Expansion of magnetic flux concentrations: comparison of observations and simulations

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LOS “magnetic flux” in Na D:

Disk center

Limb
LOS “magnetic flux” in Na D:

Unipolar appearance  |  Bipolar appearance
Center to limb appearance of flux tubes
At disk center:
At limb:

- Disk center
- B line of sight
- Stokes V
- X-dir
Formation height: center to limb
Lines

- Hinode NFI (filtergraph): Na I D1 589.6 nm line (filter 160 mÅ from line core): upper photosphere
  - Lande g & log(gf): 1.33 & -0.194

- Hinode SP (spectropolarimeter) 630 nm Fe I lines: middle photosphere (630.1 nm slightly higher than 630.2 nm)
  - Lande g & log (gf): 630.1nm 1.67 & -0.718  630.2nm  2.5 & -1.235

![Stokes V amplitude graph]

\[ B [G] \]

\[ B [G] \]
3 Approaches

1. Observations:
   - SOT Na D Stokes V filtergrams
   - SOT SP Fe 630 nm circular polarization maps

2. Thin flux tube model

3. MURAM simulations
   - Potential field BC for B-field
   - Vertical BC
Hinode Na D Stokes V filtergrams
“measurable” quantity for expansion

Radial cut:

Center side peak

Limb side peak

\[
\text{Ratio} = \frac{\text{Center side peak}}{\text{Limb side peak}}
\]
In Na D magnetic features are dominantly unipolar at disk center, bipolar towards the limb.
• Limb side peak becomes more prominent towards the limb
Fe 630 nm

- In Fe bipolar features are seen close to the limb, but not as dominant as in Na D
Fe unipolar features

- In unipolar features peak amplitude decreases towards the limb: less radial LOS
Fe bipolar features

- As in Na D limb side peak becomes larger towards the limb
**Thin flux tube approximation**

- Total pressure balance inside and outside the tube:
  \[ P_{\text{mag, interior}} + P_{\text{gas, interior}} = P_{\text{gas, exterior}} \]

  - Recipe: Choose external and internal atmosphere, \( B \) at \( z=0 \), \( r \) at \( z=0 \) → compute Wilson depression, shift and compute \( B_z, \text{div}B=0 \) → \( B_r \), radius from flux conservation

- \( 0^{\text{th}} \) order in \( B_z \), \( 1^{\text{st}} \) in \( B_r \)
Internal and external atmospheres

- **External** (Fontenla et al 2007)
  - Quiet Sun (QS)

- **Internal** (Fontenla et al 2006)
  - Plage (H)
  - Facular (P)
Most important factor for expansion is the radius: radius $\uparrow \rightarrow$ expansion $\uparrow$

Note: $H_p < r_0$
Synthetic data

- 630 Fe I lines LTE synthesis with STOPRO
- Na D nLTE synthesis with H. Uitenbroek's RH
- Vary the LOS inclination = 0°, 20°, 40°, 60°, 70°, 75° →
  Synthetic center-to-limb variation of radial cuts
Synthetic Fe 630 nm radial cuts

Close to disk center:

- $r_0 = 140 \text{ km}$
- $200 \text{ km}$
- $400 \text{ km}$
- $600 \text{ km}$

630.1 nm

630.2 nm
Synthetic Fe 630 nm radial cuts

Close to disk center:

Towards the limb

$\mu = 1.0$ area

$0^\circ$

$20^\circ$

$\mu = 0.94$ area

$40^\circ$

$60^\circ$

$\mu = 0.50$ area

$r_0 =
140$ km
200 km
400 km
600 km

630.1 nm
630.2 nm
Synthetic Fe 630 nm radial cuts

Close to disk center:

- $\mu = 0.94$ area
- $\mu = 0.84$ area
- $\mu = 0.77$ area
- $\mu = 0.50$ area
- $\mu = 0.34$ area
- $\mu = 0.26$ area

r0=
- 140 km
- 200 km
- 400 km
- 600 km

- 630.1 nm
- 630.2 nm

Towards the limb

- 0°
- 20°
- 40°
- 60°
- 70°
- 75°
Synthetic Na D radial cuts

Close to disk center:

Towards the limb:

Very close the limb:

- Na D cuts are not as bipolar as Fe?
  - Na D formed higher
  - Observations Na D more bipolar
• What if the SOT NFI filter is “shifted? Look at amplitude instead

![Graph showing Stokes V amplitude and Filter signal.](image)
Synthetic NaD radial cuts

Close to disk center:

- More bipolar in Stokes V amplitude than SOT filter
  - Fe is still more bipolar in appearance..
  - Big tubes have ratios comparable to observations

Towards the limb:

- 40°
  - $\mu = 1.0$ airmpl
- 60°
  - $\mu = 0.94$ airmpl

Very close the limb:

- 70°
  - $\mu = 0.94$ airmpl
- 75°
  - $\mu = 0.36$ airmpl
Why does Fe appear more bipolar very close to the limb?

- nLTE, Zeeman saturation.... ??

![Graphs showing normalized ratios](image)

- **60°**
  - Norm. ratio vs. distance
  - Mm

- **70°**
  - Norm. ratio vs. distance
  - Mm

- **75°**
  - Norm. ratio vs. distance
  - Fe Na
  - Mm

r0=600km, B0=1300G
MuRaM simulations

- Non-gray radiative transfer
- 24Mm x 24Mm x 1.68 Mm (576 x 576 x 120)
- Potential field upper BC
- Vertical field upper BC
Vertical field BC

*Bz*, side view of box

*Bx*, side view of box

Bx, at z=400 km

horizontal cut
Potential field BC

Bz, side view of box

Bx, side view of box

Bx, at z=400 km
horizontal cut

X [Mm]

Z [Mm]
Expansion of individual “flux tubes”

Large scale “Canopy”

Vertical BC

Potential BC
Synthetic 630 nm radial cuts

Vertical BC

\[ \mu = 1.0 \]
\[ \mu = 0.94 \]
\[ \mu = 0.77 \]
\[ \mu = 0.50 \]
\[ \mu = 0.34 \]
\[ \mu = 0.26 \]
\[ \mu = 0.17 \]

Potential BC

Limb

Limb
Synthetic Na D radial cuts

Major caveats:

Close to the top of the box

simulations not necessarily very valid

large gradients in T, B & v, especially at inclined LOS
Synthetic Na D radial cuts

Vertical BC

μ=1.0
μ=0.94
μ=0.77
μ=0.5
μ=0.34
μ=0.26
μ=0.17

Potential BC

Limb
Summary & open questions 1/2

- Bipolar features become more prominent towards the limb in the observations
  - More prominent in NaD
  - Ratio of peaks a “measure” of expansion
- Thin flux tubes have to be **thick** to produce the bipolar signal
- Choice of BC makes a big difference in MuRaM, top of the box is problematic
  - NaD shows the canopy
Summary & open questions 1/2

- Does the ratio scale with total flux of feature (do stronger features expand more)?
- Differences between 630.1 and 630.2 nm
- How about thin flux sheets?
- Does Fe also sample horizontal INW fields (larger Zeeman sensitivity)?: unipolar at limb, more diffuse...
- ...

Thank you!
Potential field BC

Bz, side view of box

Bx, at z=400 km
horizontal cut

Bx, side view of box