Local helioseismic investigation of emerging active regions

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& using MHD simulations from

M Rempel (NCAR/HAO) & R Stein (MSU)
helioseismic surveys of emerging ARs (EARs)

- advantage of consistent analysis applied to many regions:
  - statistical (e.g. compare populations of emerging vs non-emerging regions)
  - enhance signal-to-noise (e.g. ensemble averaging)

- prior ring-diagram surveys (Komm, Howe & Hill 2009; 2011)
  - larger, broader survey than this one (flows & active region evolution)

- prior NWRA survey (GONG; Leka et al. 2013; Birch et al. 2013; Barnes et al. 2014)
  - goal: detect subsurface “precursors” of emerging flux
  - holography of ~100 ARs and 100 quiet regions
  - 0-20 Mm below photosphere & up to 28 hr. prior to emergence

- ongoing NWRA/MPS Survey (HMI-SDO data)
  - goal: explore physics of emergence & extend prior survey in time and depth
  - holography analysis & ensemble averages of ~100 EARs (2010 - 2012)
EAR selection

- discussed earlier by Hannah...
- “clean” emergence for simplicity in interpretation
- use HARP information + visual inspection of magnetograms
- definition of emergence time, time intervals, identical to prior GONG survey
- results here use 80 cleanest EARs
holography

- deep-focus geometry results
  - 3 Mm focus depth shown
- travel-time shifts
  - EW, NS differences (flows)
  - mean shifts (EW & NS; wave-speed perturbations)
- EW, NS shifts as proxies for flows
  - avoids inversions (for now)
  - take simple operations (e.g. horizontal divergence component) on vector travel-time shifts
single AR (NOAA 11136)

EW, NS diffs dominated by supergranulation

mean travel-time reduction
ensemble average (~80 EARs)

- prograde flow
- diverging flow
- converging flow (especially visible in NS shifts)
horizontal component of divergence

- converging flows from -30hr; changes to outflows $t > t_0$
- amplitude $\sim \sigma_{SG}$ (RMS in quiet-Sun supergranulation)
- also observed “in-out” travel-time differences
time evolution of in-flows -> out-flows

amplitude of pre-emergence converging flows not strongly dependent on resulting AR size.

post-emergence outflows increase with AR size
magnetoconvective simulations of emerging flux

M Rempel (custom runs provided; as per Rempel & Cheung 2014 ApJ)

<table>
<thead>
<tr>
<th></th>
<th>- 98 Mm</th>
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<tbody>
<tr>
<td>-29.6 hr</td>
<td>-24.3 hr</td>
<td>-19.0 hr</td>
</tr>
<tr>
<td>-13.6 hr</td>
<td>-8.3 hr</td>
<td>-2.9 hr</td>
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<tr>
<td>+2.4 hr</td>
<td>+8.7 hr</td>
<td></td>
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<tr>
<td></td>
<td>- 48 Mm</td>
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R Stein (“mhd48-1” see Stein & Nordlund 2012 ApJL)

Note: Stein’s simulation emerges a pore (not sunspot!) through convection of horizontal field at the bottom - included for context only!
MURaM simulations (Rempel & Cheung 2014)

upward advected semi-torus: torus radius=16Mm

\[ B = B_o e^{-r^2/r_o^2} \quad \frac{r}{r_o} \leq \sqrt{2} \]

<table>
<thead>
<tr>
<th>identifier</th>
<th>Upward flow</th>
<th>total flux</th>
<th>tube radius ( r_o )</th>
<th>field strength ( B_o )</th>
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</thead>
<tbody>
<tr>
<td>“MR 280”</td>
<td>280 m/s</td>
<td>10^{22} Mx</td>
<td>4.3 Mm</td>
<td>20 kG</td>
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<tr>
<td>“MR 140”</td>
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<td>10^{22}</td>
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<td>20</td>
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<tr>
<td>“MR 140a”</td>
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<td>5 x 10^{21}</td>
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<td>10</td>
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<tr>
<td>“MR 140b”</td>
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</tbody>
</table>

140m/s = average convective upflow at bottom (18Mm)
divergence comparisons: averaged EARs & simulations

observations more consistent with gentler emergence

caveats:
$10^{22}$ Mx flux in Rempel simulation larger than typical EAR in sample
deeper, further (back) in time?

- nothing obvious in mean shifts below ~few Mm (σ ~ 0.4 sec)
deeper, further continued...

- nothing obvious in flows; divergence signatures either...

- noise at 54 Mm ≤ 1 sec (EW, NS) 0.4 sec (mean)
conclusions

- near-surface magnetic and mean travel-time shifts present in ensemble-averaged maps ~30 hr prior to “emergence time”

- pre-emergence converging flows, followed by outflows and prograde flows

- plausible sources are supergranulation boundaries

- comparisons with MHD simulations suggest emergence is “gentle” with upflows not much greater than convective flows

- lots more to do...

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evolution of prograde feature