Observations of emerging flux tubes

Lidia van Driel – Gesztelyi

Katholieke Universiteit Leuven, Belgium
Mullard Space Science Lab., University College London, UK
Observatoire de Paris-Meudon, LESIA, France
Konkoly Observatory, Budapest, Hungary

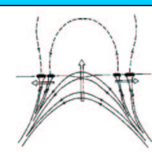
Outline

- Classical picture of flux emergence: (fragmented) Ω-loop
- Main characteristics of bipolar active regions (ARs)
- Multi-wavelength detailed picture of flux emergence
- Asymmetry in the Ω-loop – eastward tilt
  ephemeral regions – E- W asymmetry – westward tilt?
- Signatures of twist in emerging flux tubes
- Emergence of non-Ω-loop flux tube geometries: flux “ball”
  U-loop
- Emergence of flux tubes deformed by deep CZ vortices
- Summary

Scenario of magnetic flux emergence

Formation of bipolar active regions:

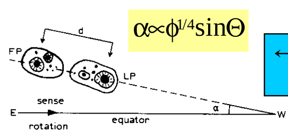
- appearance of a small, bipolar bright plage in Ca II H&K line (Fox, 1908)
- arch filament system in Hα connects faculae of opposite polarity (Bruzek, 1967) with ascending loop top ($v \leq 10$ km/s) and draining material along the legs ($v \leq 50$ km/s), lifetime of individual fibrils ≈ 20 min
- hot (bright) EUV and X-ray loops appear above the AFS loops
- dark photospheric lanes (alignment of granulation) parallel to the overlying AFS with lifetime of ≈ 10 min, $v \approx 3$ km/s, **B** ≈ 600 Gauss
- opposite polarities move apart ($v \leq 2$ km/s – first half hour $v \approx 1.3$-0.7 km/s next six hours) (Harvey & Martin, 1973)
- sunspots form by coalescence of pores/smaller spots
- bipole orientation may be arbitrary initially, but in about 1-4 days it becomes correct – nearly parallel to the equator, with the p polarity closest to it (Joy's law).
- this sequence of events is pictured as the emergence of Ω-loops.



Flux, lifetime and inclination of bipolar ARs

Region	magnetic flux (Mx), one polarity	lifetime
large (with sunspots)	$5 \cdot 10^{21}$ - $3 \cdot 10^{22}$	weeks-months
small (no spots, maybe pores)	$1 \cdot 10^{20}$ - $5 \cdot 10^{21}$	days-weeks
ephemeral	$3 \cdot 10^{18}$ - $1 \cdot 10^{20}$	hours (mean: 4.4)

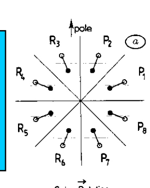
effect of Coriolis force

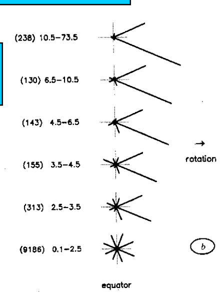


$\alpha \propto \phi^{1/4} \sin\Theta$

← Schrijver & Zwaan, 2000
Harvey, 1993 →

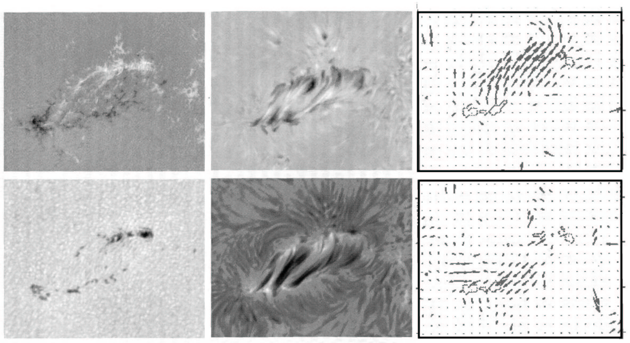
Joy's law has a latitudinal dependence: the tilt angle increases from 1° near the equator to 7° at 30° (Fisher, Fan & Howard, 1995). The dispersion around that angle increases with decreasing size (flux) of Ars (Harvey, 1993) dispersion is latitude-independent → effect of turbulence





normalized distribution of tilt angles

A well-observed example



- elliptical shape outlined by pores (long axis: 55 Mm) separation rate of pores of opposite polarities: 0.73 ±0.07 km/s (v_p=0.46 ±0.05 v_f=-0.28 ±0.05)
- counter-streaming of facular points of opposite polarities (v_p=0.61 ±0.04 v_f=-0.24 ±0.05), highest shear velocities are in the middle of the EFR

Strous 1994; Strous et al, 1996; Strous & Zwaan 1999 :
AR 5617 on 29-July-89: 7.5 hours after the emergence began, observed an EFR for 1.5 hour with the SOUP tunable filter at the Swedish VST on La Palma

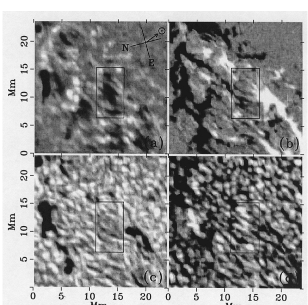
Leuven 575 universiteit

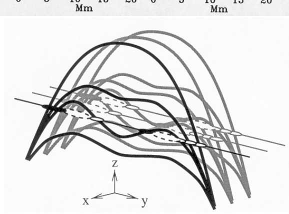
Observatoire de Paris

UCL MSSL

Fine structure of the flux emergence

Shows such a complexity of detail that is not described by the simple emergence model of an Ω-loop.





- Small-scale emergence events are characterised by transient darkening of lanes (2 Mm, 10 min) in the continuum → upflows, weak or no magnetic field followed by bright facular grains at their end(s) grains → downflows, magnetic field concentrations
- There is not a single magnetic inversion line, both polarities are found all over the AR.
- Flux emergence happens recurrently in a number of locations all over the AR, with a λ = 8 Mm.
- Facular motion, unipolar facular alignments, emergence locations, flux emergence events, subsequent footpoint motion, separation, Hα loops all line up in the same direction.
- **The emerging flux tube is frayed in two systems:**
  (i) in vertical stacks arranged in slightly curved, nearly parallel sheets
  (ii) many flux tubes emerge in multiple locations (undulatory flux tubes)

Leuven 575 universiteit

Observatoire de Paris

UCL MSSL

Questions…

• Why a wavy pattern?
The undulating emerging loops may arise from the **undulatory or Parker instability** (Parker, 1953; Matsumoto et al. 1993; Caligari et al. 1995)

• Why is the loop so fragmented?
Rising flux tubes fragment quickly (Longcope et al, 1996), unless stabilised by **twist in the flux tube** (Emonet & Moreno-Insertis, 1998).

• So this emerging flux tube was not twisted?
Then it probably wouldn't have made it all the way up to the photosphere… (Emonet & Moreno-Insertis, 1998).

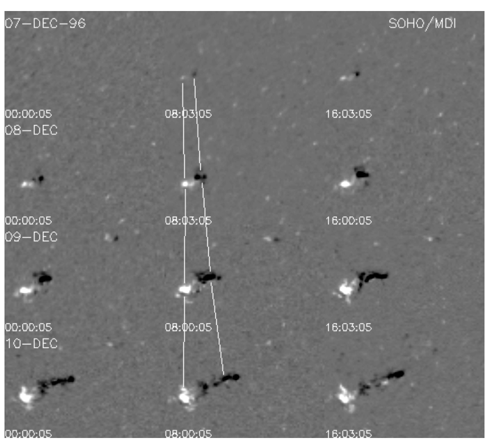
• This **fragmentation** is likely to occur **right under the photosphere**, and may be due to the fact that the flux tube can only emerge piece-by-piece.

Do you agree?

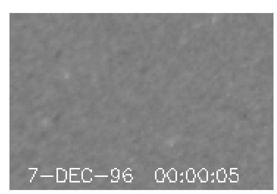
Leuven universiteit

UCL MSSL

Emergence of a bipolar active region



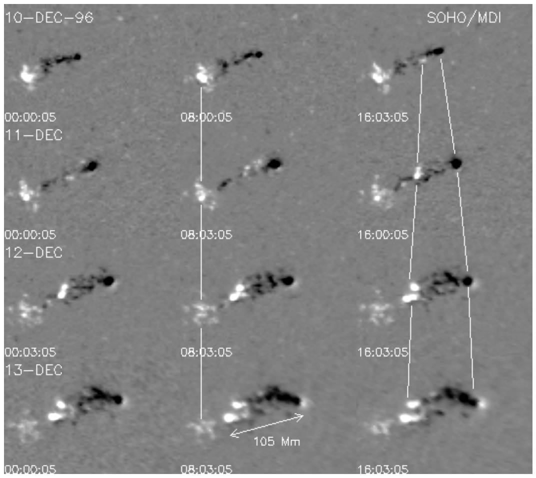
Note the main features:
• as the p & f spots separate, p moves faster westward than the f spots eastward
• the p spots form an elongated pattern of negative polarity in the direction of their motion → asymmetric inversion line

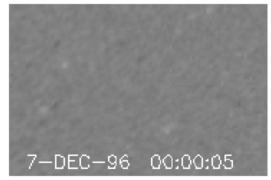


Leuven universiteit

UCL MSSL

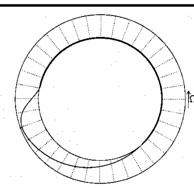
A more complete story of a bipolar AR

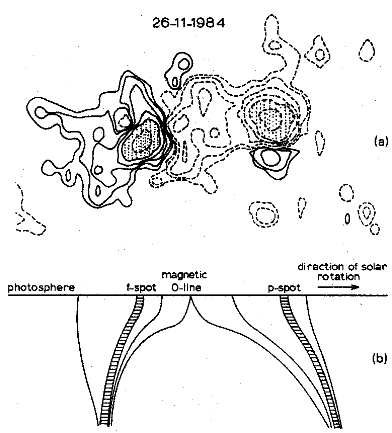




Large active regions are formed by **several EFRs** that surface separately but in **close proximity**, in **rapid succession** within a few days (Schrijver & Zwaan, 2000).

Asymmetries in bipoles -- inclination





Bipolar regions have **asymmetric** characteristics:
- leading (p) spots move faster westward than trailing (f) spots eastward
- the magnetic inversion line is (statistically) closer to the f spot than to the p spot (van Driel-Gesztelyi and Petrovay, 1990; Cauzzi, Moreno-Insertis and van Driel-Gesztelyi, 1998)

↓

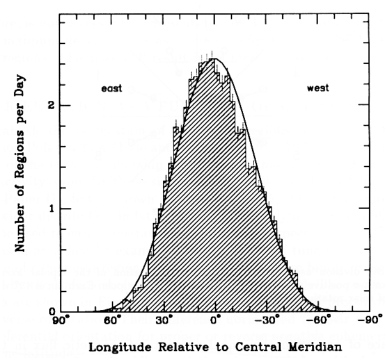
Emerging flux tubes are systematically inclined eastward, trailing the rotation.
This is in good agreement with simulation results of Caligari et al. (1995) and Abbett et al. (2001), and due to the conservation of angular momentum during the emergence.

- p spots are larger and more stable than f spots, which are more fragmented

→

Plasma flows induced by the Coriolis force (Fan et al. 1993 Fan & Fisher, 1996)
→ somewhat controversial

E-W asymmetry of ERs



There is a significant E-W asymmetry in the **distribution of ephemeral regions**. Harvey (1993) found for 9492 ERs a heliographic **offset of 2.8°±1.1°**:
52% of ERs emerge on the eastern,
48% on the western hemisphere.

possible interpretation: the **flux tubes** of ERs **lean westward** by about 3°

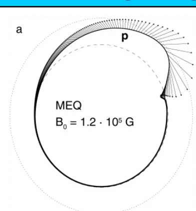
Howard (1991), based on the different longitudinal dependence of the average flux of p and f spots for emerging (growing) regions, deduced an strong (≈ 25°) westward inclination of their magnetic fields.

Questions…

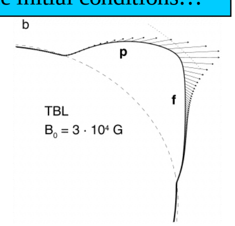
What is the true tilt of emerging flux tubes relative to the vertical?
Asymmetries in emerging active regions indicate an Eastward tilt, while **E-W asymmetries** in the heliographic longitude distribution of ERs and the mean AR flux values both **indicate a Westward tilt**.

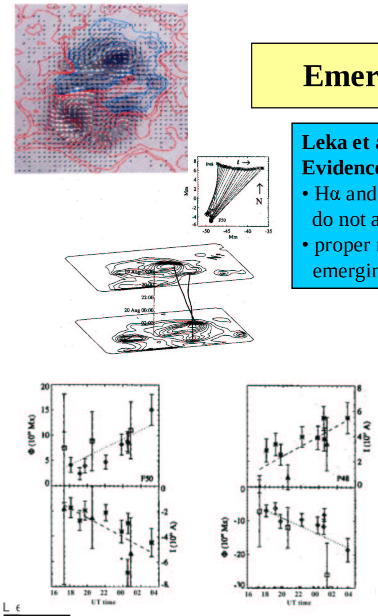
What causes this contradiction?
Maybe we observe the field line tilt in different solar layers using these two approaches. Asymmetries in ARs reflect field line inclination under the photosphere while the E-W asymmetries in the photosphere – are they both true?

Simulations of magnetic flux emergence mainly agree with an Eastward tilt, but the resulting emerging flux tube shape depends on the initial conditions…



initial conditions:
← mechanical equilibrium
thermal equilibrium →
(Caligari et al, 1998)





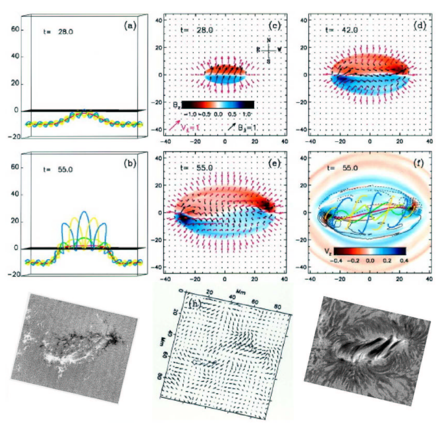
Emergence of twisted flux

Leka et al, 1996 -- AR 7260 in August 1992
Evidence:
• Hα and X-ray structures associated with the emerging bipoles do not agree with potential magnetic extrapolations
• proper motions of spots indicate the emergence of deformed (kink?) emerging flux tube geometry

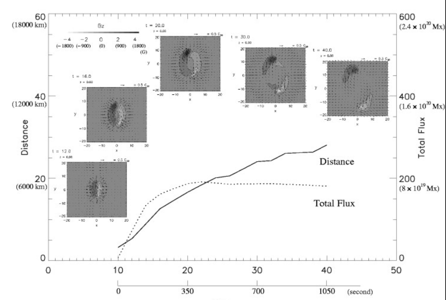
• the bipoles are co-spatial with significant vertical electric currents
• all the above signatures imply the same sense of twist
• currents increase together with the emerging flux

Wang & Abramenko (2000) found similar results from the analysis of AR 7321.
Other authors (e.g. Ishii et al. 2000) use Hα morphology and sunspot motions to argue that flux emerges twisted.

Even Strous' AR was twisted…



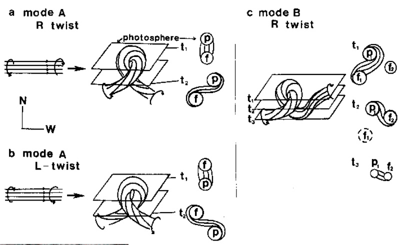
Fan (2001)

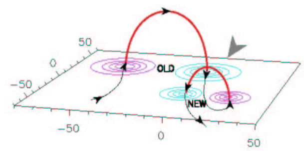


Magara & Longcope (2001)

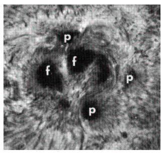
Simulations of emergence of twisted Ω-loops provide pictures amazingly similar to those observed by Strous (1994)…
AR 5617 showed all the main characteristics of emerging ARs: it was both **asymmetric** (inclined flux) and **twisted**.

If the flux is even more twisted…

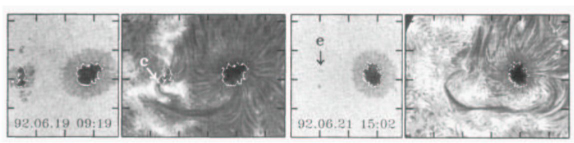




then we can get a kinked Ω-loop, which may form a « stitch » (Pevtsov & Longcope, 1998) ...



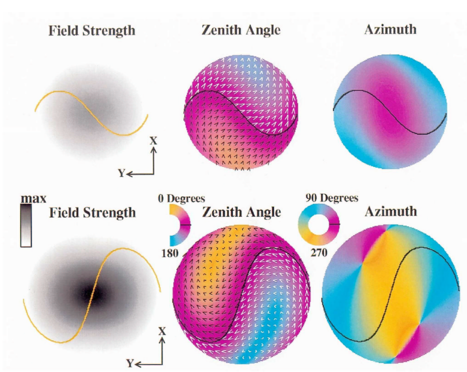
or form « knotted » δ-spots (Tanaka, 1991), which are born and die locked together (Zirin & Liggett, 1987) …



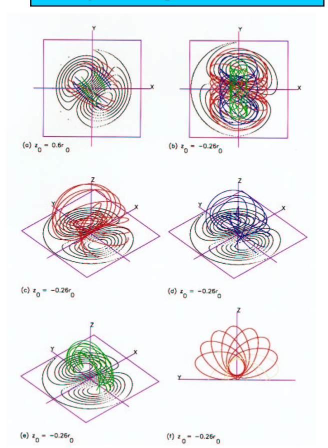
and sometimes can even form a flux « ball »…

Emergence of a flux « ball »

Is it the result of a disconnected knotted flux tube, which went through subsequent relaxation?

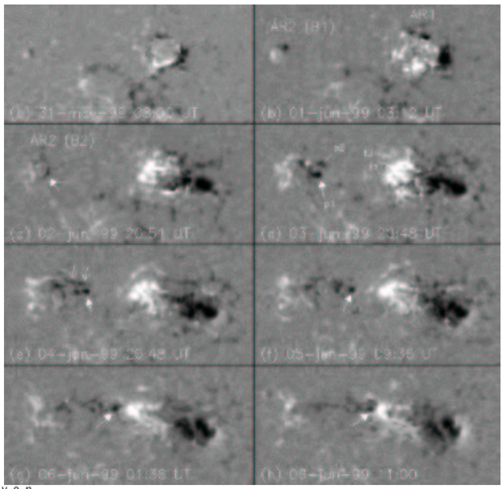


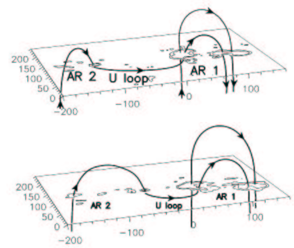
Distribution of the vector magnetic field in the photosphere (Lites, Low et al. 1995) .



3-D field line geometry

Emergence of a U-loop

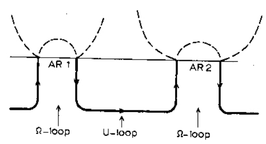




van Driel-Gesztelyi, Malherbe & Démoulin (2000)

31 May – 06 June 1999
NOAA 8562 & 8567

What is a U-loop?

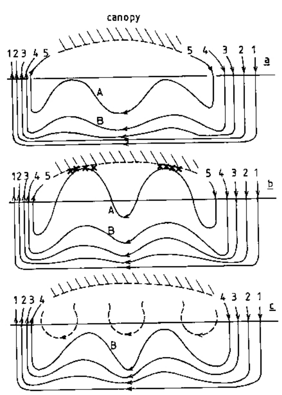


Schrijver & Zwaan (2000)

While **Ω-loops** are indispensable to explain the **emergence** of ARs, **U-loops** are important to understand their **decay** (Zwaan, 1992).

They can be created e.g. **between two adjacent Ω-loops** that have emerged from the **same toroidal flux strand**, or by sub-surface reconnection.
They **have difficulties to emerge** (matter is trapped in their concave-up part, and has to disengage from the plasma (Parker, 1984) → **sea-serpent process** (Spruit et al, 1987).

The existence of U-loops can explain puzzling observations of **in-situ disappearance** of large amount **of flux** from ARs and active nests (instead of submergence).



Spruit et al. (1987)
The sea-serpent process creates a pepper&salt magnetic field and remains unnoticed…

This was a U-loop, because…

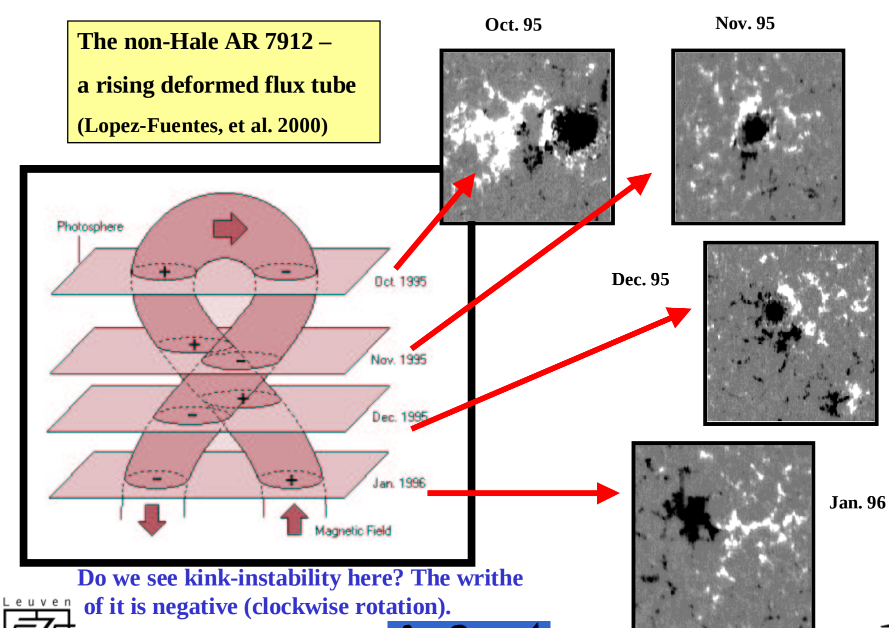
- The **proper motion** of the p spots of AR2 indicates a **concave-up flux tube geometry** instead of the usual Ω shape.
- The **elongated shape of the p magnetic field concentrations** of AR2 in the direction of their proper motion indicate a **high inclination** to the vertical.
- The **polarity separation** in AR2 was ≈ 3 times larger than in other ARs with the same flux content (Tian et al. 1999), the balance between buoyancy & tension force was different than in usual Ω-loops.
- The p spot(s) of AR2 and the f spots of AR1 **moved towards one another** both in longitude and latitude – a low-probability event, if accidental.
- When the opposite polarities of the two ARs collided their **cancellation** was **”clean”,** it was not accompanied by important flare activity (≤C1.3)

This observation provides one of the **first direct evidences** for the emergence of a U-loop in the photosphere. (van Driel-Gesztelyi, Malherbe &Démoulin, 2000)

The non-Hale AR 7912 –

a rising deformed flux tube

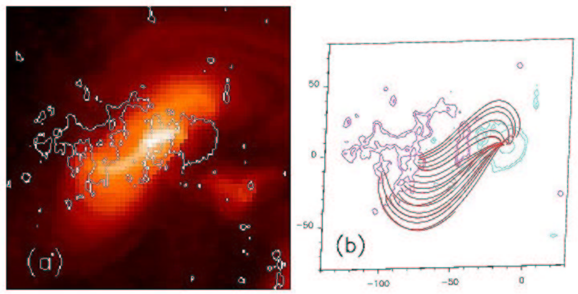
(Lopez-Fuentes, et al. 2000)



Do we see kink-instability here? The writhe of it is negative (clockwise rotation).

The non-Hale AR 7912 – in which sense is it twisted?

Twist (the turning of the field lines around the flux-tube axis) is another important parameter of the flux tube.



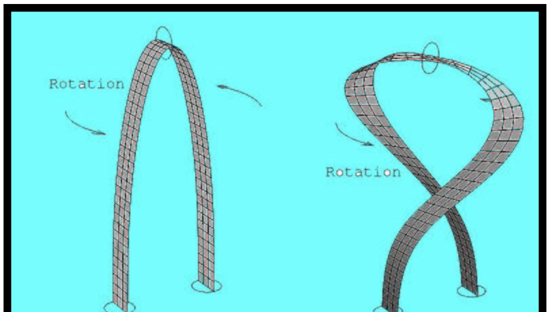
From lfff extrapolations a value of α = 0.03 Mm^{-1} was found (to fit the SXT loops) $\rightarrow$ positive sign... so positive twist (AR 7912 followed the hemispheric rule for the twist on the South hemisphere, Pevtsov et al, 1995).

Leuven 575 universiteit

Observatoire de Paris

UCL MSSL

The non-Hale AR 7912 – the origin of the distortion



López-Fuentes, Démoulin, Mandrini, van Driel-Gesztelyi (2000)

The kink mode requires that the handedness of the magnetic twist and the writhe of the flux tube be of the same sign

- this is not the case here.

We suggest that the peculiar evolution of AR 7912 may be a simple interaction with convective motions.

Photospheric or shallow subphotospheric large-scale flows can not explain such a long turning time.

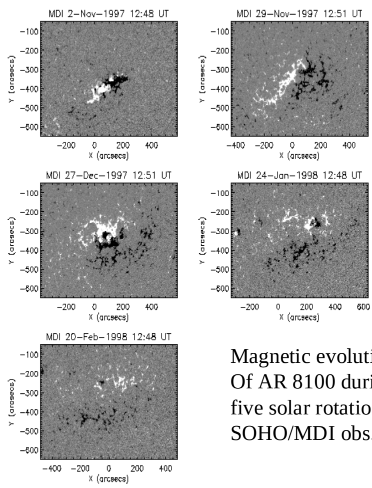
The AR starts as a normal Ω loop at the overshoot region and, as it travels through the CZ, it is deformed by deep-rooted motions having a rotational component.

This observation suggests that disconnection is a slow process…

Leuven 575 universiteit

Observatoire de Paris

UCL MSSL

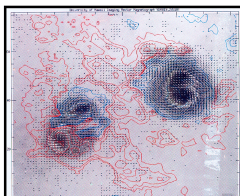


Magnetic evolution Of AR 8100 during five solar rotations, SOHO/MDI obs.

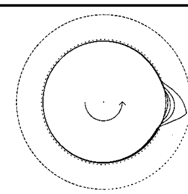
A Hale-oriented region which turned to become non-Hale…

Another example of the emergence of similarly distorted flux tube (Green et al. 2002).

Such deformed flux tubes are rare, but not unique, so the role of deep-rooted vortices seem to be of some importance…



Summary → Questions



We find that emerging flux tubes are inclined to the vertical, twisted, distorted, frayed and fragmented. What is the physics behind these observations?

- In spite of being twisted, emerging flux tubes get fragmented and frayed – where, why?
- ARs show a latitude-independent dispersion of tilt – effect of turbulence, where, how deep?

top of CZ physics

- rising flux tubes can be distorted severely by deep vortices in the CZ
- U-loops do indeed exist and their emergence can explain in-situ flux disappearance

both

- the flux tubes are inclined to the vertical -- however, in which sense?
- the flux emerges with inherent twist -- where do flux tubes get twisted?
- flux emergence has a clustering tendency – what is the explanation?

CZ and tachocline physics