Characteristic Dependence of Umbral Dots on their Magnetic Structure

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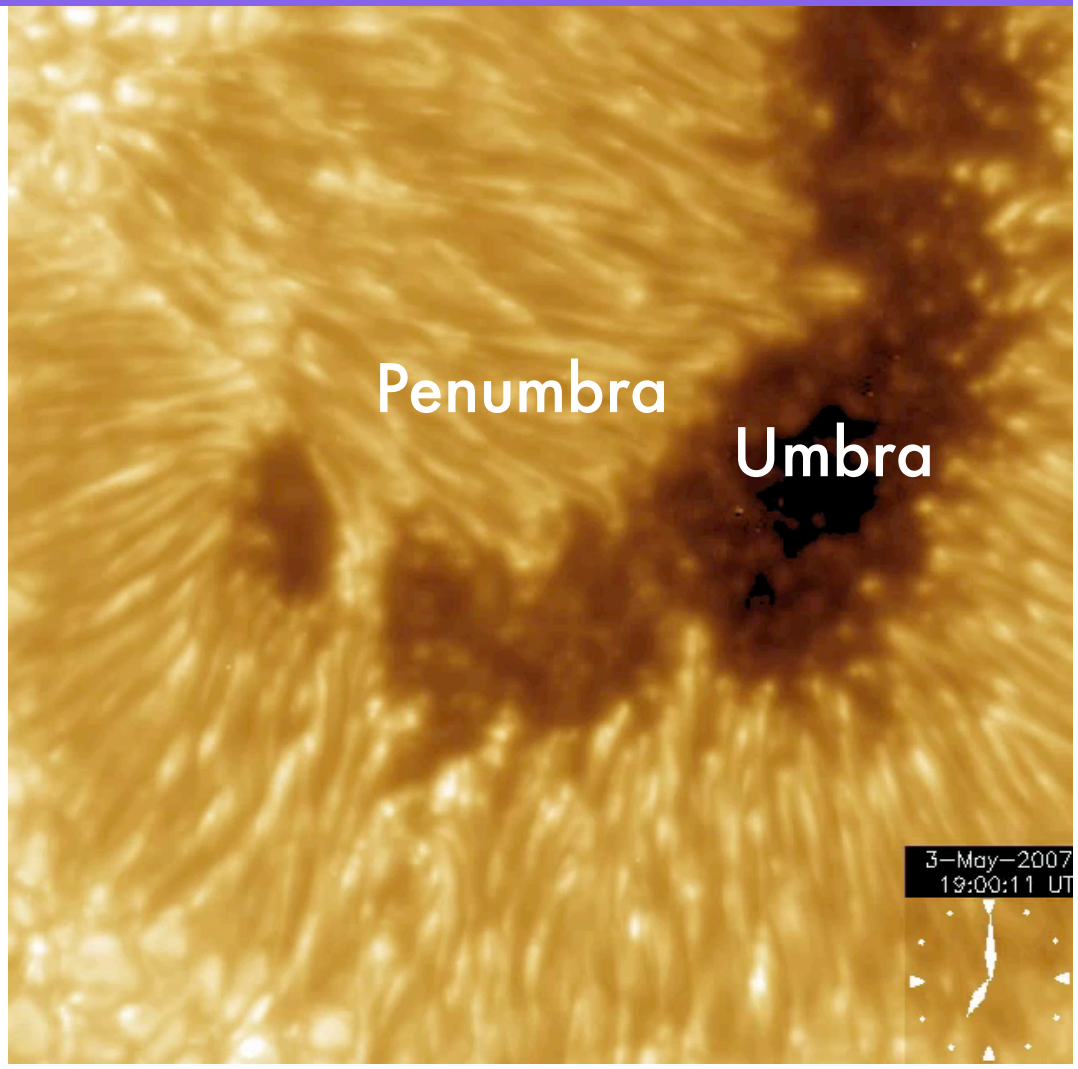
Introduction

- Umbral dot (UD)

Size	~300 km
Lifetime	5-40 min typically 10 min
Proper motion	peripheral: 0.5-1 km/s umbra inward central: almost static
Field strength	2000-2500 Gauss ~40 Gauss weaker
Doppler velocity	upflow 30 - 100 m/s



Hinode SOT G-band Courtesy to T.J.Okamoto

Background

- Observation
- Theory

Observation		Theory
The brightness of umbra is 5%-20% of I_{quiet}	⇔	The convection is suppressed by magnetic field
Field strength of umbra is at most 3500Gauss	⇔	If the convection is suppressed entirely, the umbra should have > 5000Gauss
umbral dot ~500K hotter than umbra	⇔	Magnetoconvection should take place

Danielson (1964), ApJ, 139, 45

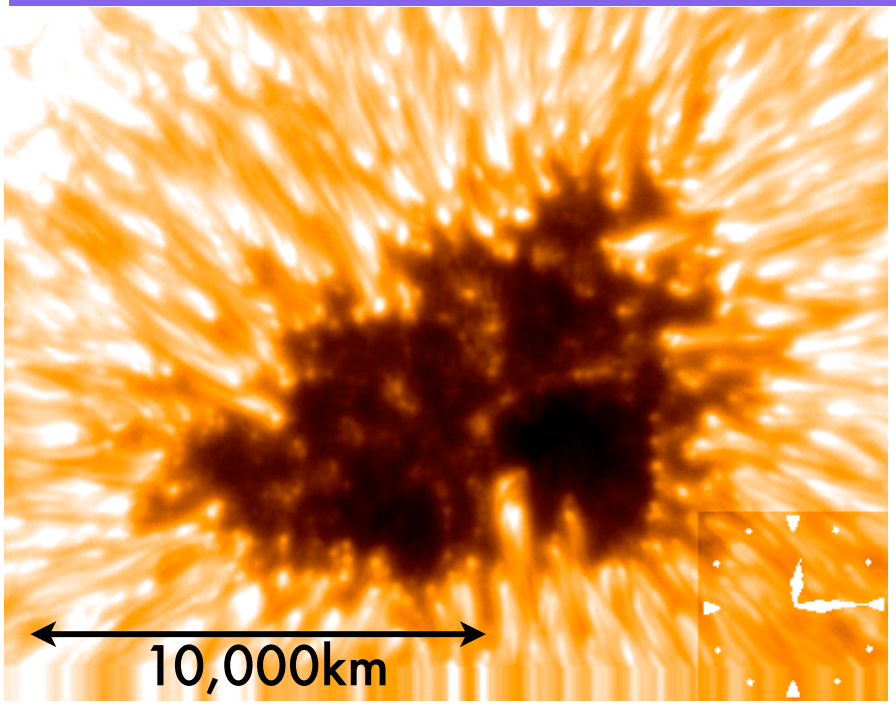
Deinzer (1965), ApJ, 141, 548

Motivation

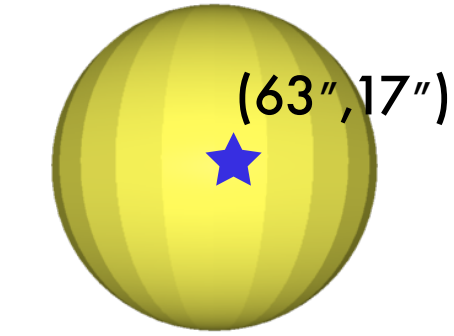
- **High- resolution data obtained by the *Hinode* satellite**
- **Magnetoconvection origin**
  - size, lifetime, proper motion, ...
  - magnetic field, field inclination
  - correlation between magnetic field and UD
- **Comparison with 3D MHD simulations**
  - structure of sunspot
  - energy transport in sunspot

applicable to the physics in accretion disk, low T stars, ...

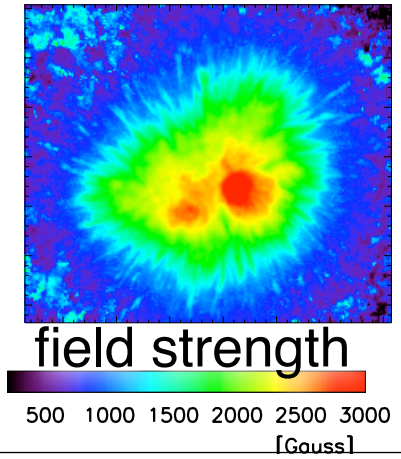
Data

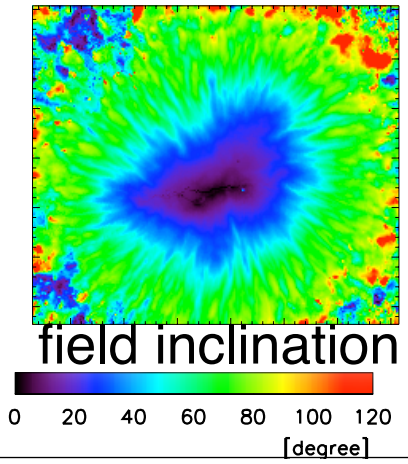


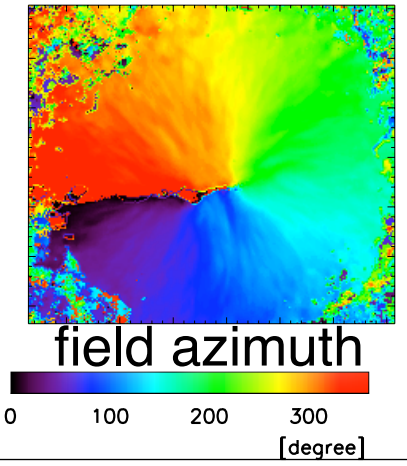
- *Hinode* Solar Optical Telescope
- March 1, 2007
- imaging: blue continuum
  - 25s cadence, 2 hrs duration
  - spatial resolution 0.054″(40km)
- spectropolarimeter: Fe I 6302Å
  - 15 min to scan 20000km area
  - spatial resolution 0.16″(100km)



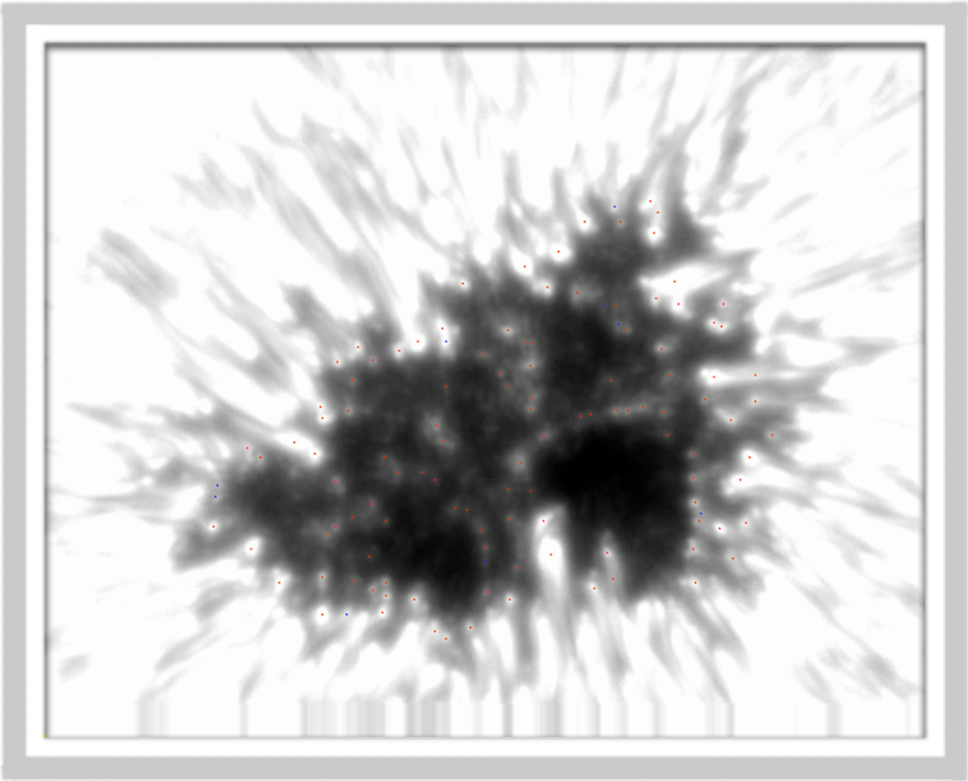
Position of the target







Analysis

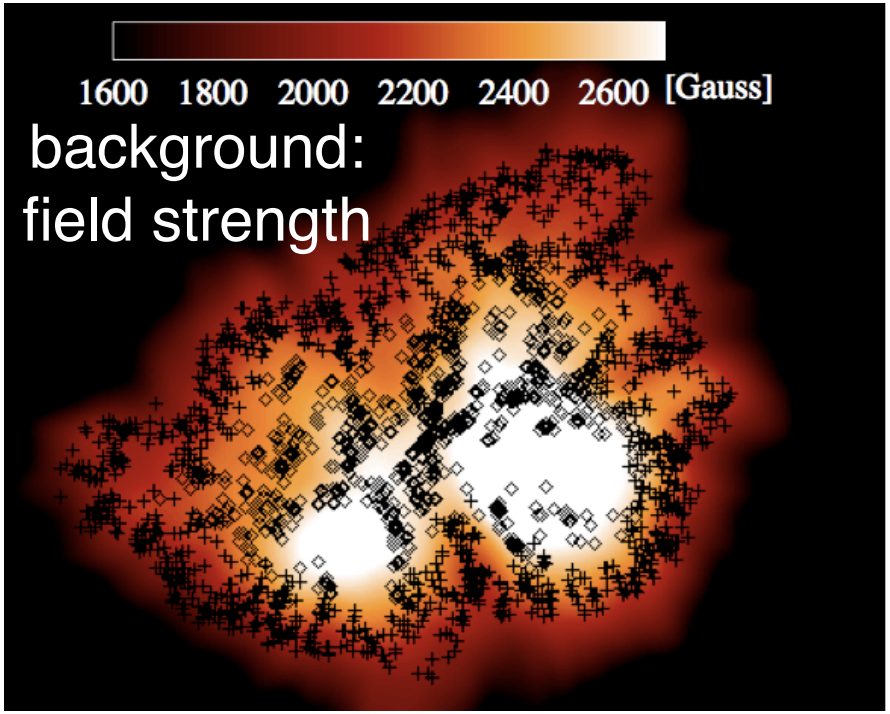


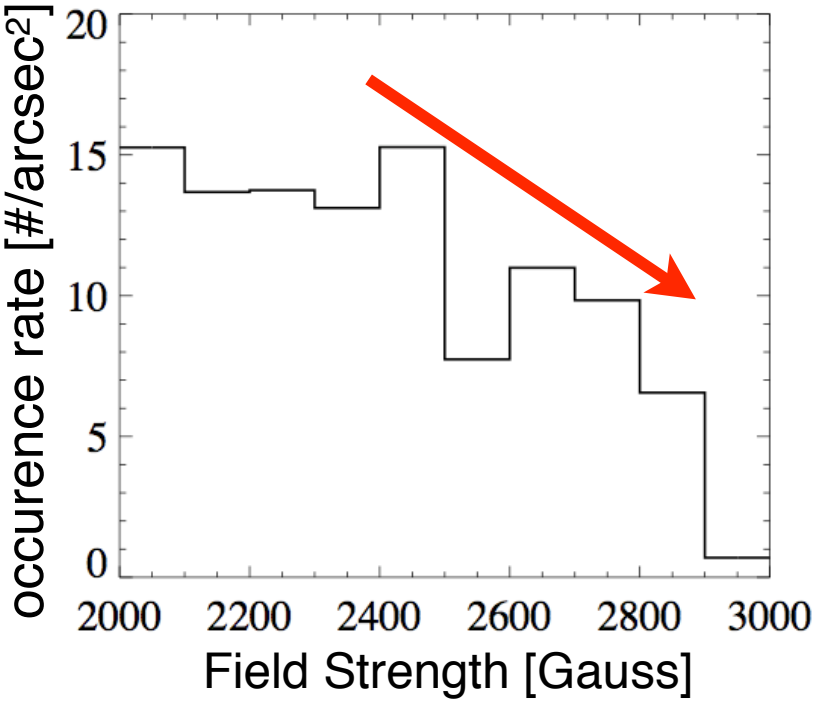
- Automatic detection
  - peak position with $I_{peak}>1.3\times I_{bg}$
  - The continuation between successive frames

- Total amount of UDs is 2268
  (average 124 per frame)
- UD parameters
  - lifetime
  - size
  - brightness ratio
    (I_{peak} / $I_{background}$)
  - average speed
  - velocity orientation

Result 1/4

- Spatial distribution
  - Fewer UDs in stronger fields⇒ Suppression of convection
  - Cellular patterns⇒ reflect the global substructure?



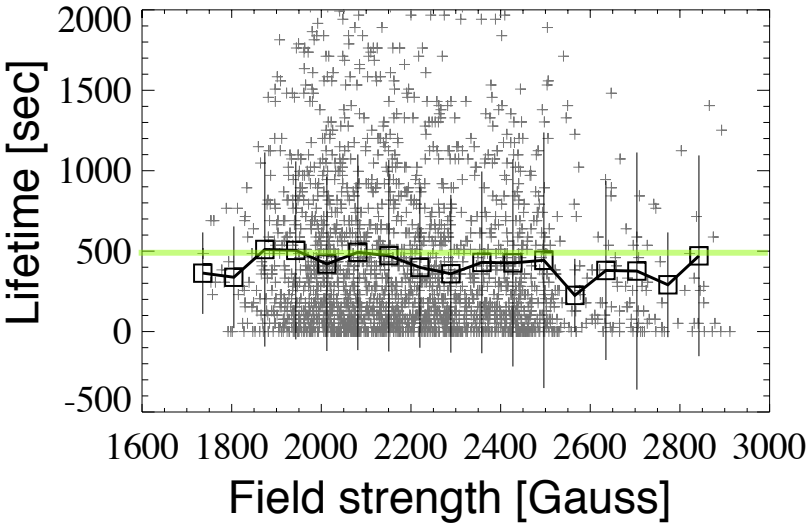


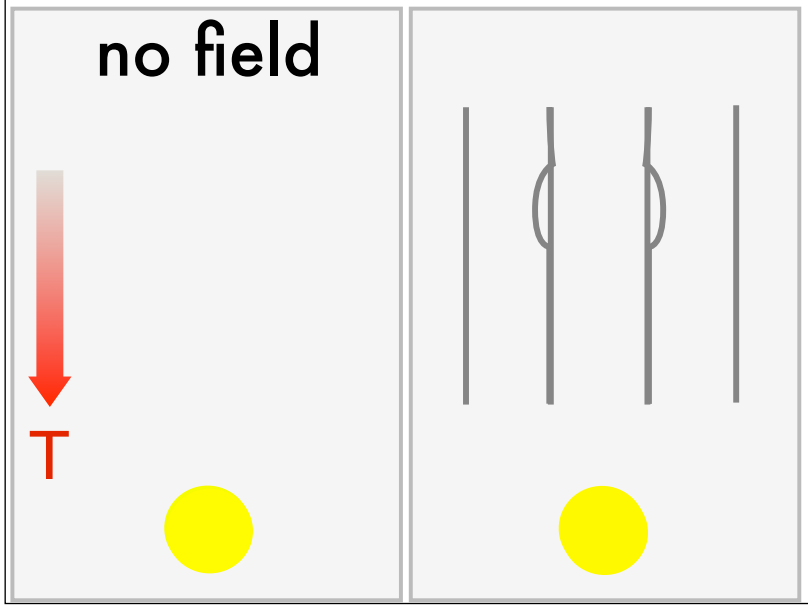
Result 2/4

- Correlations
  - lifetime

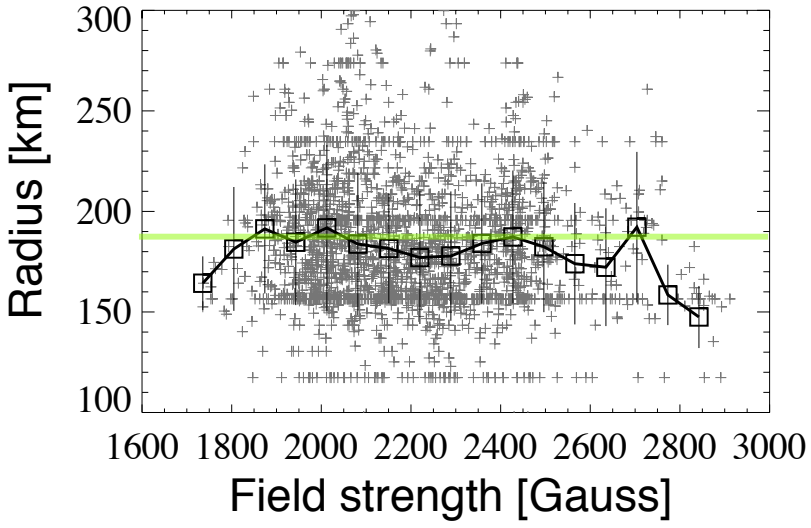
    almost constant
  - size

    almost constant
    smaller in strong field (?)



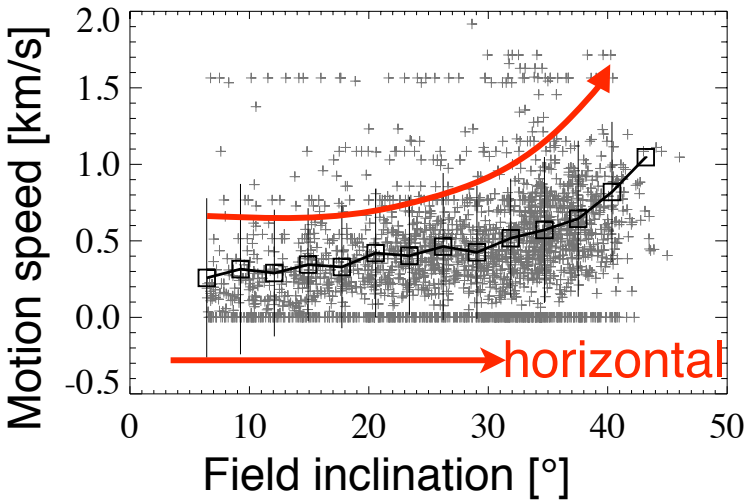


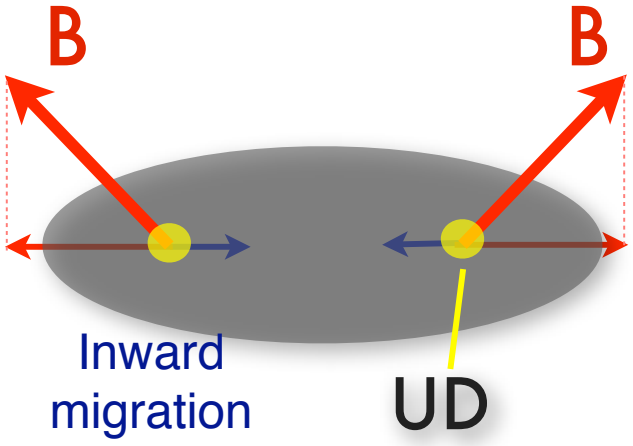
buoyancy and size are inversely correlated to ***B***

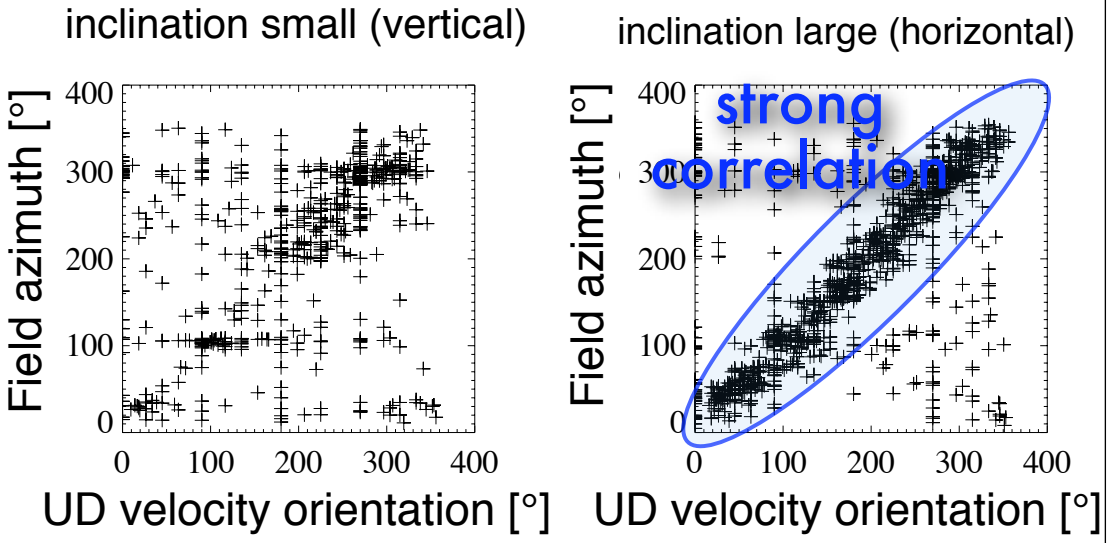


Result 3/4

- Velocity analysis
  - speed…faster in more inclined field regions
  - orientation
    - horizontal ***B*** toward center
    - vertical ***B*** weak correlation

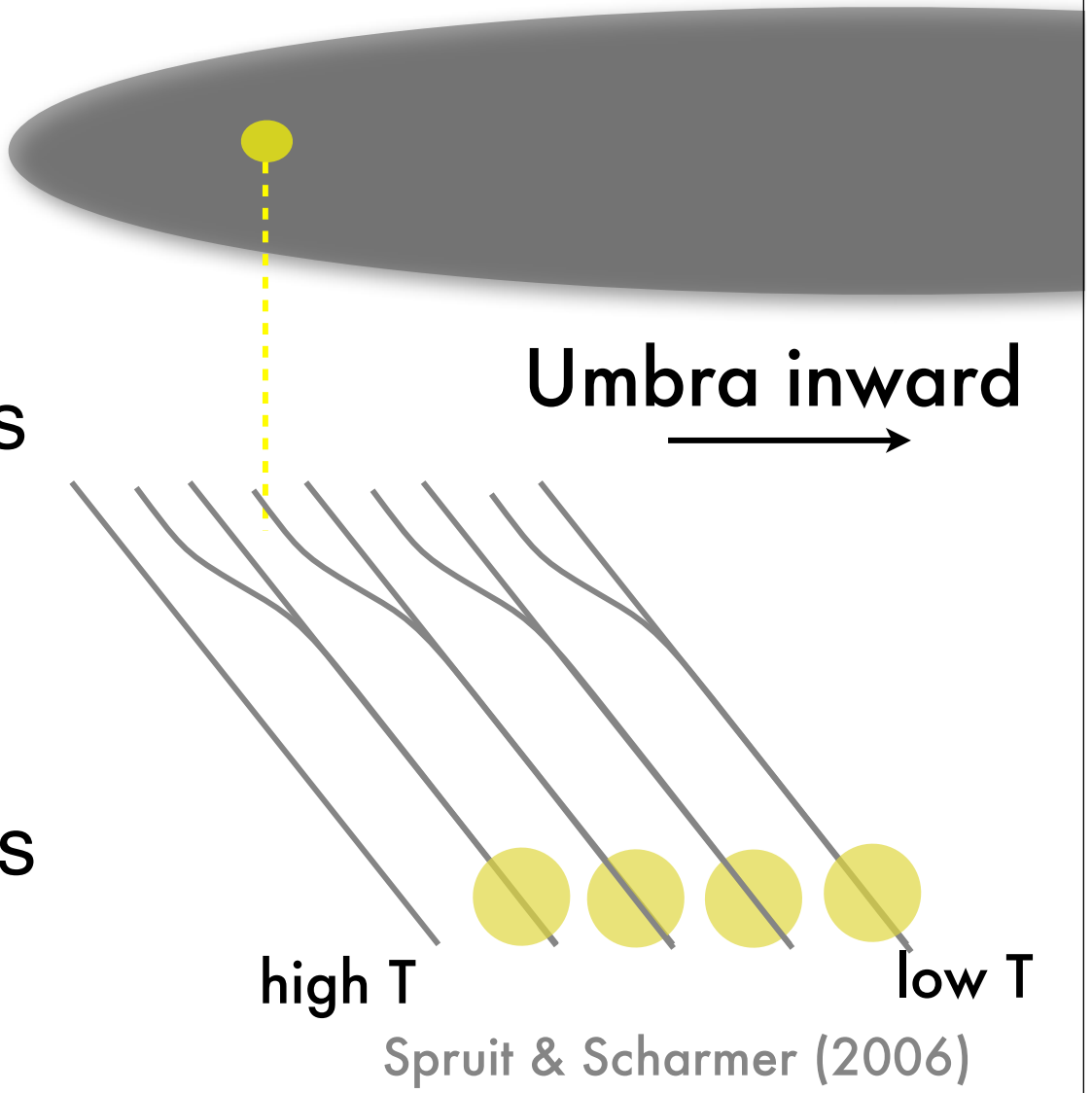






Inward migration

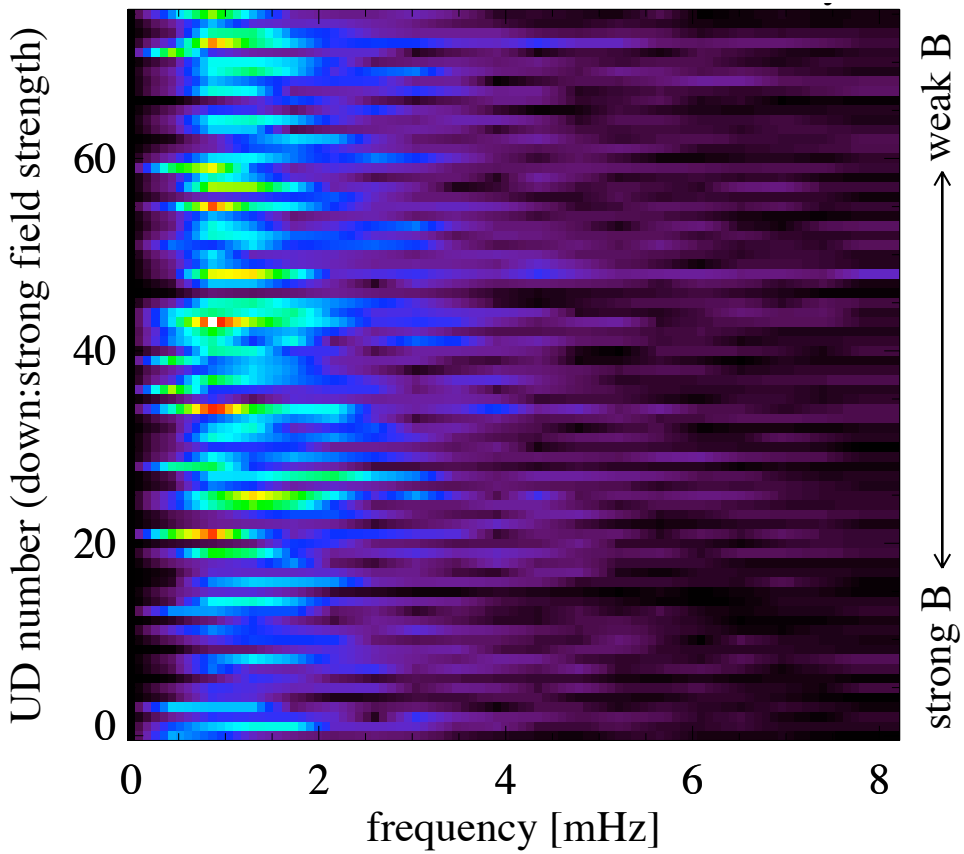
1. ascending, cooling
2. bending of field lines
3. a reduction of ***B***
4. ascending of hot gas

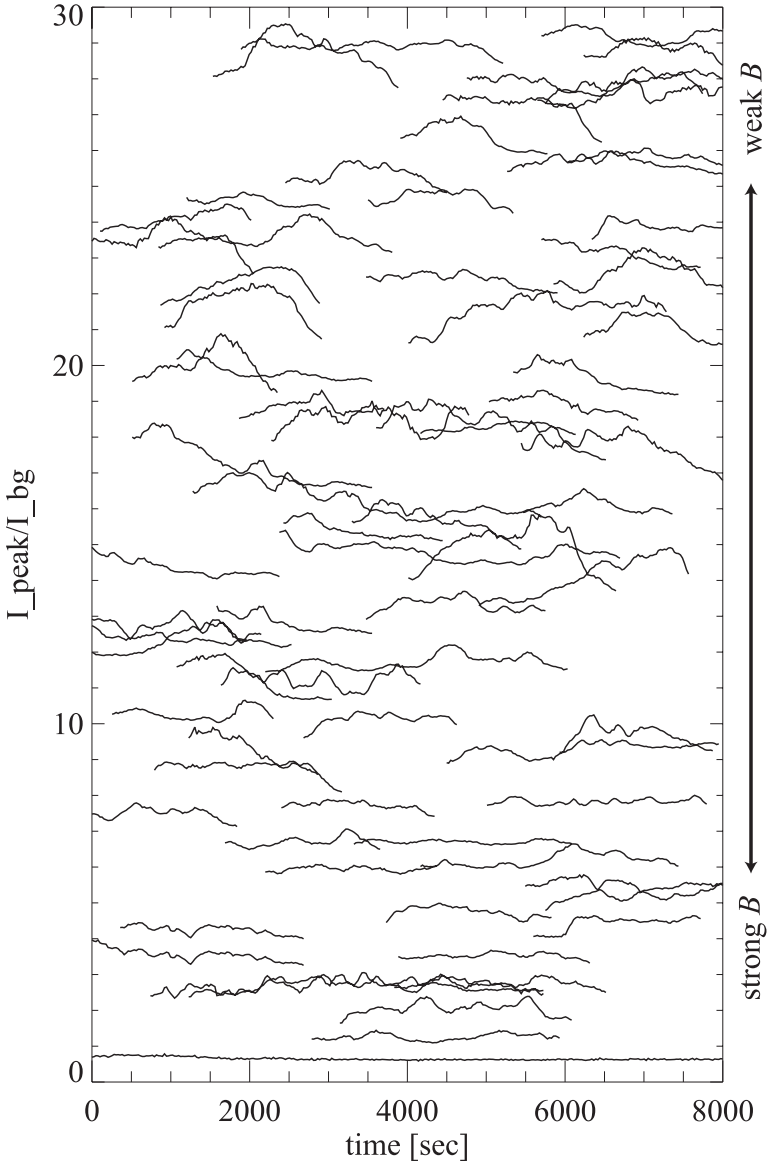


Spruit & Scharmer (2006)

Result 4/4

- Oscillatory light curve
  - strong power in 1-2 mHz (8-16 min) component





Summary

umbral dot is the target which can directly measure the interaction between magnetic field and convection

- UDs are fewer in strong magnetic field regions
- Lifetime and size of UDs show almost no dependence on field strength
- UDs move faster towards the center of the umbra in the oblique field regions
- The oscillatory light curve of UDs may be explained as the successive appearance of another UD

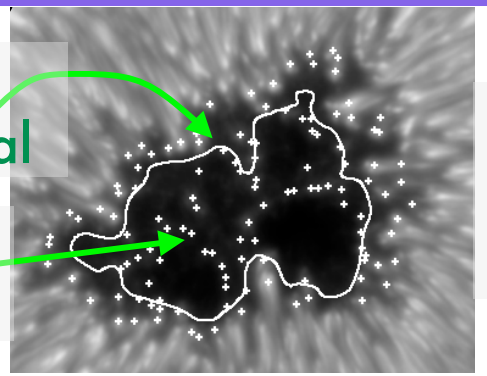
Backup slides

Result 1/4

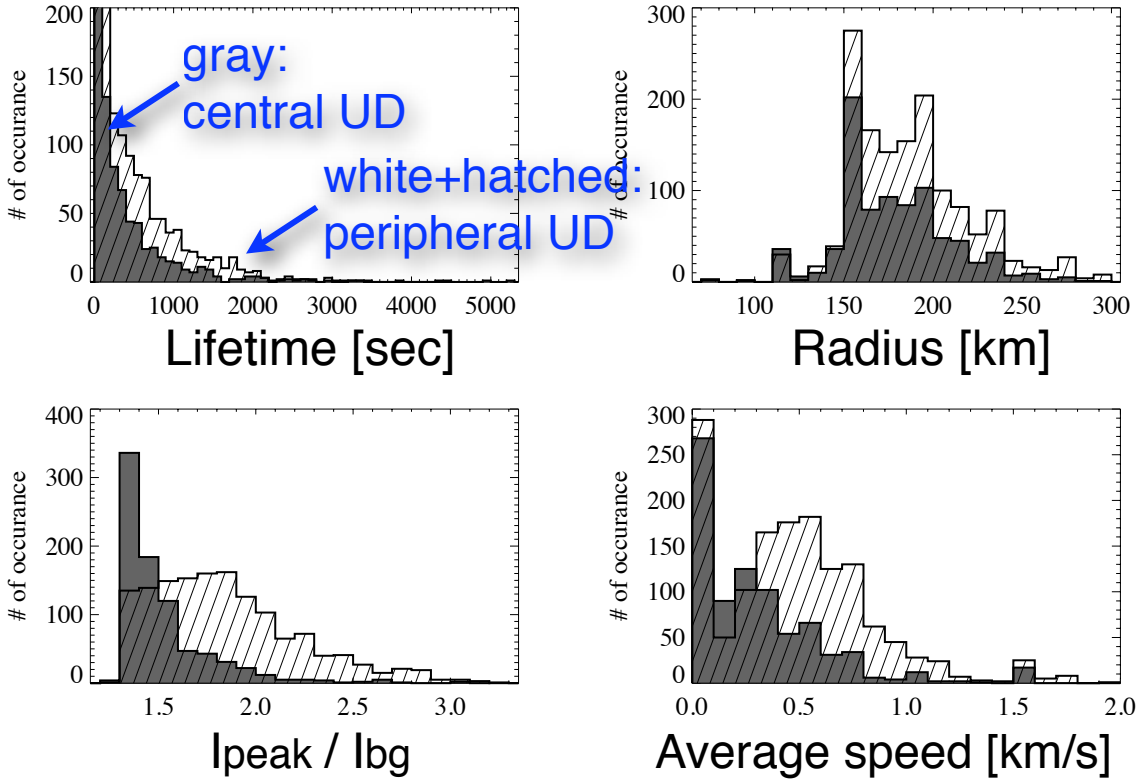
- Histogram

	average	central	peripheral
lifetime	7.4min	6.5min <	7.8min
Radius	184km	178km <	187km
Ipeak / Ibg	1.73	1.51 <	1.85
average speed	0.44 km/s	0.33 km/s <	0.50 km/s

The same as the previous studies



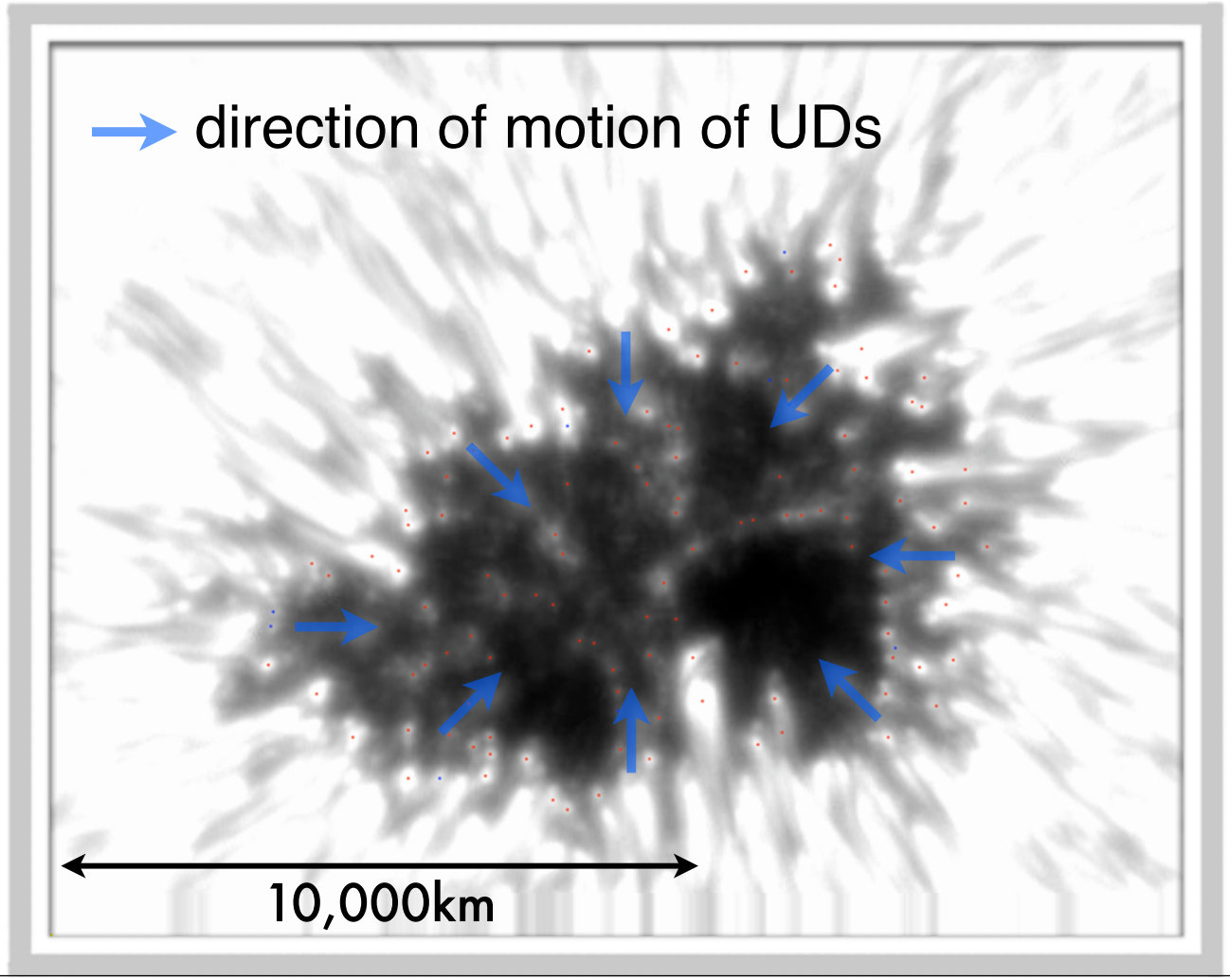
boundary
I_{quiet}=0.2



Proper motion

- Velocity analysis

Important

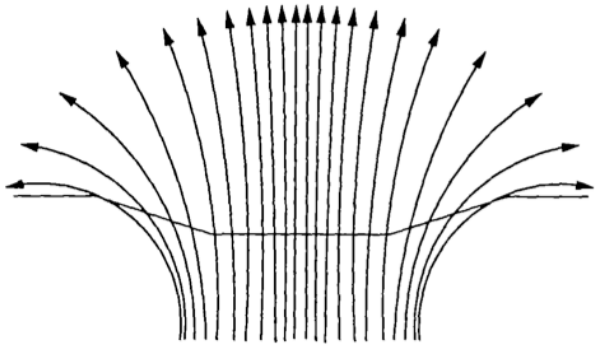


Central (oblique ***B***)

- inward migration

Peripheral (vertical ***B***)

- almost no motion



Side view

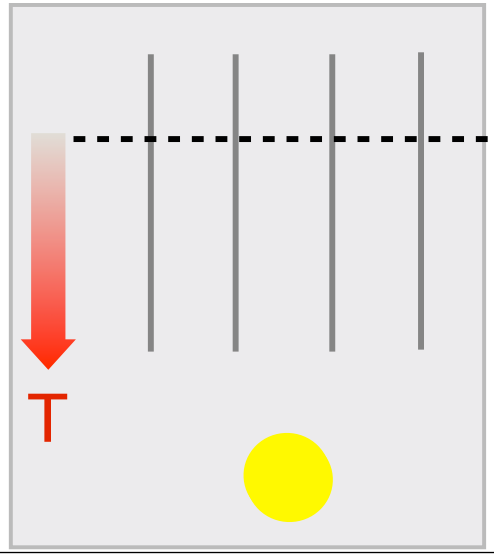
Lifetime

- What determines the lifetime of UDs?

cooling time
radiative cooling time

No!

about 10sec ≪ 600min



cooled at the surface

duration of the supply
size / rise velocity

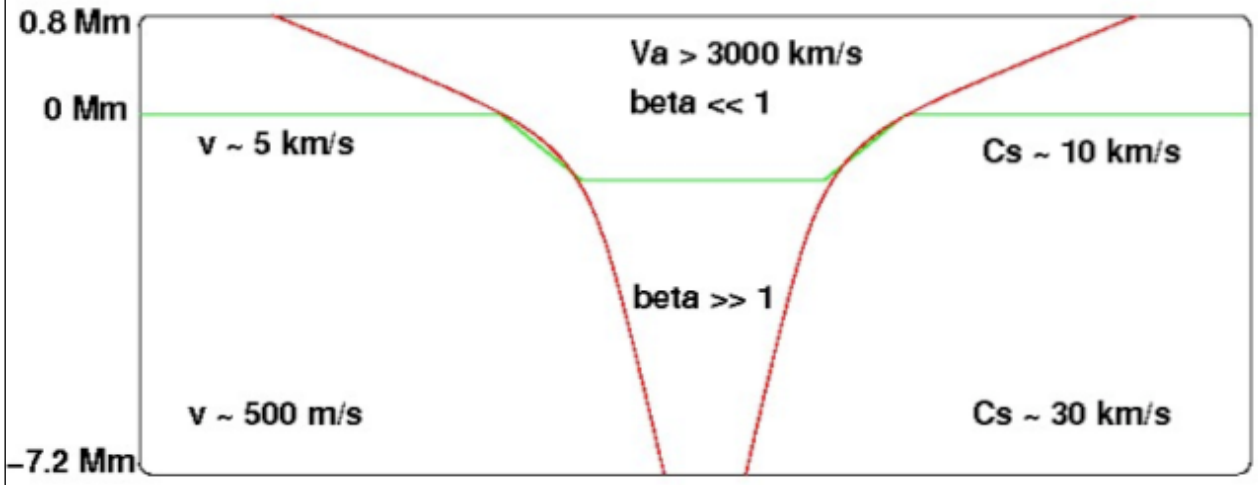
Maybe Yes!

size~300km、
lifetime~600sec、
∴ rise velocity~0.5km/s

If ***B*** is strong, both size and rise velocity is smaller.
Then lifetime is constant.

Magnetoconvection

- Important parameters
  - ζ ... magnetic / thermal diffusivity
  - Q... Chandrasekhar number (Field strength)
  - R... Rayleigh number (adiabatic gradient)



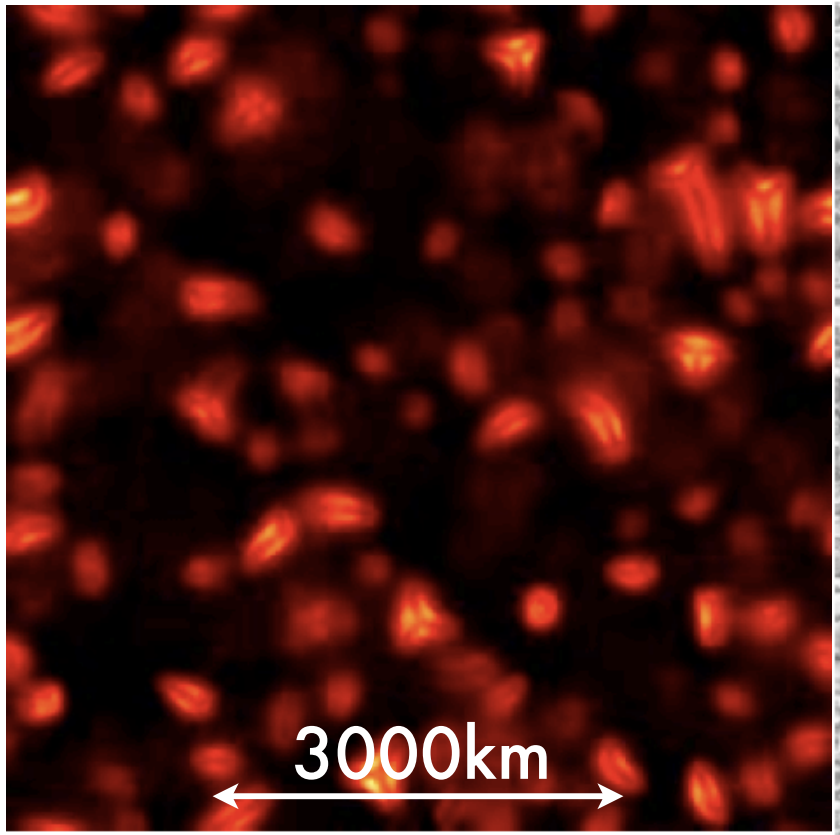
Rempel (2008)

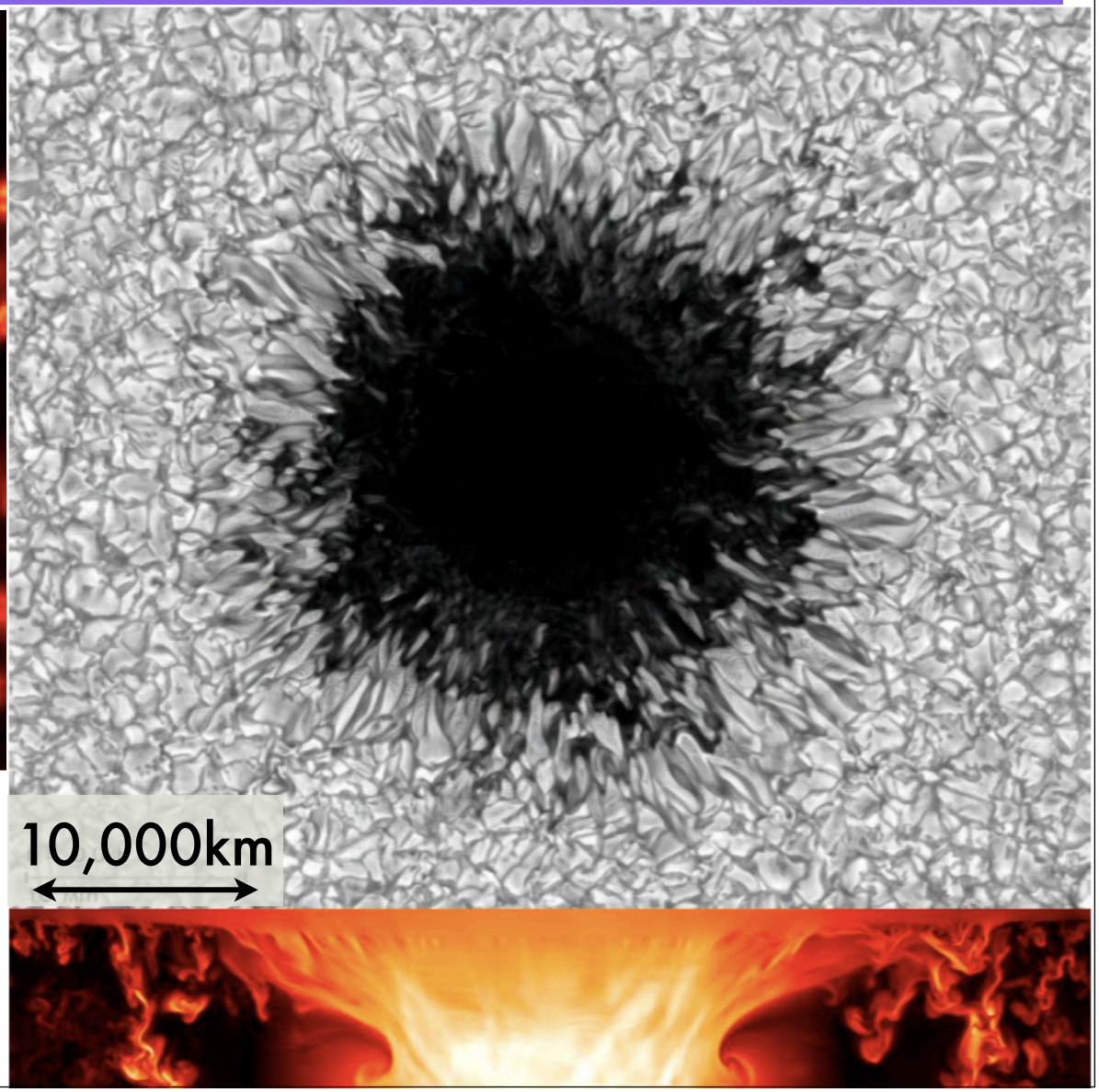
Table 1. Properties of a model umbra with $B_0 = 3000$ G.

z (km)	P (dynes cm^{-2})	v_A (km s^{-1})	ζ
0	2.7 x 10^5	8.1	0.003
100	6.3 x 10^5	6.8	0.008
500	3.8 x 10^6	4.7	0.056
1000	1.1 x 10^7	3.1	0.29
2000	5.3 x 10^7	1.7	3.1
4000	4.1 x 10^8	0.8	32

Weiss (1981) J. Fluid Mech

Recent MHD simulation





up: Schüssler&Vögler(2006)
right: Rempel(2008)

magnetic field⇒

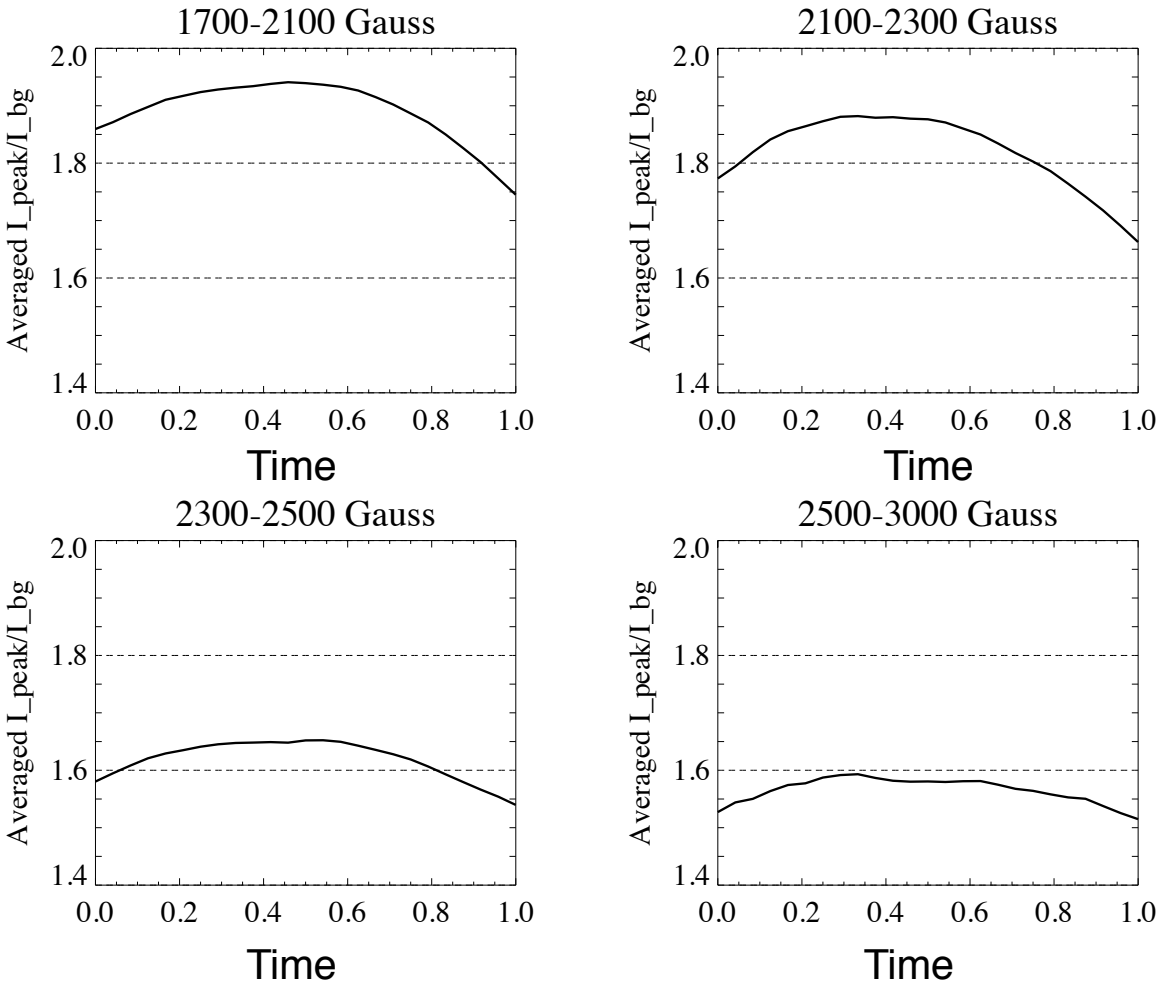
Lightcurve 1/2

- characteristic lightcurve
  - weaker fields

bighter
fast brightening
& slow darkning

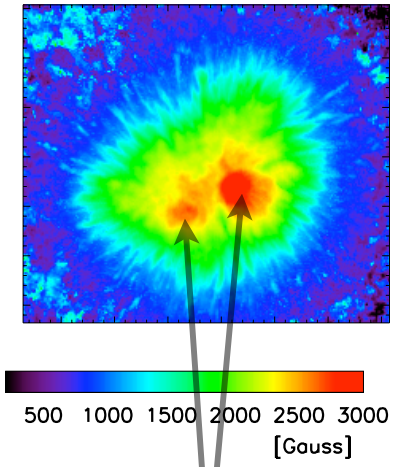
  - stronger fields

darker
smaller fluctuation
symmetric brightening
& darkning

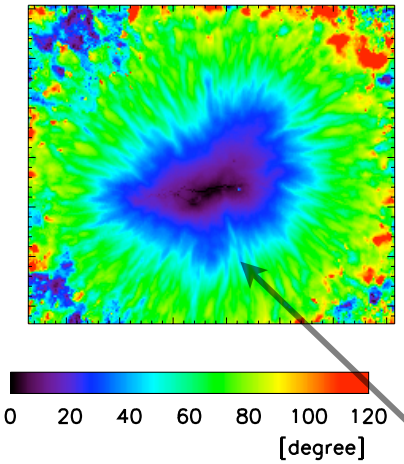


Analysis 2/2

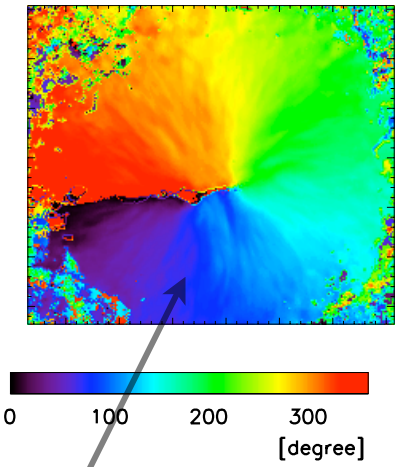
field strength B

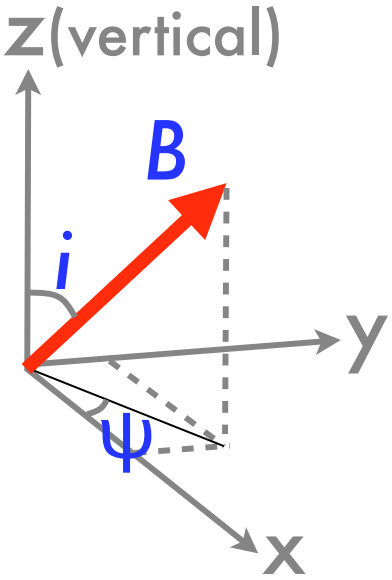


field inclination i



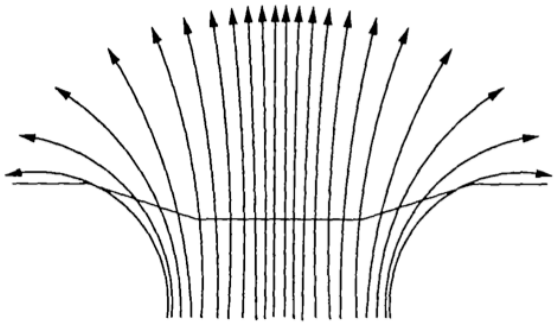
field azimuth ψ





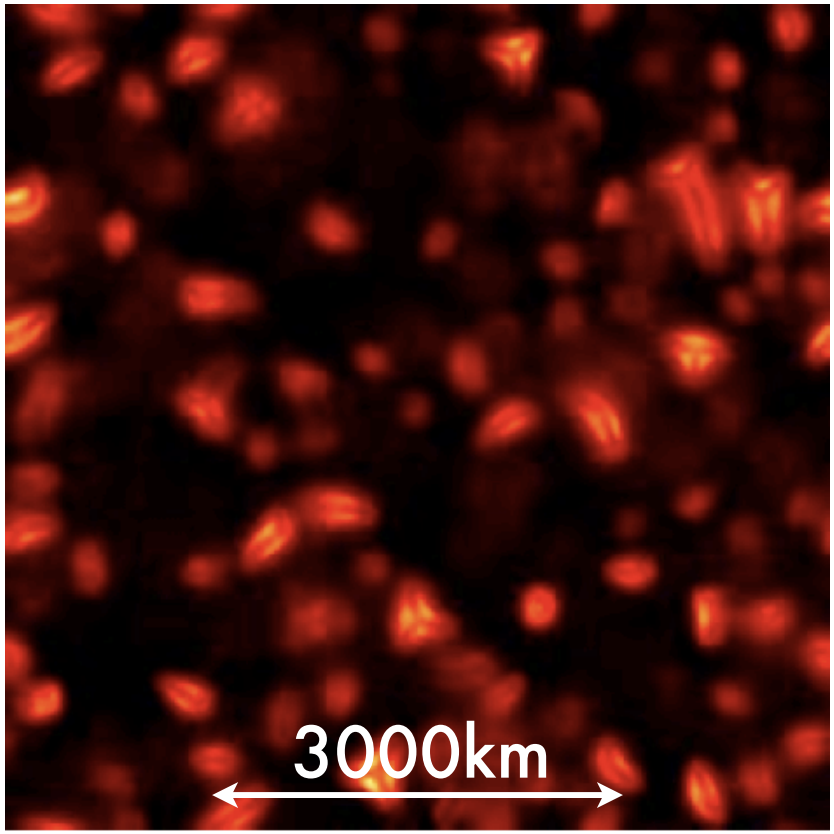
especially strong field region dark core

isotropic distribution

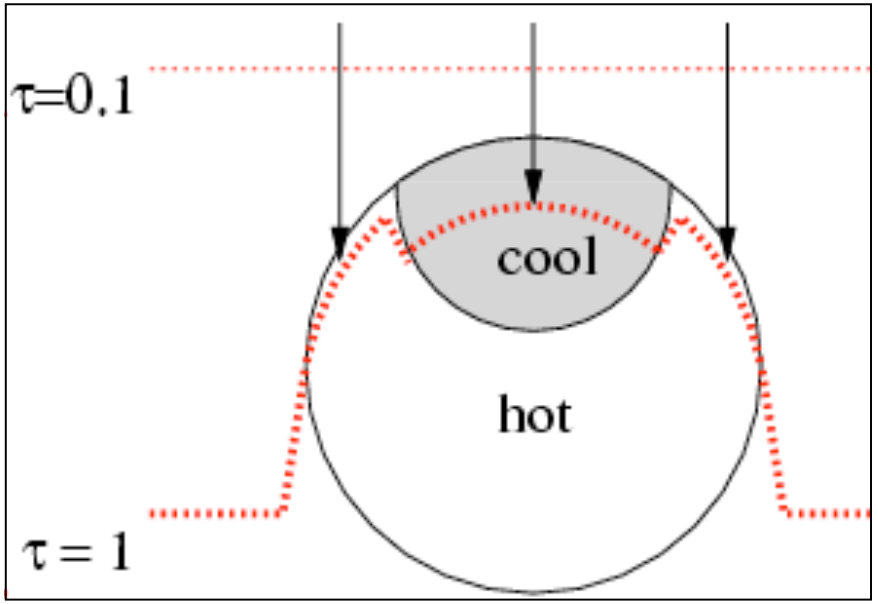


- Magnetic field at UD's occurrence site
  - field strength, field inclination, field azimuth

Dark lane



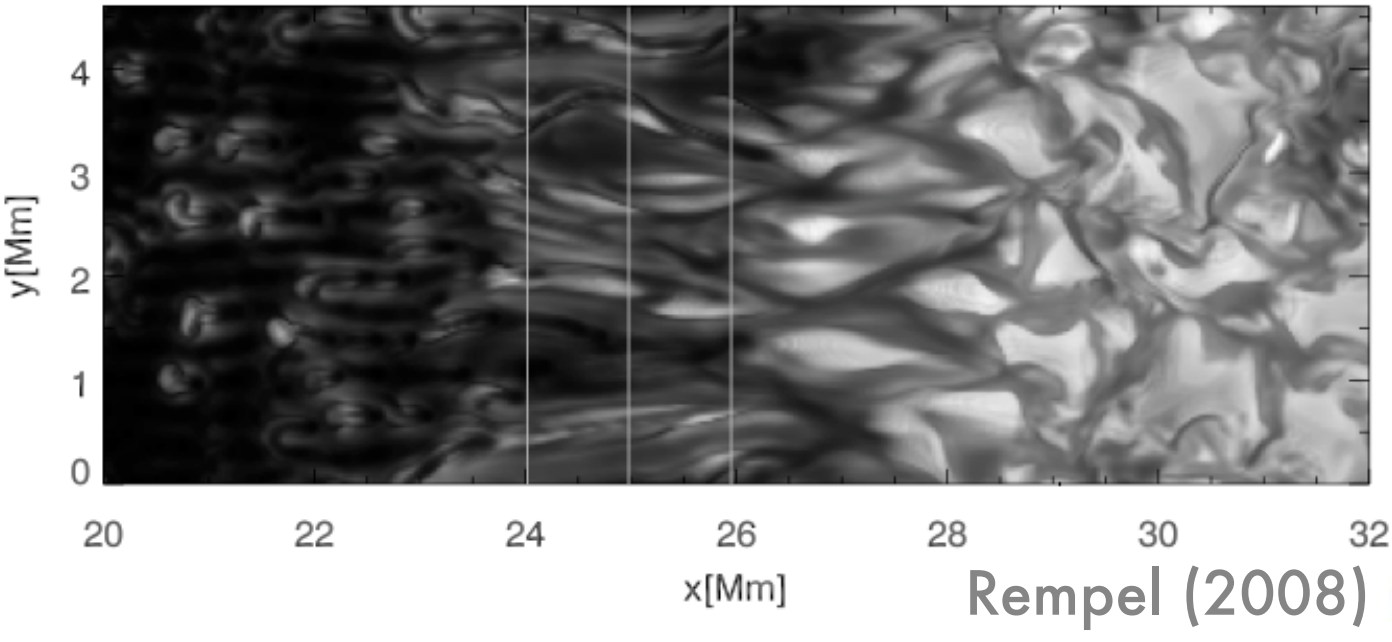
- topにcoolでdenseな material
- 観測される高さτ=1が cool materialを横切る



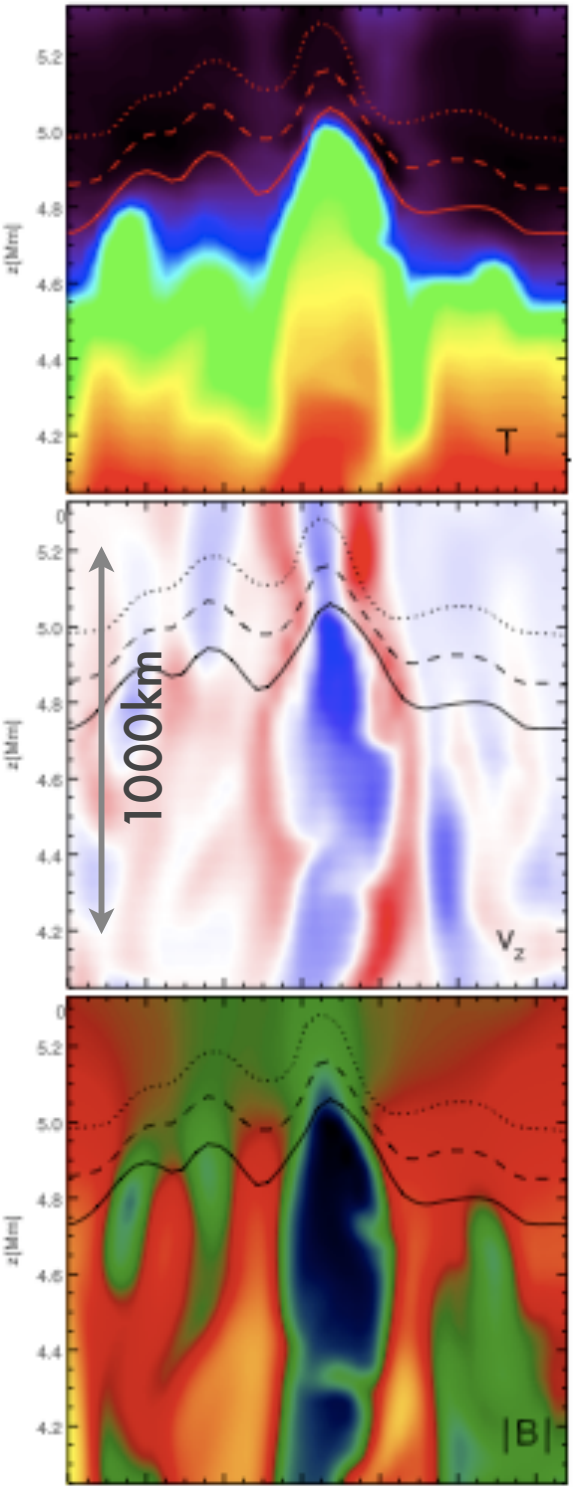
Sütterlin et al. (2004)

MHD simulation

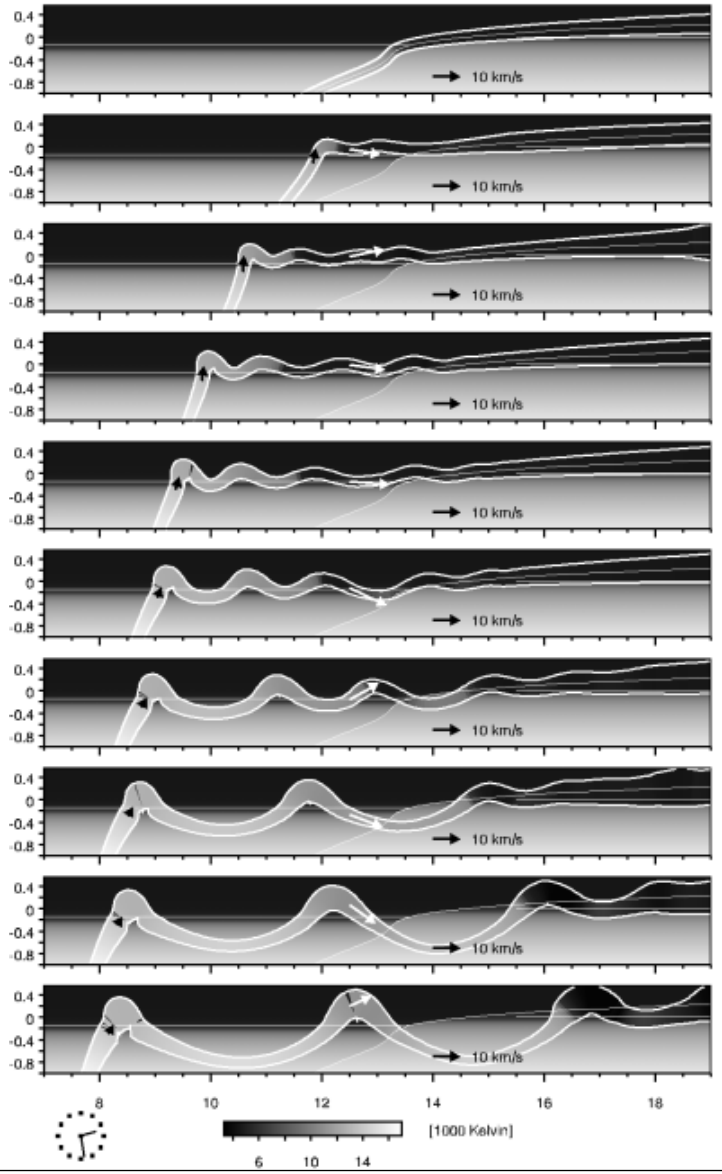
- 下降流はまだ観測されていない
- central UDとperipheral UDは、磁場の傾きが違うだけ



Rempel (2008)

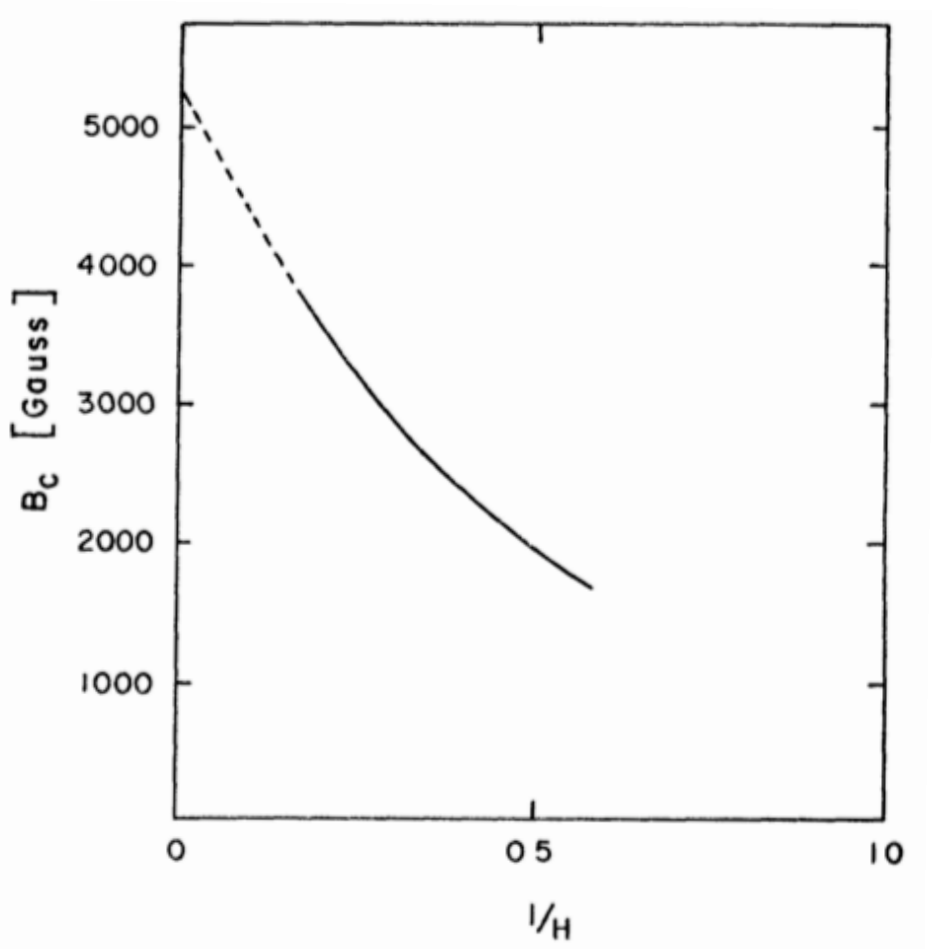


Inward migration



- Schlichenmaier et al. (2002)
- moving tube model
- **磁束管の浮上に伴う足元の inward motion**
- central UDは再現できない
- penumbraの明るさを説明できない

Mixing length theory



Deinzer (1965)

- 対流の効率を決めるパラメーター

l / H

l... Prandl's mixing theory
(周囲の物質と混合する距離)

H... pressure scale height

l/H→1　磁場なし

l/H→0　対流を完全に抑制