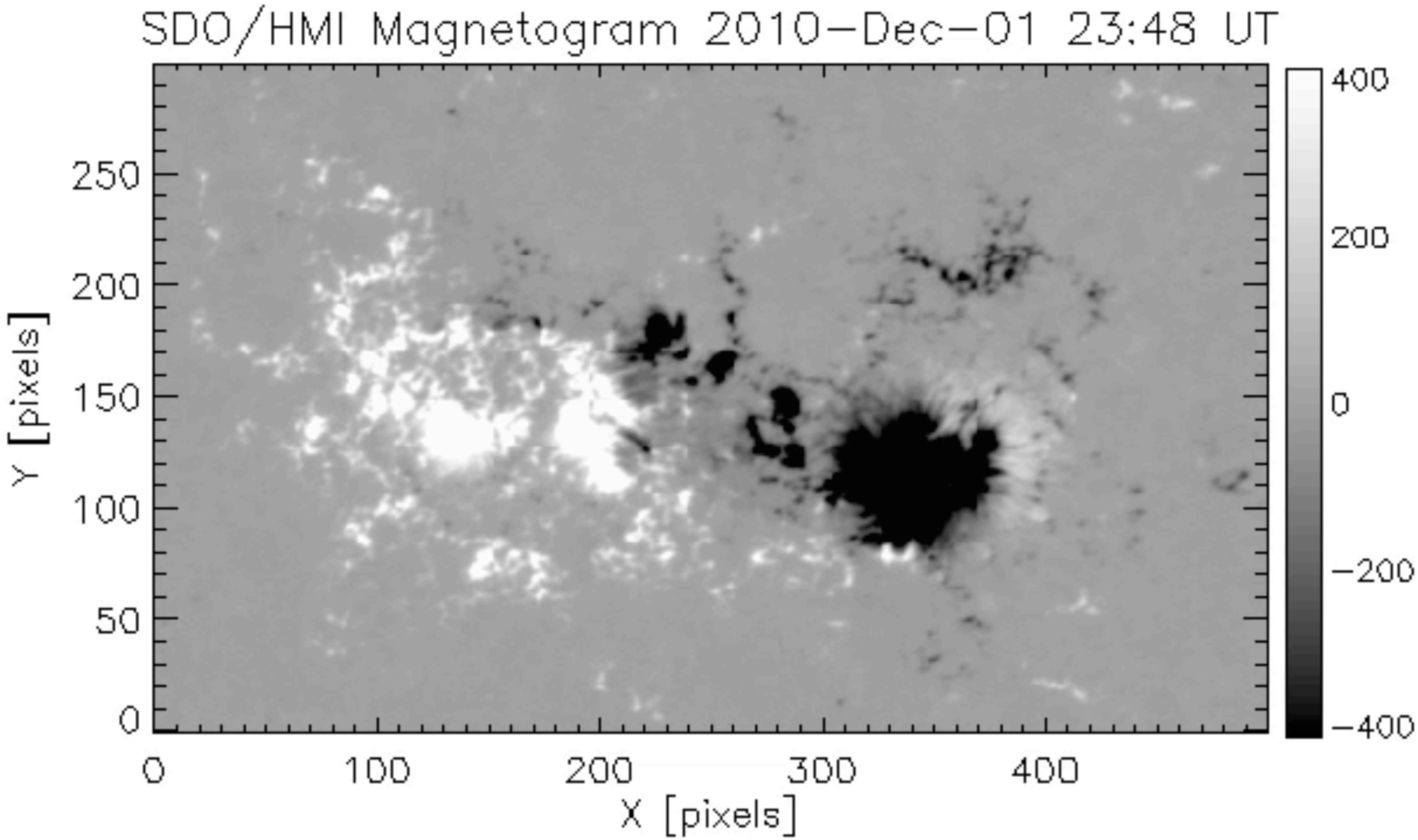


- Transports the magnetic flux from the deep interior
- Creates active regions
- Sometimes causes eruptions such as flares and CMEs

Observational and Numerical studies

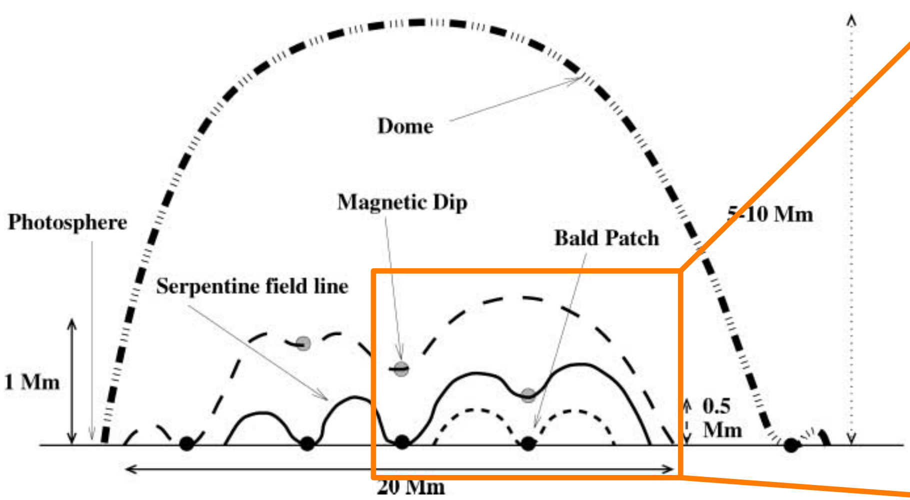
3. Birth of Active Regions

- 5-day Observation of AR 11130: Small-scale Features

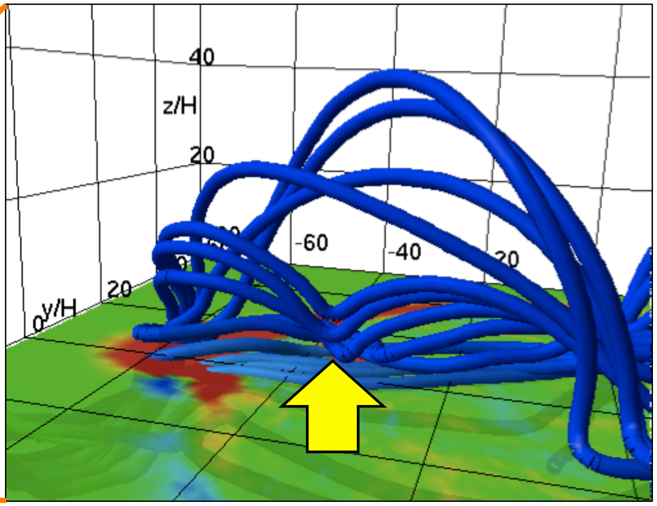


3. Birth of Active Regions

- 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 → Ellerman bombs
    - ✓ Later simulated by Isobe et al. (2007) and Archontis & Hood (2009)



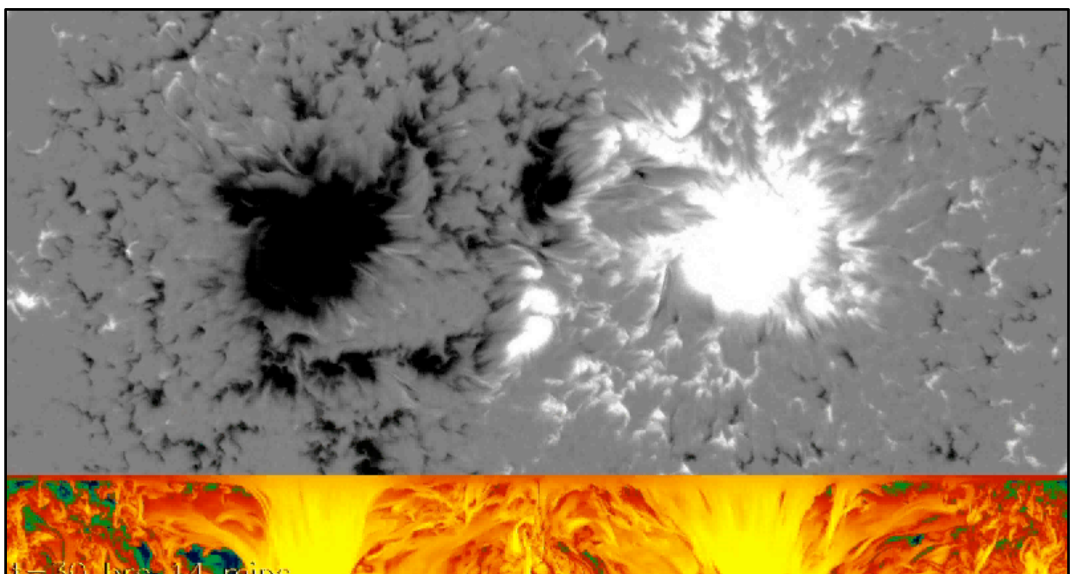
Pariat et al. (2004)

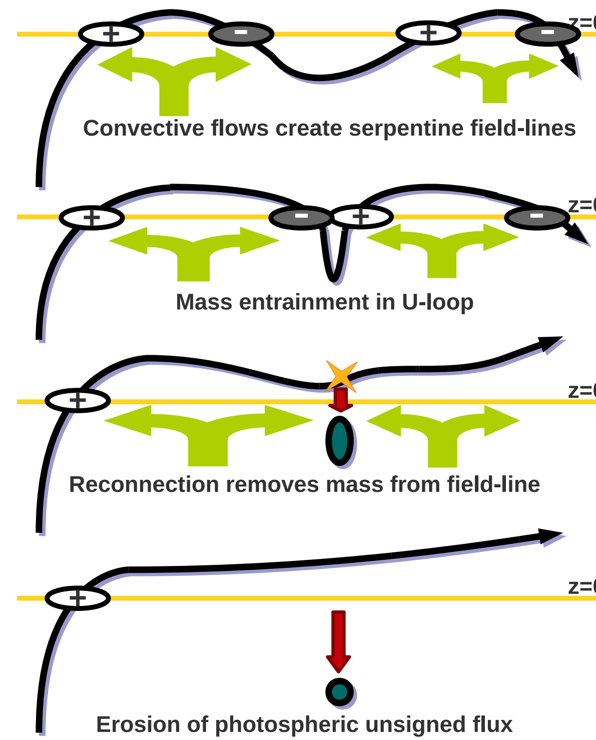


Toriumi et al. (2012)

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

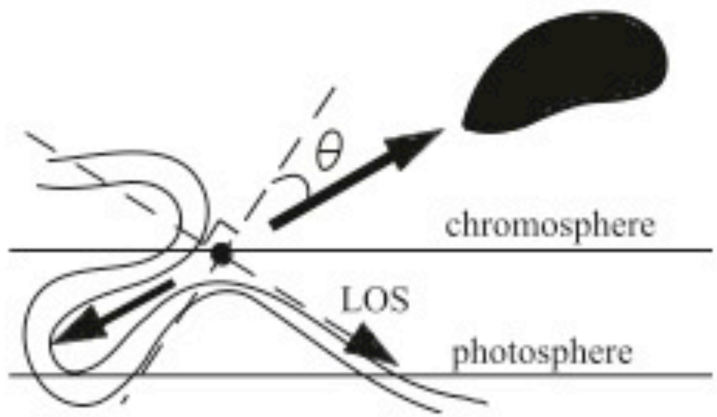


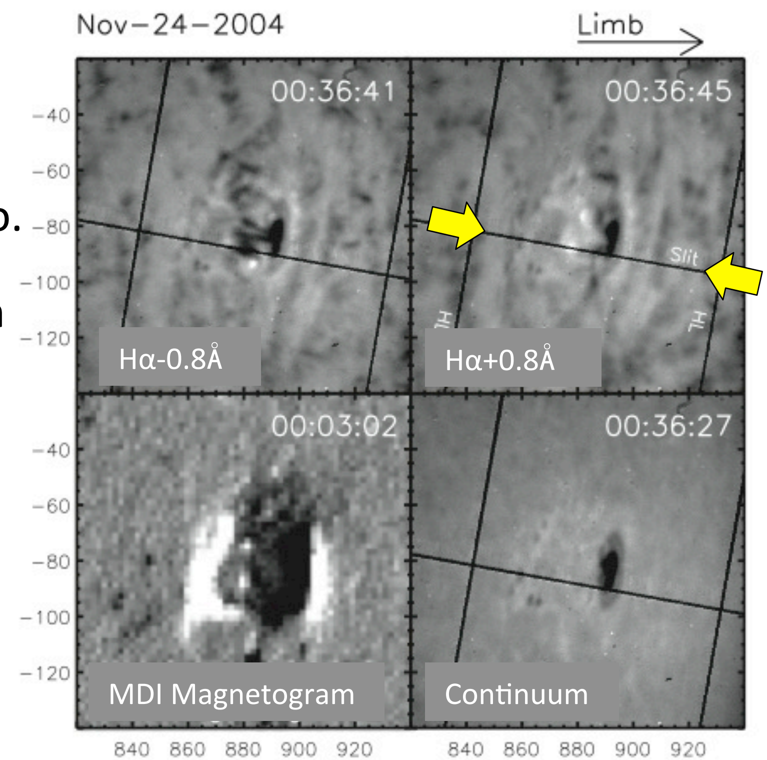


Cheung et al. (2010)

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

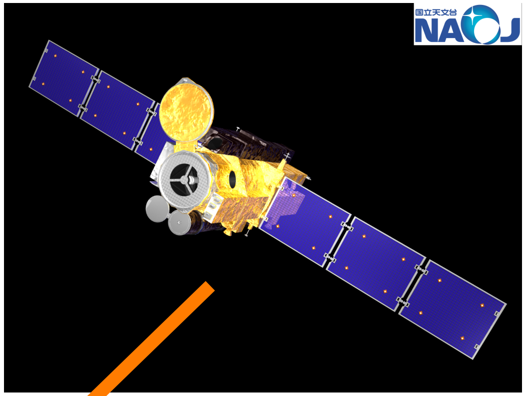


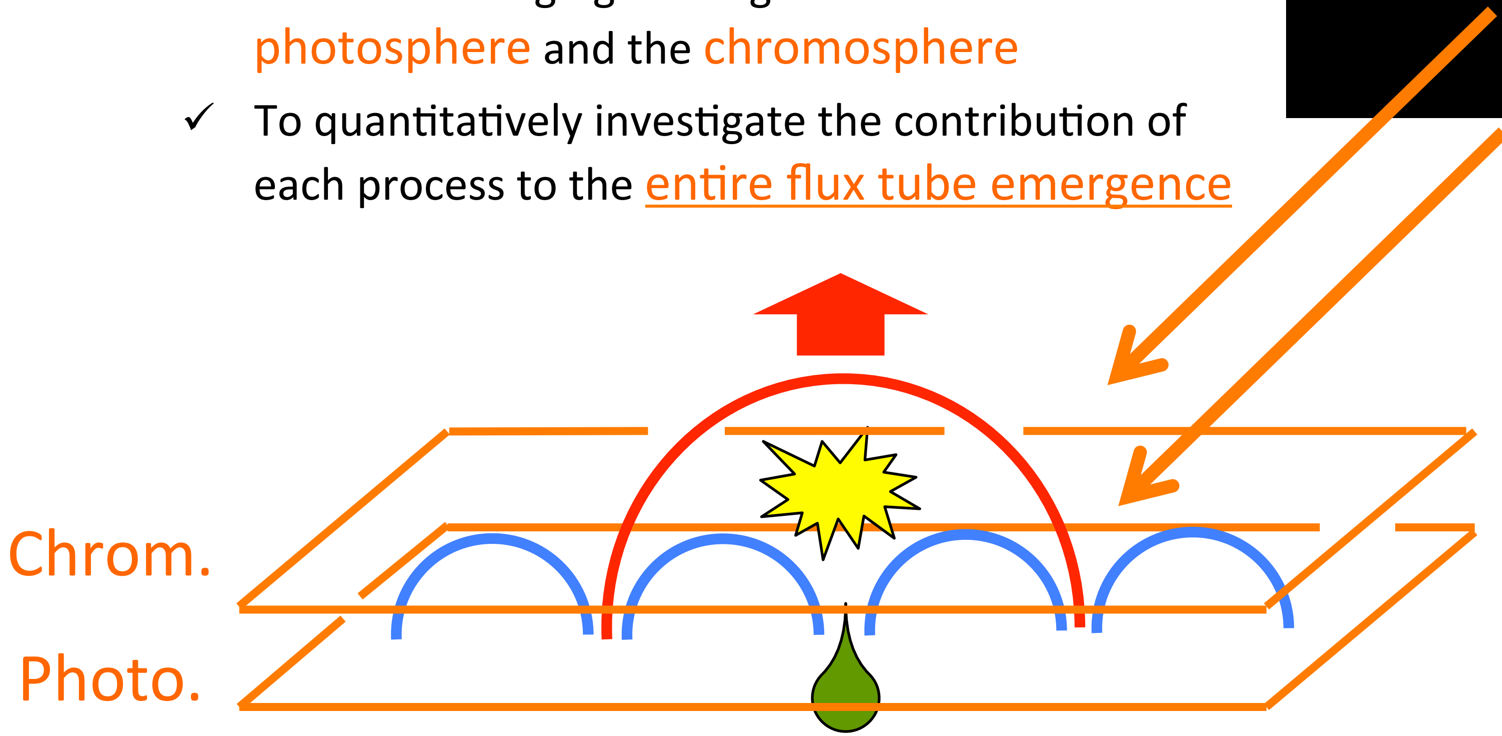


Matsumoto et al. (2010)

3. Birth of Active Regions

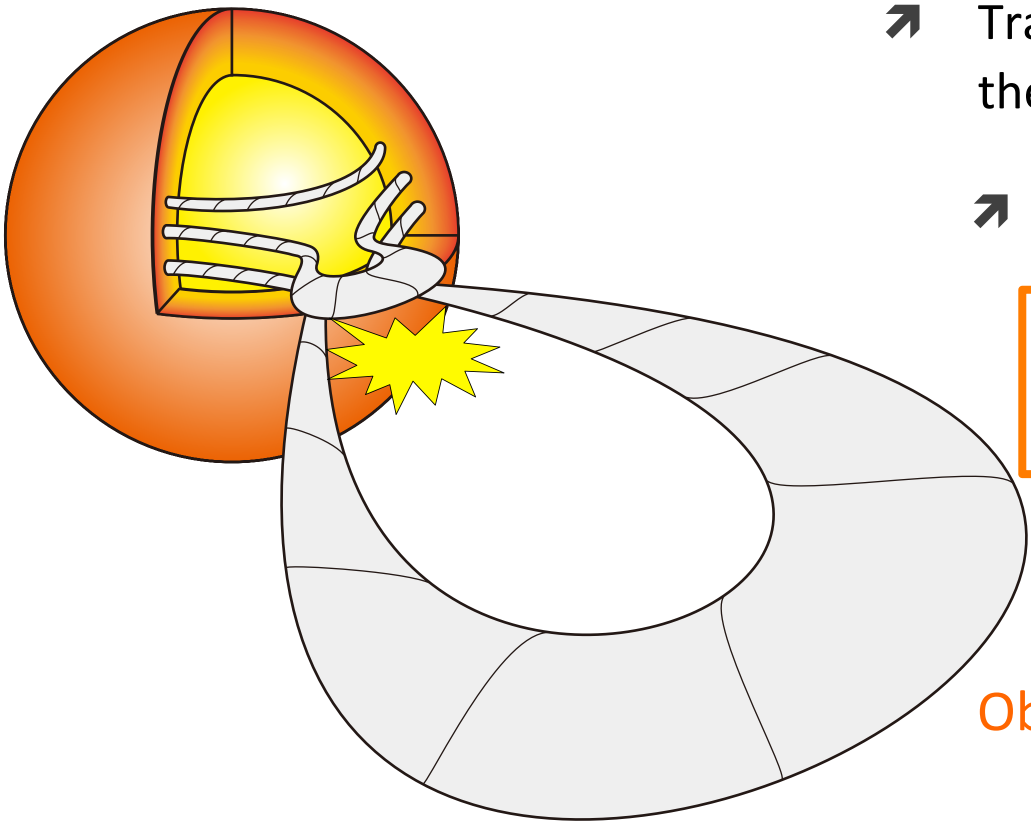
- Resistive Emergence Process
  - Future Observation → Hinode and Solar-C
    - ✓ Spectro-Polarimetry : SOT and SUVIT
    - ✓ Scan the emerging flux region at the photosphere and the chromosphere
    - ✓ To quantitatively investigate the contribution of each process to the entire flux tube emergence





1. Introduction

- Importance of Flux Emergence

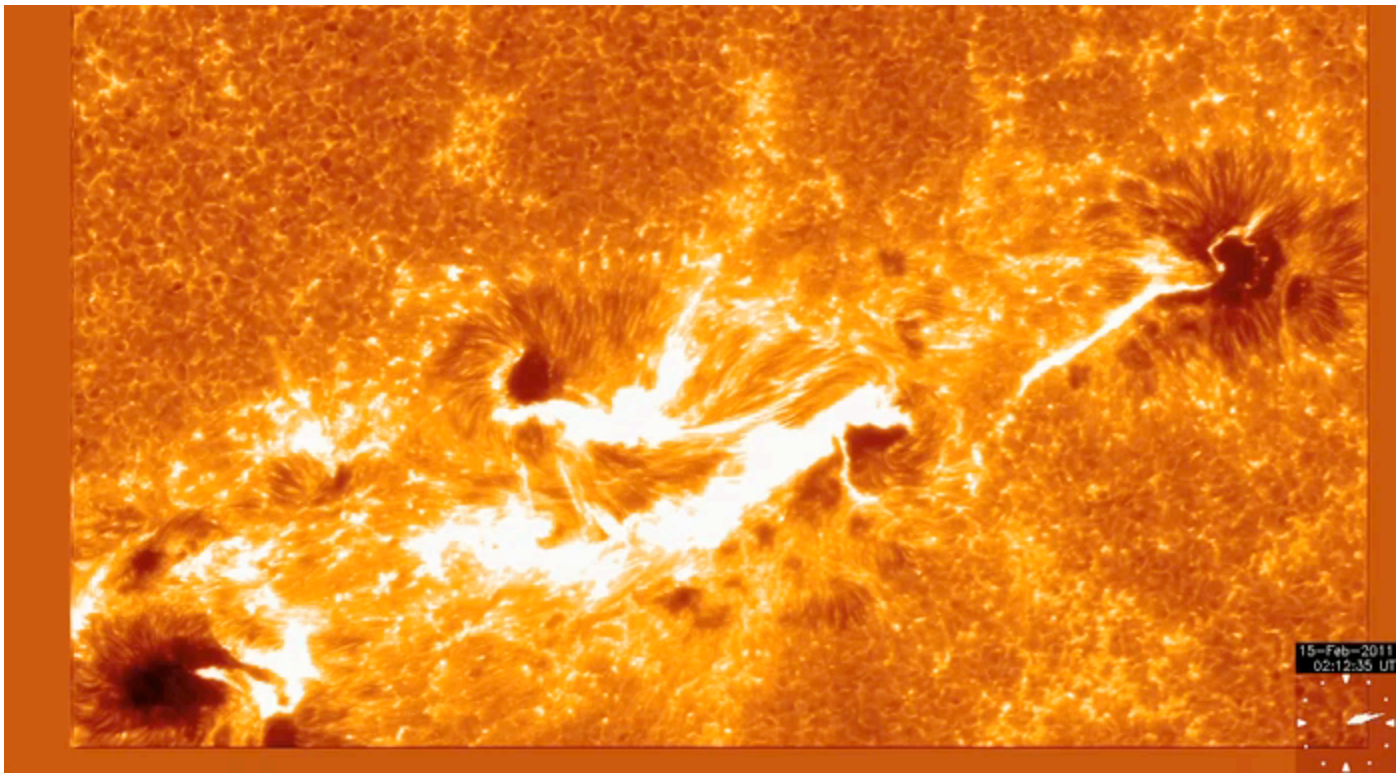


- Transports the magnetic flux from the deep interior
  - Creates active regions
    - Sometimes causes eruptions such as flares and CMEs

Observational and Numerical studies

4. Formation of a Flaring Active Region

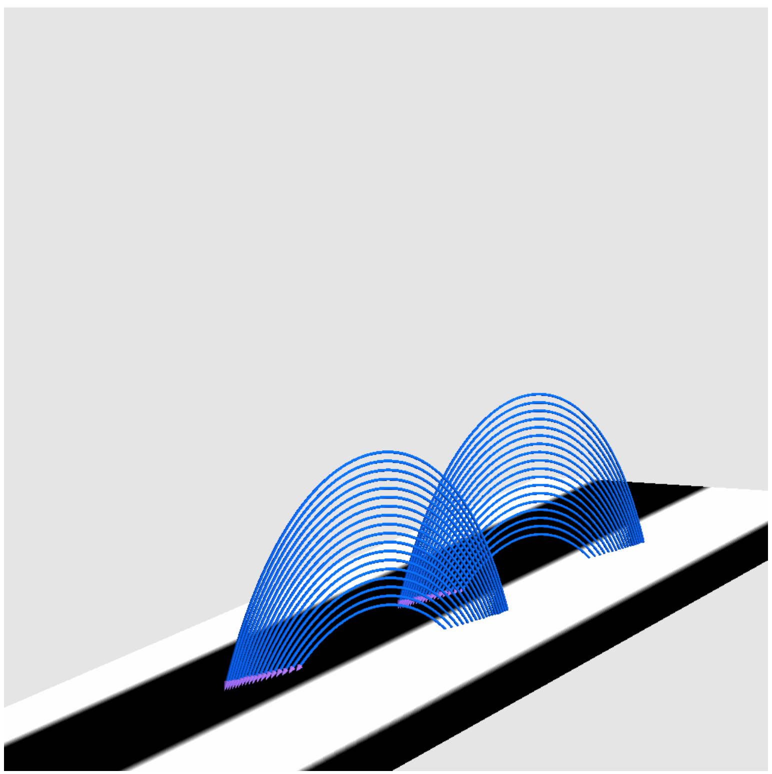
- Flaring AR: NOAA 11158
  - ✓ Produced a series strong flares including X2.2-class event
  - ✓ Highly sheared PIL in the central δ-sunspots



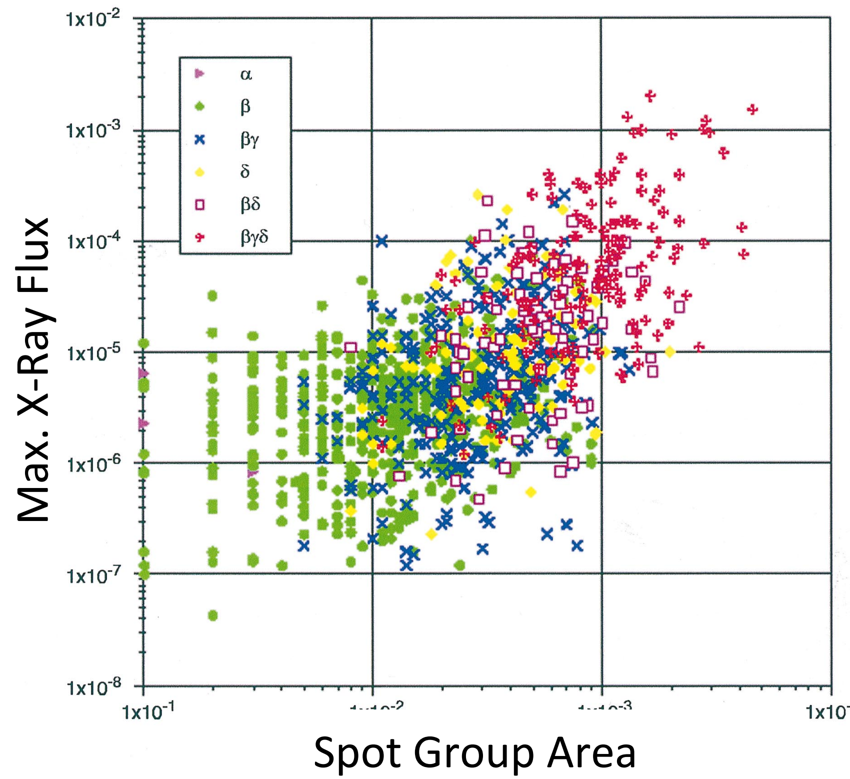
Hinode/SOT : movie courtesy of T. Okamoto

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



4. Formation of a Flaring Active Region

- Previous Studies
  - Kusano et al. (2012)
    - Reconnection between the
  - Sammis et al. (2000)
    - δ-sunspots produce many

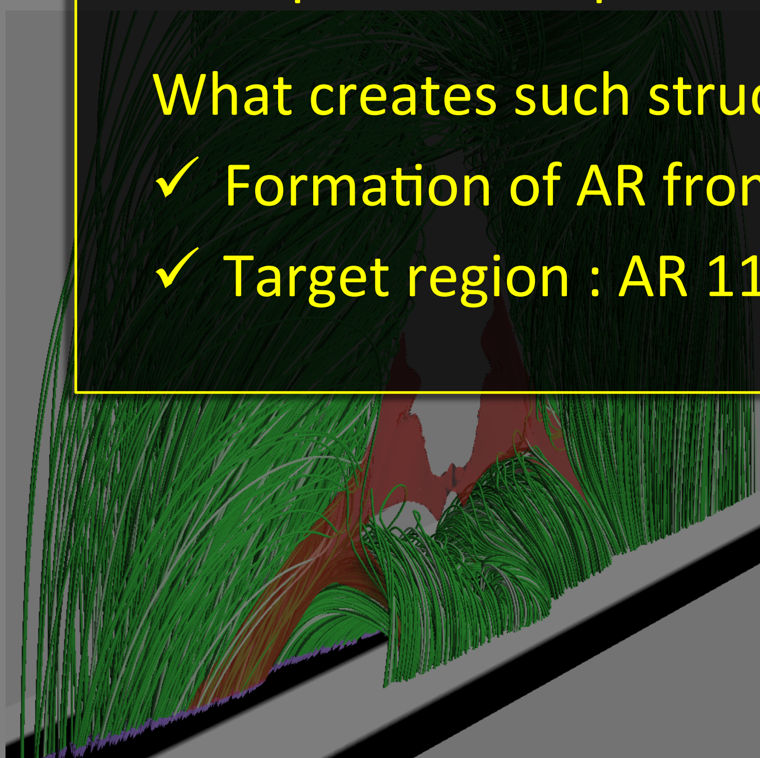
Sheared PIL, coronal arcade, and δ-sunspots

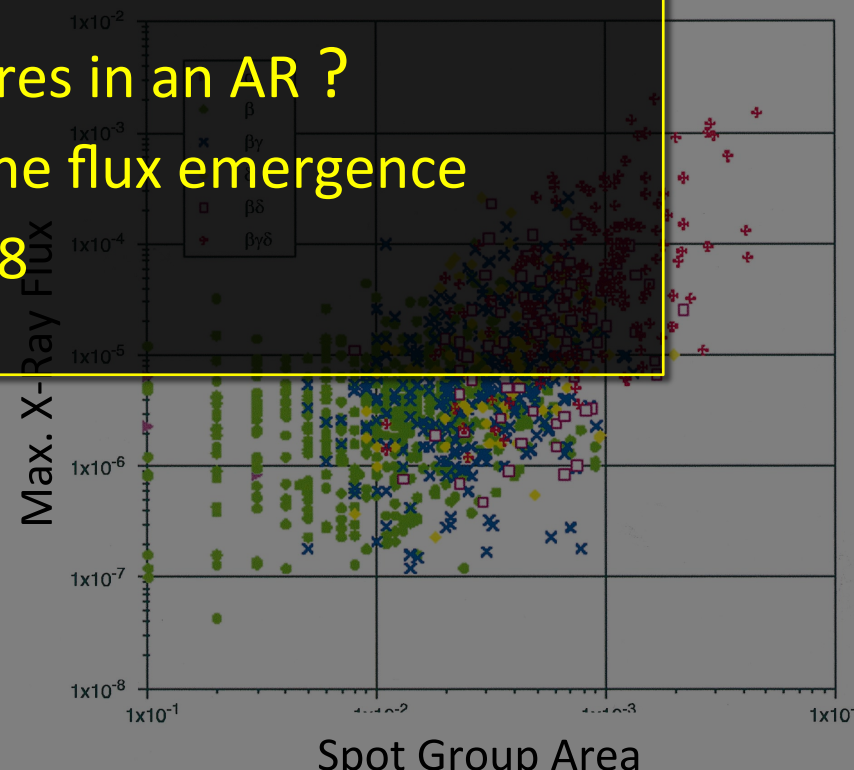
✓ Important for production of intensive flares

What creates such structures in an AR ?

✓ Formation of AR from the flux emergence

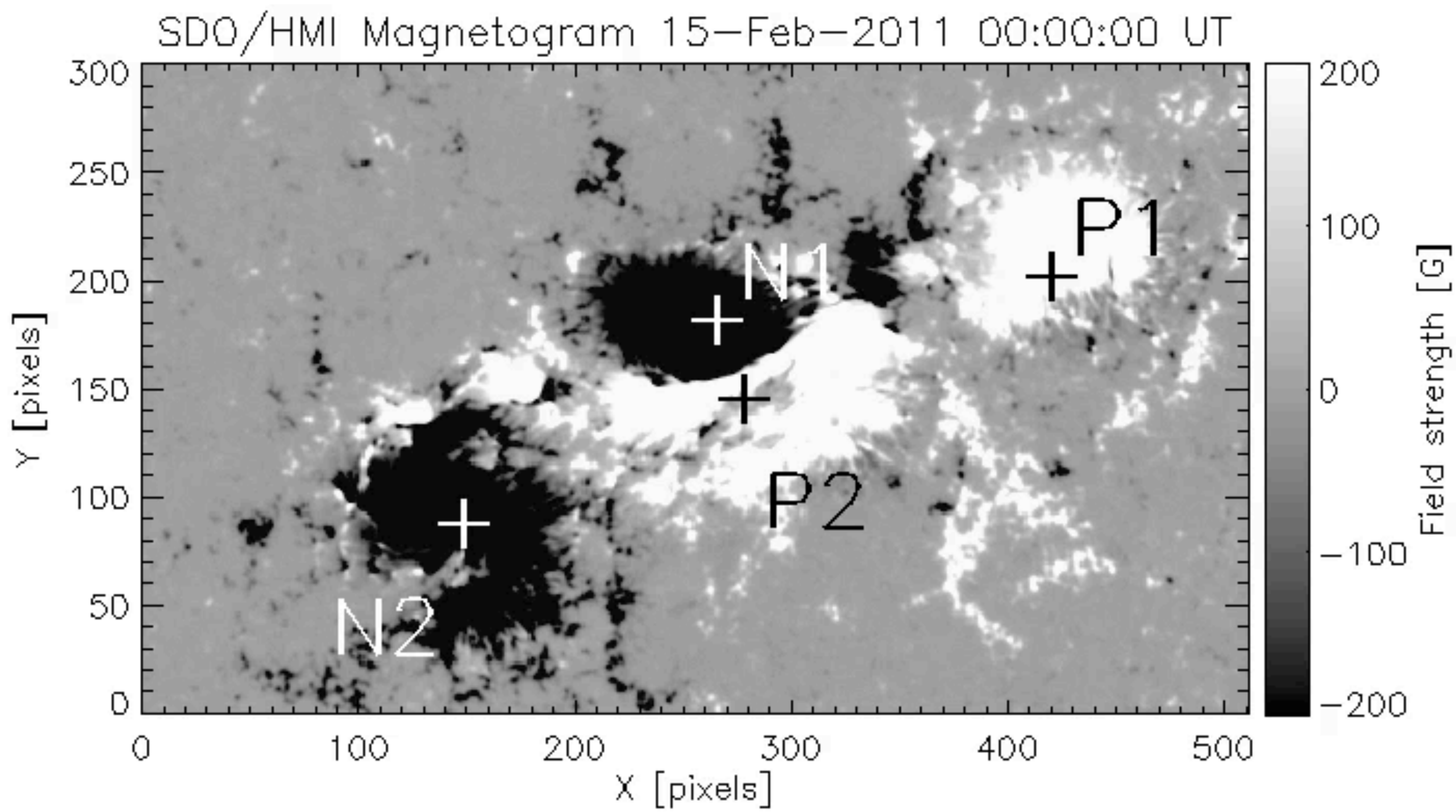
✓ Target region : AR 11158





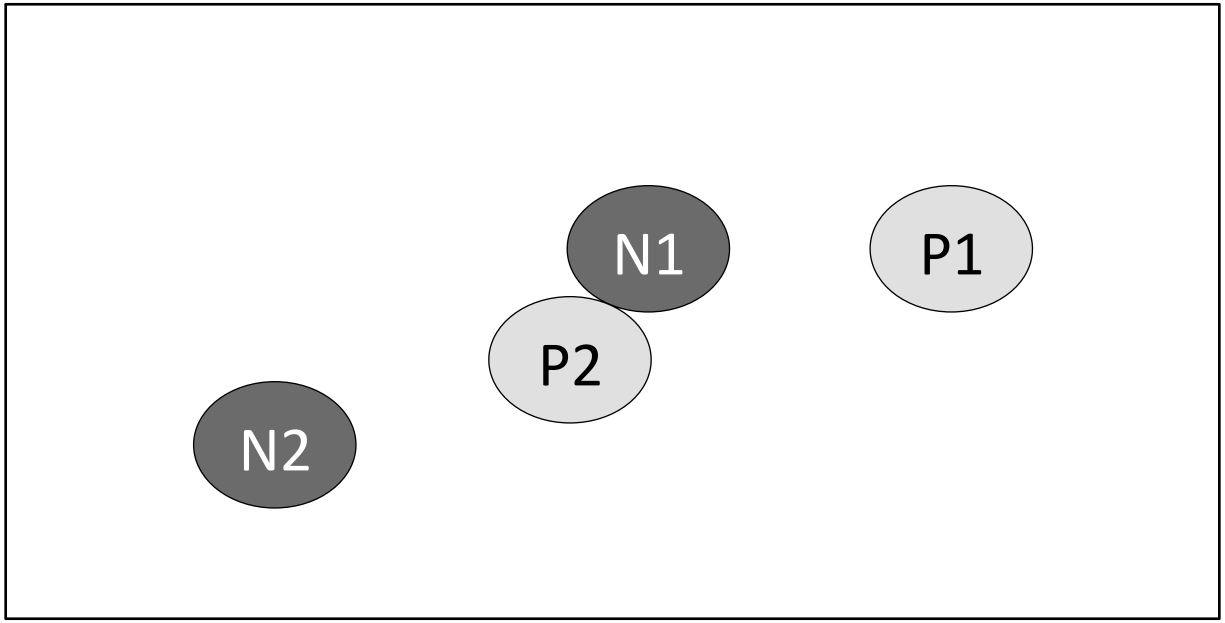
4. Formation of a Flaring Active Region

- 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



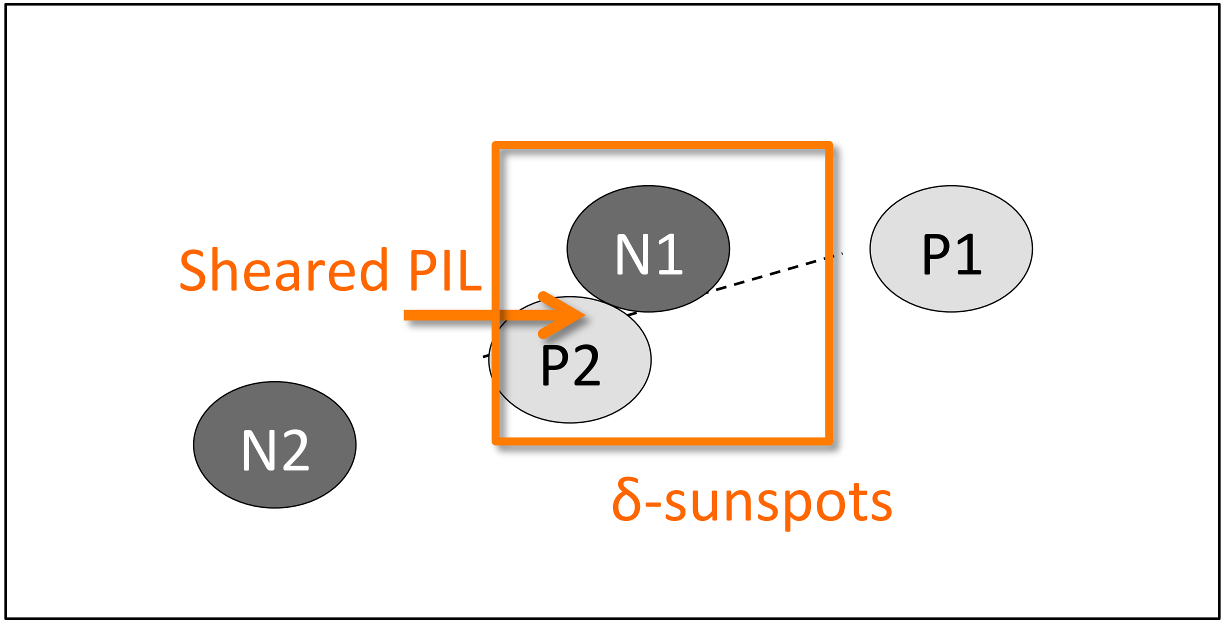
4. Formation of a Flaring Active Region

- Photospheric Evolution
  1. P1-N1 / P2-N2 appear at the surface



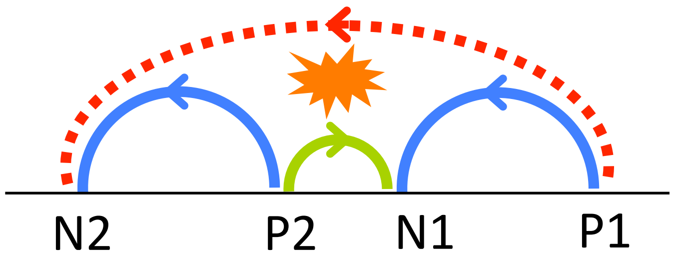
4. Formation of a Flaring Active Region

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

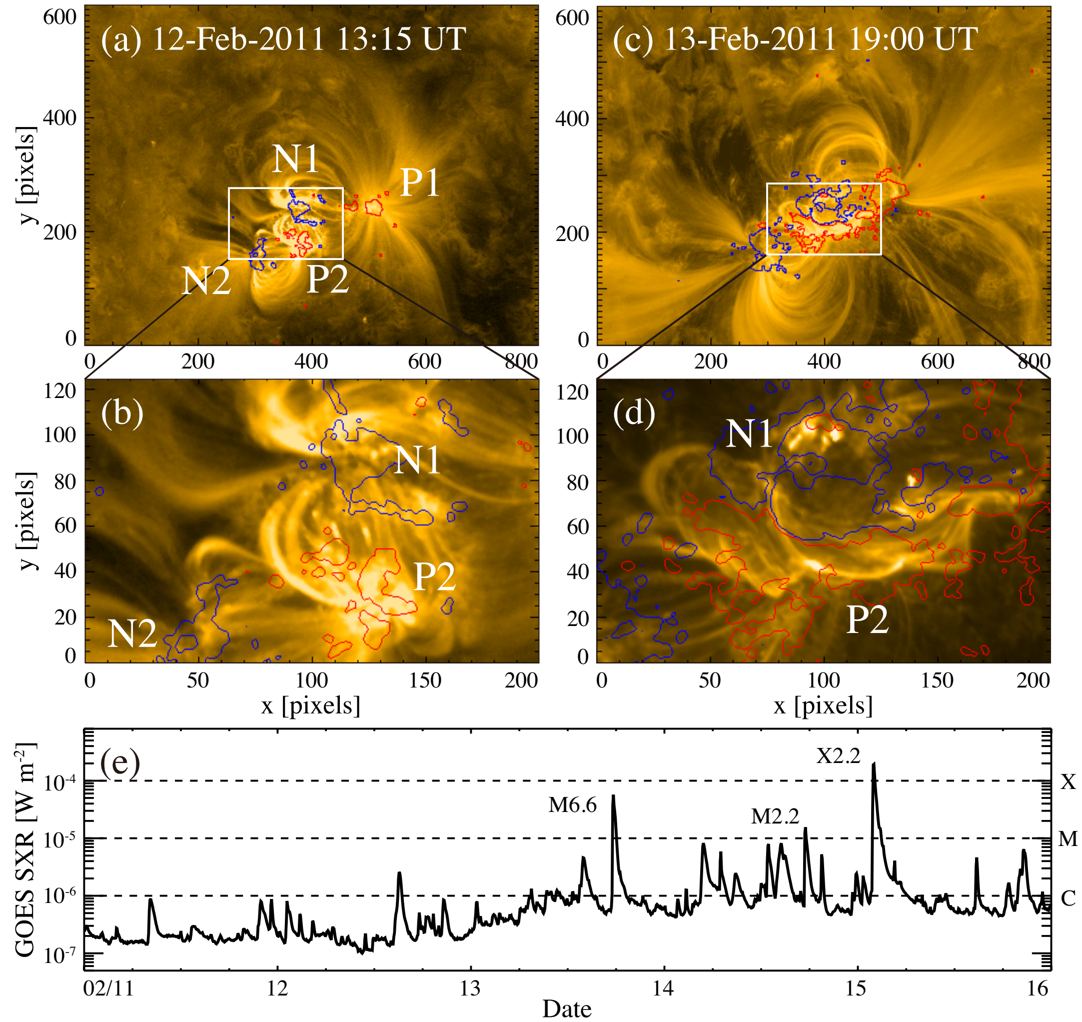


4. Formation of a Flaring Active Region

- 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

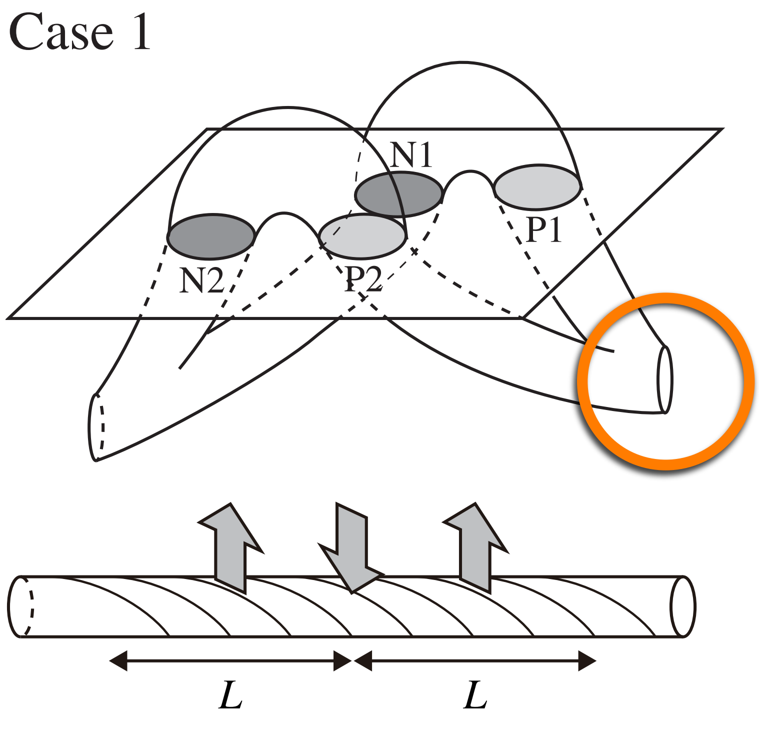


SDO/AIA 171Å

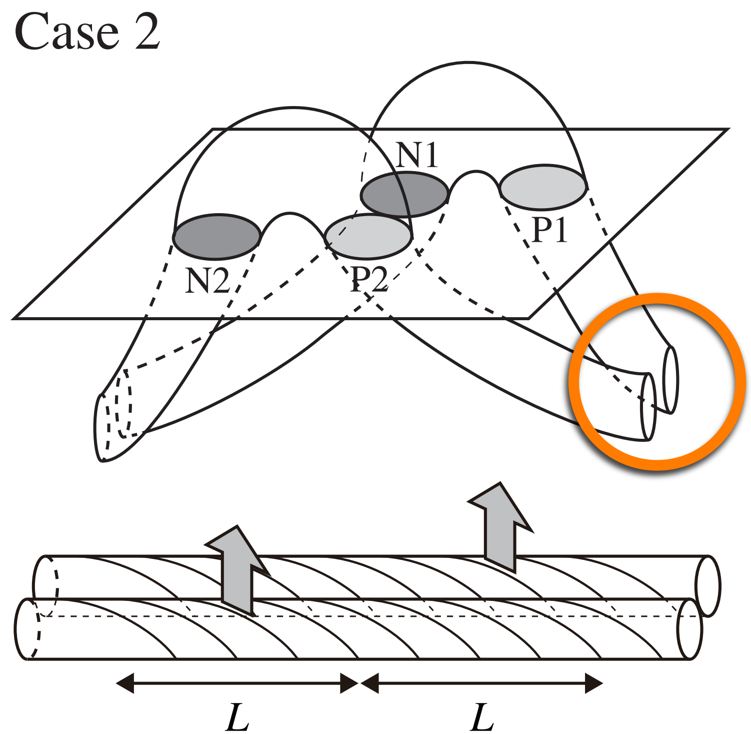


4. Formation of a Flaring Active Region

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



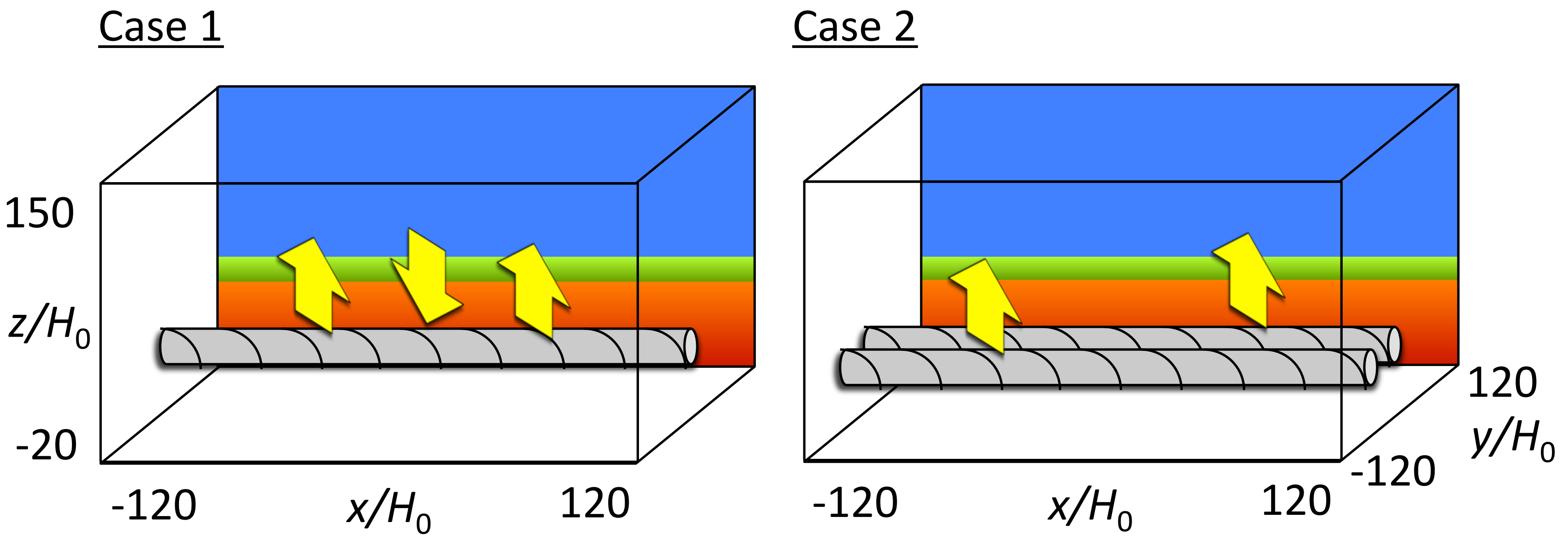
Emergence of a single split tube



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



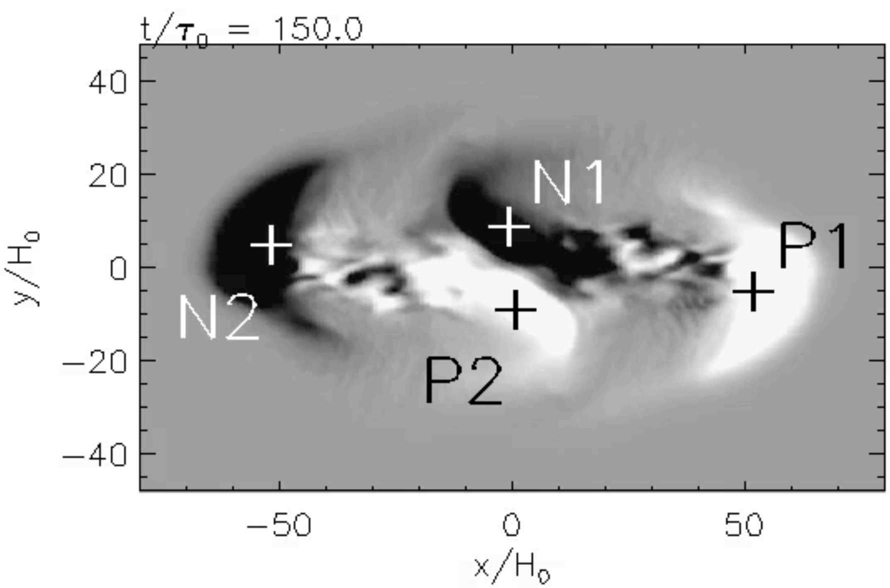
Mimic the splitting by sinking the middle part

- Length: H_0 = 200 km
- Time: τ_0 = 25 s
- Field strength: B_0 = 300 G

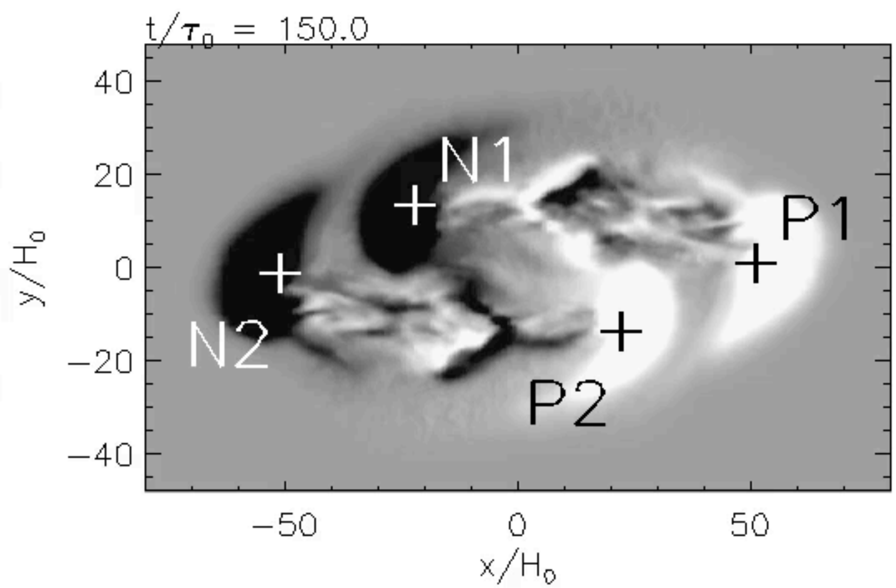
4. Formation of a Flaring Active Region

- Formation of AR 11158
  - Results: Magnetogram

Case 1 : single split tube



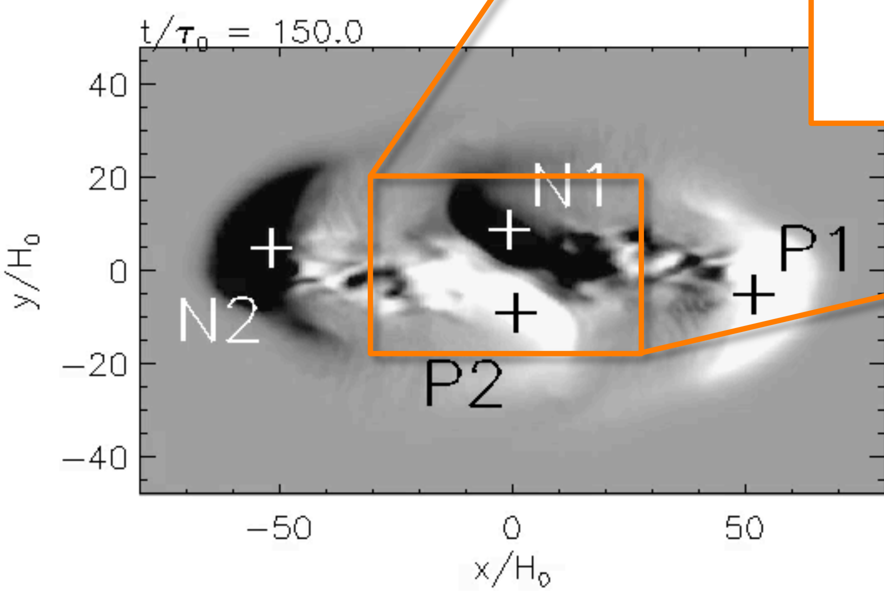
Case 2 : two independent tubes



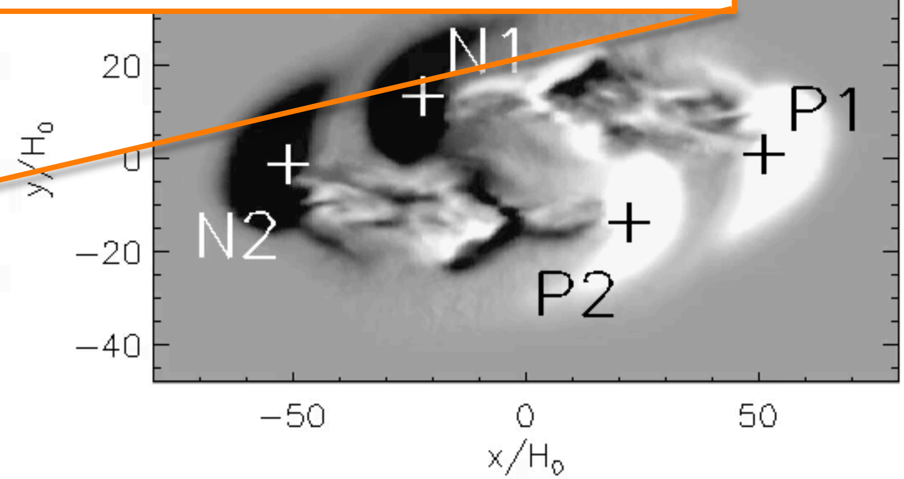
4. Formation of a Flari

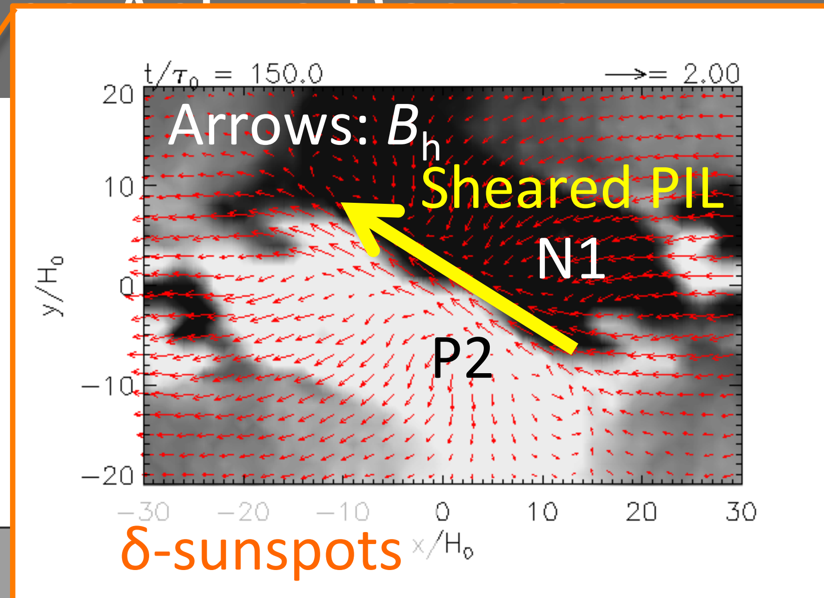
- Formation of AR 11158
  - Results: Magnetogram

<u>Case 1 : single split tube</u>



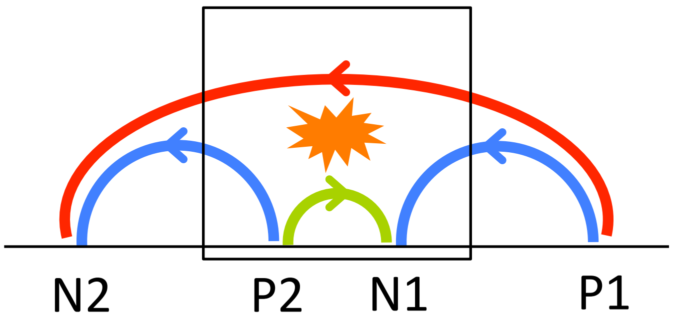
<u>ubes</u>



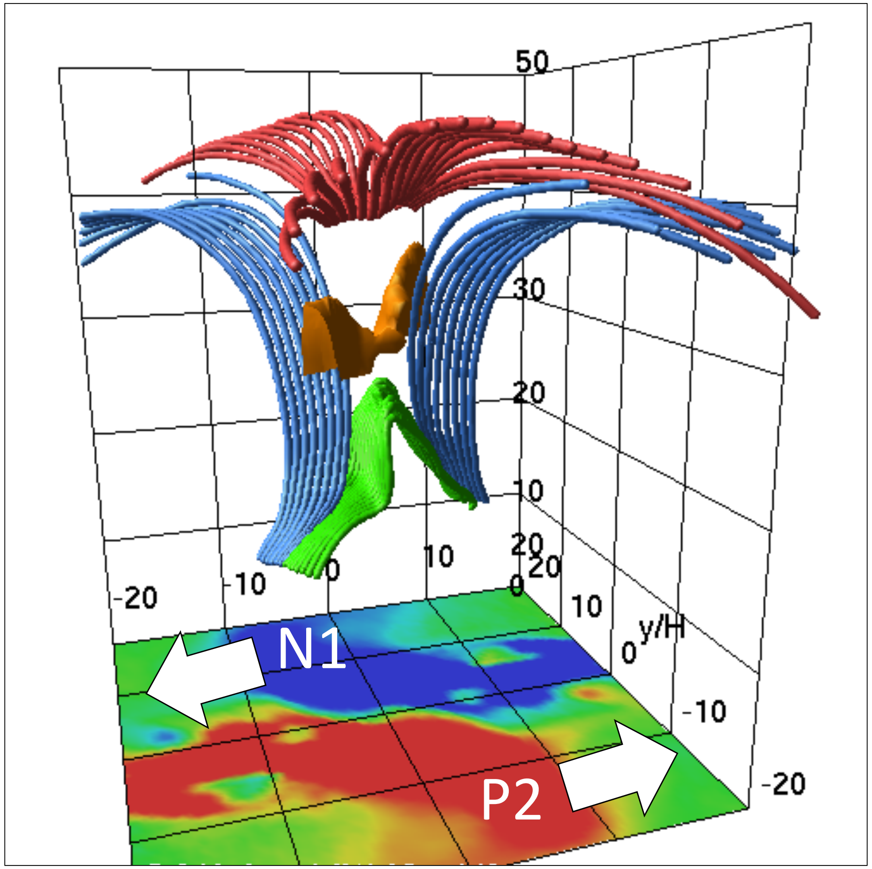


4. Formation of a Flaring Active Region

- 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.

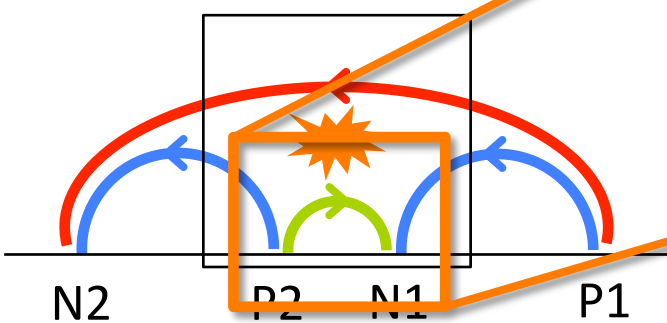


Case 1 (t/τ_0 = 120)

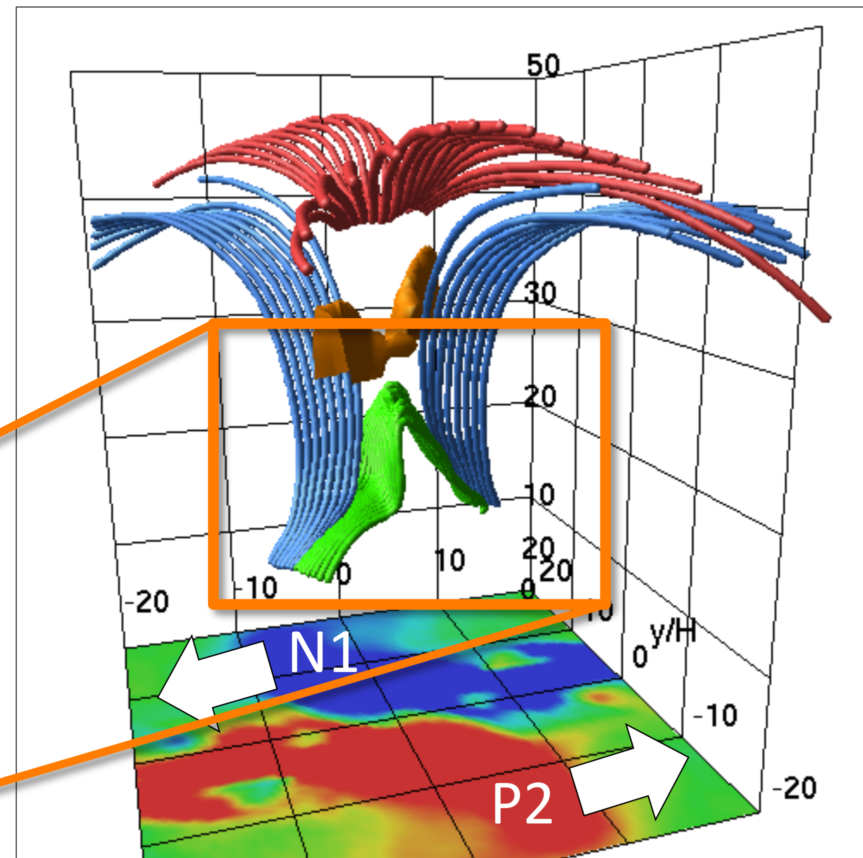


4. Formation of a Flaring Active Region

- 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.

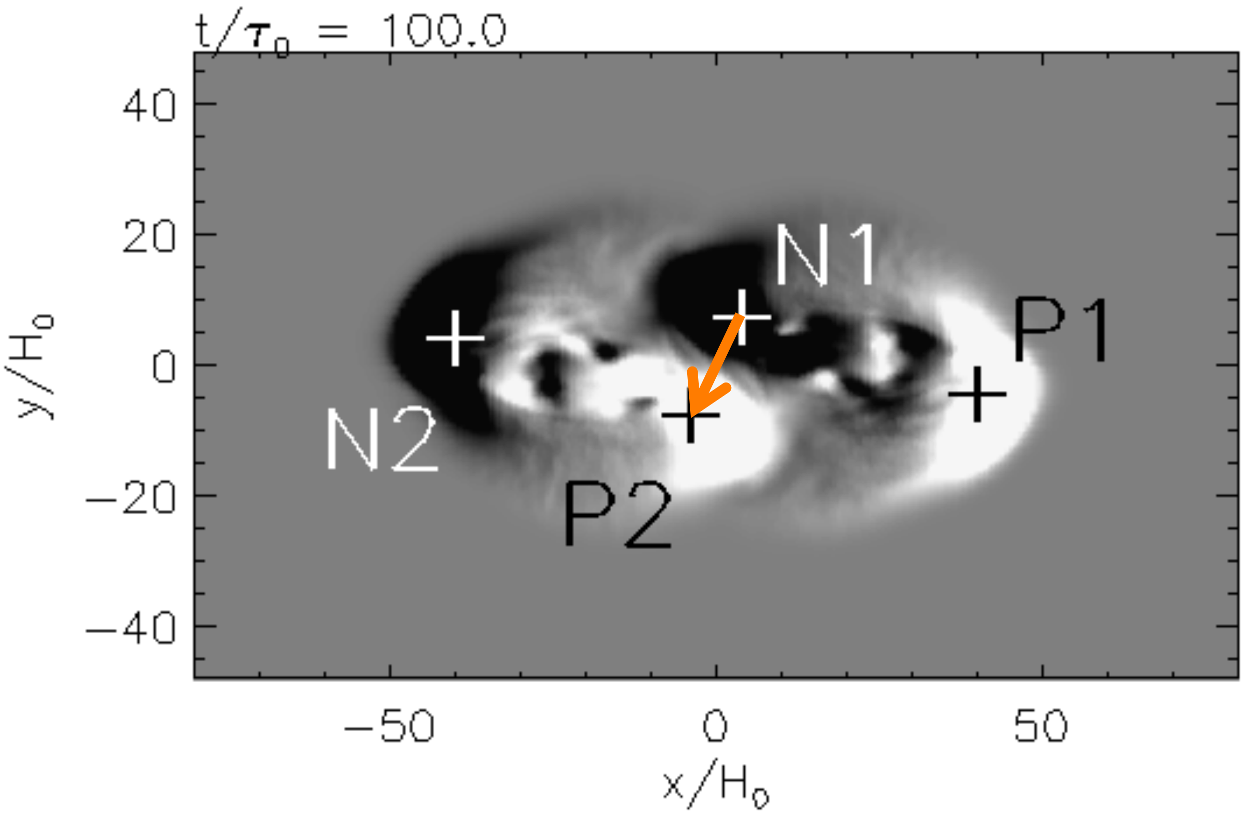


Case 1 (t/τ_0 = 120)



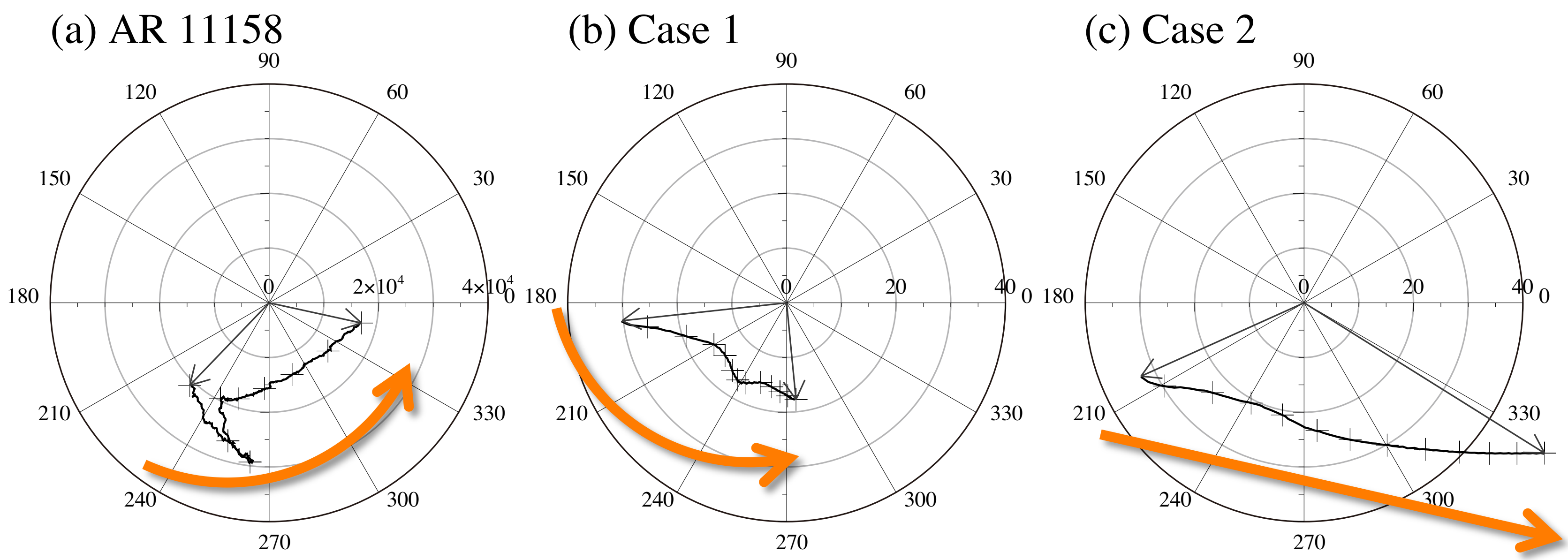
4. Formation of a Flaring Active Region

- 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

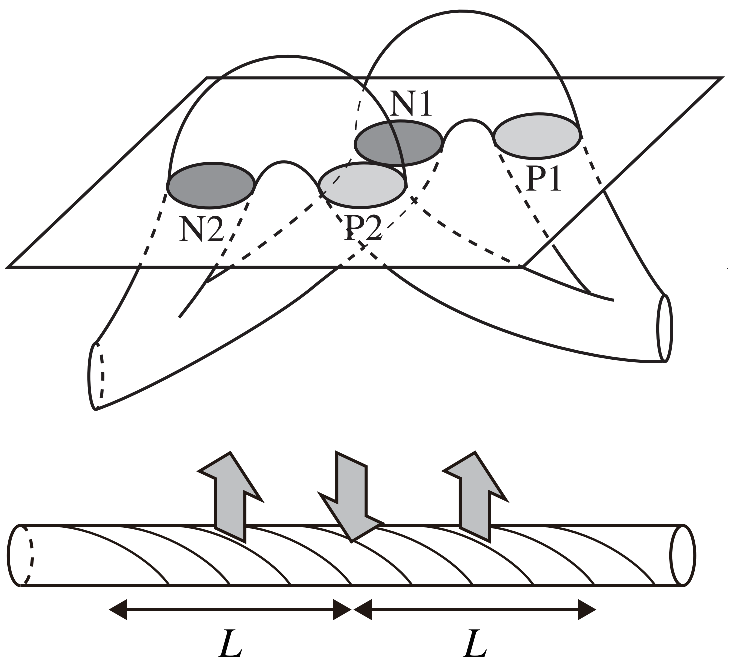


- In AR 11158, N1→P2 vector rotates and the length becomes shorter.
- Only Case 1 shows a similar trend. In Case 2, N1 and P2 simply fly by.

4. Formation of a Flaring Active Region

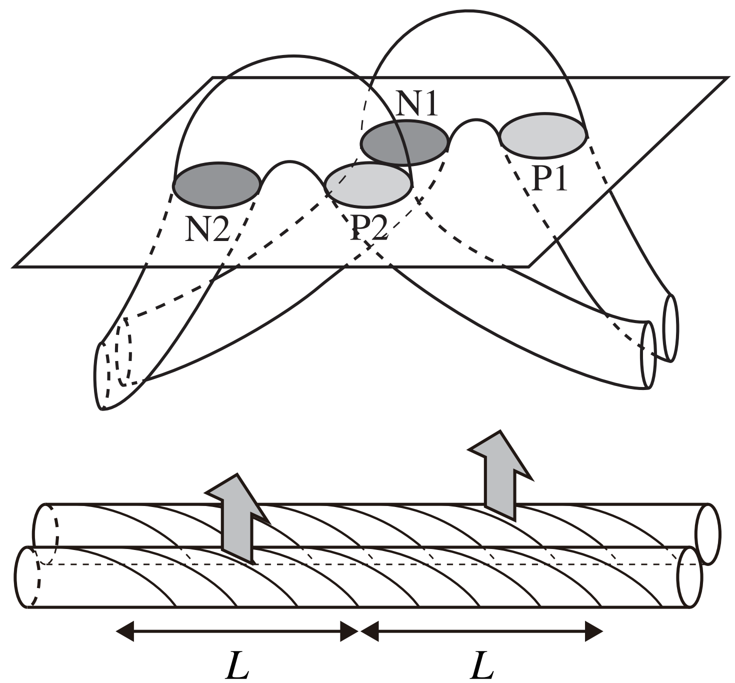
- Formation of AR 11158
  - Conclusion: Case 1 is more likely the case

Case 1



Emergence of a single split tube

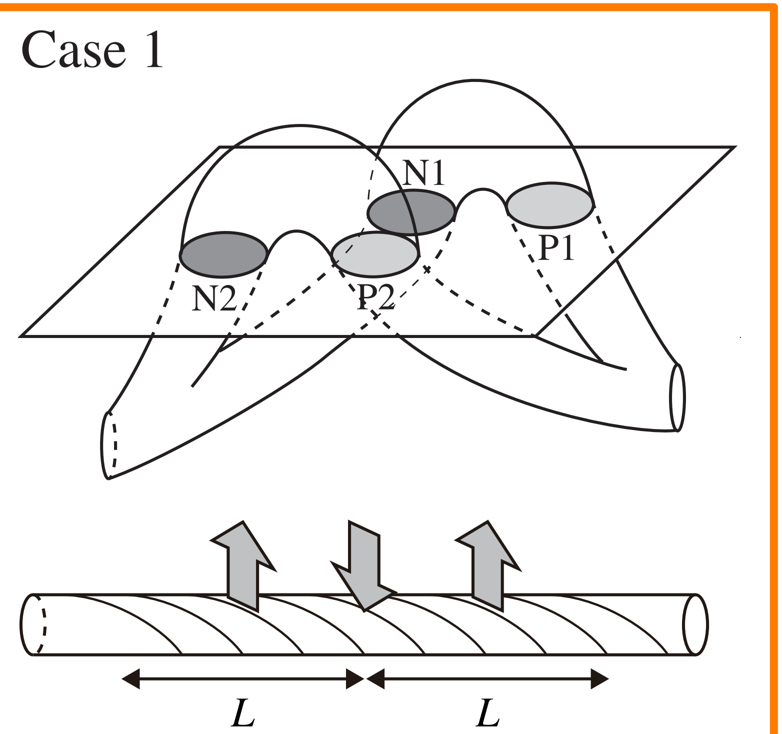
Case 2



Emergence of two independent tubes

4. Formation of a Flaring Active Region

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



Emergence of a single split tube

- ✓ 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

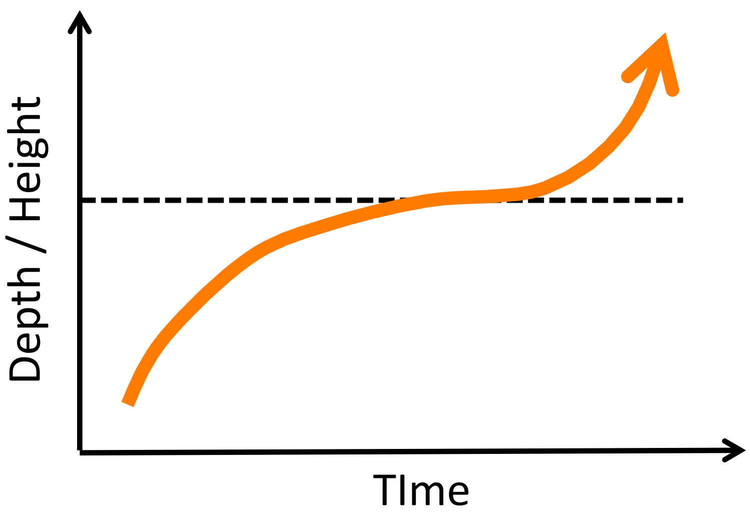
  which is responsible for the flares

- ✓ 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!