Properties of sunspot formation as seen from high-resolution observations

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Sunspot Formation, NORDITA Stockholm, 9-13 March 2015

Outline

- Sunspots: based on NOAA11024 (in collaboration with R. Schlichenmaier & R. Rezaei)
  - Magnetic flux emergence. Formation of Active Regions
  - Twist in emerging magnetic flux ropes
  - Magnetic halo (canopy) beyond the spot intensity boundaries
  - Gathering the emergent magnetic flux
  - The role of light bridges during sunspot formation
  - A counter-Evershed flow previous to the penumbra formation
- Conclusion: Scenario on sunspot formation

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Sunspots: based on NOAA 11024

Overall evolution of NOAA 11024

MDI/SoHO

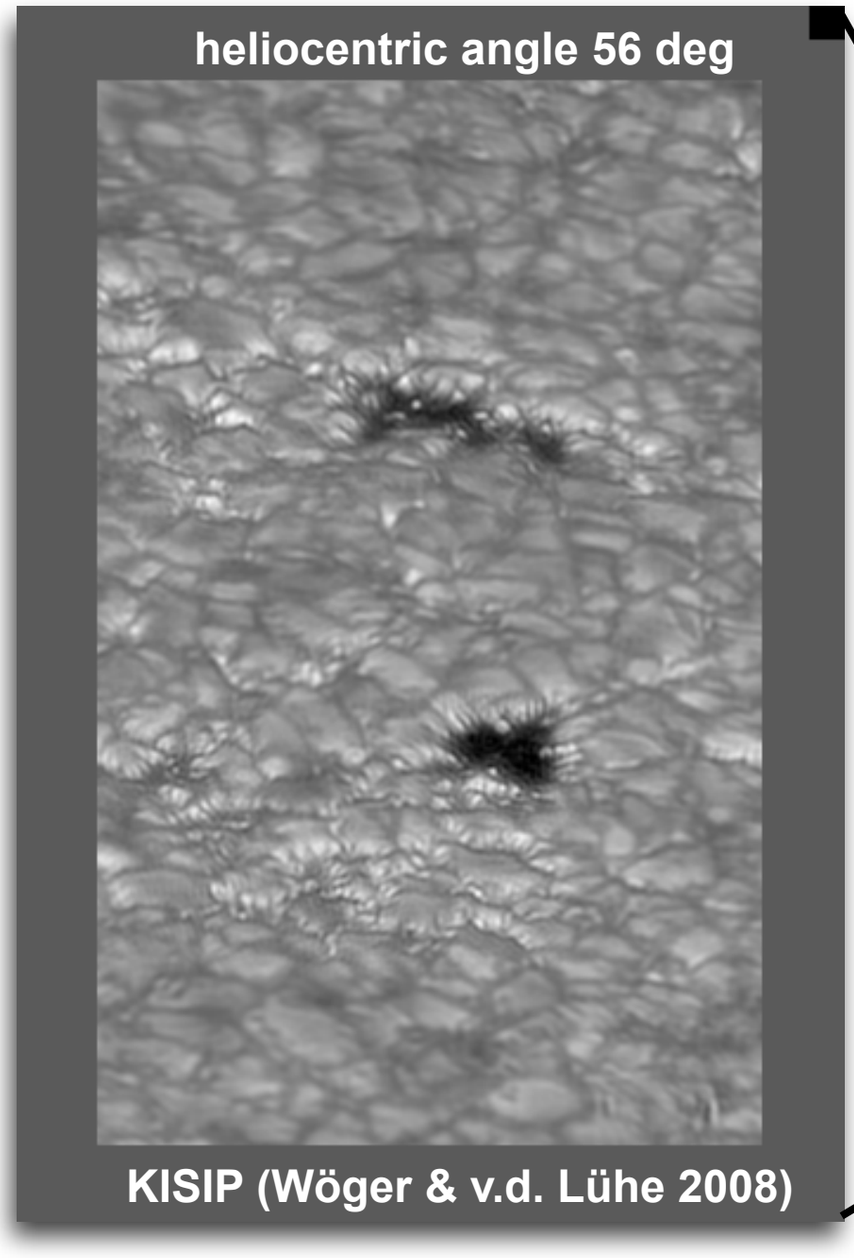
continuum

magnetogram

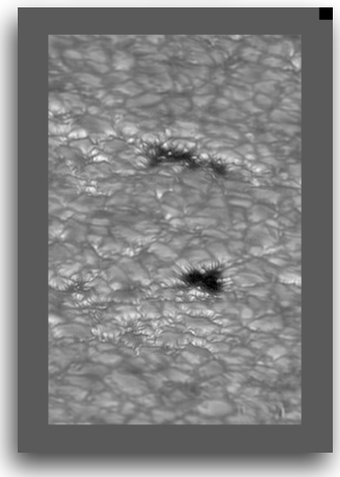
Observations July 1-10, 2009

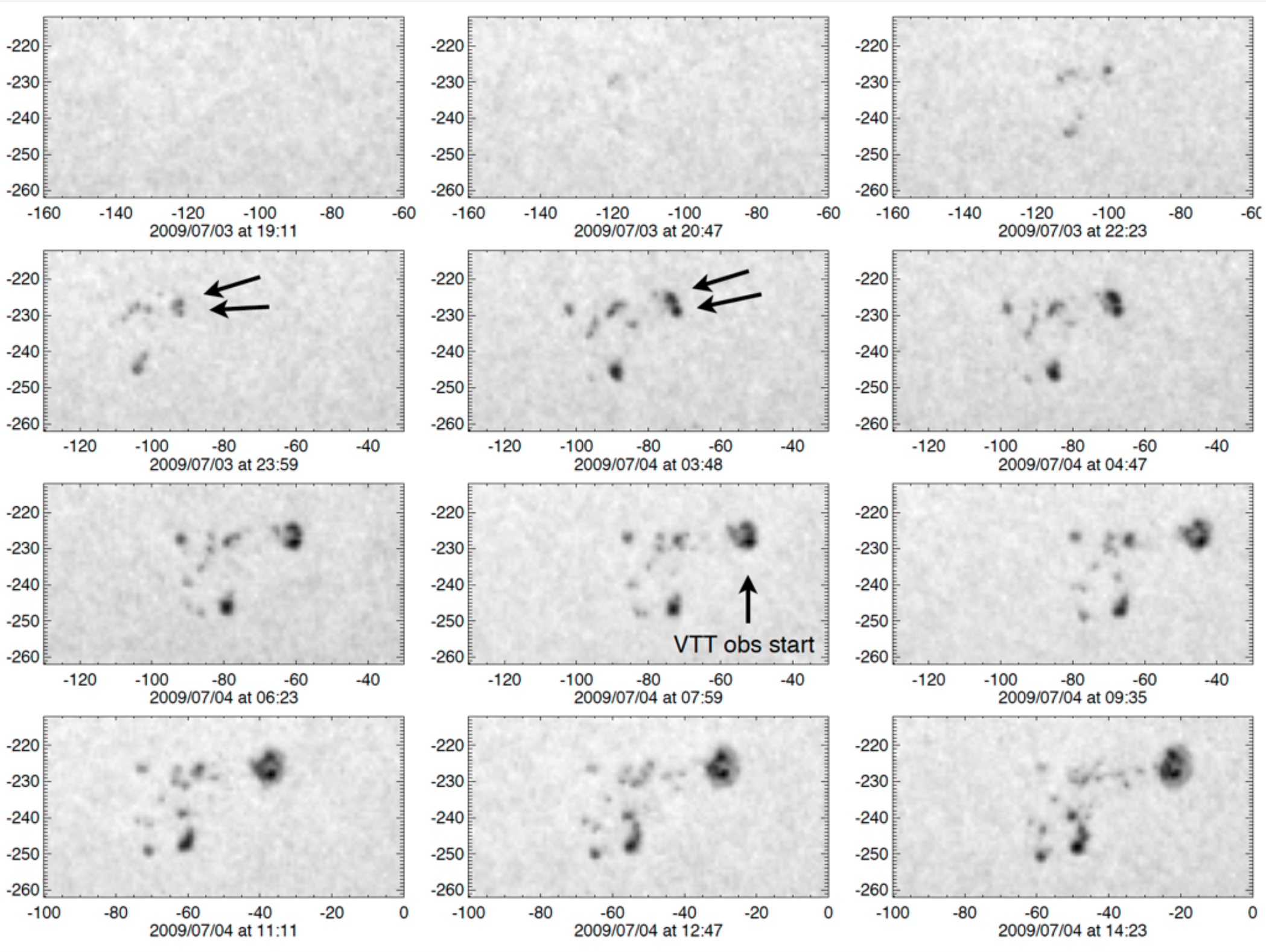
Observations at the German VTT

July 1, 2009: two pores only visible with high resolution



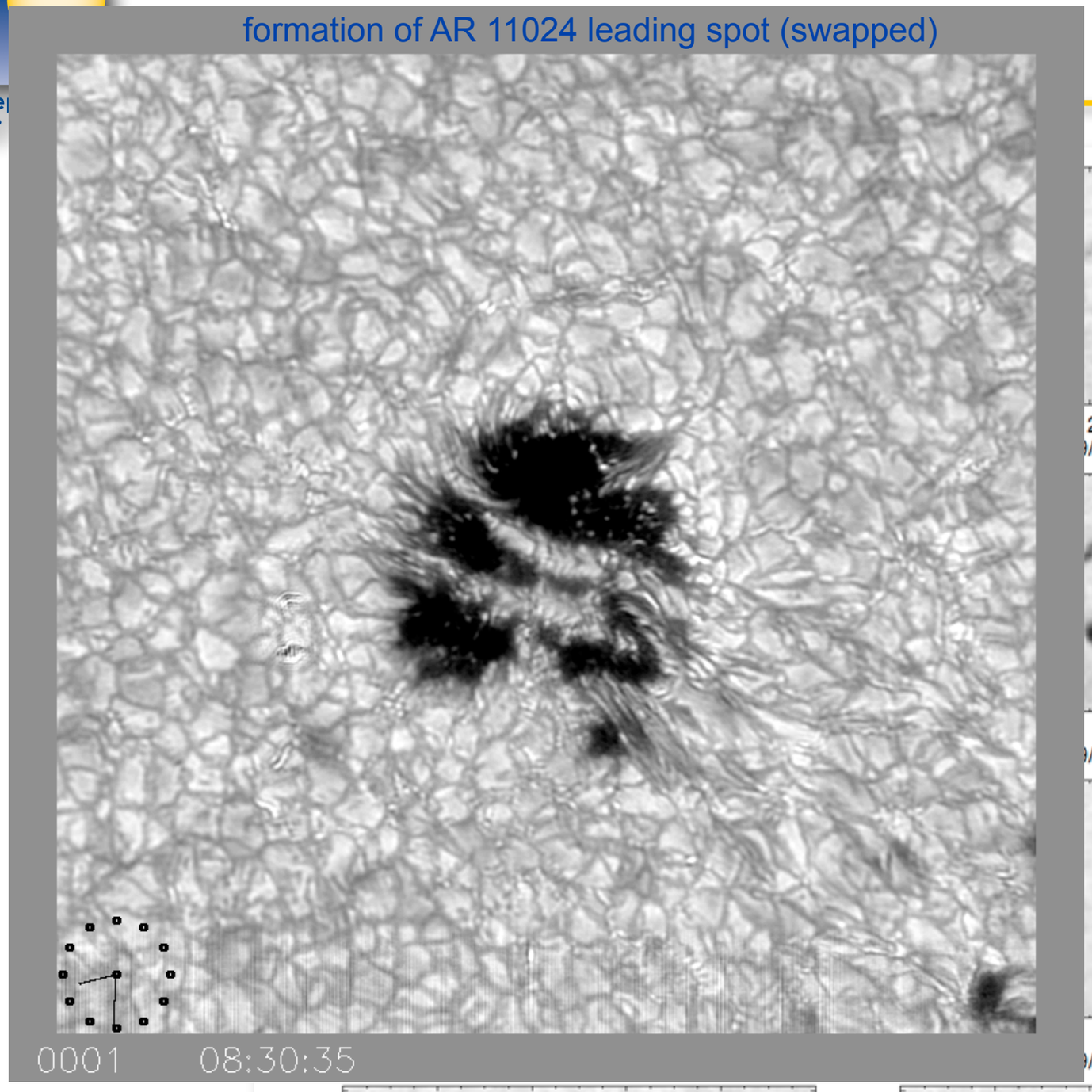
Formation and evolution of NOAA 11024





From *Schlichenmaier, Rezaei & Bello González (2012), ASPC, 455,61*

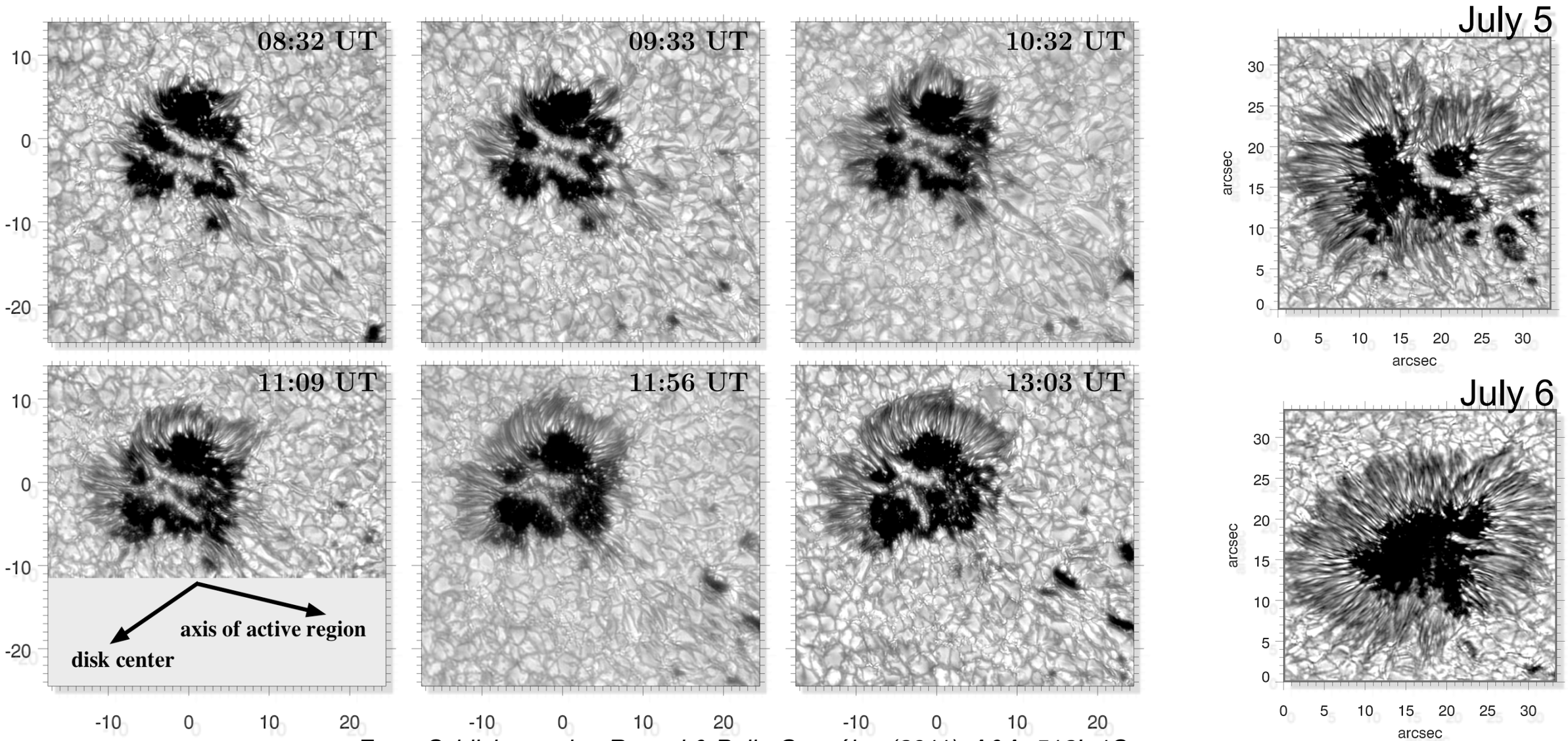
Formation AR 11024



From *Schlichenmaier, Rezaei & Bello González (2012), ASPC, 455,61*

From a protospot to a fully-fledge sunspot

- VTT (70 cm, Tenerife), July 4, 2009: *NOAA 11024* leading spot (~ 28deg)

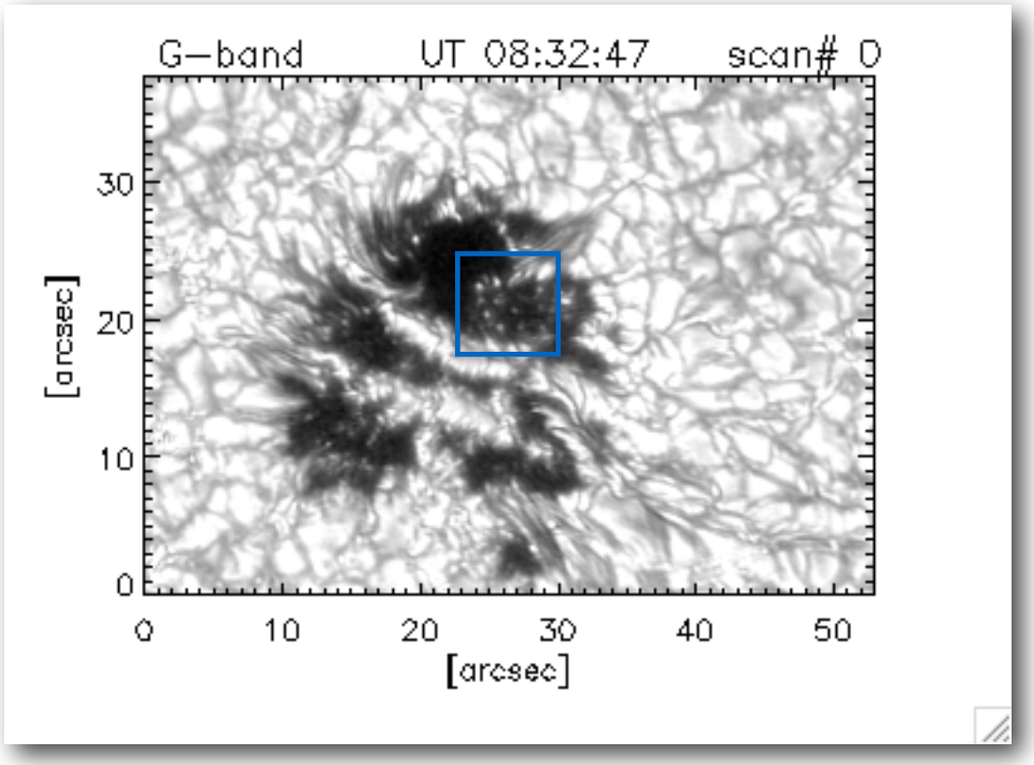


From *Schlichenmaier, Rezaei & Bello González (2011), A&A, 512L,1S*

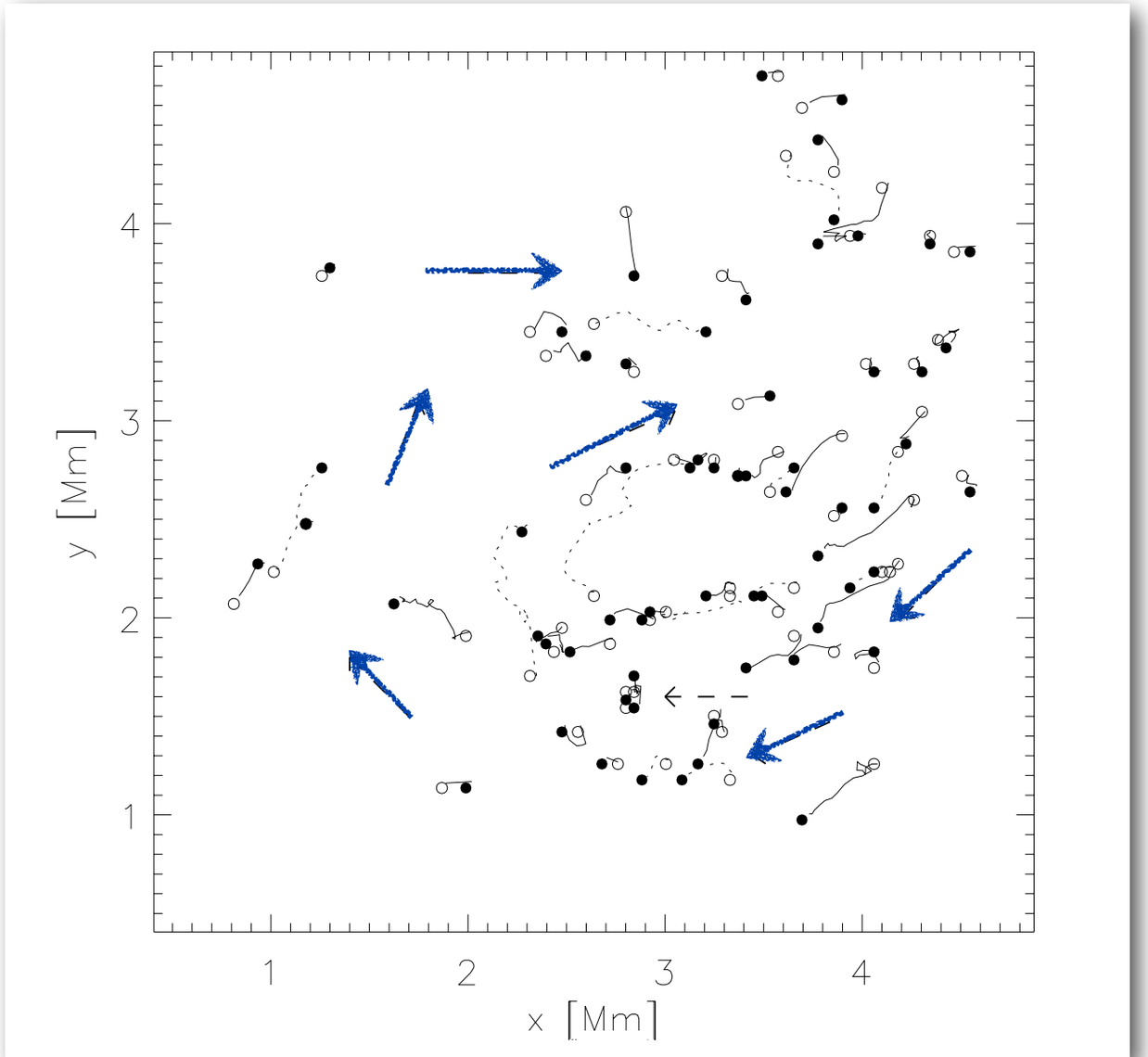
- G-band (403±0.5nm), speckle reconstructed

2. Twist in emerging magnetic flux ropes inferred from photospheric proper motions

Twist in emerging magnetic flux ropes inferred from photospheric proper motions

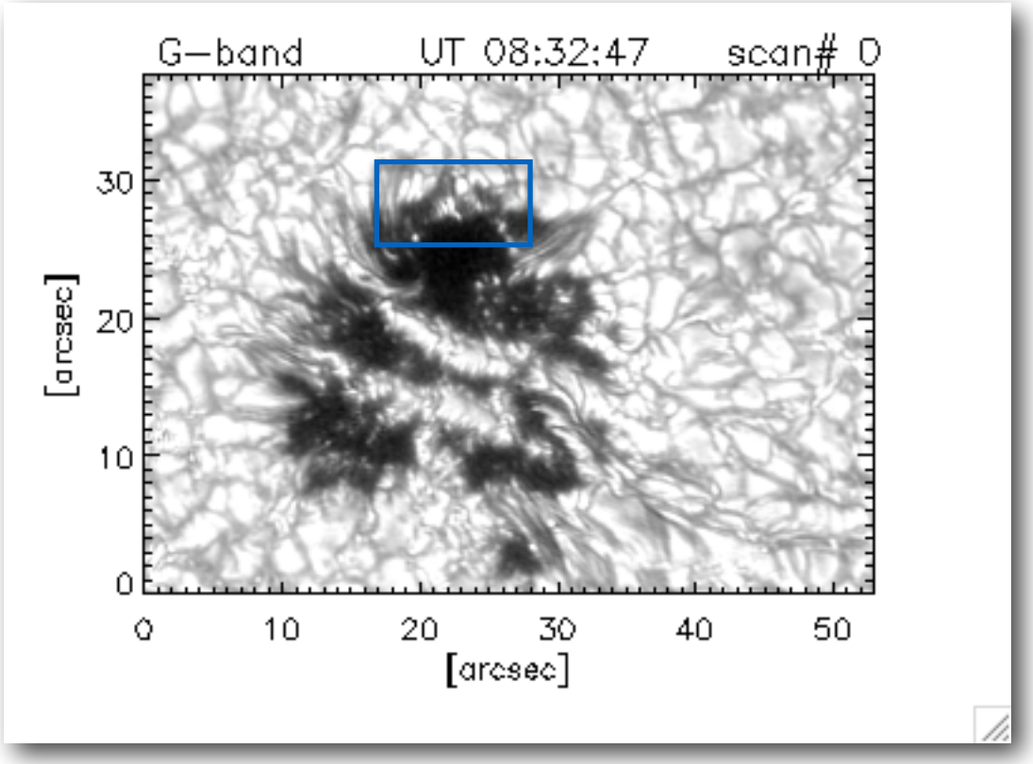


- Track of umbral dots proper motion (2h sequence)
- UDs outline a vortex motion with speeds up to 550 ms^{-1}



From *Bello González, Kneer & Schlichenmaier (2012), A&A, 538, 62*

Twist in emerging magnetic flux ropes inferred from photospheric proper motions



- Track of proper motions in magnetic features in the umbral border previous to the penumbra formation
- Speeds ~300 ms^{-1}

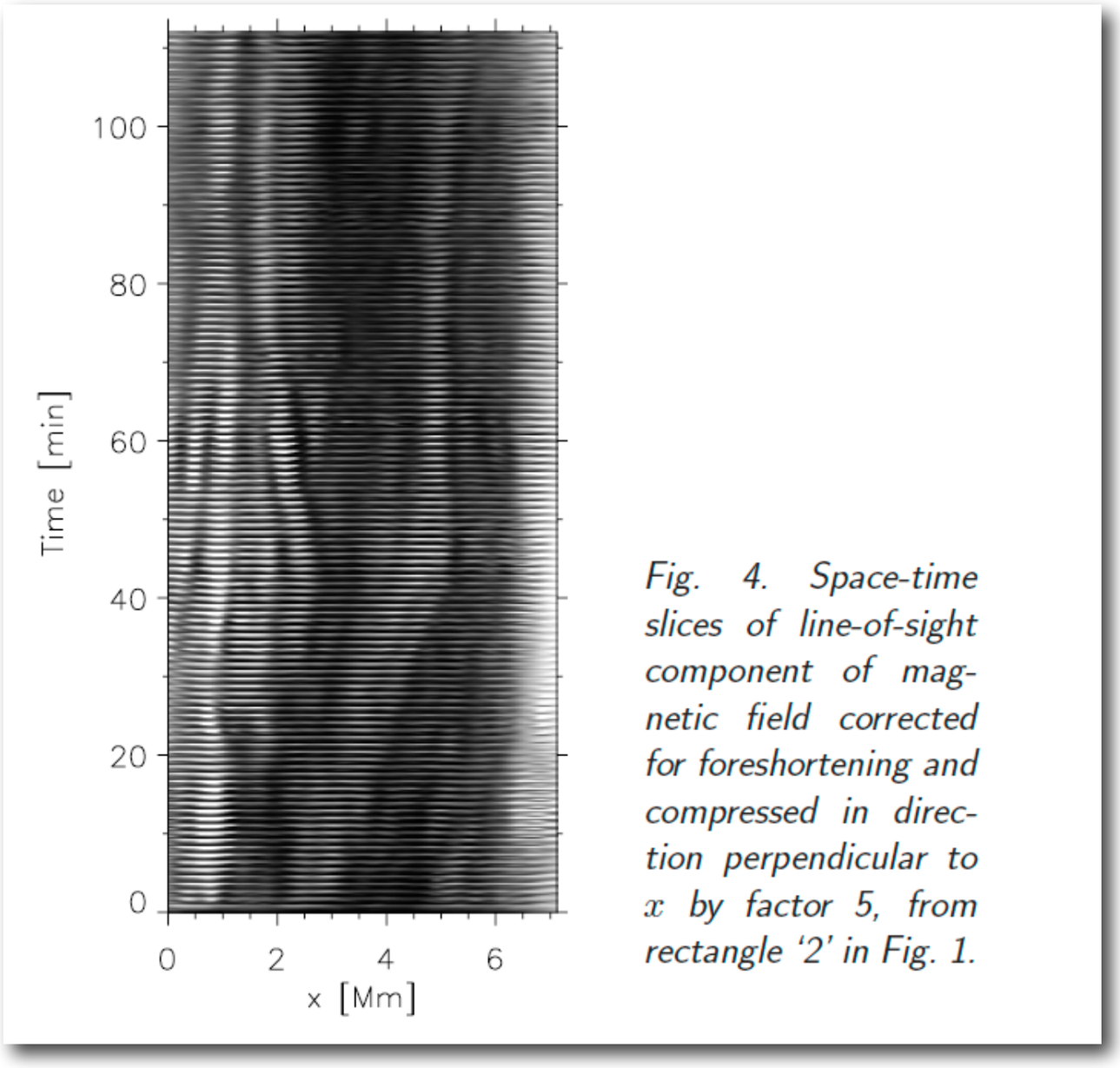
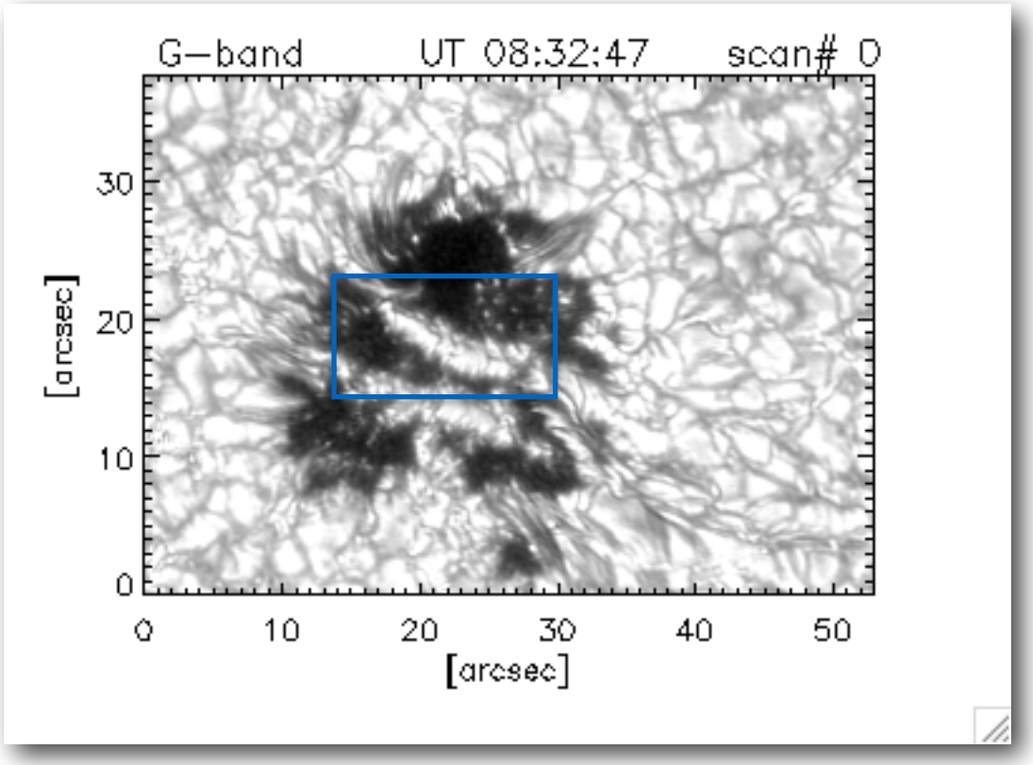
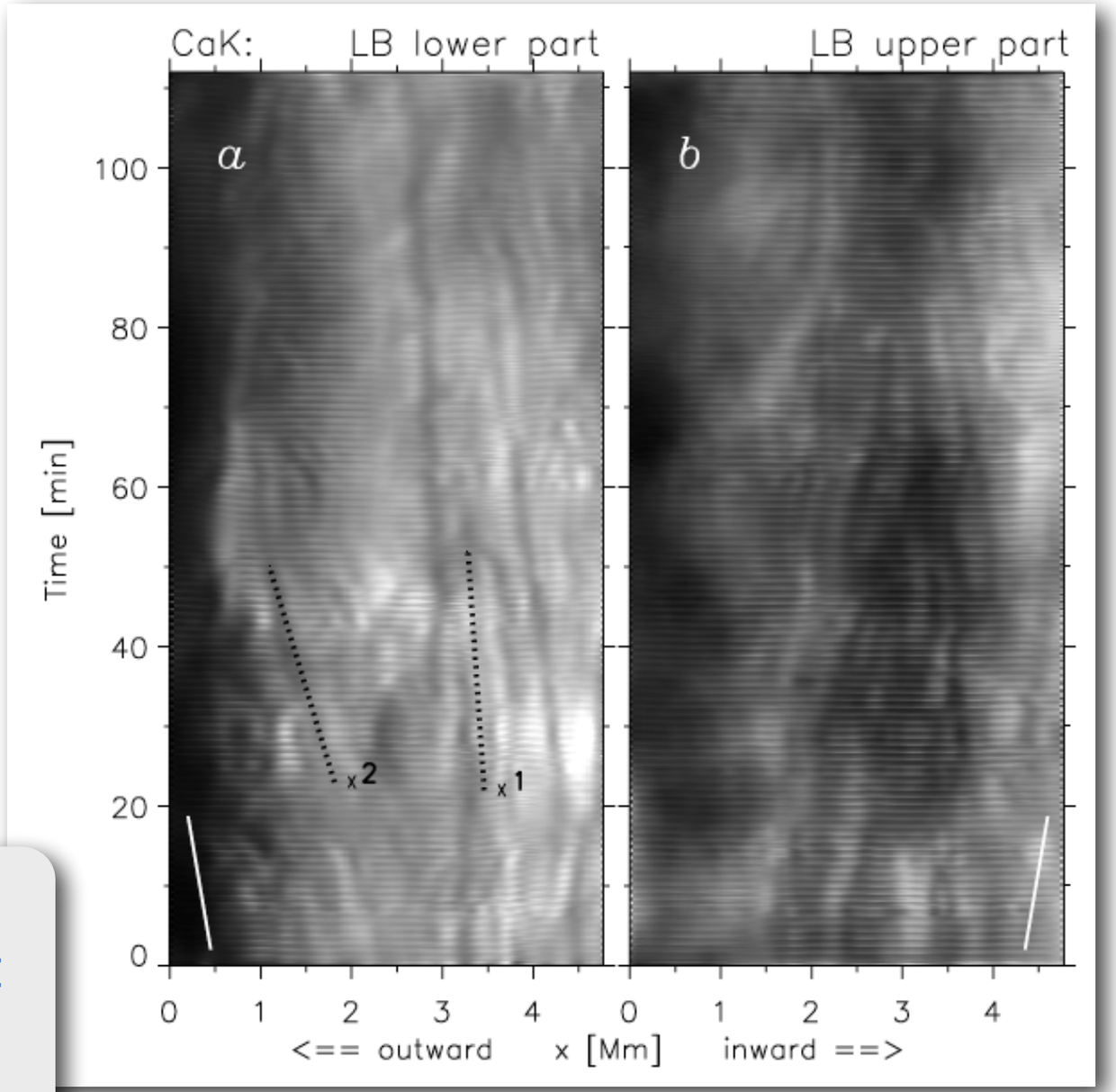


Fig. 4. Space-time slices of line-of-sight component of magnetic field corrected for foreshortening and compressed in direction perpendicular to x by factor 5, from rectangle '2' in Fig. 1.

From *Bello González, Kneer & Schlichenmaier (2012), A&A, 538, 62*

Twist in emerging magnetic flux ropes inferred from photospheric proper motions

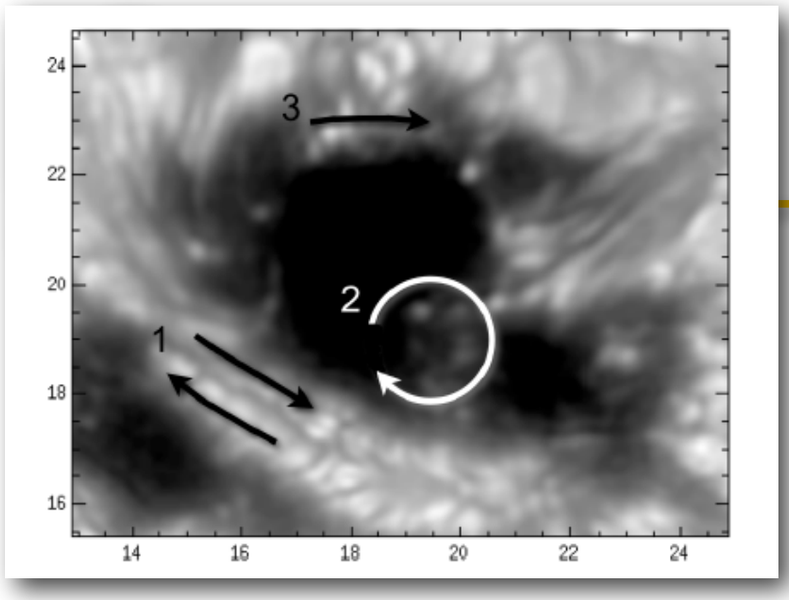




- Track of proper motions in the upper light bridge for 2h
- Shear motions with speeds ~100-500 ms^{-1}

From *Bello González, Kneer & Schlichenmaier (2012), A&A, 538, 62*

Twist in emerging magnetic flux ropes inferred from photospheric proper motions

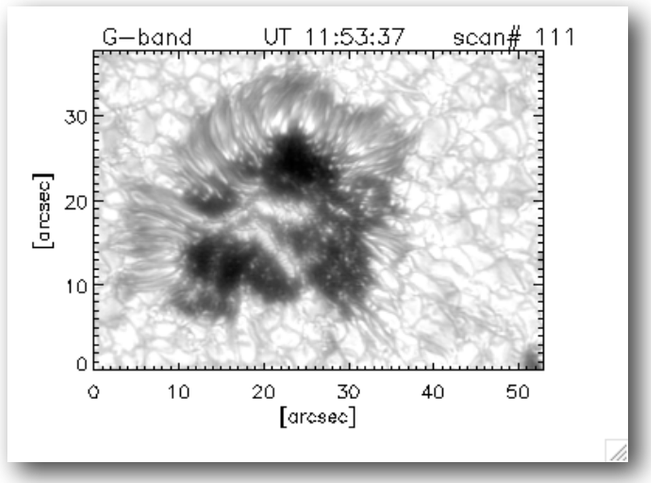


Further properties of this active region...

- the sunspot developed out of two coalescent individual pores separated by a light bridge

- no signature of an overall rotation that some sunspots undergo during their evolution; instead, individual rotation of one part of the spot

- the penumbral filaments formed later around the umbral core show a clear curvature, additional indication of a twist in this part of the umbra



- several flares were emitted by this AR during the emergence phase (Valori et al. 2011). Flare energy generation is thought to be favoured by twisting processes in emerging flux ropes (Schrijver et al. 2008; Padinhatteeri & Sankarasubramanian 2010).

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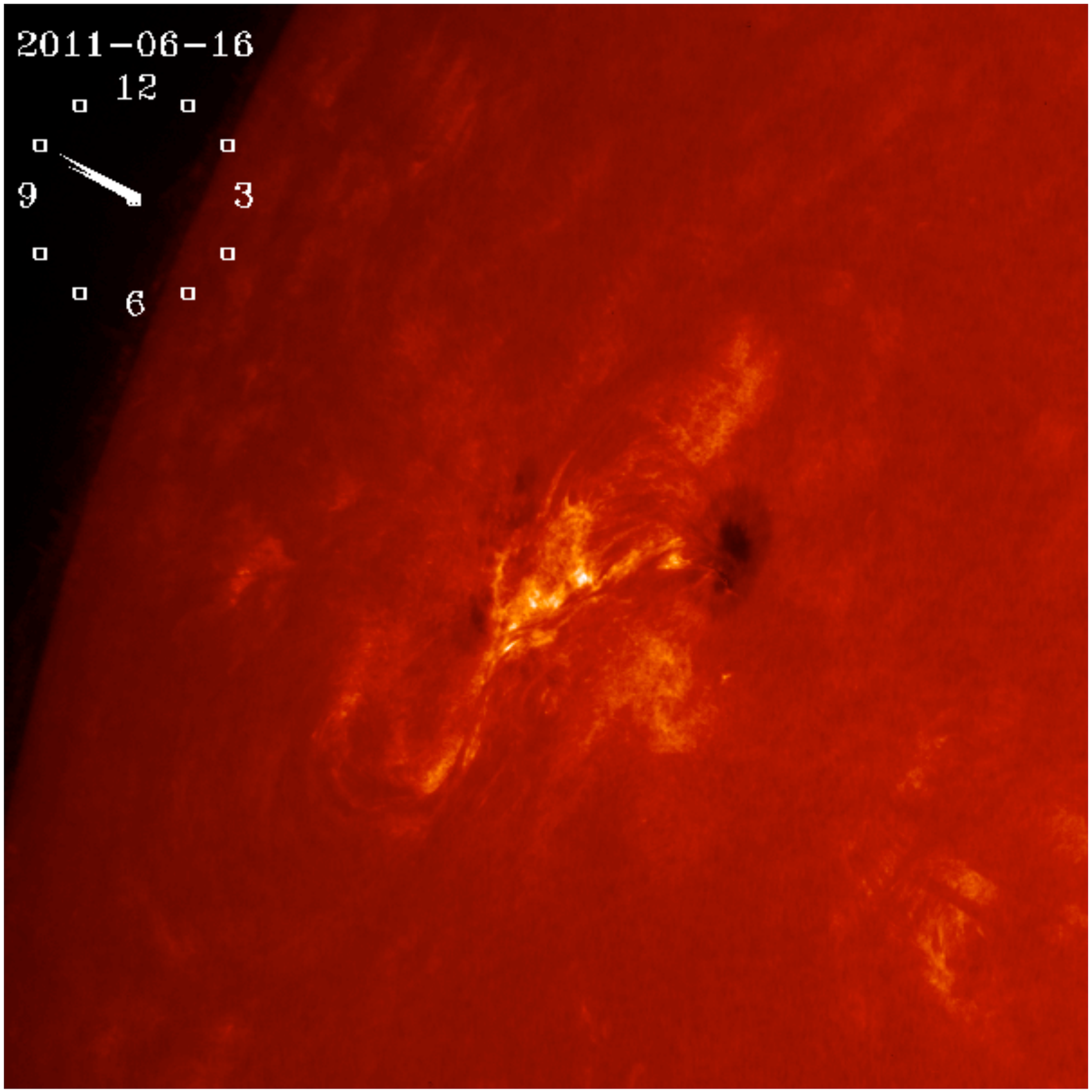
Twist in emerging magnetic flux ropes inferred from photospheric proper motions



AIA 304 Å & AIA 4500 Å @ SDO 2011

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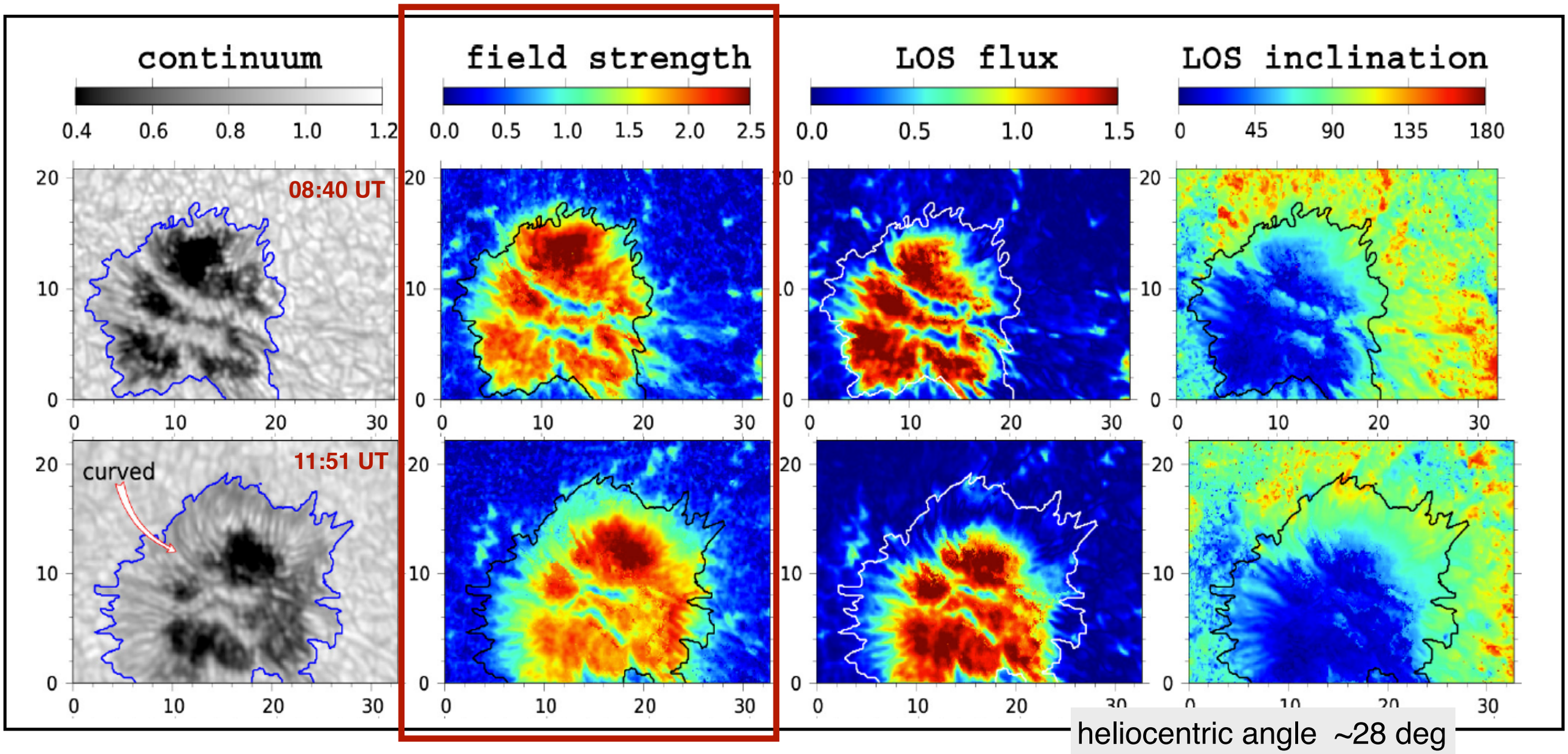
3. Magnetic halo (canopy) beyond the spot intensity boundaries: signature of penumbra formation

Magnetic halo beyond the intensity boundaries: signature of penumbra formation

08:40 UT: Previous to penumbra becoming visible in intensity, kG fields are present



11:51 UT: Once penumbra is formed, both intensity and magnetic boundaries of the spot coincide

From *Rezaei, Bello González & Schlichenmaier (2012), A&A, 537, A19*

Magnetic halo beyond the intensity boundaries: signature of penumbra formation

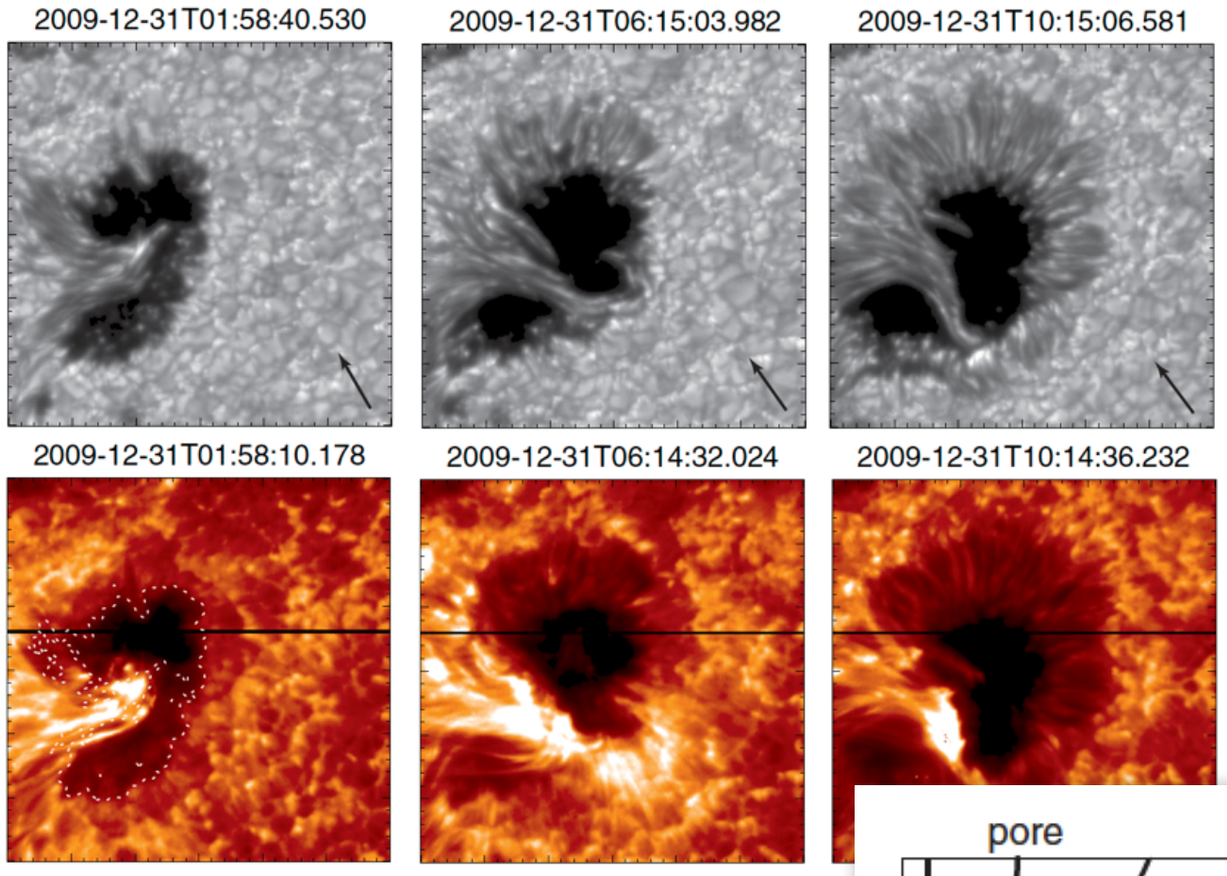


Figure 1. Evolution of the sunspot seen in the *G* band and Ca II H about every 4 hr. North is up and ea
300 pixels). The horizontal line in the Ca II H images indicates the position of the slit center for generati
pointing to the disk center and the dotted line is the umbral edge.
(A color version of this figure is available in the online journal.)

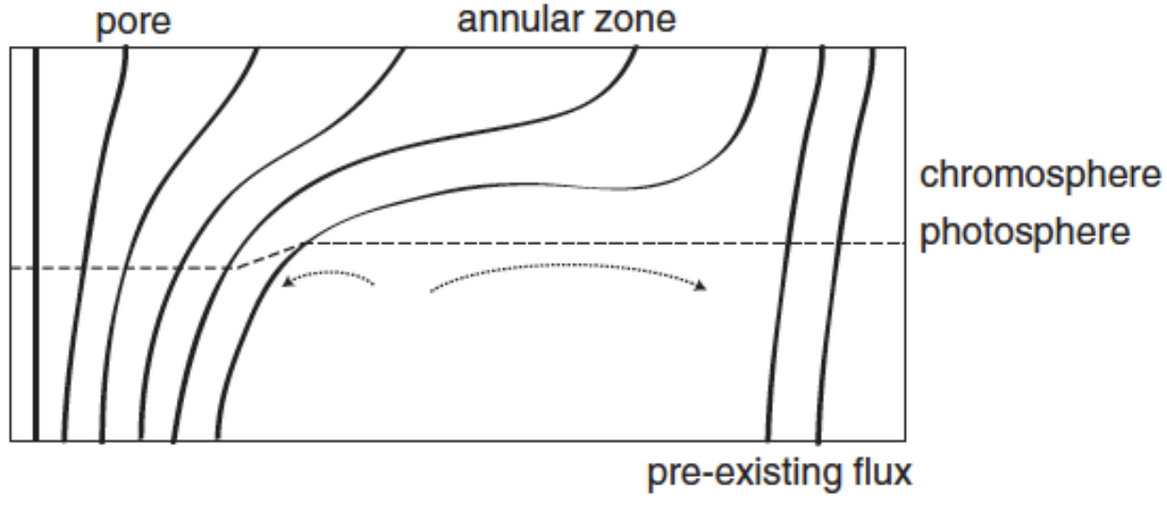


Figure 5. Magnetic field structure before the penumbral formation. The nearly horizontal dashed line indicates the photospheric ($\tau = 1$) level. The dotted lines with the arrow head are large-scale gas flows in the subsurface layer.

Magnetic halo beyond the intensity boundaries: signature of penumbra formation

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VELOCITY AND MAGNETIC FIELD DISTRIBUTION IN A FORMING PENUMBRA

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ABSTRACT

We present results from the analysis of high-resolution spectropolarimetric and spectroscopic observations of the solar photosphere and chromosphere, obtained shortly before the formation of a penumbra in one of the leading polarity sunspots of NOAA active region 11490. The observations were performed at the Dunn Solar Telescope of the National Solar Observatory on 2012 May 28, using the Interferometric Bidimensional Spectrometer. The data set is comprised of a 1 hr time sequence of measurements in the Fe I 617.3 nm and Fe I 630.25 nm lines (full Stokes polarimetry) and in the Ca II 854.2 nm line (Stokes *I* only). We perform an inversion of the Fe I 630.25 nm Stokes profiles to derive magnetic field parameters and the line-of-sight (LOS) velocity at the photospheric level. We characterize chromospheric LOS velocities by the Doppler shift of the centroid of the Ca II 854.2 nm line. We find that, before the formation of the penumbra, an annular zone of 3″–5″ width is visible around the sunspot. In the photosphere, we find that this zone is characterized by an uncombed structure of the magnetic field although no visible penumbra has formed yet. We also find that the chromospheric LOS velocity field shows several elongated structures characterized by downflow and upflow motions in the inner and outer parts of the annular zone, respectively.

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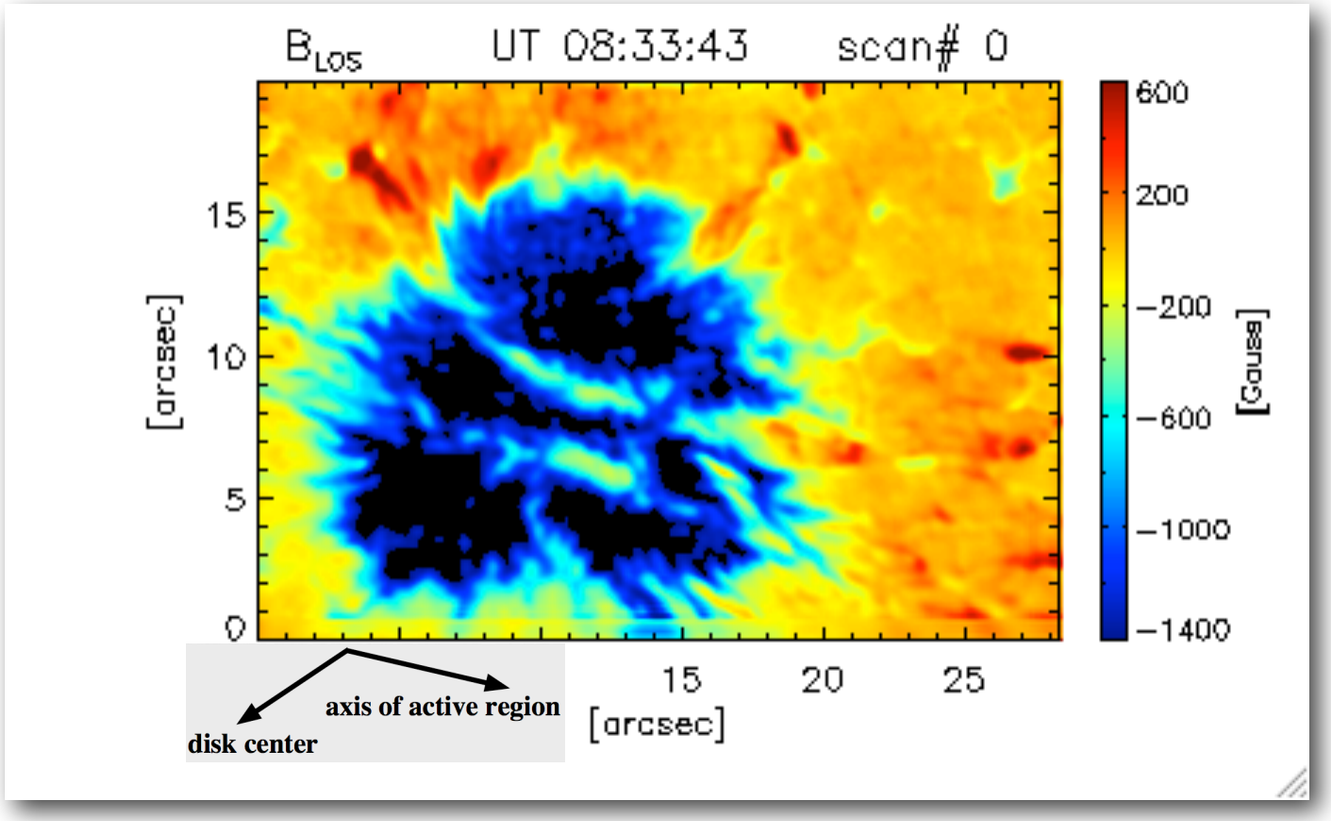
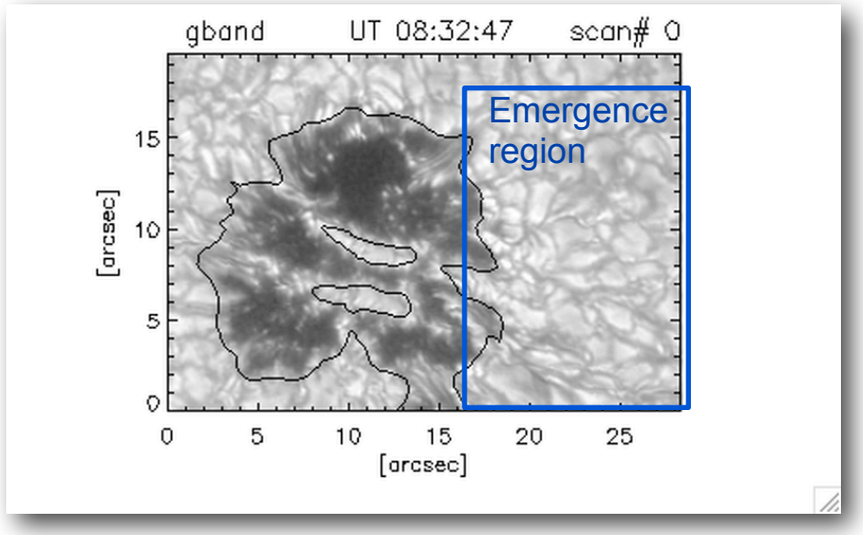
4. Gathering the emergent magnetic field

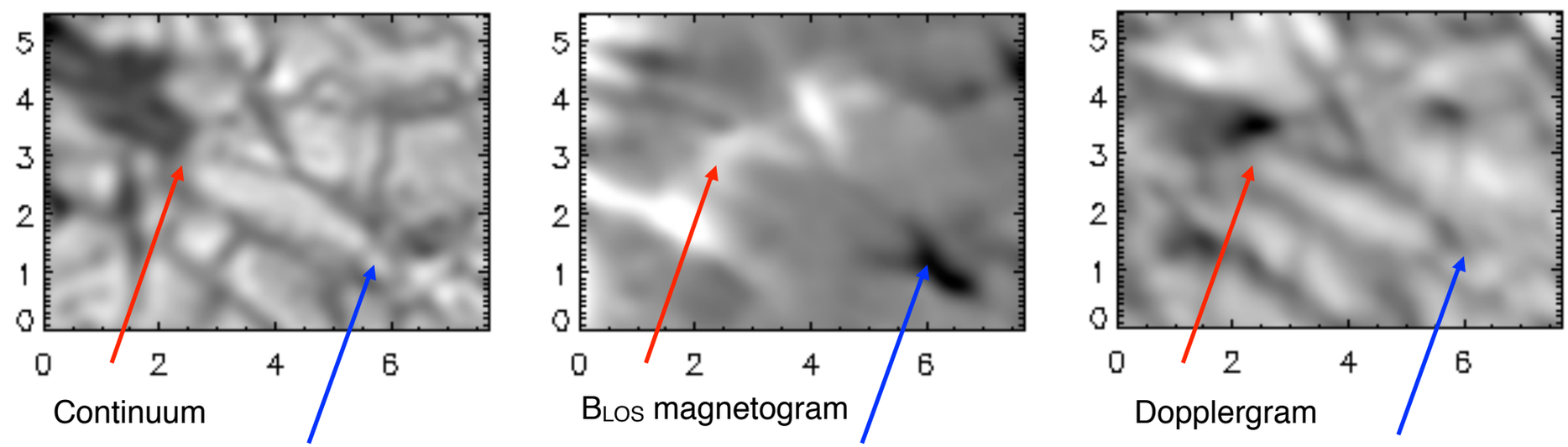
Gathering the emergent magnetic field



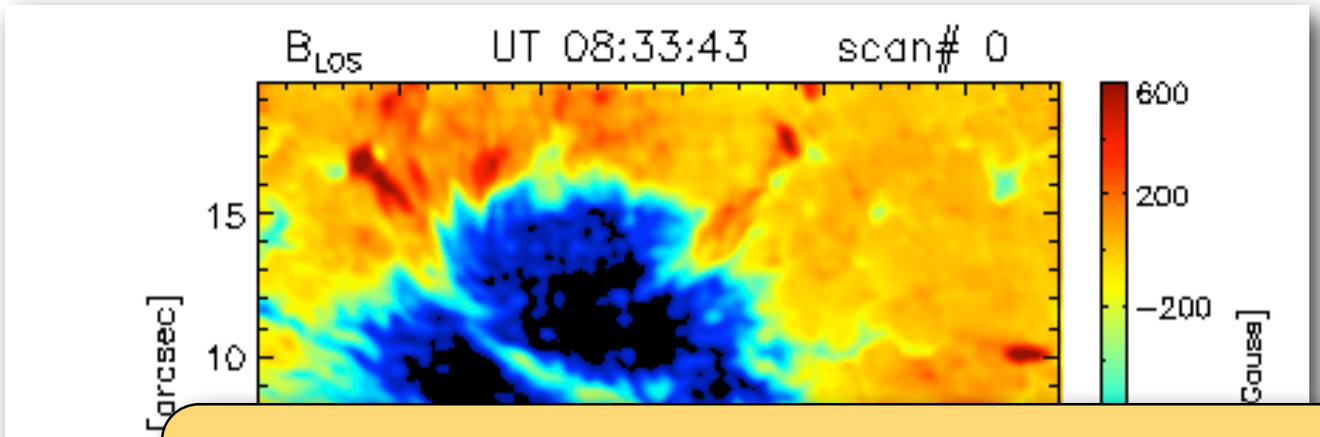


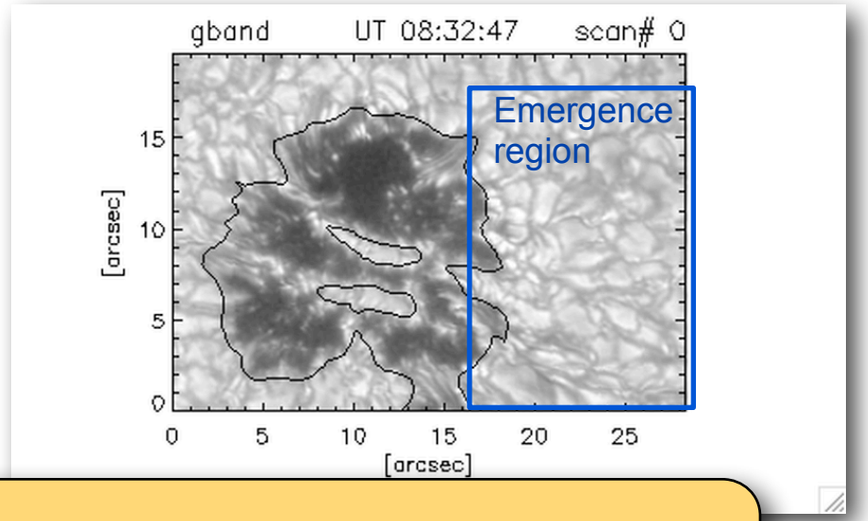
- As the protospot develops, it gathers the newly emergent (seen as serpentine fields) magnetic flux of its own polarity.
- No pores are joining this spot

Example of magnetic bipole



Gathering the emergent magnetic field





- Total **magnetic flux increases** in 4h

  1.6×10^{21} Mx ➡ 2.4×10^{21} Mx

  which means a typical fully-fledged sunspot (**~10^{22} Mx**) in 2.3 days

- Newly emerged magnetic concentrations carry typically 3×10^{18} Mx

  ➡ the sunspot flux gathering time rate should be 1-2 magnetic concentrations per minute

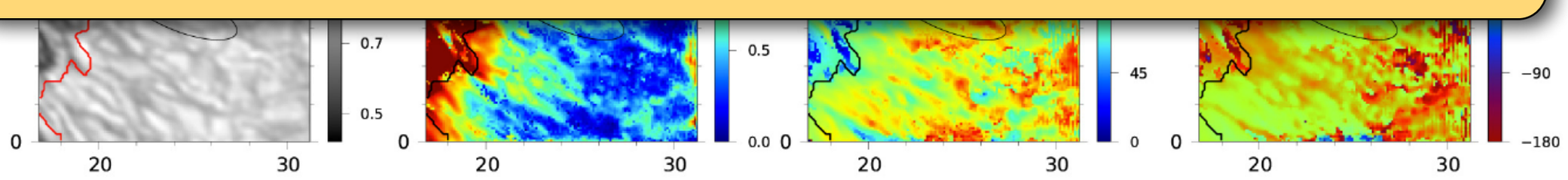


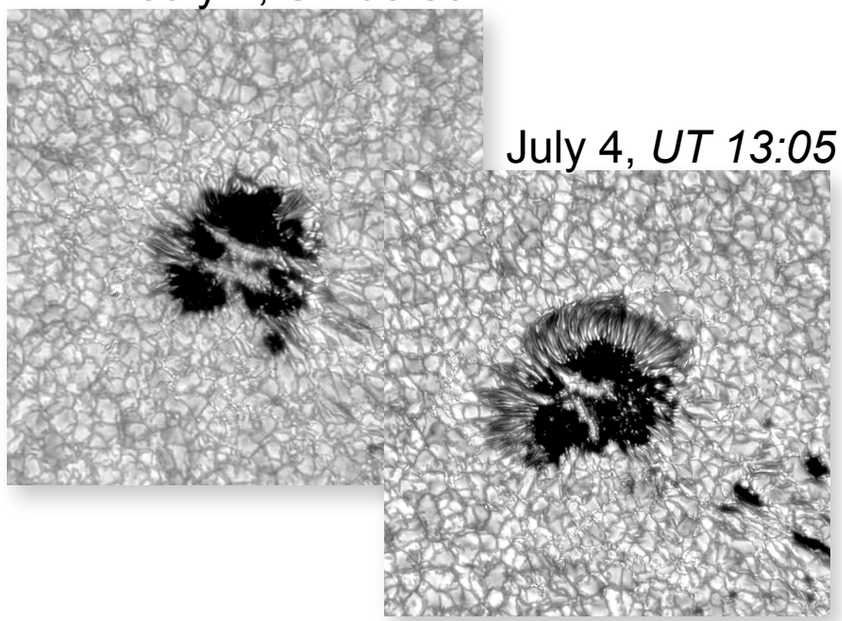
Fig. 9. Elongated granule and the corresponding bipole (marked by ellipse) in GFPI data. *Left to right*: continuum intensity (normalized to quiet Sun), magnetic field strength between zero and 1.5 kG, inclination, and azimuth (deg) in the local reference frame. The coordinates of the selected area shown here correspond to the middle-top panel of Fig. 6.

From *Rezaei, Bello González & Schlichenmaier (2012), A&A, 537, A19*

Magnetic flux during sunspot formation

July 4, *UT 08:30*

July 4, *UT 13:05*



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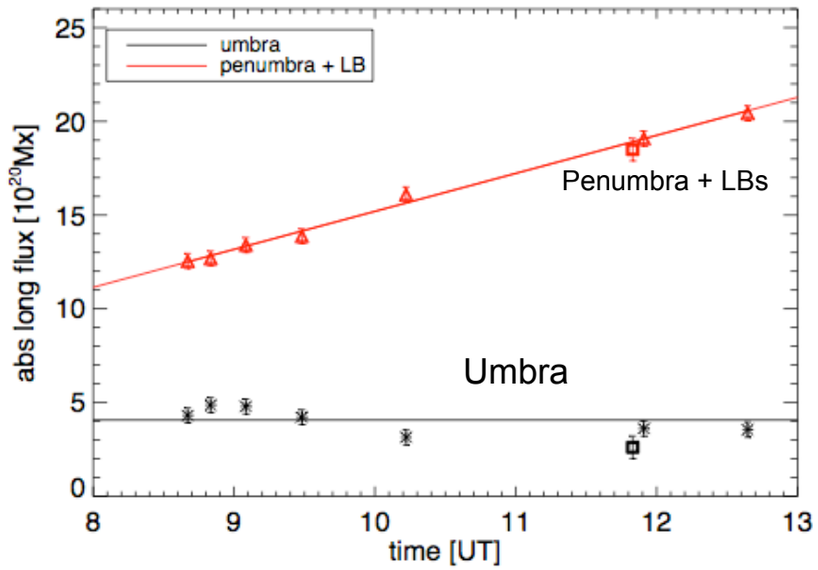
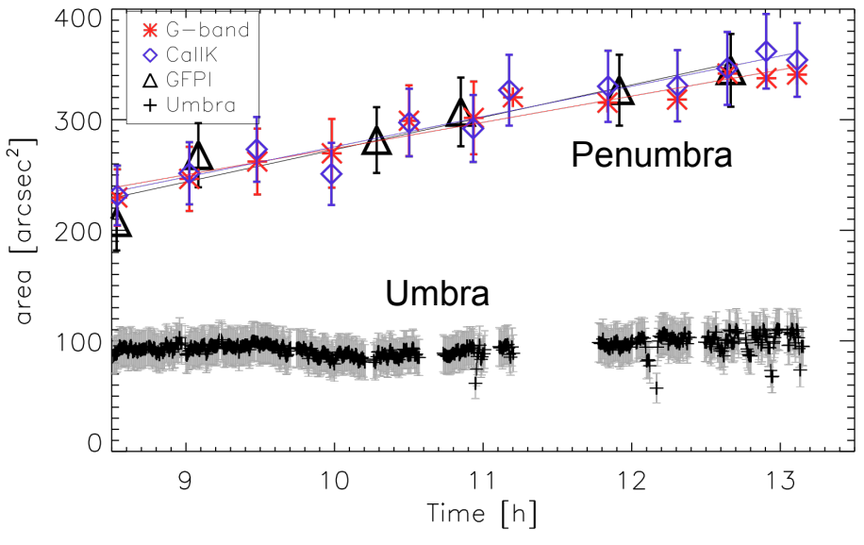
Sunspot flux increase

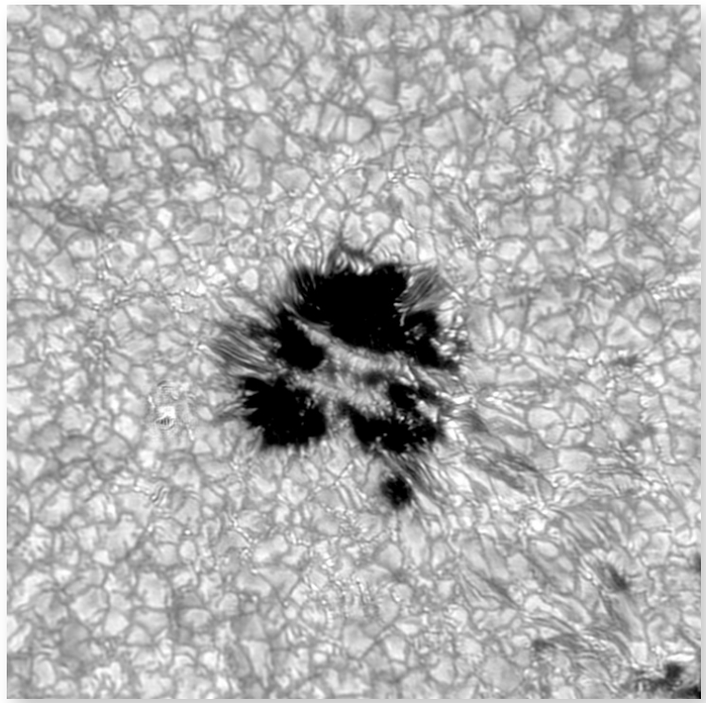


Sunspot area increase

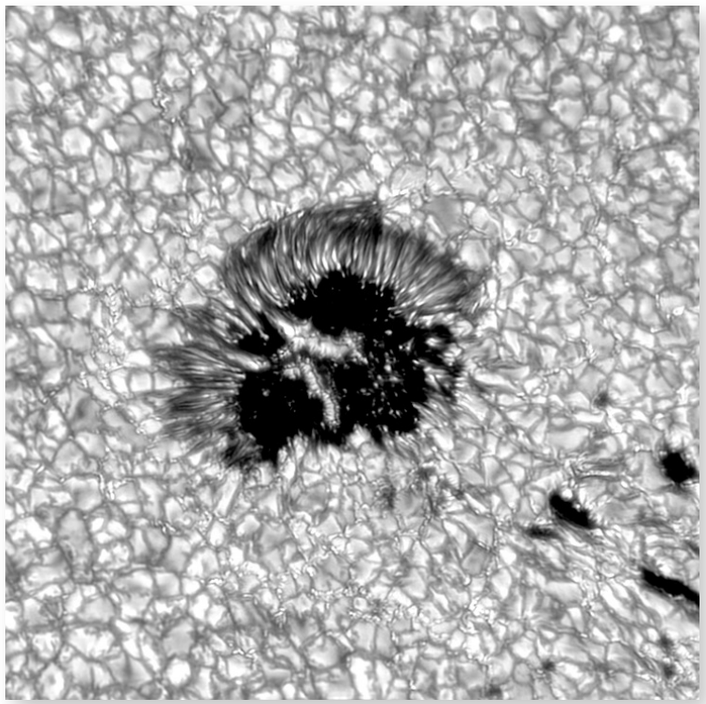


Penumbra formation

July 4, *UT 08:30*



July 4, *UT 13:05*



Penumbra formation

- Stable penumbra forms in the side opposite to the emergence site, i.e., the emerging (vertical) fields in the emergence site prevent penumbra from stably forming

- Penumbra forms at expenses of both, surrounding granulation & umbral areas

- Penumbra colonises umbral areas only until a certain B_{ver} value is achieved. This B_{ver} appears to be common to the inner penumbral boundaries of all sunspots ->

-> see talk by R. Schlichenmaier on Thursday afternoon!

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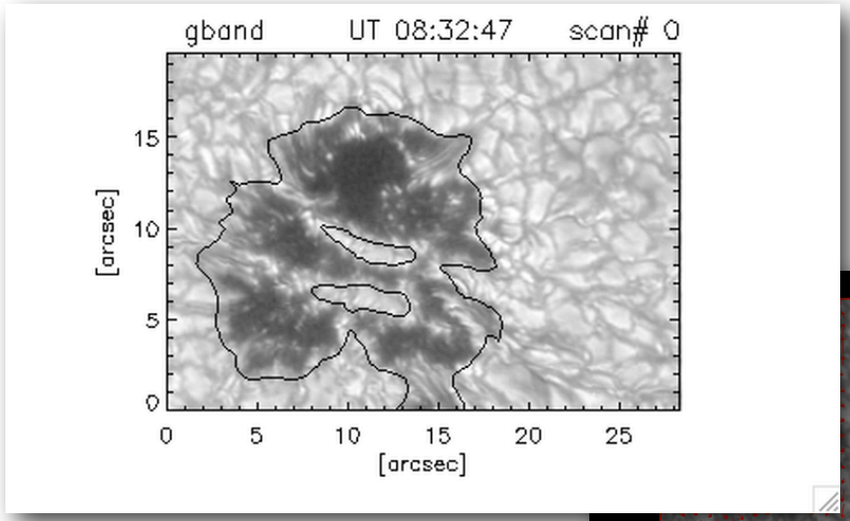
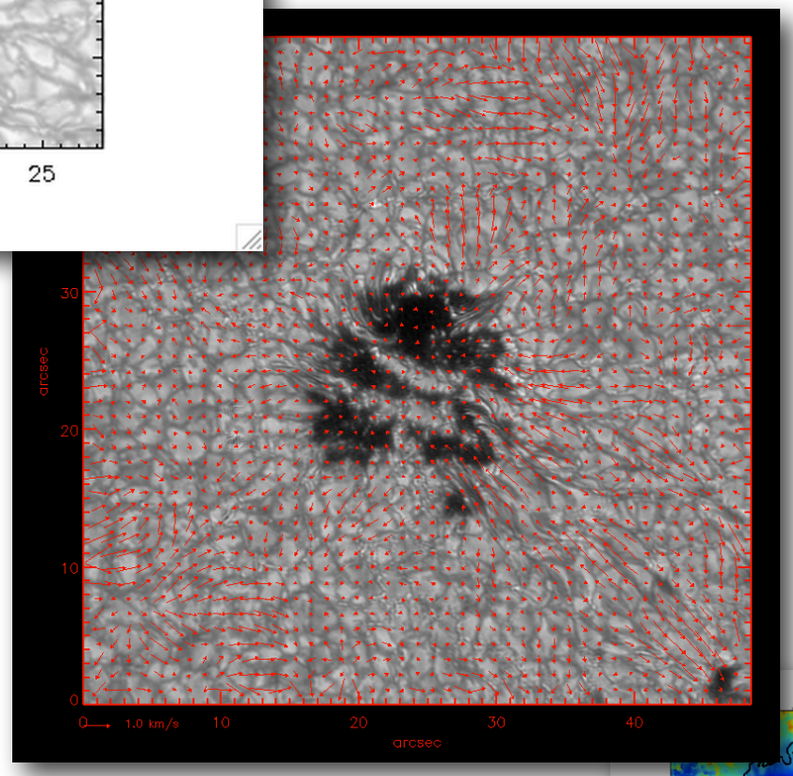
5. The role of light bridges during sunspot formation

The role of light bridges during sunspot formation



- Light bridges appear to be a natural path for the new emerging flux to ‘join’ the spot



horizontal motions from local correlation tracking

- LB magnetic field inclination becomes more vertical (more umbral-like) with time

- LB area decreases with time until disappearing (after 2 days)

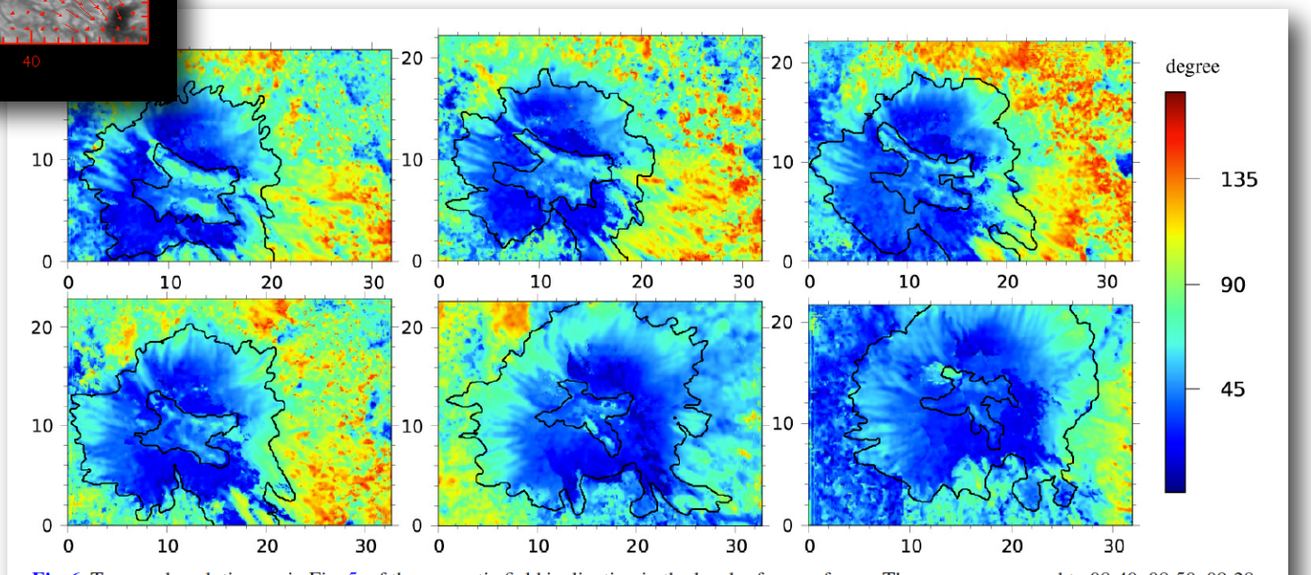
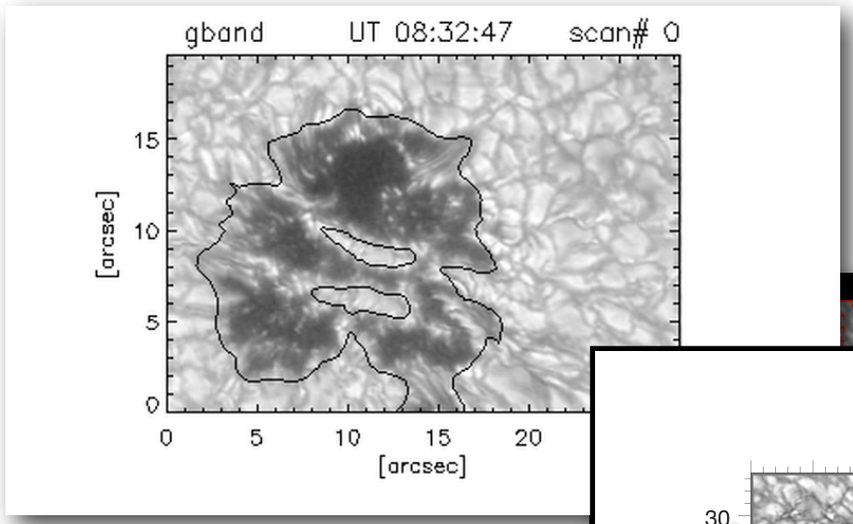


Fig. 6. Temporal evolution, as in Fig. 5, of the magnetic field inclination in the local reference frame. The maps correspond to 08:40, 08:50, 09:28, 10:13, 11:54, and 12:38 UT. The inner contours outline LBs. The outer contours are the same as in Fig. 5.

- LBs gather the incoming surrounding flux and ‘saturate’ thus becoming more umbral-like, finally fading away as umbral dots

The role of light bridges during sunspot formation



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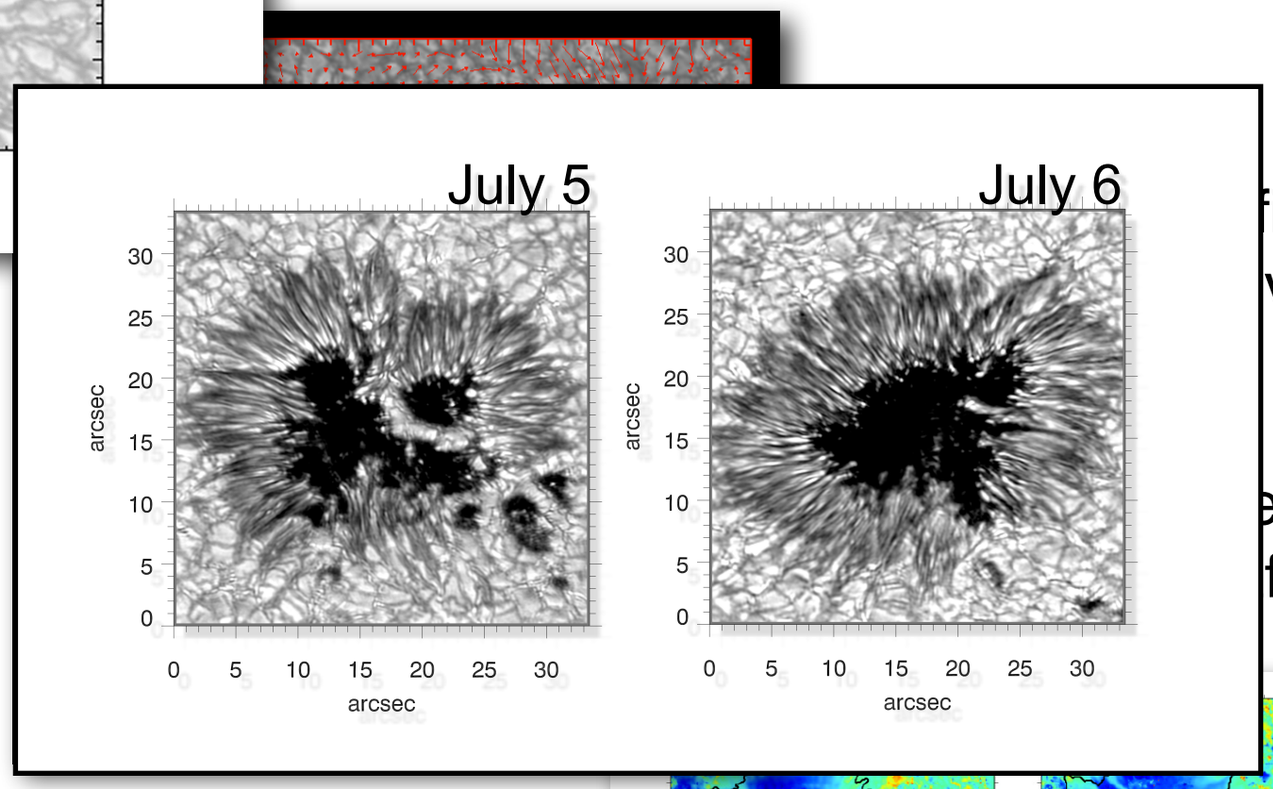
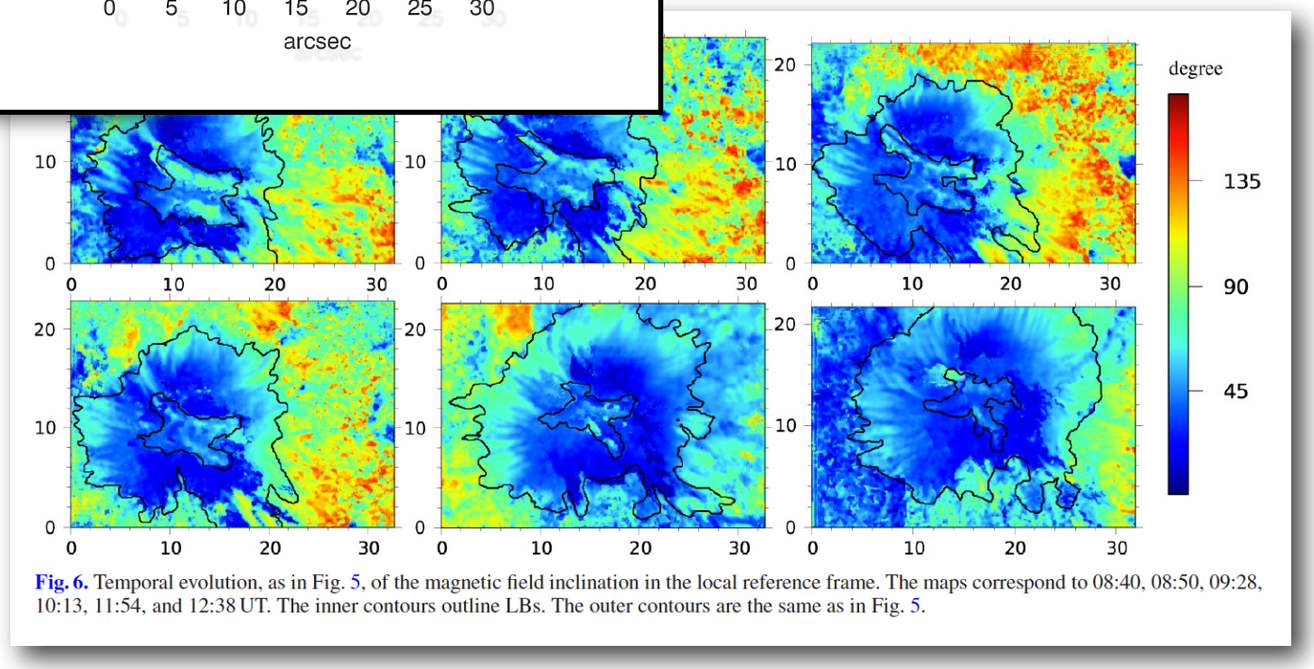


horizontal motions from local correlation tracking

field inclination vertical (more umbral-

eases with time until fter 2 days)



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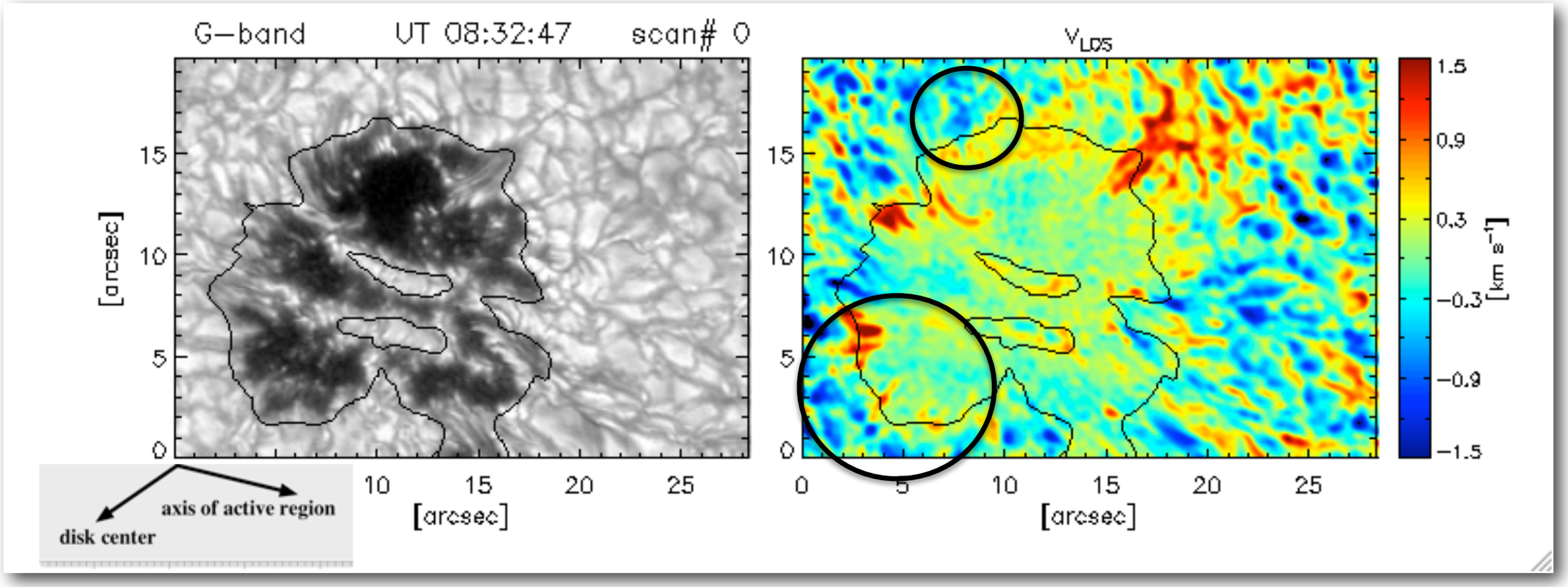
6. Observations of a counter-Evershed flow previous to the penumbra formation

Counter-Evershed flow previous to the penumbra formation

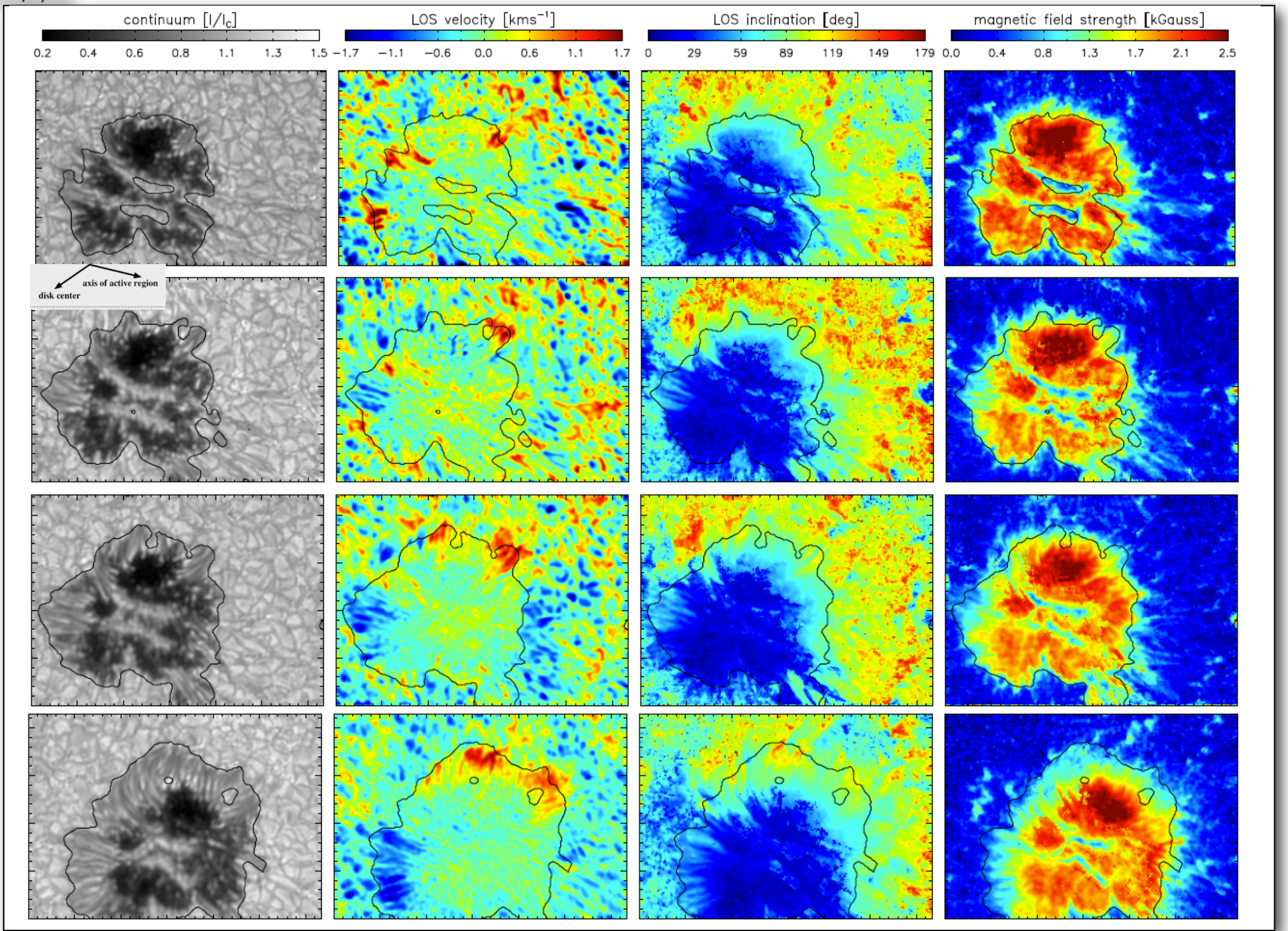
heliocentric angle ~28 deg



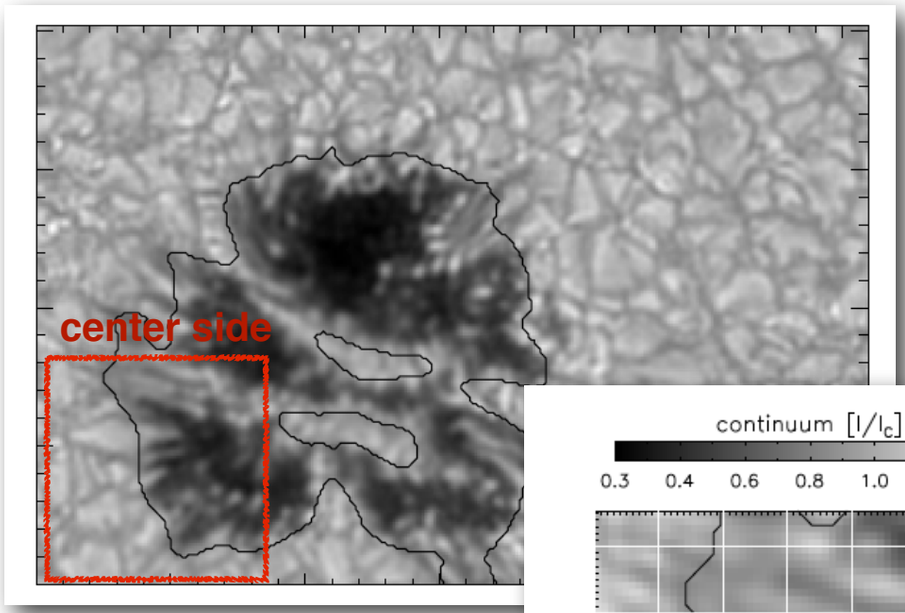
G-band intensity

Dopplermaps from (COG method)

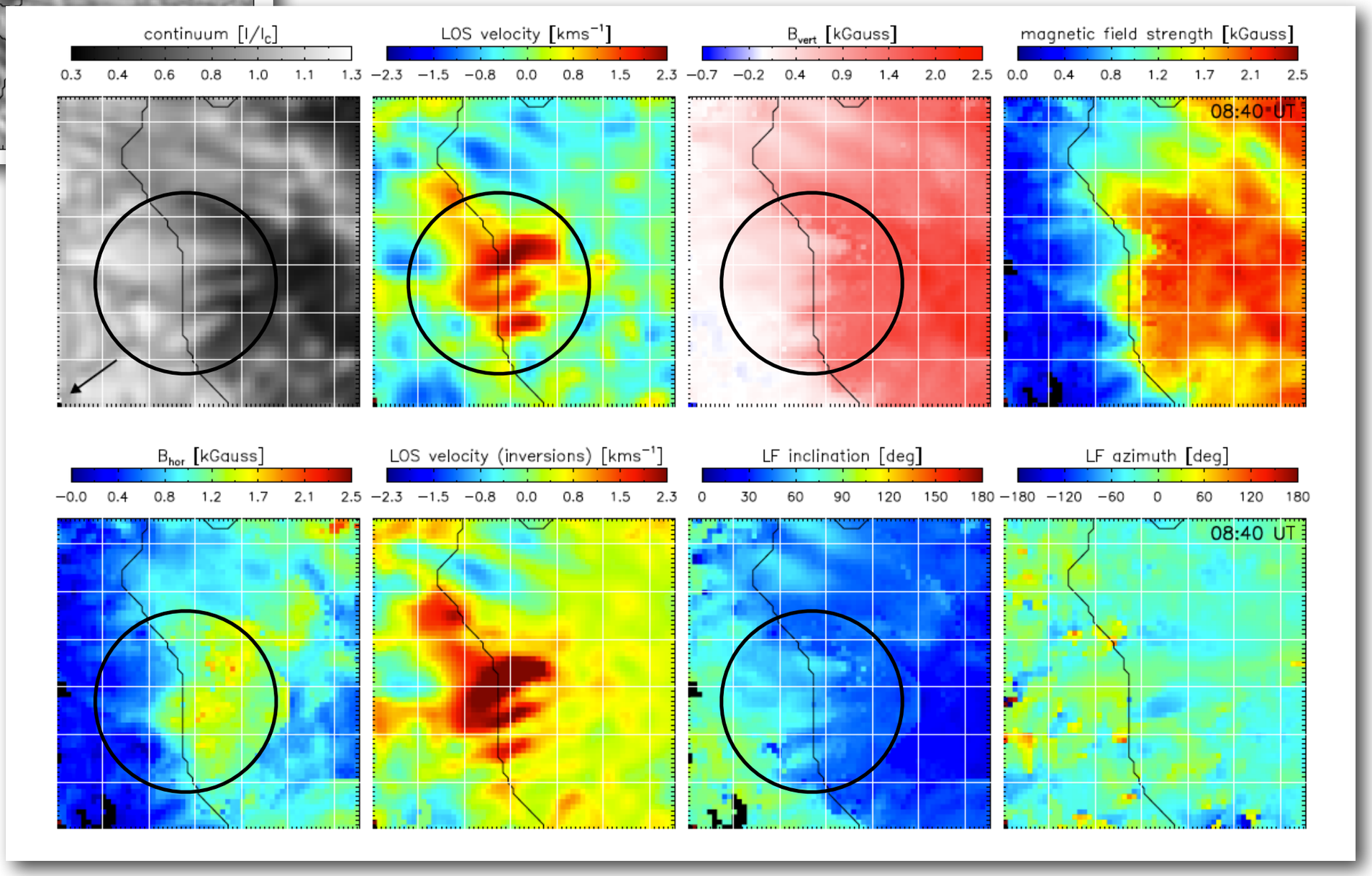
Counter-Evershed flow previous to the penumbra formation



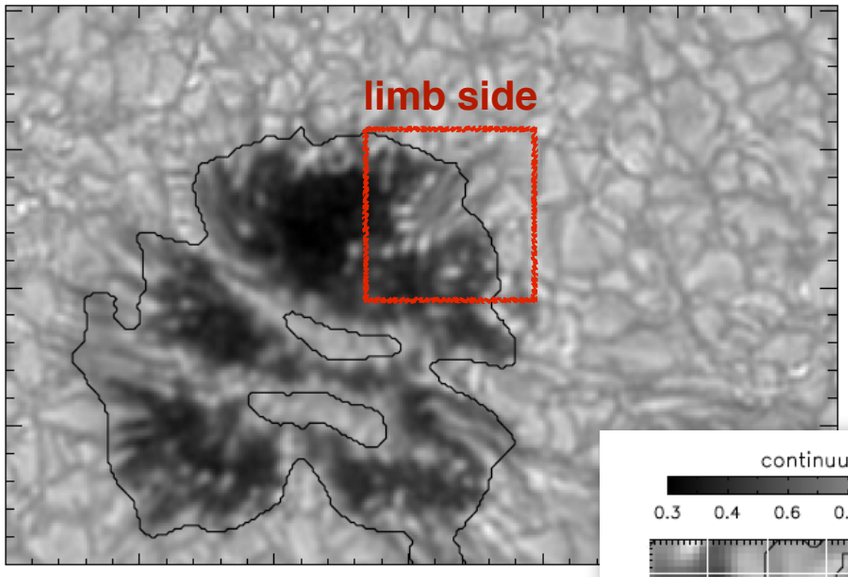
Counter-Evershed flow previous to the penumbra formation



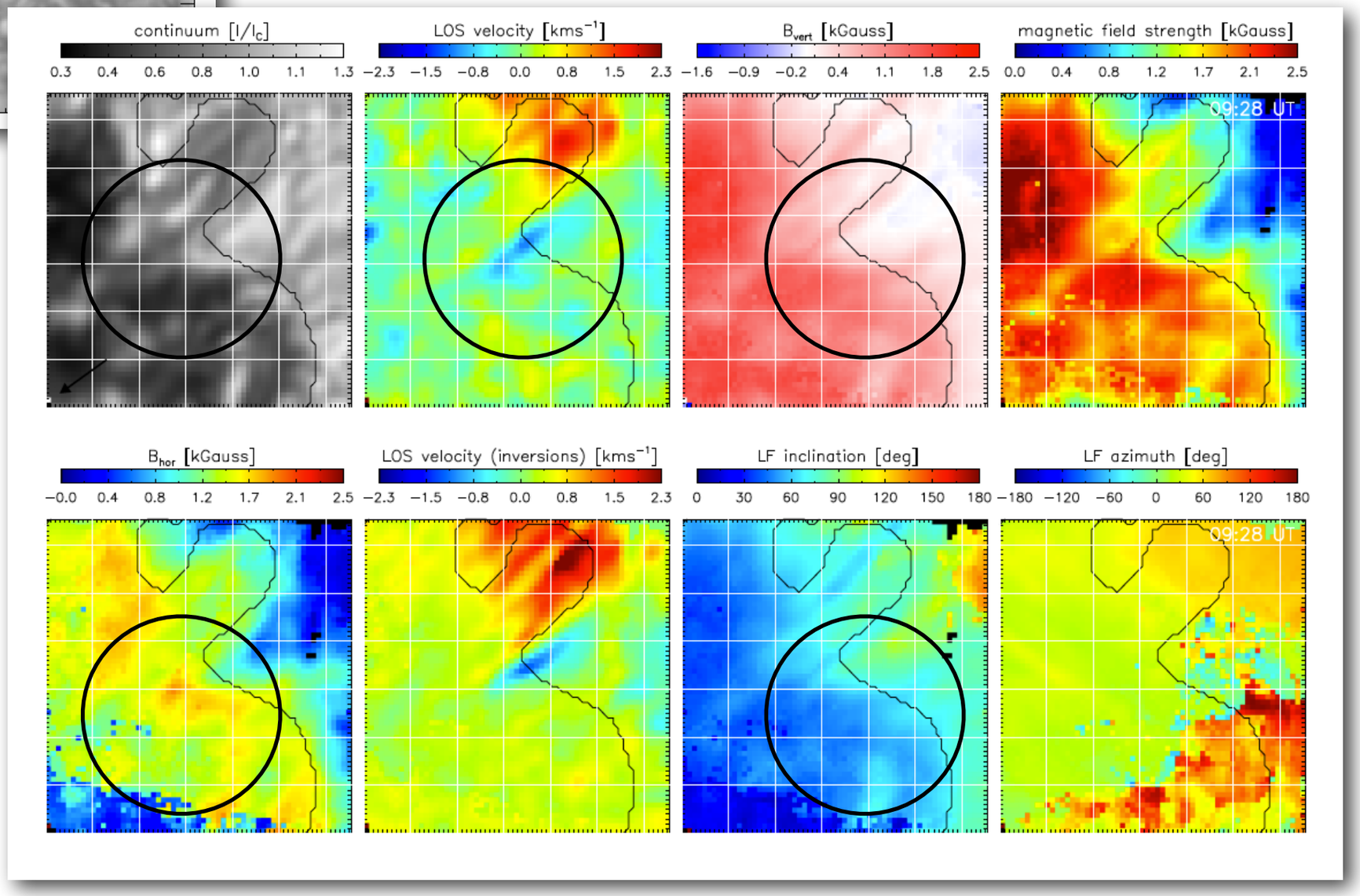
- Red-shifted flows in the spot center-side:
  - show filamentary structure
  - associated with abnormal granules
  - with close to horizontal magnetic field inclinations



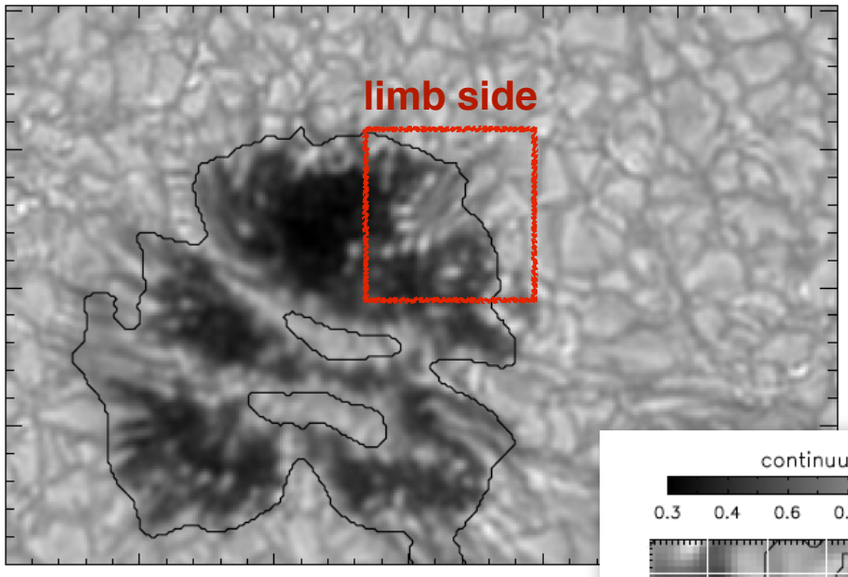
Counter-Evershed flow previous to the penumbra formation



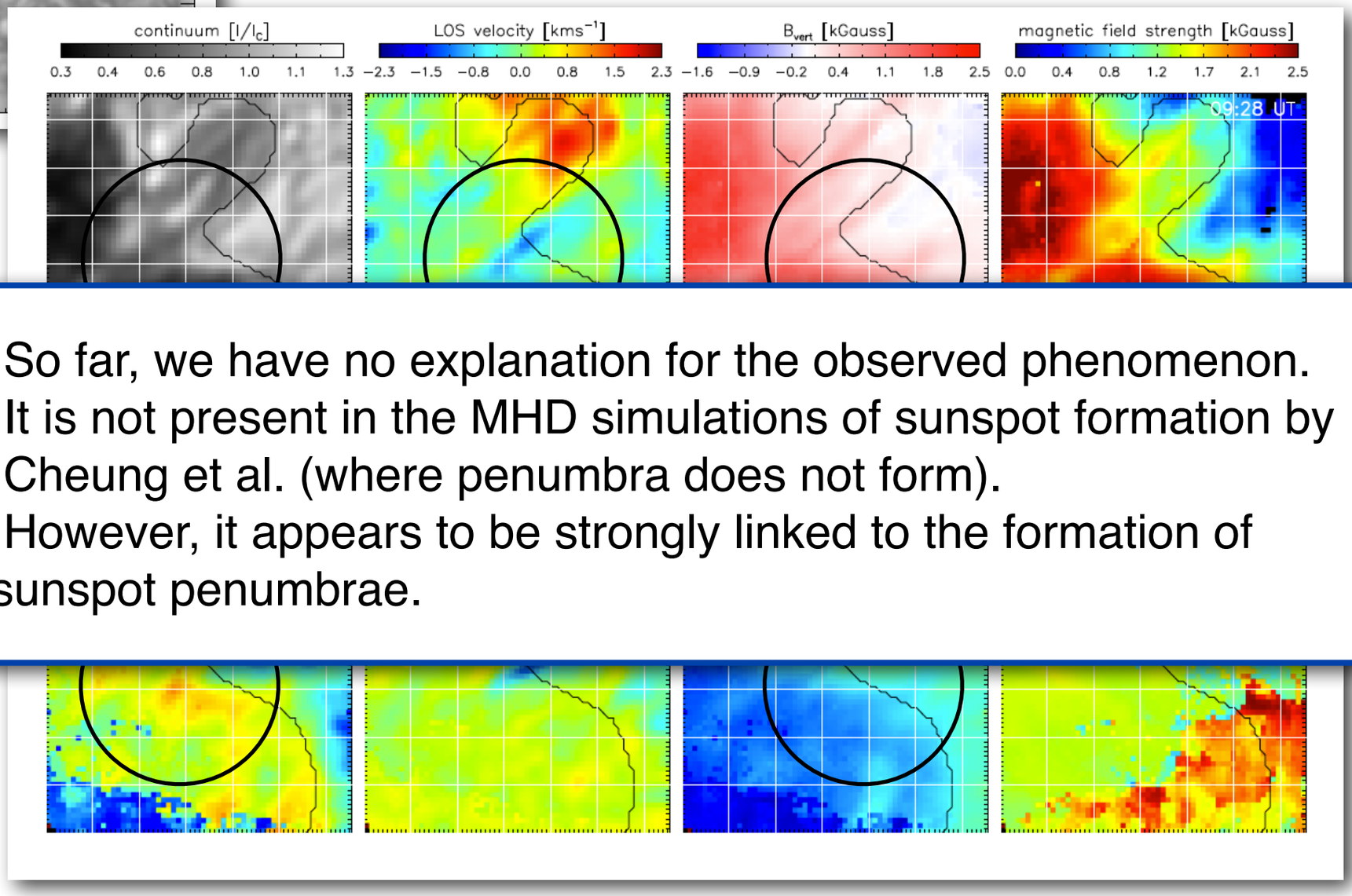
- Blue-shifted flows in the spot limb-side:
  - show filamentary structure
  - associated with abnormal/elongated granules
  - with close to horizontal magnetic field inclinations



Counter-Evershed flow previous to the penumbra formation



- Blue-shifted flows in the spot limb-side:
  - show filamentary structure
  - associated with abnormal/elongated granules
  - with close to horizontal magnetic field inclinations



So far, we have no explanation for the observed phenomenon. It is not present in the MHD simulations of sunspot formation by Cheung et al. (where penumbra does not form). However, it appears to be strongly linked to the formation of sunspot penumbrae.

From *Bello González, Rezaei & Schlichenmaier, in preparation*

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Conclusion:

Scenario for sunspot formation

Scenario for sunspot formation

1. The magnetic field of the AR may originally stem from one thick, deeply rooted flux rope

2. During its rise through the convection zone, the rope splits into smaller strands

3. Different twists develop for each rope strand owing to the effect of turbulent convective buffeting during the flux rise

4. When emerging at the surface, the various strands appear first as small loops of flux tubes

5. These emerging loops stretch the granules along the AR axes, thus the granules become elongated and with magnetic footpoints of opposite polarity

6. Next, footpoints of same polarity combine to form pores with their own field twists

7. Then, pores coalesce to form a protospot; the protospot already shows signatures of a canopy

8. At this point, pores are components of the protospot but keep their magnetic identity, showing their own signatures like, e.g., magnetic twist

9. Light bridges form from granules trapped in between the regions of strong fields (pores). They either possess their own rotational motion or are entrained by the untwisting of the nearby magnetic fields

10. Light bridges (less magnetised) are the natural path for the new incoming flux to enter and join the forming spot, until they eventually (magnetically) saturate

11. The magnetic flux is re-arranged within the physical boundaries of the magnetic funnel of the forming spot while the spot continues gathering new flux from the site of emergence

12. At this point we can still observe signatures of untwist in the part of the flux rope linked to this umbral core

13. The spot magnetic funnel has to re-adjust to the new incoming flux and the effects exerted by the upper layer boundaries

14. The spot funnel opens on the side opposite to the emergence site, the field lines become more horizontal

15. At this point, the penumbra can be seen at the chromospheric level (*Shimizu et al. 2010*), and a counter-Evershed flow at the photospheric level appears

16. The spot continues gathering flux on the emergence-site side and the field lines reach a critical inclination (close to horizontal) on the opposite site

17. Onset of the Evershed flow and formation of stable penumbral filaments

18. Eventually, the thick rope has emerged in total, light bridges might fade away as umbral dots and a mature umbra with a complete penumbra has formed