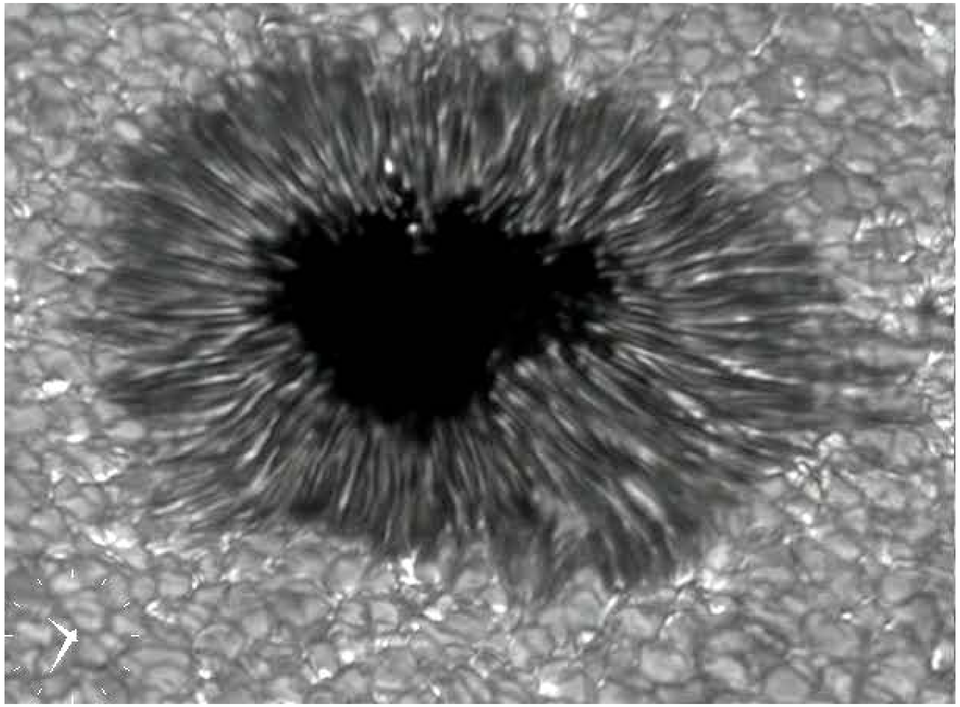
The Evershed flow and the brightness of the penumbra

Luis R. Bellot Rubio
Instituto de Astrofísica de Andalucía (CSIC)
Granada, Spain

Sunspots: general appearance



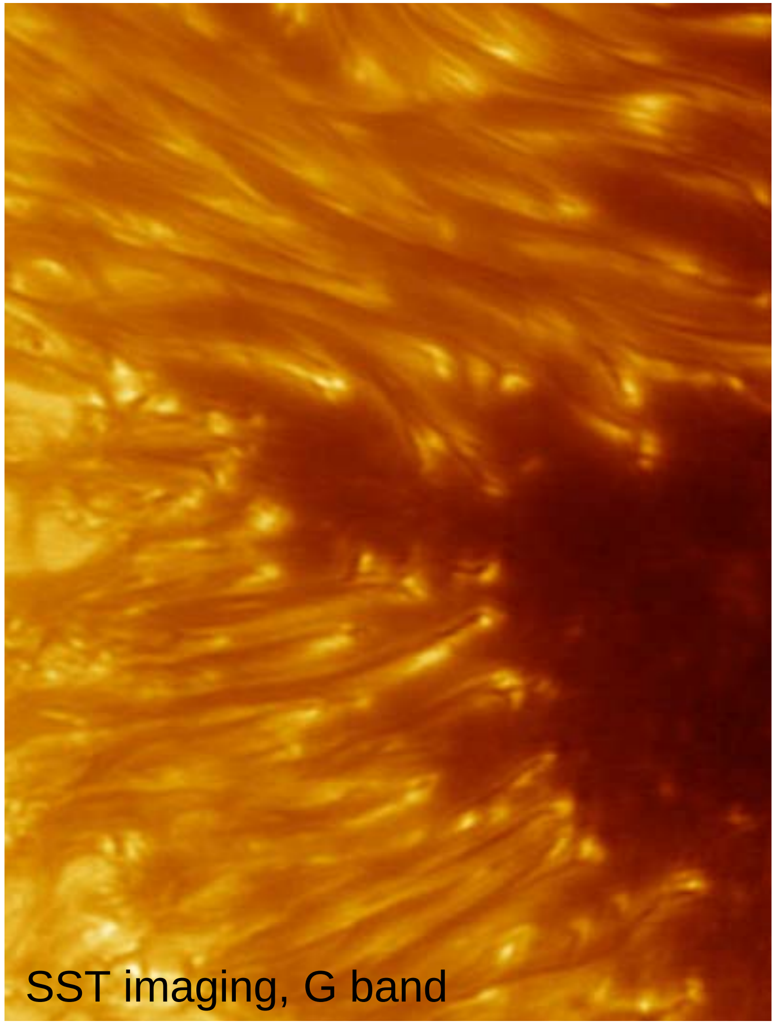
AR 8704, DOT (La Palma), G-band @ 0.2"

– Sunspot brightness:
  - Umbra: 0.2 F_{QS}
  - Penumbra: 0.7 F_{QS}
– Magnetic fields inhibit convective motions → umbra is cooler than quiet sun (Biermann 1941)
– What causes the surplus brightness of the penumbra?

The penumbra is formed by bright and dark filaments oriented radially

Sunspots: brightness structure

Scharmer et al., Nature (2002)



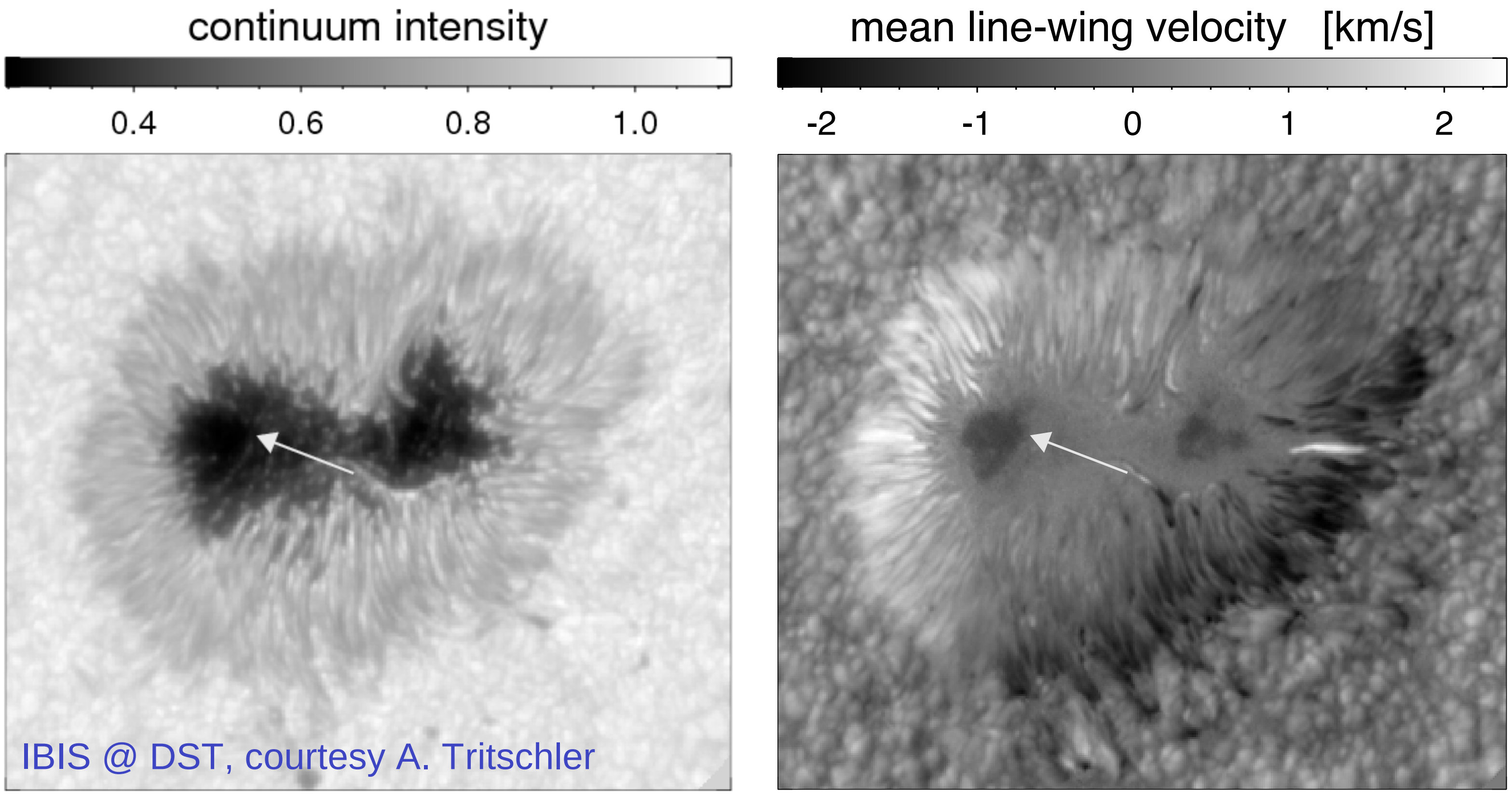
Penumbral filaments exhibit a central dark lane surrounded by two narrow lateral brightenings

Width of dark cores varies from <70 km up to 300 km

Lateral brightenings and dark core move together as a single entity

Sütterlin et al. (2004)
Rouppe van der Voort (2004)
Langhans et al. (2004, 2005)
Bellot Rubio et al. (2005)
van Noort & van der Voort (2008)

Sunspots: dynamic structure

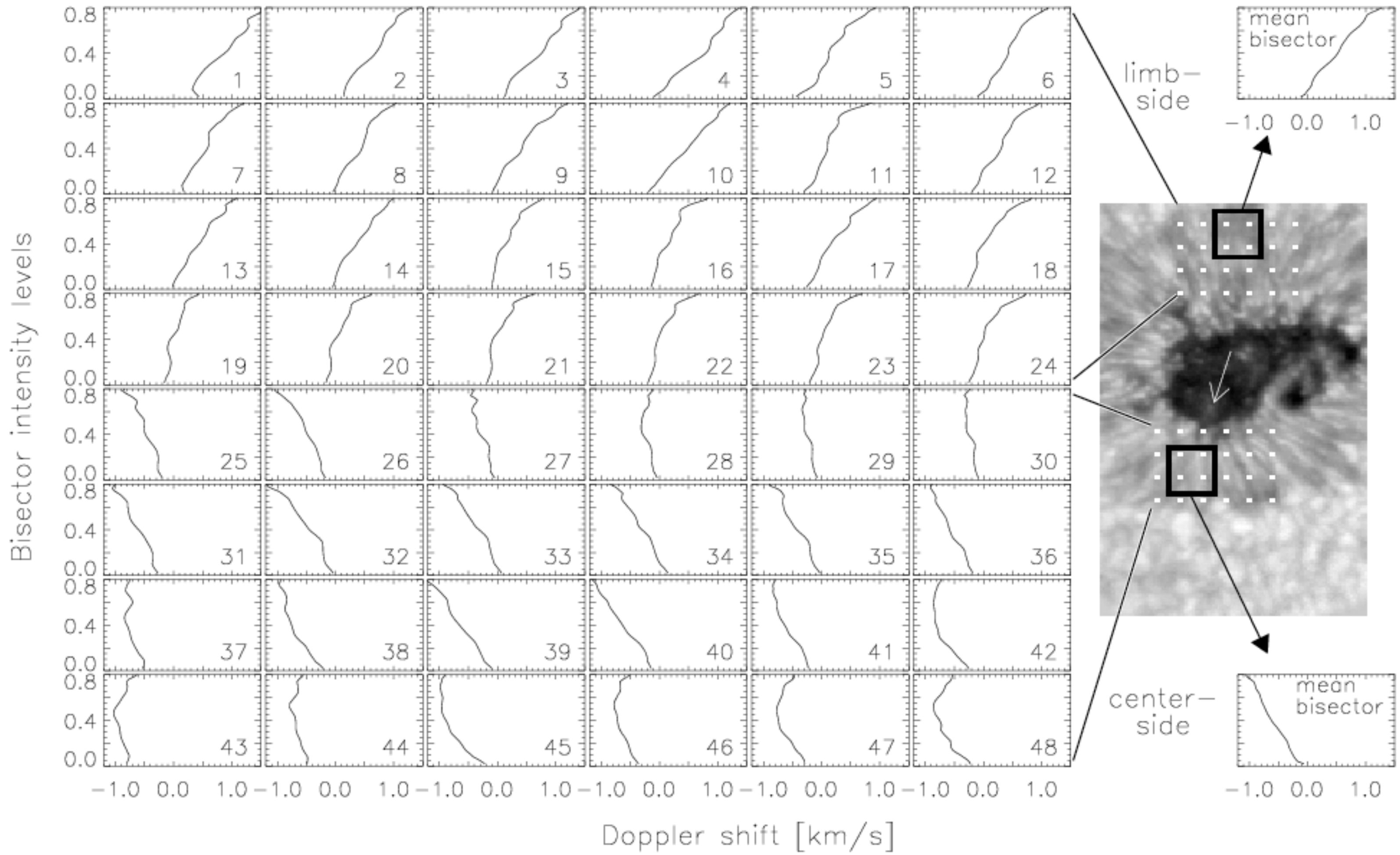


- Evershed effect: discovered in 1909 from Kodaikanal Observatory
- Nearly horizontal outflow of gas
- Line shifts and line asymmetries (e.g., Stellmacher & Wiehr 1980)

The Evershed effect

Schlichenmaier et al., A&A (2004)

Fe I 557.6 nm, TESOS@VTT, $\theta = 23^o$

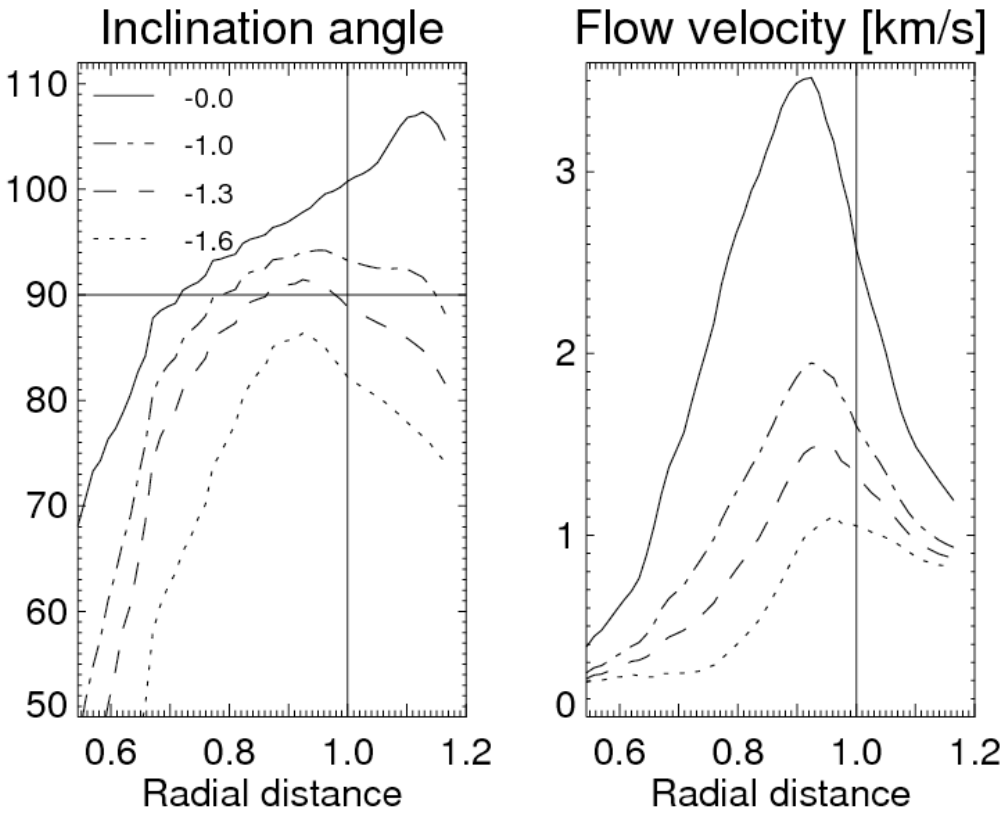


Rimmele (1995), Schlichenmaier & Schmidt (2000), Bellot Rubio et al. (2005)

The Evershed flow: geometry

Inferred from azimuthal variation of the LOS velocity

$V_{LOS}(r, \varphi) = V(r)\,[\sin\gamma \sin\theta \cos\varphi + \cos\gamma \cos\theta] \equiv A \cos\varphi + B$



Bellot Rubio et al., A&A (2006)

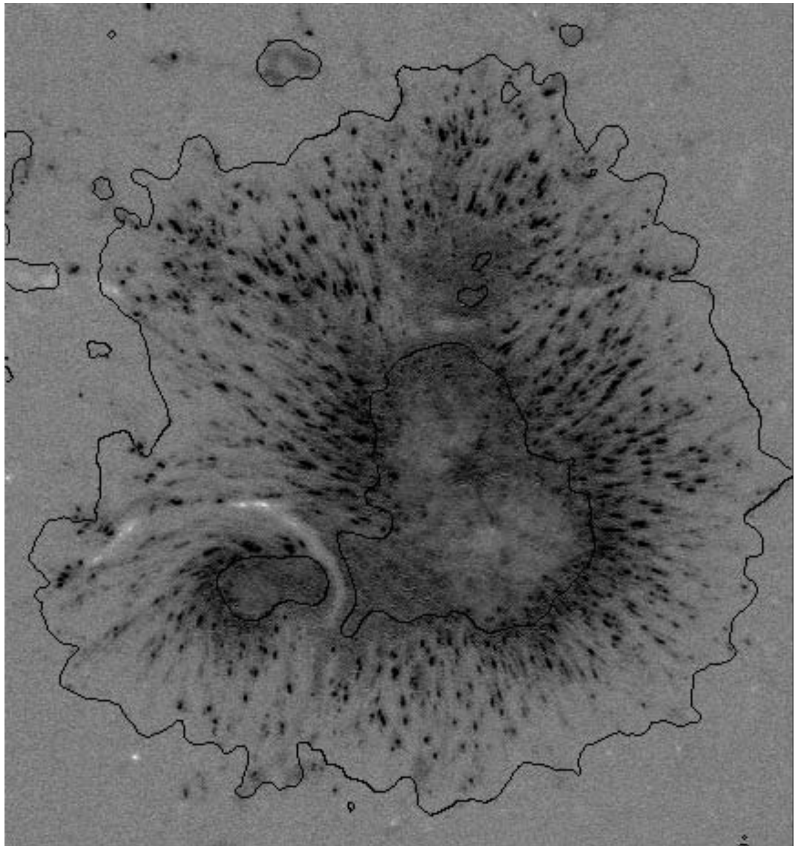
Deep layers:
Flow is nearly horizontal, returning to solar surface in the mid penumbra

High layers:
Flow is less inclined and weaker

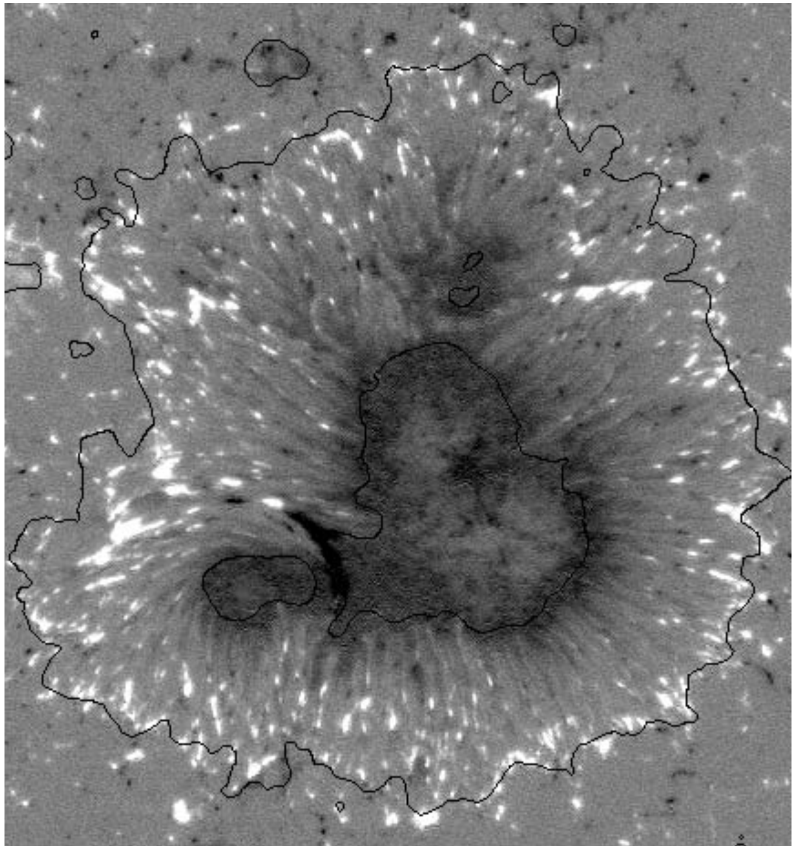
Schlichenmaier & Schmidt (2000); Bellot Rubio et al. (2003); Tritschler et al. (2004); Langhans et al. (2005)

Sources and sinks of the Evershed flow

Stokes V at -277 mÅ (strong blueshifts)



Stokes V at +277 mÅ (strong redshifts)



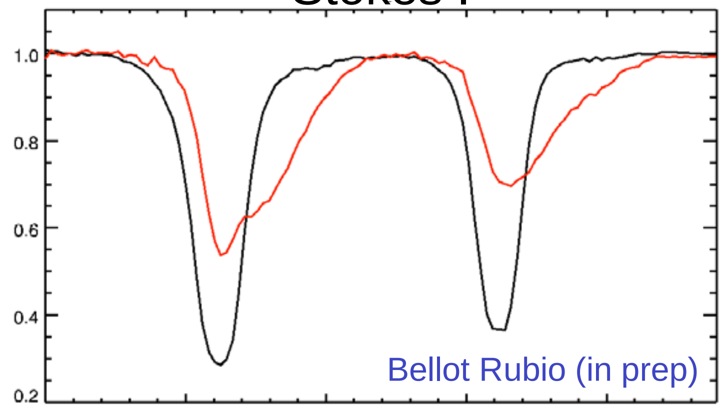
Hinode/SP, $\theta \sim 5^o$, courtesy K. Ichimoto

The Evershed flow appears as a hot upflow in bright penumbral grains and returns to solar surface in mid and outer penumbra

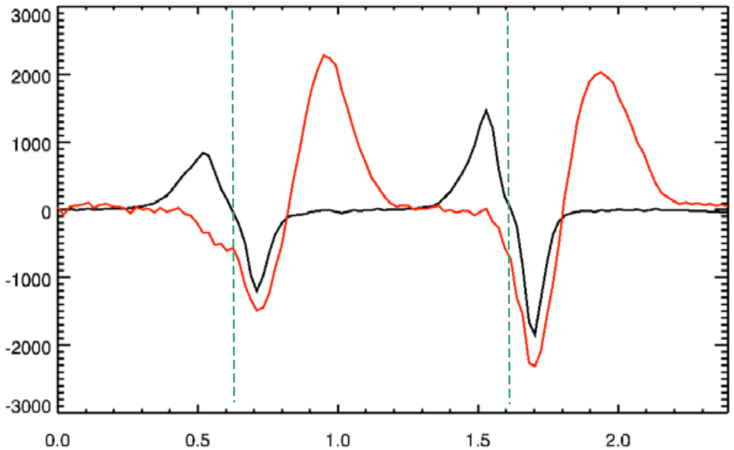
Johanneson (1993), Rimmele (1995), Westendorp Plaza et al. (1997), Schlichenmaier & Schmidt (1999), Rimmele & Marino (2006), Ichimoto et al. (2007)

Supersonic Evershed flows occur in the penumbra

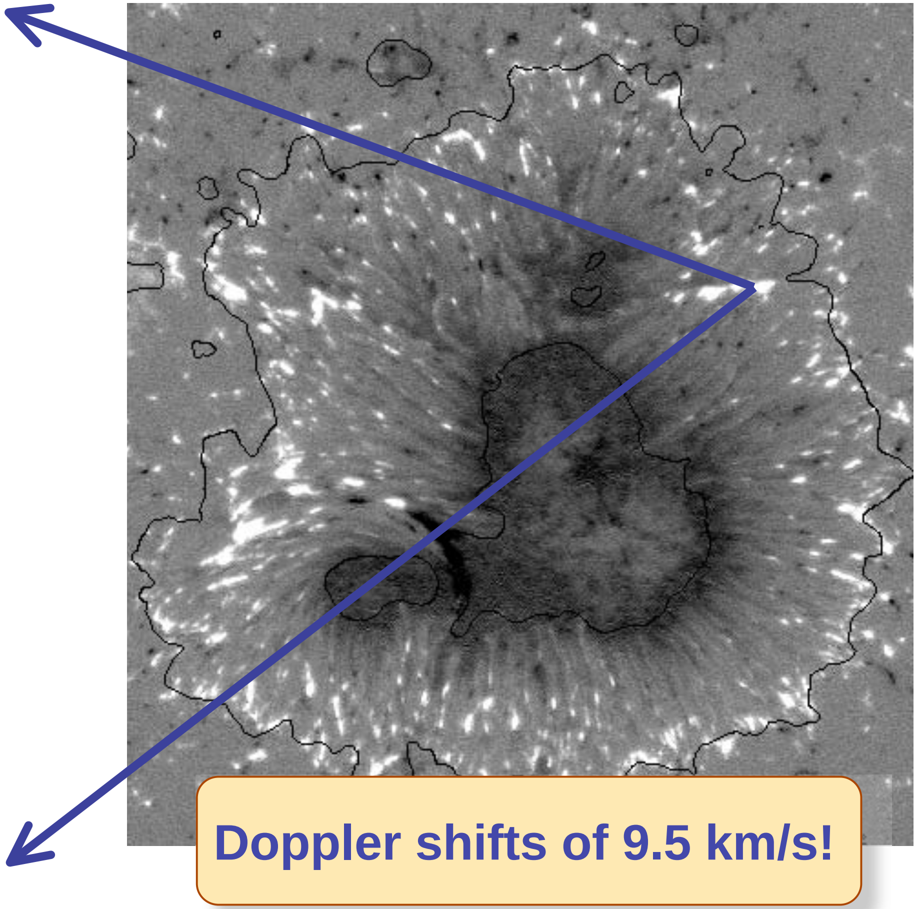
Stokes I



Stokes V



Stokes V at +277 mÅ (strong redshifts)



Evershed flow is magnetized and often supersonic, confirming results from earlier observations and numerical models

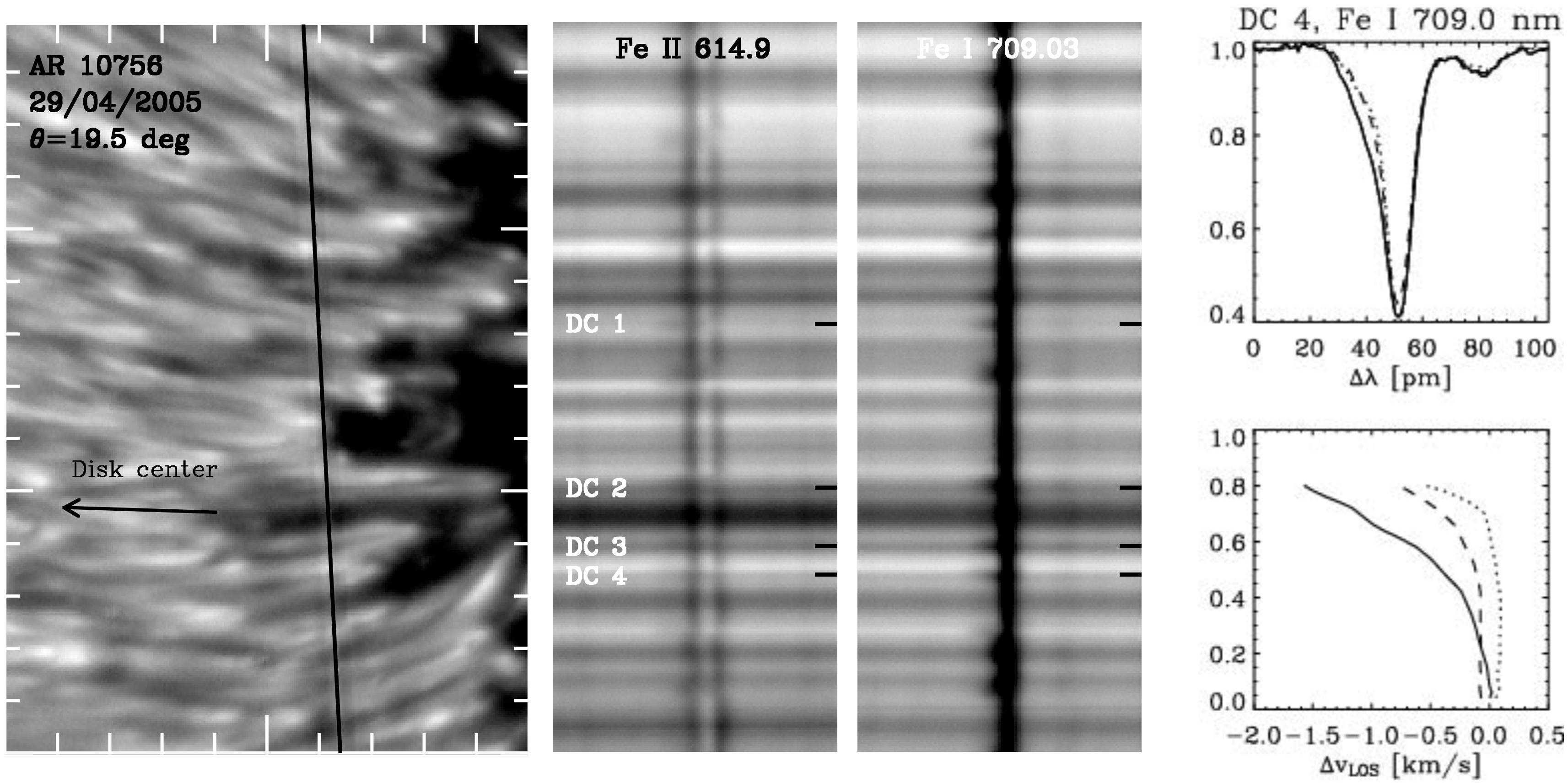
Bumba (1960), Wiehr (1995), Schlichenmaier et al. (1998), Montesinos & Thomas (1997), Bellot Rubio et al. (2004)

Dynamic properties of dark-cored penumbral filaments

Bellot Rubio et al., A&A (2005)

Fe I 709.0 nm, TRIPPEL@SST

Langhans et al. (2005), Rimmele & Marino (2006), Rimmele (2008)



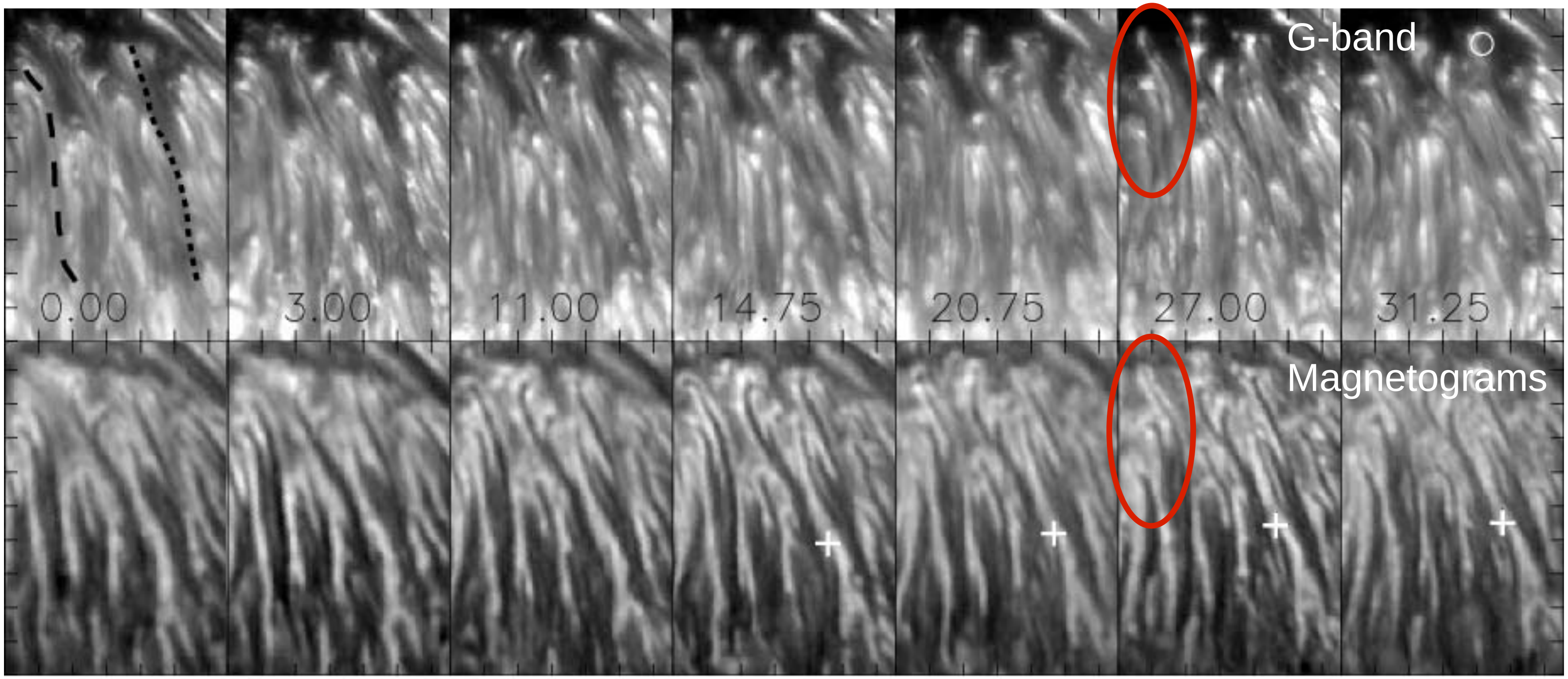
Evershed flow occurs preferentially in the dark cores of penumbral filaments, where it is directed *upwards* and associated with slightly weaker fields

Magnetic properties of dark-cored penumbral filaments

Langhans et al., A&A (2007)

Fe I 630.25 nm, SOUP@SST, $\theta = 15^{o}$

Langhans et al. (2005), van Noort & Rouppe van der Voort (2008)



Dark cores show smaller *magnetogram signals* than lateral brightenings, suggesting more inclined (and perhaps weaker) fields

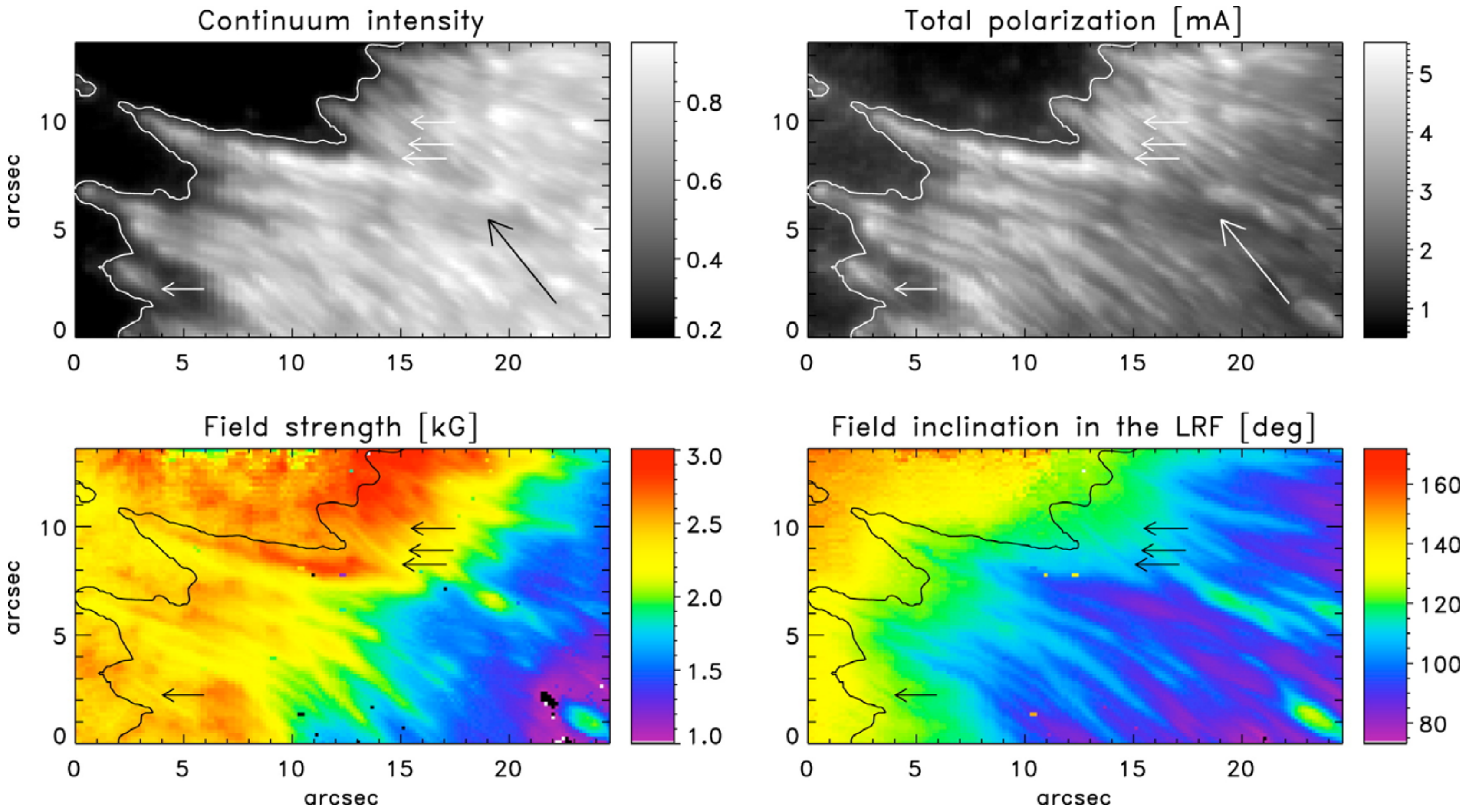
Dark cores do NOT exhibit negative polarities

Magnetic properties of dark-cored penumbral filaments

Bellot Rubio et al., ApJL (2007)

Fe I 630.2 nm, Hinode/SP, $\theta = 8^o$, SIR inversion

Scharmer et al. (2008)



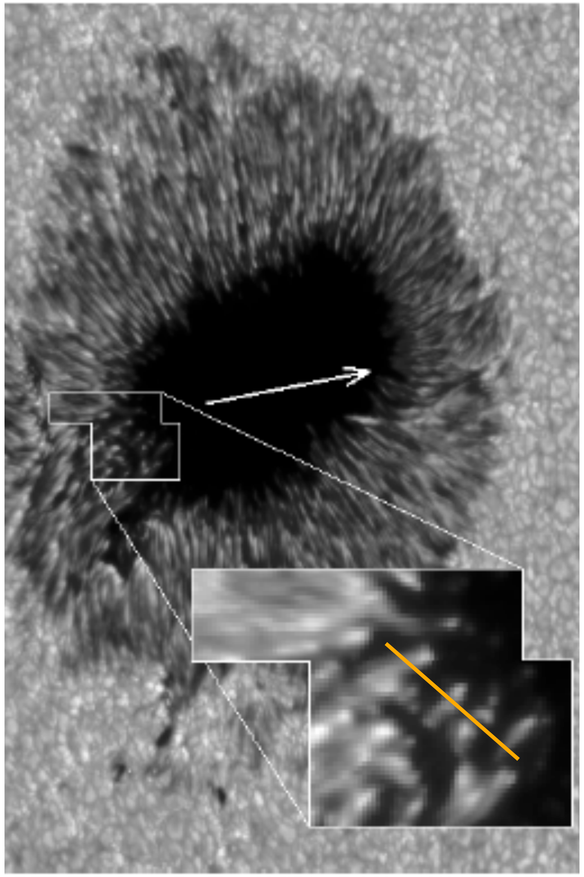
Magnetic field is weaker and more inclined in dark cores than in lateral brightenings and surroundings

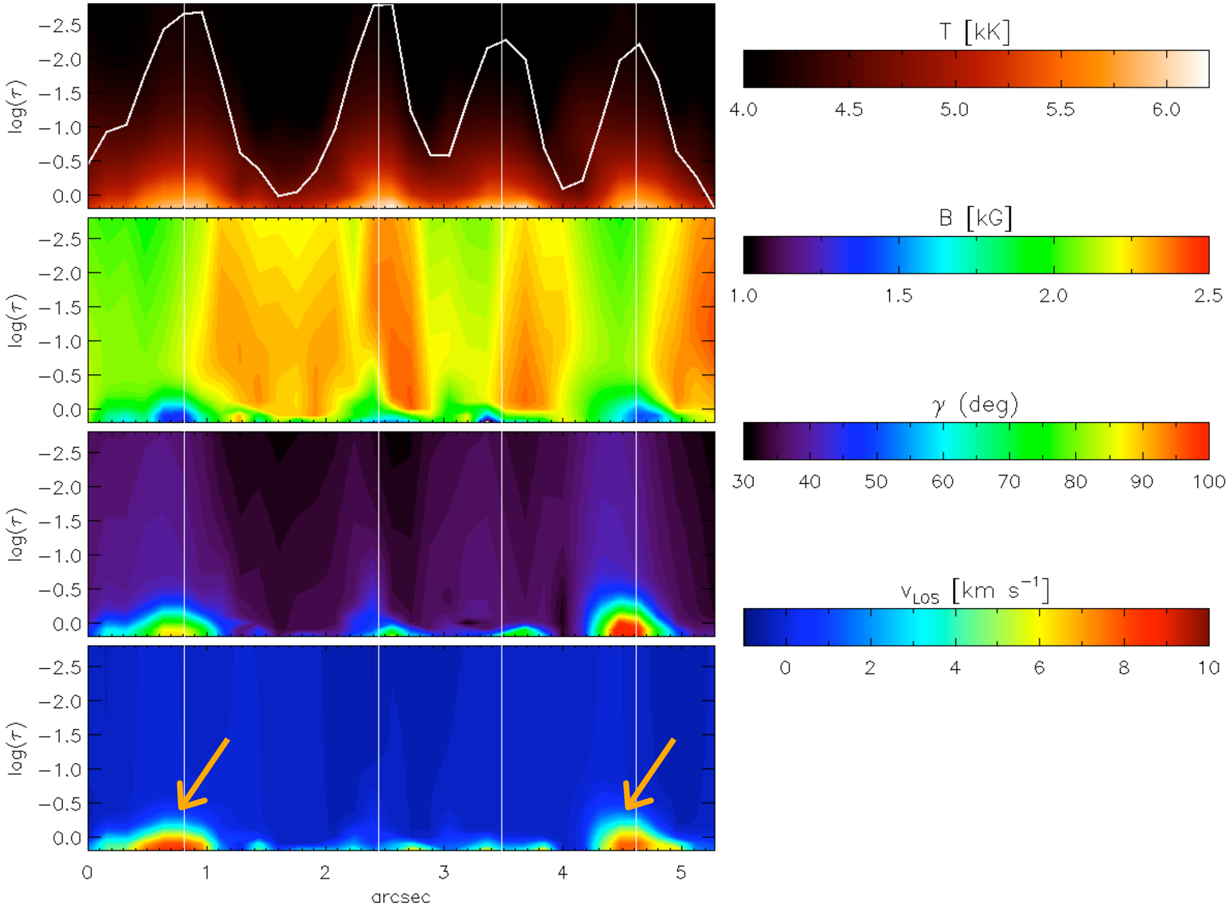
Evershed flows occur deep in the photosphere

Jurcák et al., PASJ (2007)

Fe I 630.2 nm, Hinode/SP,
θ = 50º, SIRGAUSS inversion

Bright filaments in the inner penumbra,
and the Evershed flows associated with them,
are located near τ = 1





Rimmele (1995), Westendorp Plaza et al. (2001), Bellot Rubio (2003), Schlichenmaier et al. (2004), Borrero et al. (2005, 2006)

Summary of observational facts

Penumbral filaments exhibit dark cores

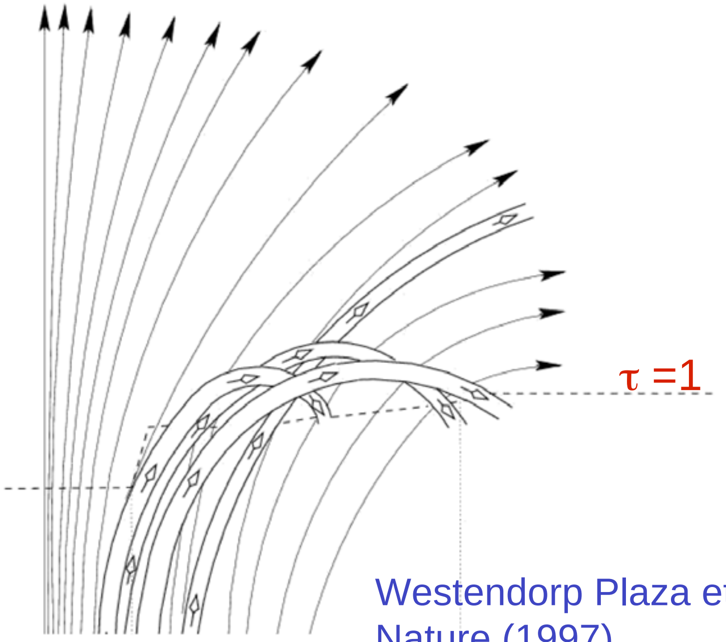
Evershed flow is magnetized

Evershed flow is associated with weaker and inclined field

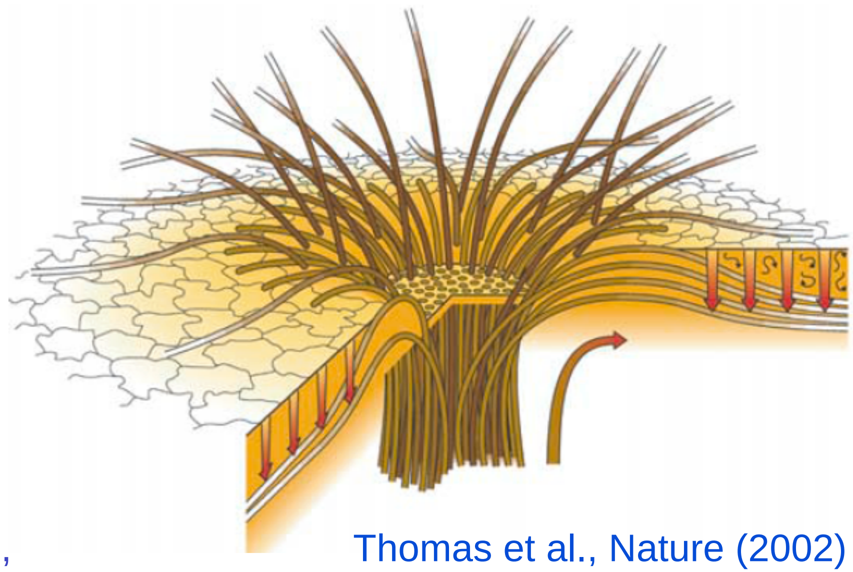
Evershed flow is supersonic

Evershed flow returns to solar surface in mid/outer PU

Evershed channels are interlaced with ambient field



Westendorp Plaza et al., Nature (1997)



Thomas et al., Nature (2002)
Brummell et al., ApJ (2008)

Can the flow explain the brightness of the penumbra?

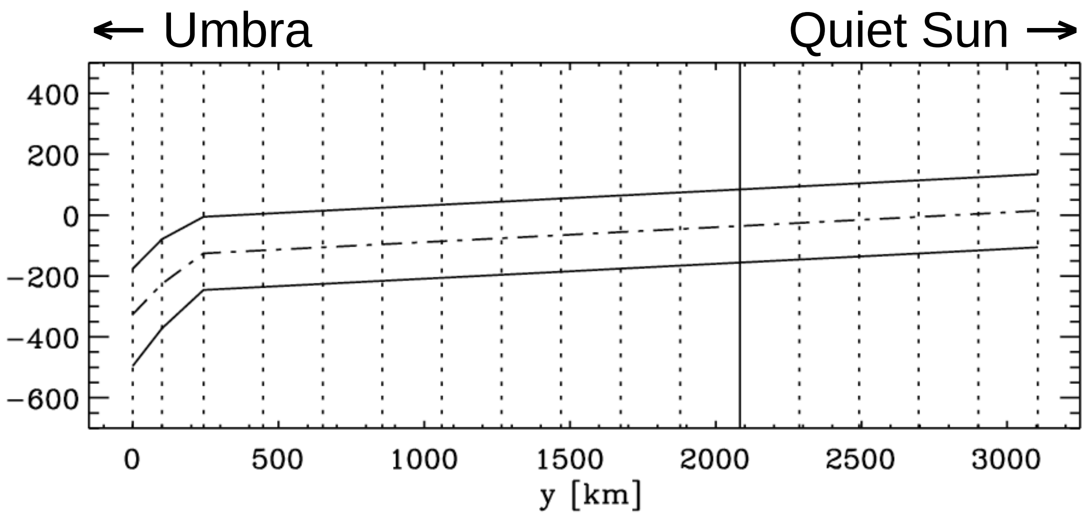
Hypothesis: Penumbral filaments are flux tubes ~100 km in radius (uncombed model of Solanki & Montavon 1993)

Model : Flux tube embedded in stronger and more vertical field
Hot Evershed flow along tube

Method: Numerical solution of 2D heat transfer equation (extends previous work by Schlichenmaier et al. 1999)

For details, see
Ruiz Cobo & Bellot Rubio 2008, A&A, 488, 749

2D heat transfer simulations: model

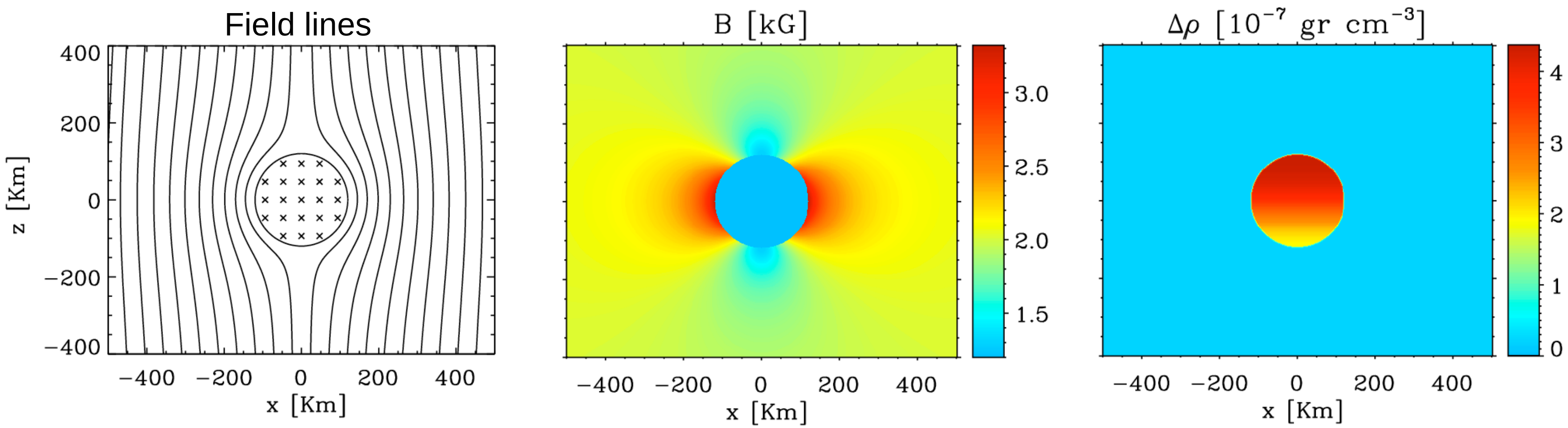


Deep-lying tube, $R = 120$ km

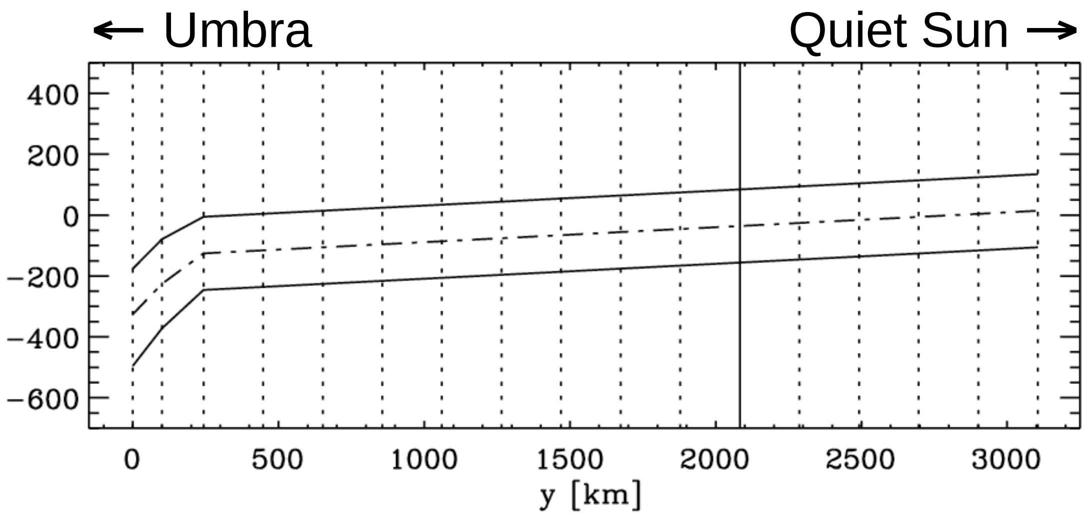
$B_t = 1200$ G $\quad \gamma_t = 45^\circ - 87^\circ$

$B_b = 2000$ G $\quad \gamma_b = 40^\circ$

$\nabla \vec{B} = 0, \ \nabla \times \vec{B} = 0$ + lateral pressure balance



2D heat transfer simulations: equations



$$\nabla\vec{F} = j^2/\sigma + \nabla\vec{F}_E$$

⬇

Temperature distribution

$$\vec{F} = \vec{F}_r + \vec{F}_c \quad \begin{cases} \vec{F}_r = -k_r \nabla T \\ \vec{F}_c = -k_c\left[\nabla T - (dT/dz)_{ad}\right] \end{cases}$$

diffusion approximation

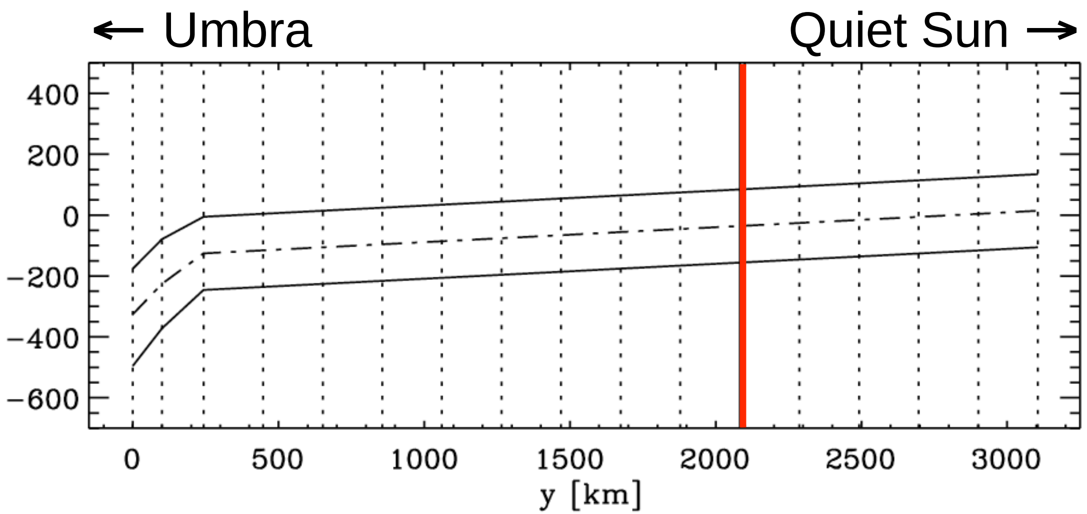
linearized mixing length

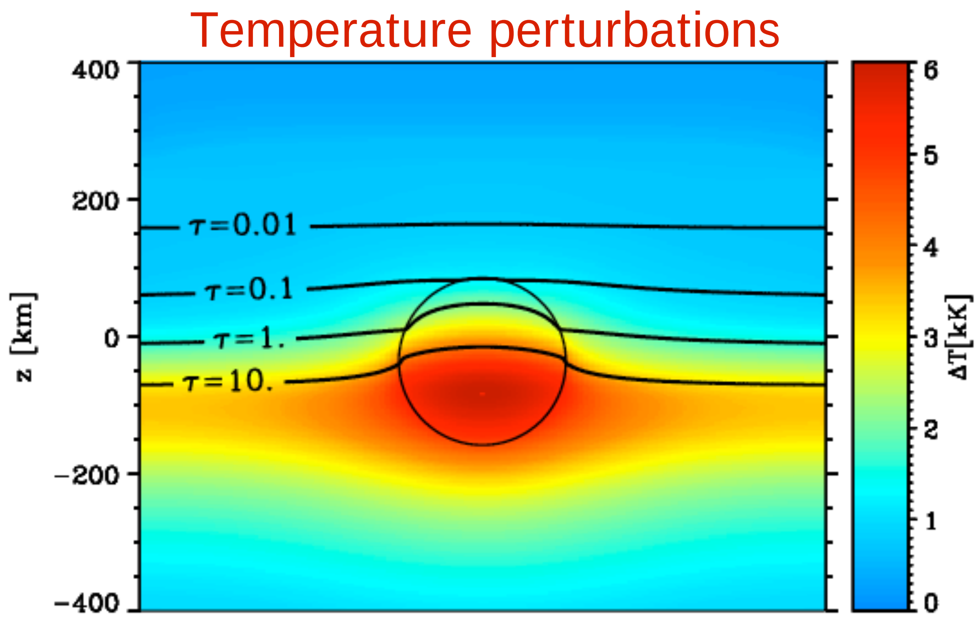
$$\nabla\vec{F}_E = \rho\, c_V \vec{V}_E \cdot \left[\nabla T - (dT/dz)_{ad}\,\vec{u}_z\right]$$

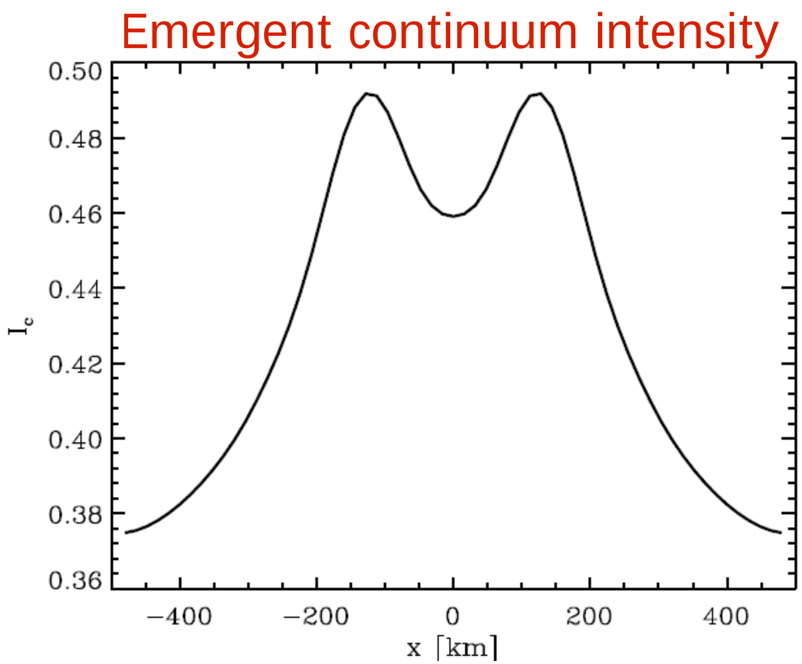
Evershed energy flux

$$V_E(y=0) = 7.0 \text{ km s}^{-1}$$
$$\Delta T(y=0) = 7500 \text{ K}$$

2D heat transfer simulations: results

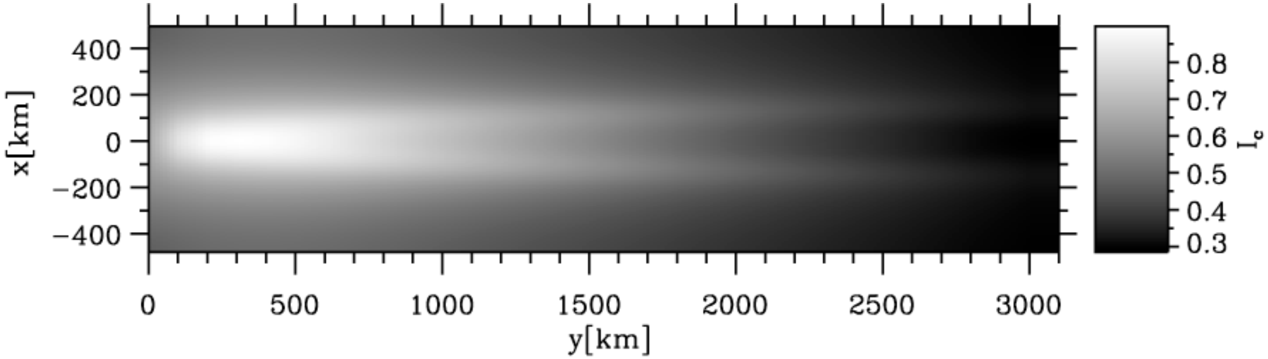






2D heat transfer simulations: results

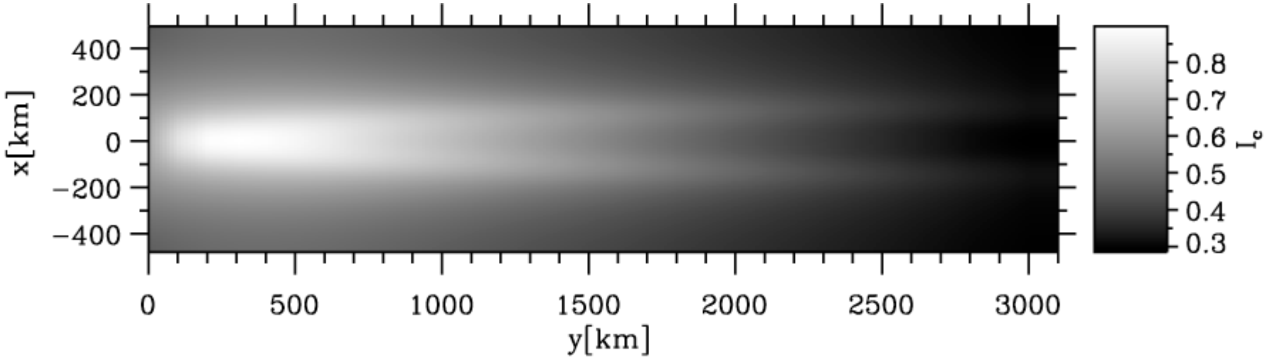
Continuum intensity (488 nm)



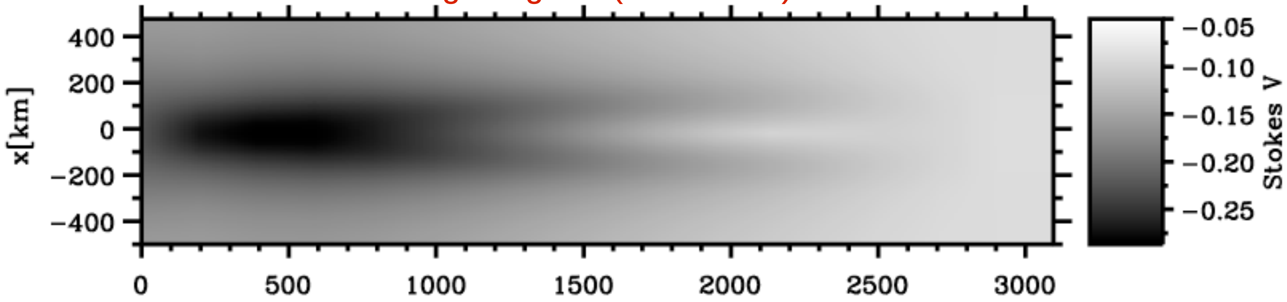
- Filament with bright head and dark core
- Distance between lateral brightenings is ~250 km
- Length of ~3000 km
- Evershed flow heats surroundings very efficiently
- Average brightness in box is ~0.5 I_{QS}
- Average brightness without flow would be ~0.06 I_{QS}

2D heat transfer simulations: results

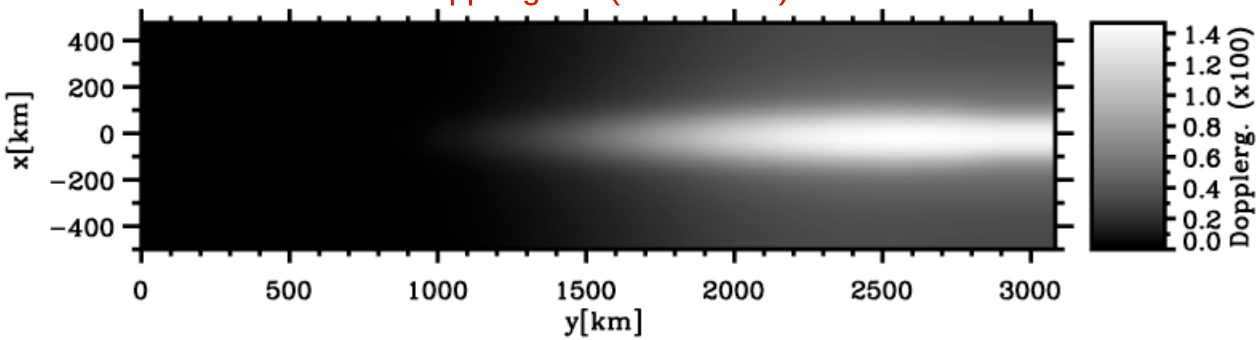
Continuum intensity (488 nm)



Magnetogram (630.25 nm)



Dopplergram (630.25 nm)



Summary

- The Evershed flow
  - Is organized on very small scales and shows filamentary structure
  - Is magnetized and sometimes supersonic
  - Is upward in the inner penumbra and downward in middle/outer PU
  - Is associated with the more inclined and weaker fields of the PU
- Hot Evershed flows along flux tubes ~100 km in radius
  - Reproduce the polarization profiles of visible and IR lines
  - Explain the existence of dark-cored penumbral filaments
  - May account for the brightness of the penumbra