Extrapolating time-series of Sunrise magnetograms
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- Motivation: Revisit coronal recycling studied by Close et al 2004/05 with SOHO/MDI
- Structure of quiet Suns upper atmosphere extrapolated from one Sunrise snapshot.
- First attempts to extrapolate a 20min time-series and monitor changes in photosphere and atmosphere.
- Very preliminary conclusions and further plans.
Revisit coronal recycling
(Close et al. 2004/05, used MDI),
with Sunrise-resolution we can study also for the first time chromospheric recycling

- Quiet Sun magnetic fields are always in motion, e.g. newly emerging flux and flux cancellation.
- Hagenaar 2001 found (using MDI) that the magnetic flux in the quiet Sun's photosphere is replaced every 14h.
- Close et al. 2005 found (using Potential fields computed from MDI) a remapping time of 1.4h for the quiet Sun coronal flux.
Method by Close et al. 2004/05
(figures and formulars on next 4 slides are taken from these two papers)

MDI magnetogram
This assumption is not true for observations with Sunrise, which resolve also internetwork flux. Close et al. considered only network elements.

Coronal field is computed by Greens function. Network elements are reduced to point sources with different strength.
Magnetic connectivity (traced by a number of field lines) is stored in connectivity matrix and monitored in time.

\[
M = \begin{pmatrix}
D_1 & D_2 & D_3 & D_4 & D_5 \\
P1 & 0 & 1 & 0 & 0 & 1 \\
P2 & 0 & 0 & 0 & 1 & 0 \\
P3 & 1 & 0 & 1 & 0 & 0 \\
N1 & 0 & 0 & 1 & 1 & 1 \\
N2 & 1 & 1 & 0 & 0 & 0
\end{pmatrix}
\]

**Figure 2.** Sketches of the possible scenarios that may arise when (a) a single fragment in frame \(i\) has split into several smaller fragments by frame \(f\), (b) several fragments in frame \(i\) have merged into a single, larger fragment by frame \(f\), and (c) several fragments merge to form a single larger fragment in frame \(i\), whilst this single fragment has split into several smaller fragments by frame \(f\). The various \(\Phi\) values represent the flux in the given fragments.
The Close et al. method is based on discrete sources, ignoring internetwork features.

Pixel size of magnetograms
MDI: 1400 km
Sunrise: 40 km

Fig. 2. One 200th of the field lines used in the calculation. The color scaling indicates height above the solar photosphere. The numerous magnetic concentrations that dapple the quiet-Sun photosphere have been termed the magnetic carpet (Schrijver et al. 1997; Weiss et al. 1996). The connections of opposite-polarity regions can clearly be seen. A Monte Carlo method is used to quantify the coronal connectivity. Sample field lines, each representing a flux $\psi_0 \sim 10^{13}$ Mx, are traced from each source until they terminate at opposing sources. Those $N_s$ field lines ending at the same source together form a single domain with net flux $\psi_n \sim N_n \psi_0$. 
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We extrapolate the photospheric measurements into the sun’s atmosphere under the force-free assumption.

\[
(\nabla \times \mathbf{B}) = \alpha \mathbf{B} \\
\nabla \cdot \mathbf{B} = 0 \\
\mathbf{B} = \mathbf{B}_{\text{obs}} \text{ on photosphere}
\]

We solve these equations with a fast fourier transformation (Alissandrakis 1981) in a 936*936*468 pixel box with resolution 40km \(\Rightarrow\) 37*37*18 Mm. A data-cube has about 5 GB.
Loop Statistics

- Wie start field line integration in black box from all pixel above threshold $|B_z| > 30 \text{G}$, here $28005$ pixels
- Some FL leave model volume (high cut, 1936, 7%)
- Or height below 1 pix, 40 km (low cut, 4181, 15%)
- Close within volume (resolved loops, 21888, 78%)
2% of the 21888 resolved loops
(selected by random number generator)

Height distribution
0.97 ± 2.20 Mm
Main findings from one snapshot

• We can resolve magnetic loops with height down to about 100km.
• Photospheric fields with high field strength usually host footpoints of longer loops.
• Most chromospheric points (height 1 Mm) are magnetically connected to strong photospheric regions.
• Chromospheric pixels (at 1 Mm) containing 90% of the magnetic energy are connected to photospheric pixels with B > 300G.
• Footpoint strength is often asymmetric with one footpoint dominating. => Network-internetwork loops.
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One Imax Snapshot of quiet Sun

We have strong magnetic elements and weaker internetwork features
Identify strong-field elements in Magnetogram.

- Identify pixel above a threshold of 300G, the equipartition strength. [To Do: other values]
- Remove isolated pixels above threshold.
- Identify pixel above threshold connected horizontal, vertical, diagonal.
- Compute center-of-gravity (x,y) for each element.
- Merge regions with center-of-gravity close (10 pixel, 400km) together.
- Number regions with amount of total flux they contain. => 37 +-5 elements in each magnetogram.
Trace elements in time

- From about 37 elements in each snapshot, only 9 elements can be uniquely traced over the whole 20 min interval.
- This are, however, the largest ones (most flux)
- In a first analysis we concentrate on this 9 strong elements.
- **To DO:** Investigate also other, smaller and shorter living one, which can be traced for several snapshots/minutes.
Trace elements in time

- 9 strong elements live 20 min or more
- Other elements emerge, cancel, fragment etc.
40 Sunrise/IMax-magnetograms with 33 s time cadence, 9 elements
Global features

Number of positive and negative Elements about equal, but positive polarity regions contain about 2.5 times more flux.
Extrapolations in Atmosphere.
What can happen?

• A Field line with one footpoint in a magnetic element connects to other (opposite polarity) element.

• Field line connects to inter-network areas, here defined as regions <300 G

• Field line does not close within Sunrise-FOV. This one we cannot investigate properly.
Averaged (for each snapshot) quantities

Positive flux regions contain double the flux as negative ones. ⇒ Most loops starting in positive regions MUST end in the weak inter-network.
|   | $|\phi|$ | $|\phi_c|$ | Height | $B_z$ | $B_{z2}$ | Net | H-cut | L-cut |
|---|-------|--------|--------|------|--------|-----|-------|-------|
| 1 | 33.78 | 6.39   | 3.04   | 499  | 102    | 0.11| 0.73  | 0.00  |
| 2 | 11.61 | 10.25  | 2.98   | 537  | 62     | 0.03| 0.12  | 0.00  |
| 3 | 5.08  | 4.47   | 2.94   | 510  | 320    | 0.41| 0.11  | 0.00  |
| 4 | 4.73  | 2.77   | 5.66   | 552  | 339    | 0.46| 0.36  | 0.01  |
| 5 | 4.64  | 4.62   | 2.45   | 560  | 465    | 0.59| 0.00  | 0.00  |
| 6 | 5.15  | 4.46   | 0.65   | 563  | 382    | 0.55| 0.00  | 0.11  |
| 7 | 3.58  | 1.36   | 6.40   | 479  | 314    | 0.33| 0.57  | 0.01  |
| 8 | 3.53  | 3.52   | 2.67   | 452  | 284    | 0.34| 0.00  | 0.00  |
| 9 | 2.97  | 2.81   | 1.94   | 542  | 408    | 0.51| 0.06  | 0.01  |
Region 2

Flux and loop heights hardly vary

Mainly network-internetwork loops
Region 3

0:00 min
Region 3

Flux and loop heights vary a lot.

Connectivity varies, loops connection strong elements dominate first 3 min and 13-17 min.
Region 8

Flux varies, but loop heights almost not.

Connectivity to other strong elements and weak internetwork fields varies in time.
Magnetic Reconnection?

- Compute Flux shared by strong magnetic elements (positive-negative).
- Use field lines as tracers. A field line represents a fluxtube with 40x40 km^2 diameter at leading footpoint.

**TO DO:**
Compute more field lines. Not only at the center of each pixel in the magnetogram, but also interpolated in between.

=> More and thinner fluxtubes, but maybe also additional Error from interpolation?
Region 3, Main connectivities

Region 3 – 6

Region 3 – inter network

Region 3 – open flux
Region 3, Minor (<1 MWb) connectivities => Reconnection
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Preliminary conclusions

- Magnetic connections between strong and weak field regions are very common and occur more often than network-network loops.
- Fraction of these asymmetric loops varies significantly between different magnetic elements and also in time.
- We hardly identify direct reconnection between strong magnetic elements, but frequently from magnetic elements to the internetwork.
- Reconnection time about 2 min or less.
Further plans

• What is the role of small and short-living magnetic elements? (flux emergence cancellation and fragmentation)
• Can we get a lower estimate for reconnection times from flux cancellation at one footpoint and upper limit from potential fields?
• Can we estimate the energy release by reconnection and possible role for heating?
• Analyze another Sunrise timeseries.
• Further suggestions from the audience are welcome!