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Statistical Analysis of Umbral Dots with Hinode Solar Optical Telescope

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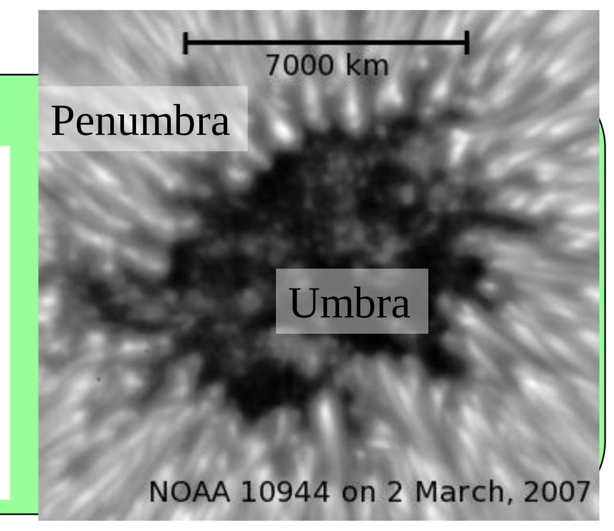
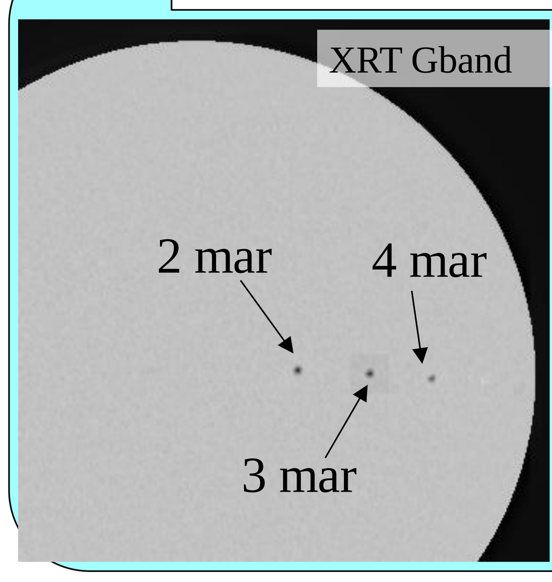
INTRODUCTION AND SCIENCE OBJECTIVE



The sunspot is one the most prominent structures in the solar photosphere, although there are many unresolved problems remaining. One of them is the source of energy transport in sunspots. Radiative energy alone is insufficient for accounting for the observed brightness of a sunspot, so any form of convective energy transport, i.e., umbral dot (UD) is essential for understanding.

We performed statistical analyses of temperature, size, proper motion, magnetic field, and Doppler velocity of UDs using high spatial resolution and seeing-free Hinode SOT data, which has been difficult for ground-based observations.

OBSERVATION



Instrument : Solar Optical Telescope on board Hinode satellite

Target : NOAA 10944 which was a stable and decaying sunspot for three consecutive days, from 2 March 2007 to 4 March 2007.
Position was (S6, W17) on 2 March, (S5, W30) on 3 March, (S6, W43) on 4 March.

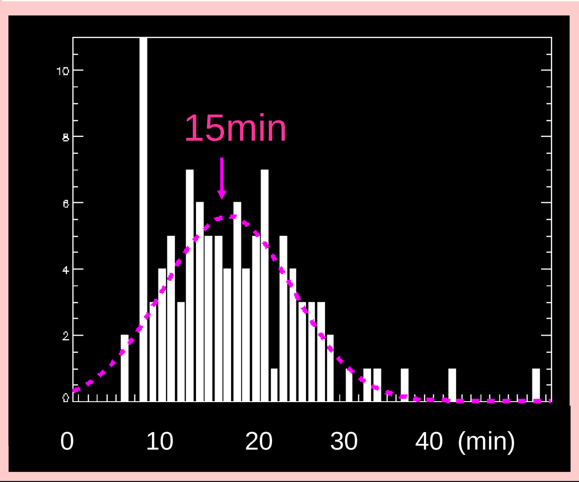
Observation : <Filtergram> blue continuum, green continuum for 3 hours [30 sec cadence, 0.054"/pixel, 56"x56" field of view]
<Spectro-polarimeter> Fe I full Stokes scanning observation with polarimetric accuracy of 0.1% [40 minutes to scan 80" area, 0.147"x0.147"/pixel, 80"x80" field of view]

＊We inverted full Stokes parameters into magnetic field and Doppler velocity using Milne-Eddington model atmosphere.

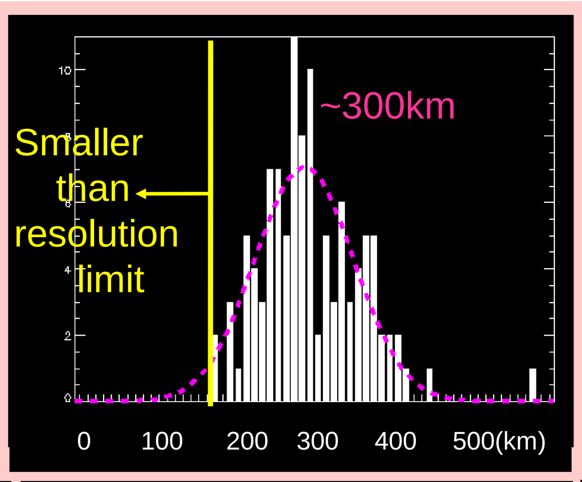
＊All filtergrams and magnetic data are transformed as if they are seen from the top. *Doppler velocity is calculated by Stokes V zero cross.

RESULTS FROM FILTERGRAM IMAGE DATA

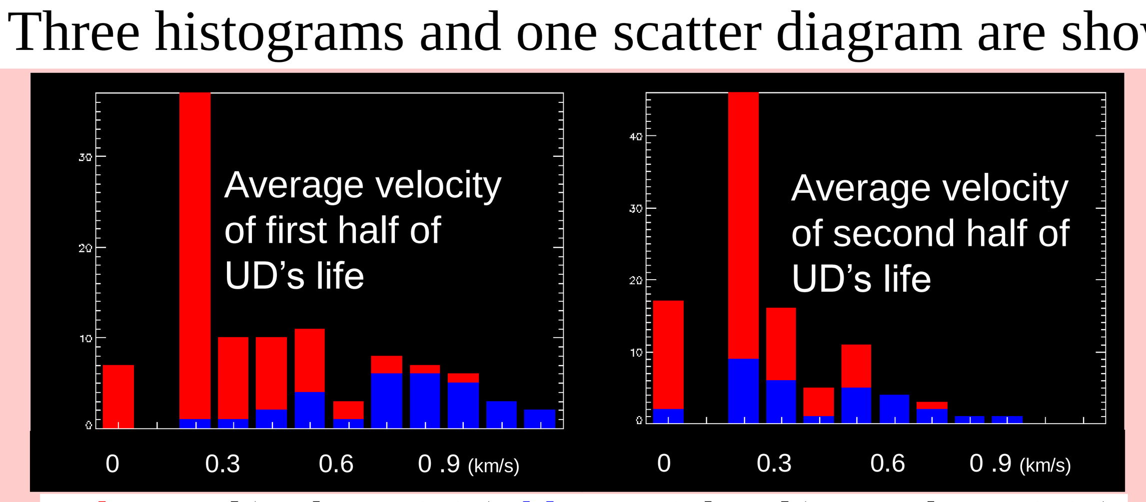
We chose the position of an UD on each frame carefully, to know its lifetime, size, and proper motion. Temperature is calculated from the intensity ratio I(blue)/I(green) assuming the black body radiation. Three histograms and one scatter diagram are shown below.



<lifetime>peak at 15min (shorter than earlier works)

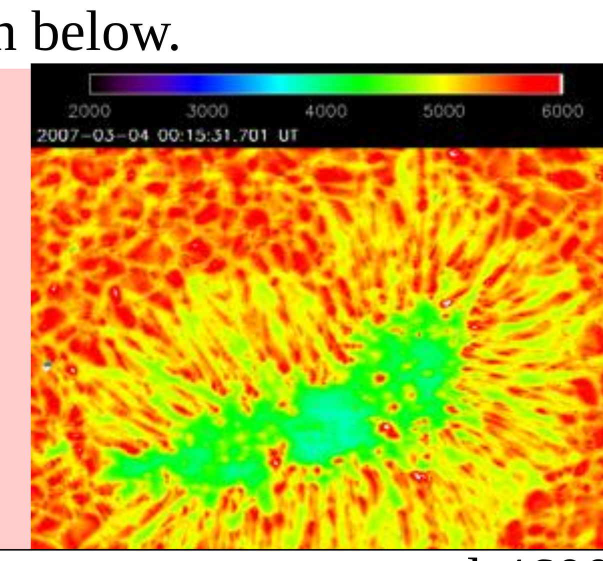


<size>peak at 300km (reach resolution limit)

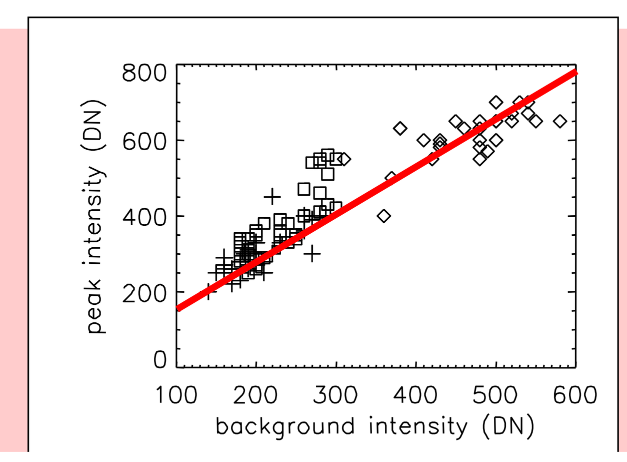


red:central(umbra origin) blue:peripheral(penumbra origin)

<proper motion>central UD: no or random motion peripheral UD: umbra inward decelerating motion



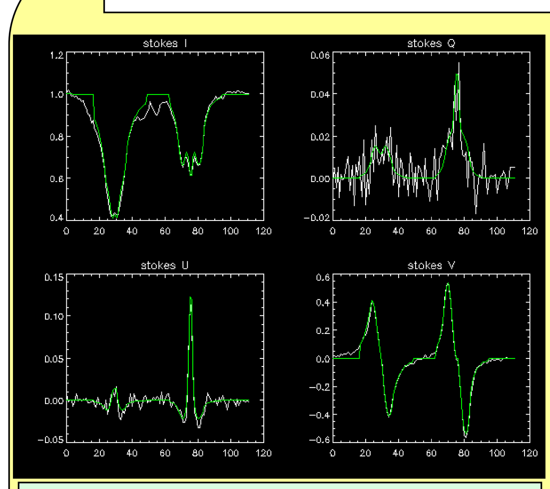
<temperature>central:4600K peripheral:5500K



+ : central □ : periophearal ◇ : light-bridge

Positive correlation between background and UD brightness.

RESULTS FROM SPECTRO-POLARIMETERIC DATA



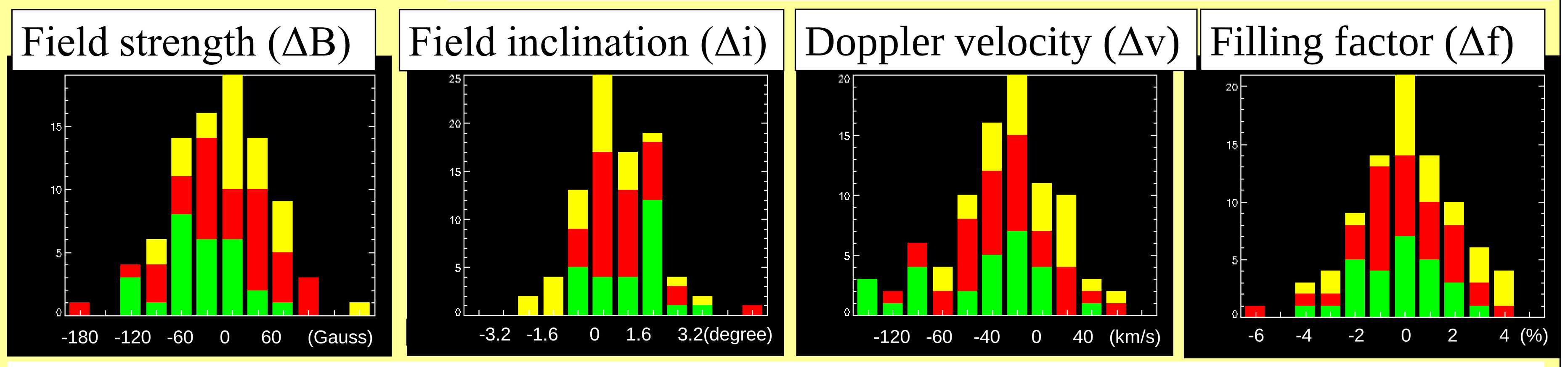
←left upper: Stokes I profile, right upper: Stokes Q, left lower: Stokes U, right lower: Stokes V

The spectra of UD are almost symmetric, so Milne-Eddington inversion can fit the spectra well. Identification of UD position was done using Fe I continuum map. At each position, we estimated the difference value between surrounding and UD position to know the UD characteristics.

<Error level>
Field strength: 35Gauss
Field inclination: 0.5°
Doppler velocity: 25m/s
Filling factor: 1.5%

Four histograms are shown below. Green color indicates UDs observed on 2 March, red color for UDs on 3 March, yellow color for UDs on 4 March.

Field strength (ΔB) Field inclination (Δi) Doppler velocity (Δv) Filling factor (Δf)



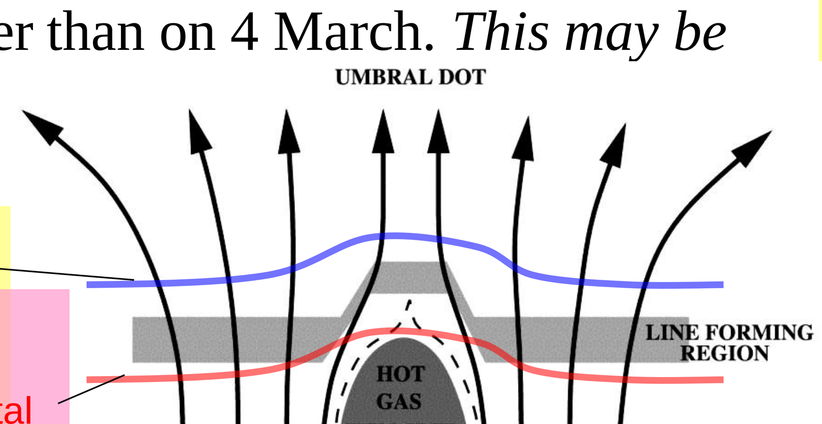
The average values on each observing days are listed as follows.

average	2 Mar (S6,W17)	3 Mar (S5,W30)	4 Mar (S6,W43)	Total average
Field strength (ΔB)	-36 Gauss	-6.9 Gauss	5.6 Gauss	-12 Gauss
Field inclination (Δi)	0.93°	0.66°	-0.20°	0.50°
Doppler velocity (Δv)	-51 m/s	-31 m/s	-12 m/s	-32 m/s

We try to explain these variations in terms of formation height differences based on center-to-limb variation. On 2 March, the sunspot was close to the disk center, so that we could see deeper layer than on 4 March. *This may be evidence for the cusp-shaped magnetic configuration of small convective cells.*

Observed at limb
Field strength : same or stronger
Field inclination: same or vertical
Doppler velocity: slow upflow

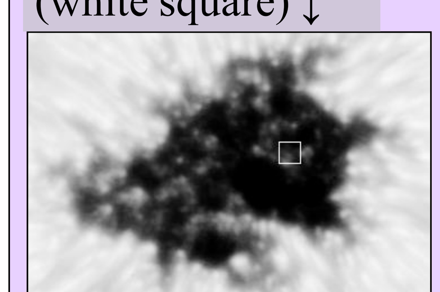
Observed at disk center
Field strength: weaker
Field inclination: horizontal
Doppler velocity: fast upflow



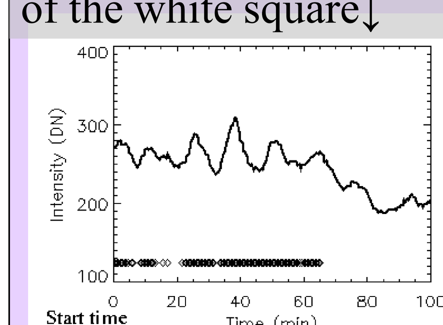
Socas Navarro et al. (2004)

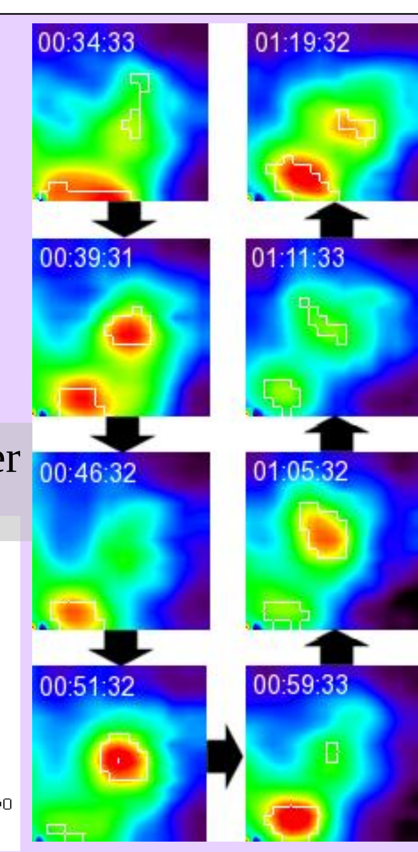
BRIGHTNESS VARIATION AND DISCUSSION

Position of the UD (white square) ↓



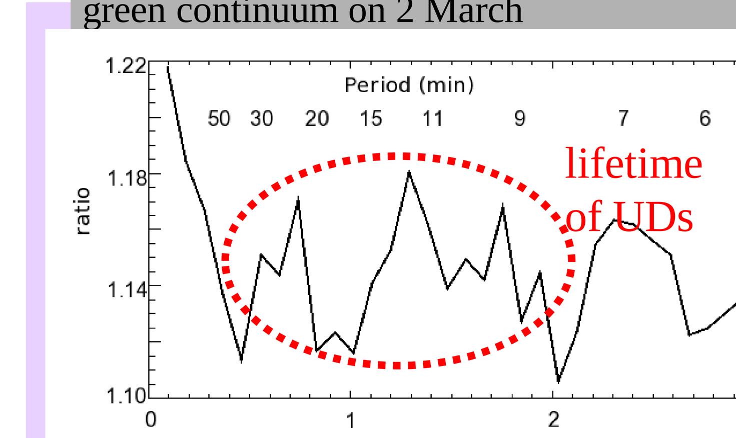
Light curve at the center of the white square↓





It is known that UDs appear to occur and recur at preferential locations. Thanks to Hinode's seeing-free observation, *we found some cases of repeating UDs.* In left figures, 6 UDs occurred in sequence, whose average lifetime is ~12 minutes. While UD occurred in sequence, the brightness did not decrease to its background level, but kept higher brightness. This may account for the shorter lifetime we found than in earlier works using ground-based unstable observation.

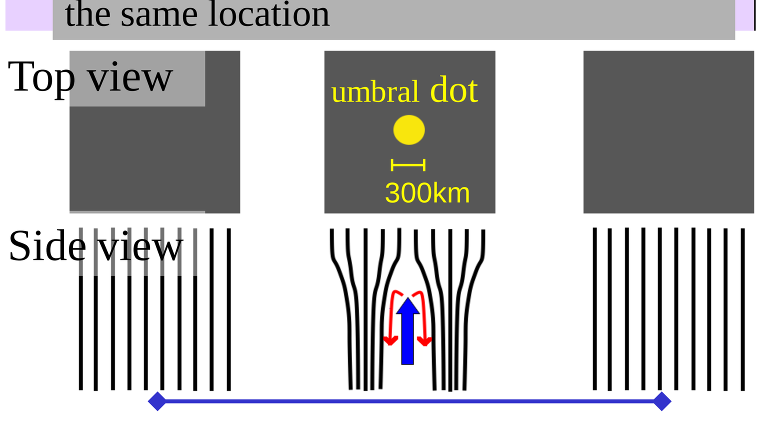
Frequency Power ratio (dot)/(surroundings) green continuum on 2 March



Right panel shows the frequency power distribution obtained by FFT of the continuum images. There is some excess in the range of 8-30 minutes oscillation within UDs, which corresponds to their lifetime. On the other hand, we could not find as many samples of repeating UDs using 3 March and 4 March data. This may indicate the critical condition of magnetic field strength has an effect on the repeating UDs.

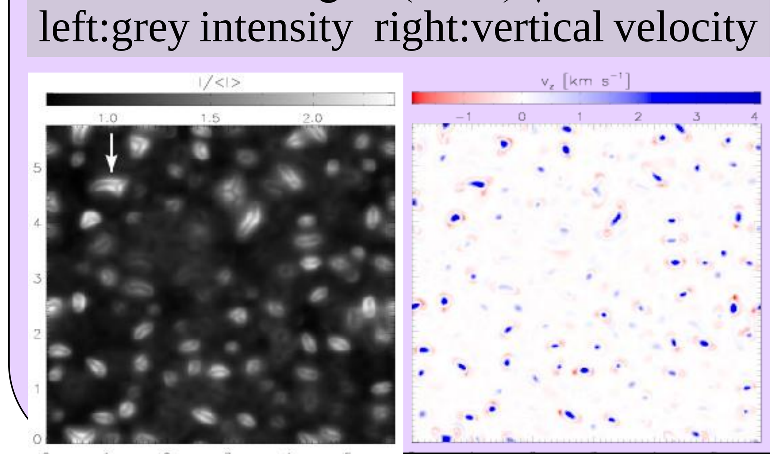
UDs include information of the deep layers (convective zone) where we can not see through. Our speculation is as follows: *On account of the dynamic motion beneath the sunspot, field-free gaps are created and UDs occur repeatedly until the gap closes.*

Schematic mechanism of repeating UDs at the same location



field-free gaps closes in 50-100 minutes

3D numerical simulation by Schüssler & Vögler (2006) ↓
left:grey intensity right:vertical velocity



Recent 3D MHD numerical simulation was done by Schüssler & Vögler (2006). In their simulation, an UD is a natural result of overstable oscillatory convection which is a preferred mode below the photosphere in the sunspot. The UD sequence and its undulatory light curve is direct evidence of overstable convection.