

Where do solar eruptions come from?

Anthony Yeates

Durham University, UK

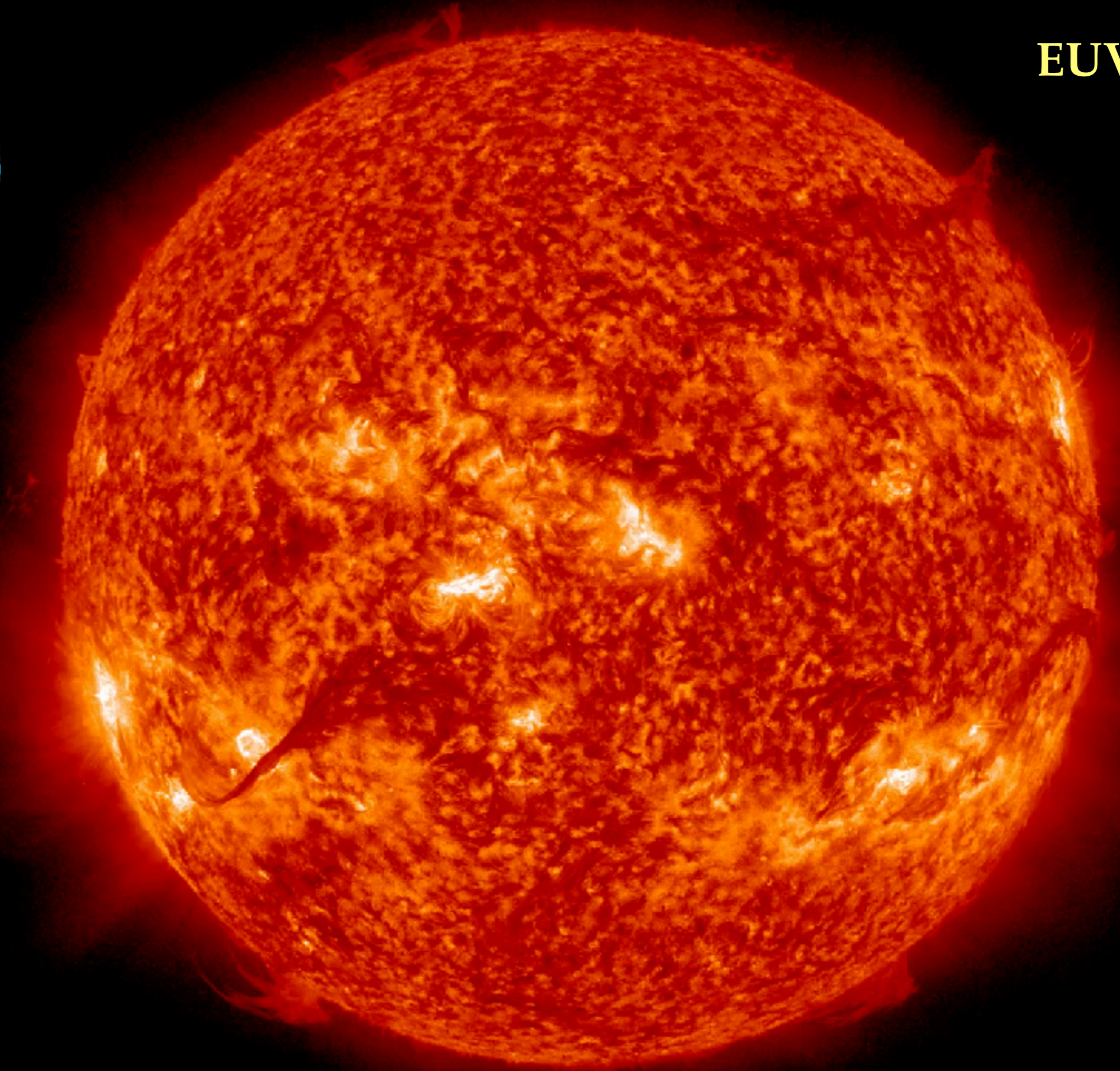
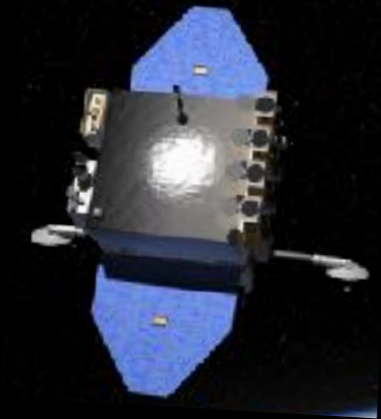


Durham
University

UK-SOSS, 19-May-2020

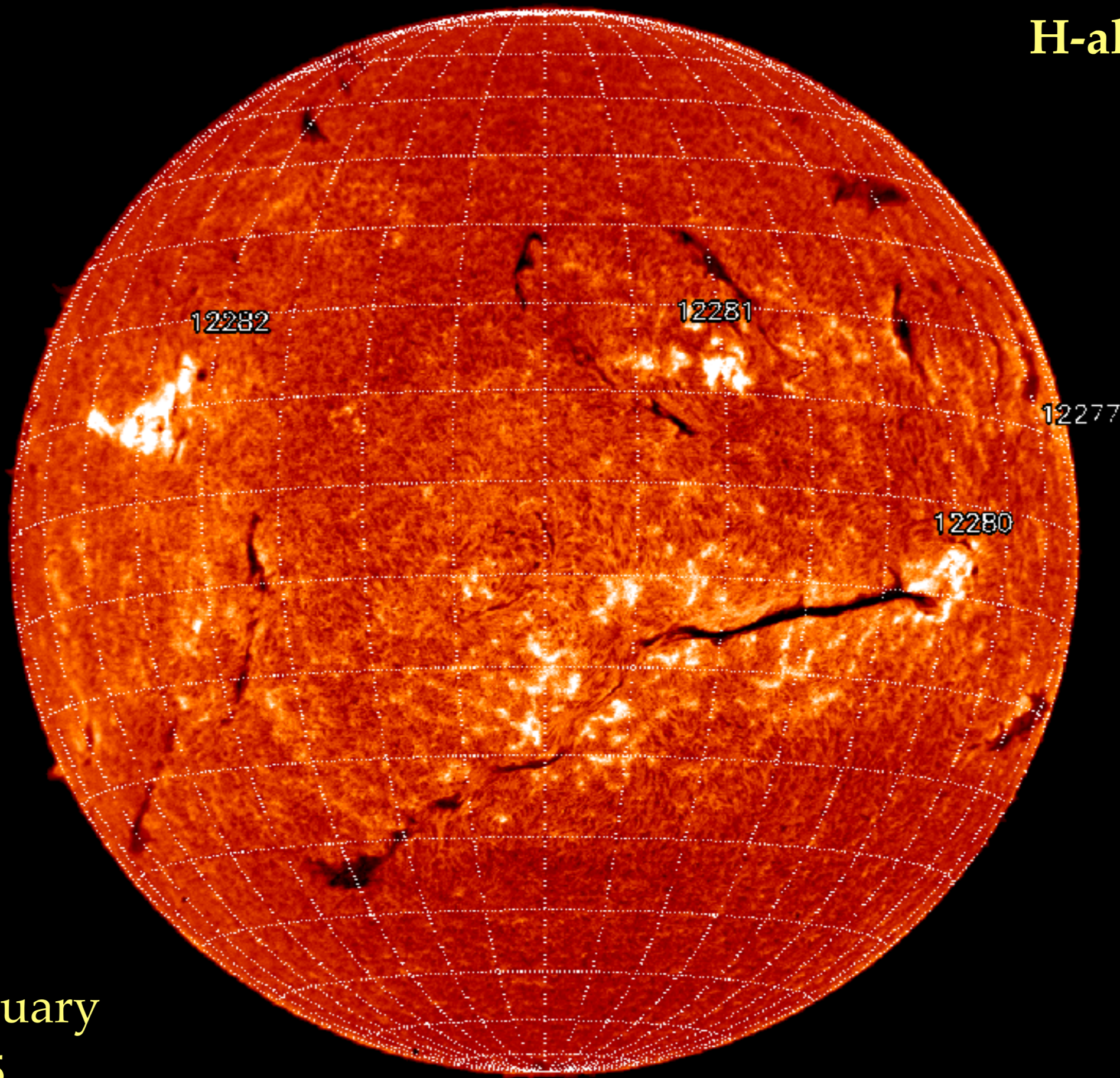


EUV



August
2012

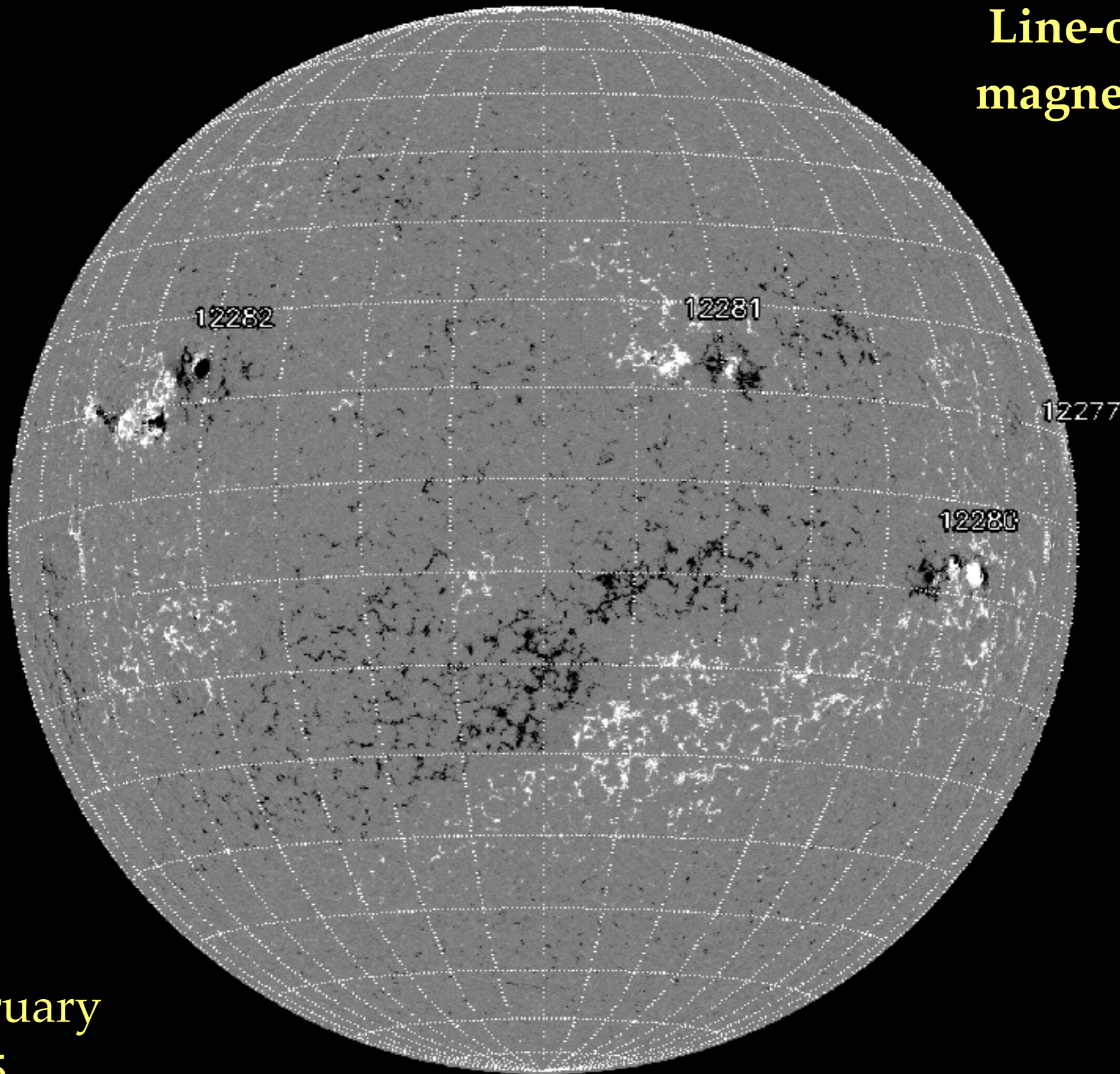
H-alpha



10th February
2015

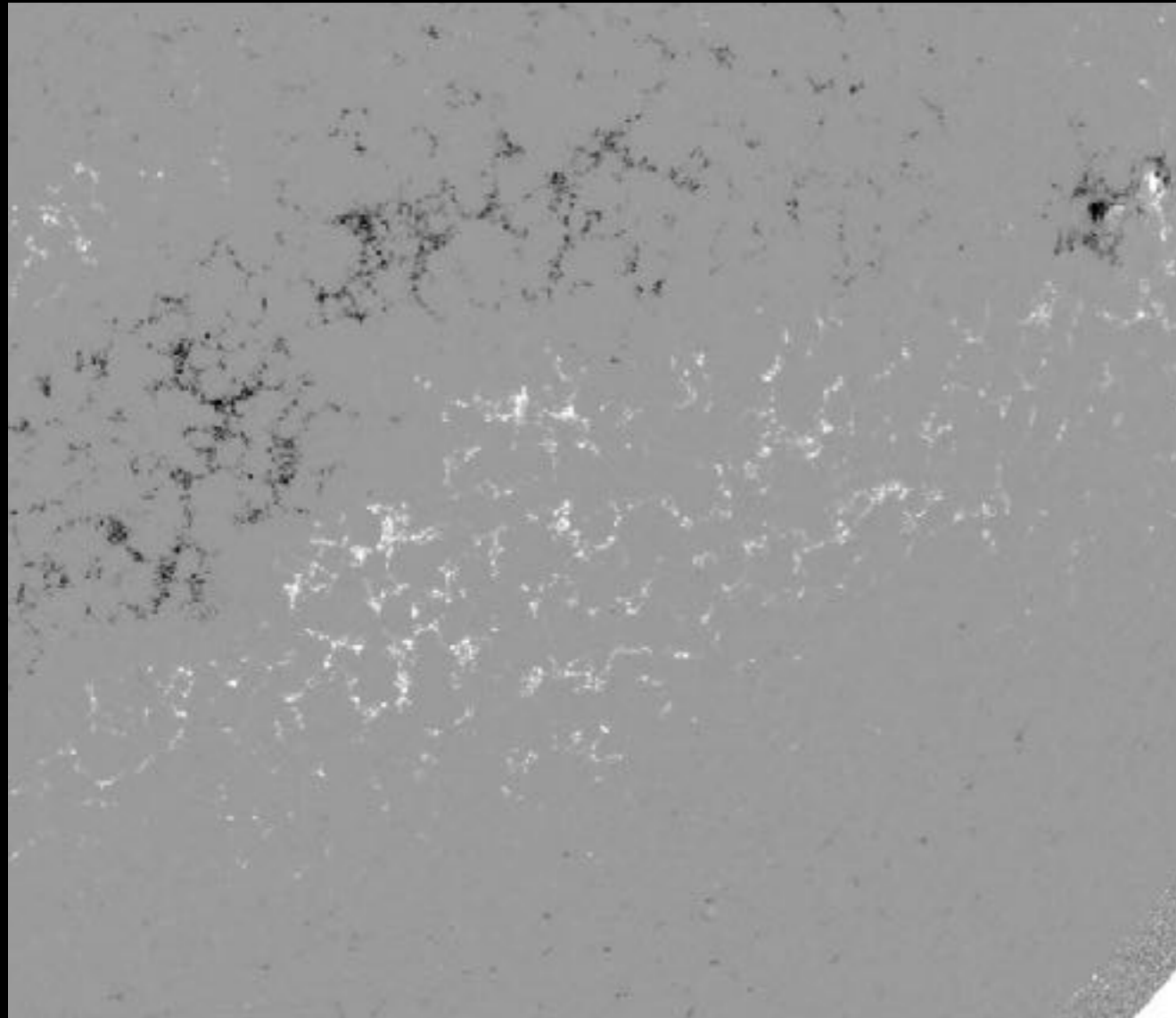
SolarMonitor.org

Line-of-sight magnetic field



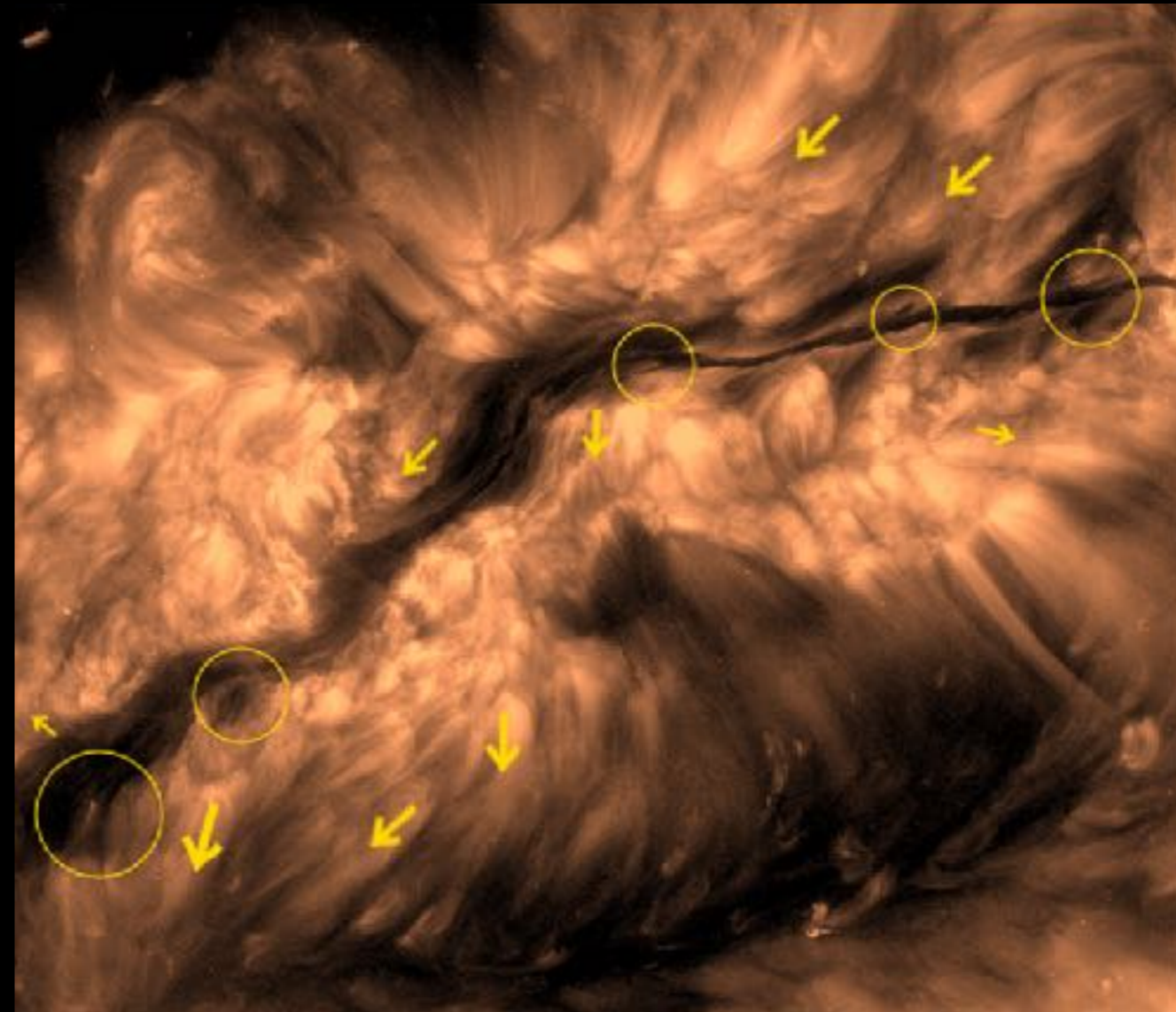
10th February
2015

**Line-of-sight
magnetic field**



**10th February
2015**

EUV

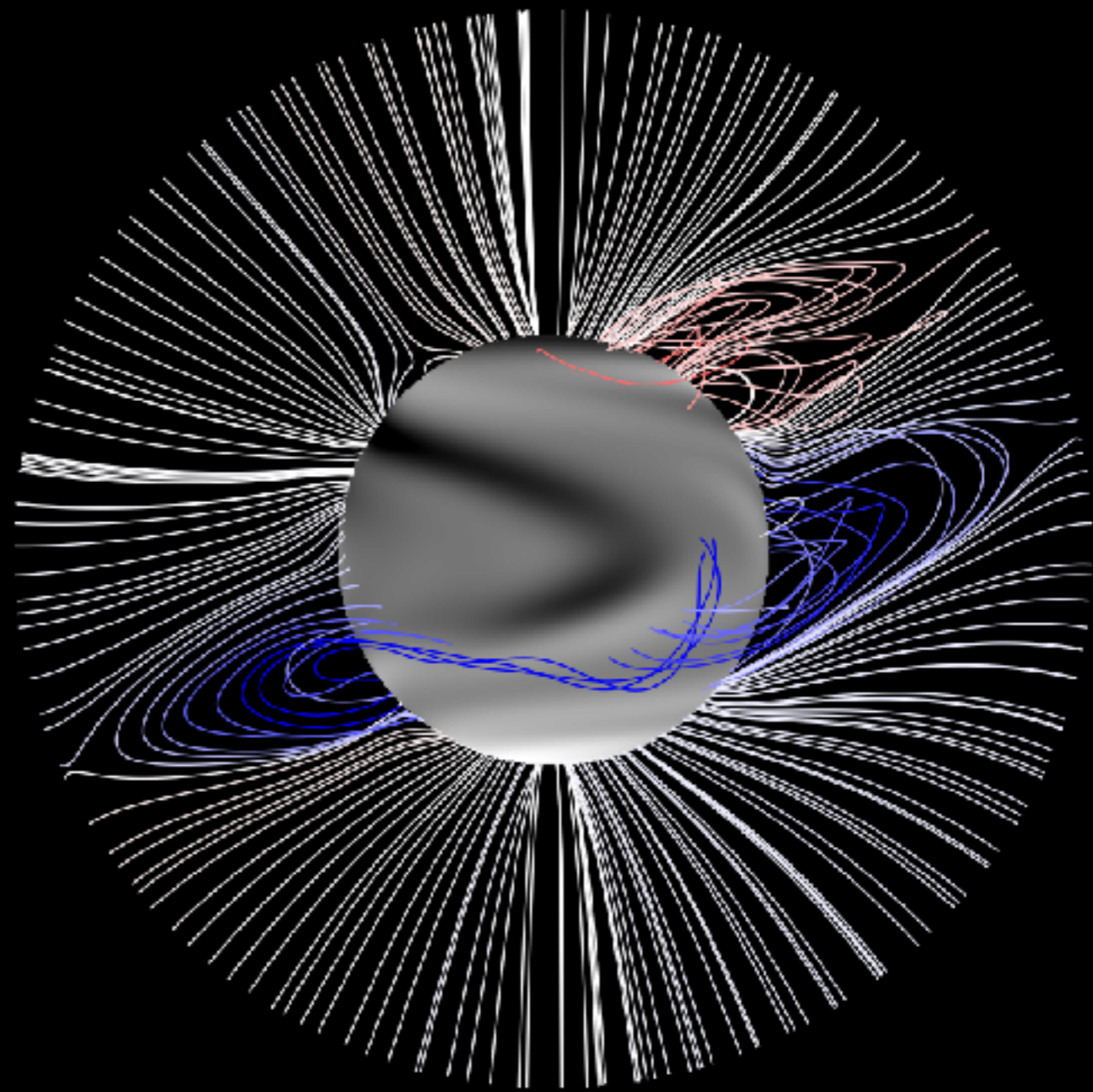
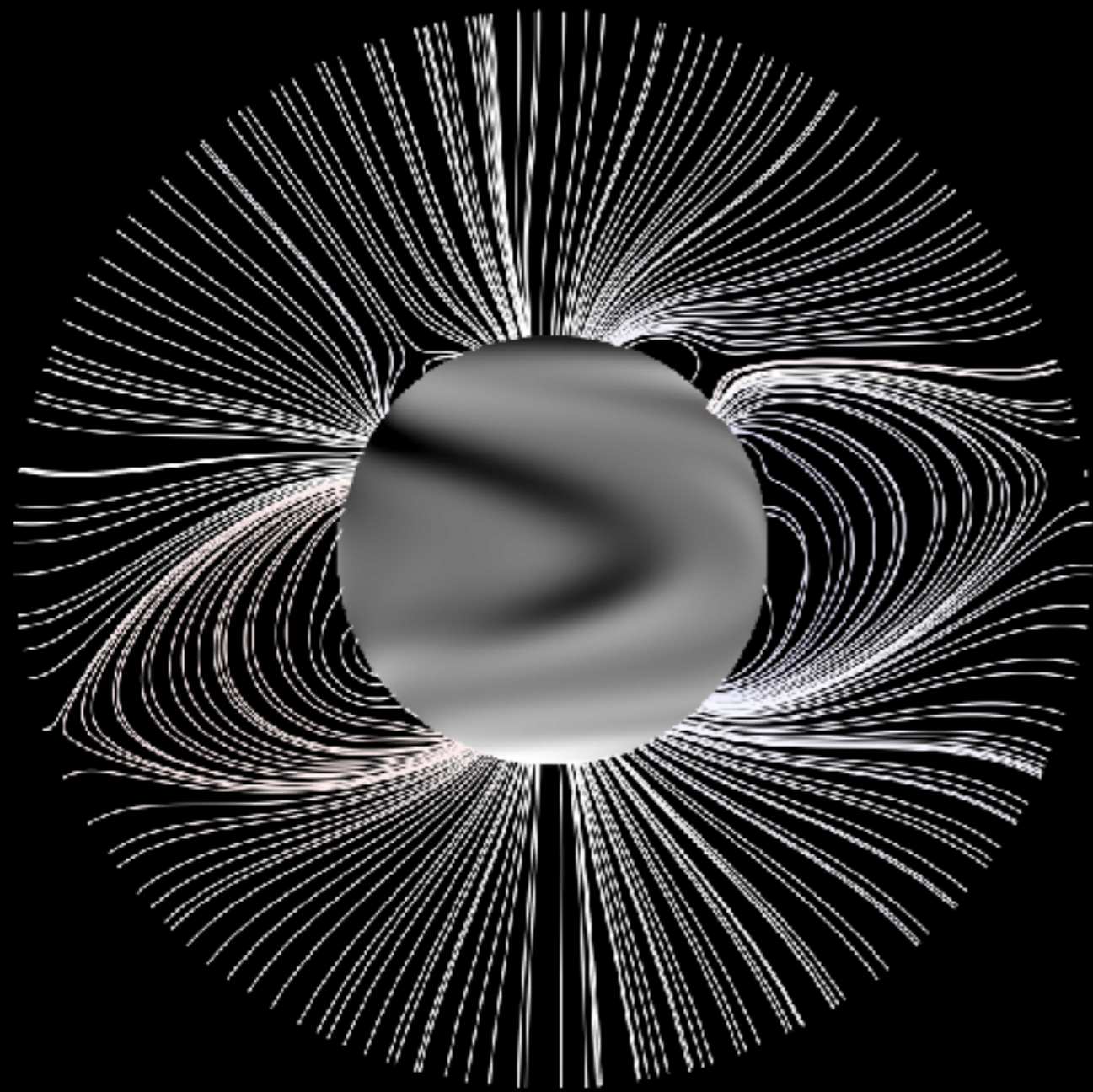


McMaken & Petrie, *ApJ* [2017]



04-Aug-12 00:00:06

(courtesy David Long)



FUNDAMENTALS OF CORONAL EVOLUTION:

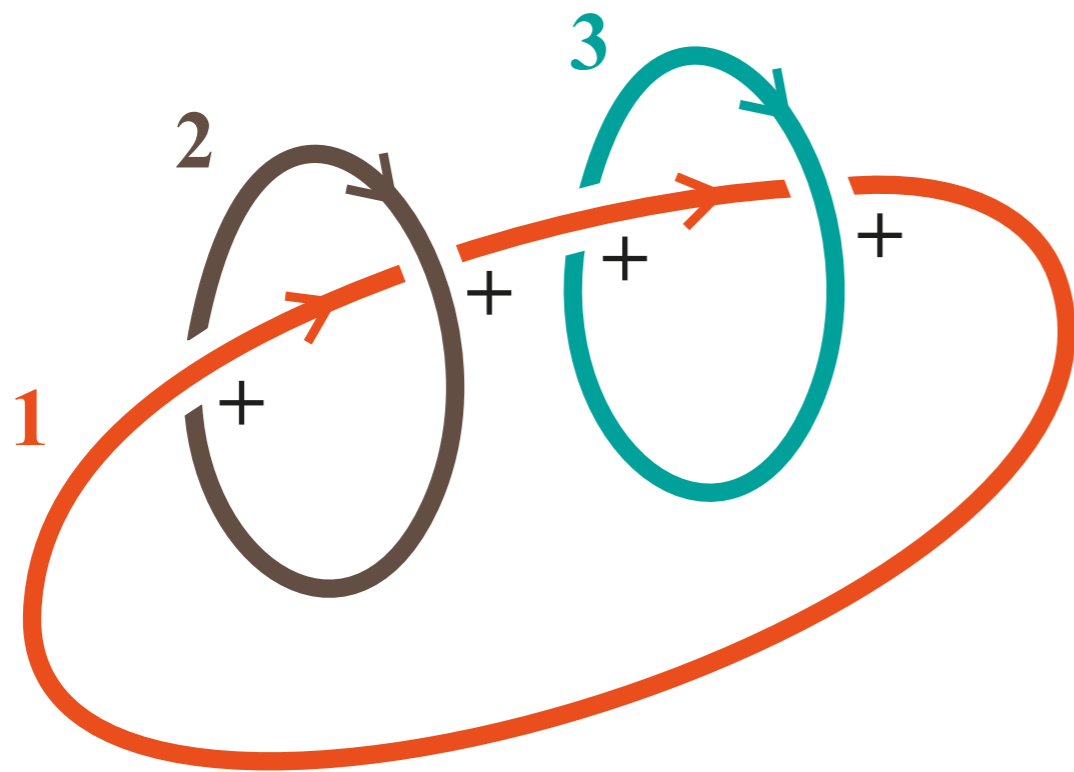
- 1. Magnetic helicity is injected by surface motions.**
- 2. It accumulates at polarity inversion lines.**
- 3. It is removed by coronal mass ejections.**

FUNDAMENTALS OF CORONAL EVOLUTION:

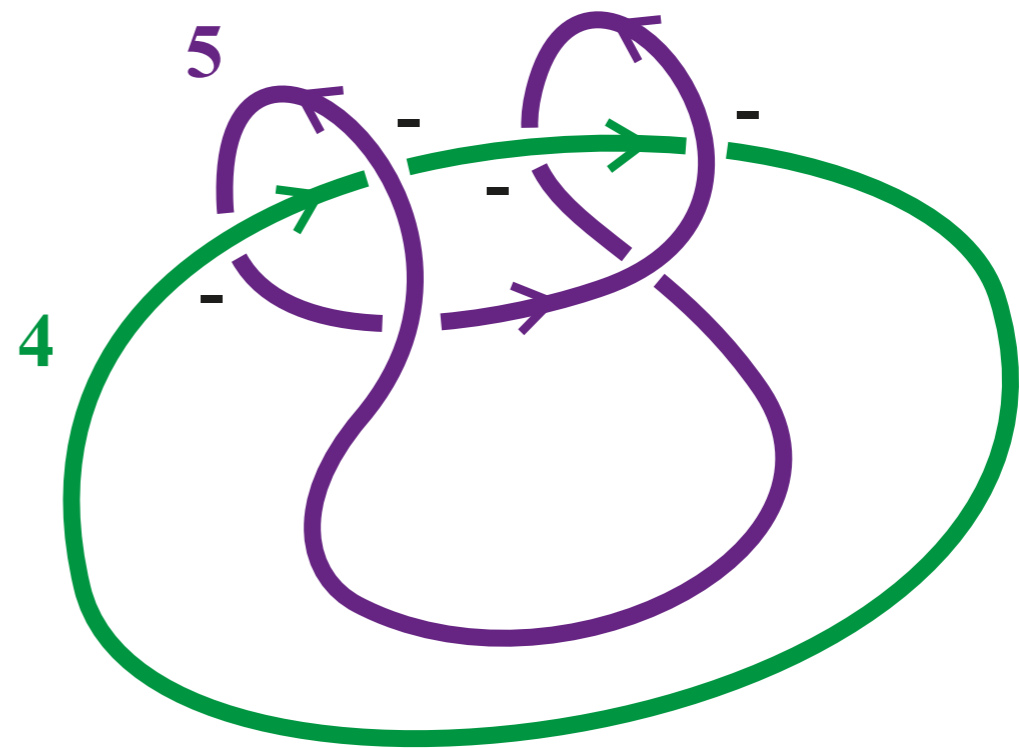
1. **Magnetic helicity** is injected by surface motions.
2. It accumulates at polarity inversion lines.
3. It is removed by coronal mass ejections.

Magnetic helicity - the net linkage of magnetic flux.

$$H = \frac{1}{2} \sum_i \sum_j L_{ij} \Phi_i \Phi_j$$



$$H = \Phi_1 \Phi_2 + \Phi_1 \Phi_3$$



$$H = -2\Phi_4 \Phi_5$$

Alfvén's theorem - magnetic flux tubes preserve their topology in a perfectly-conducting plasma.

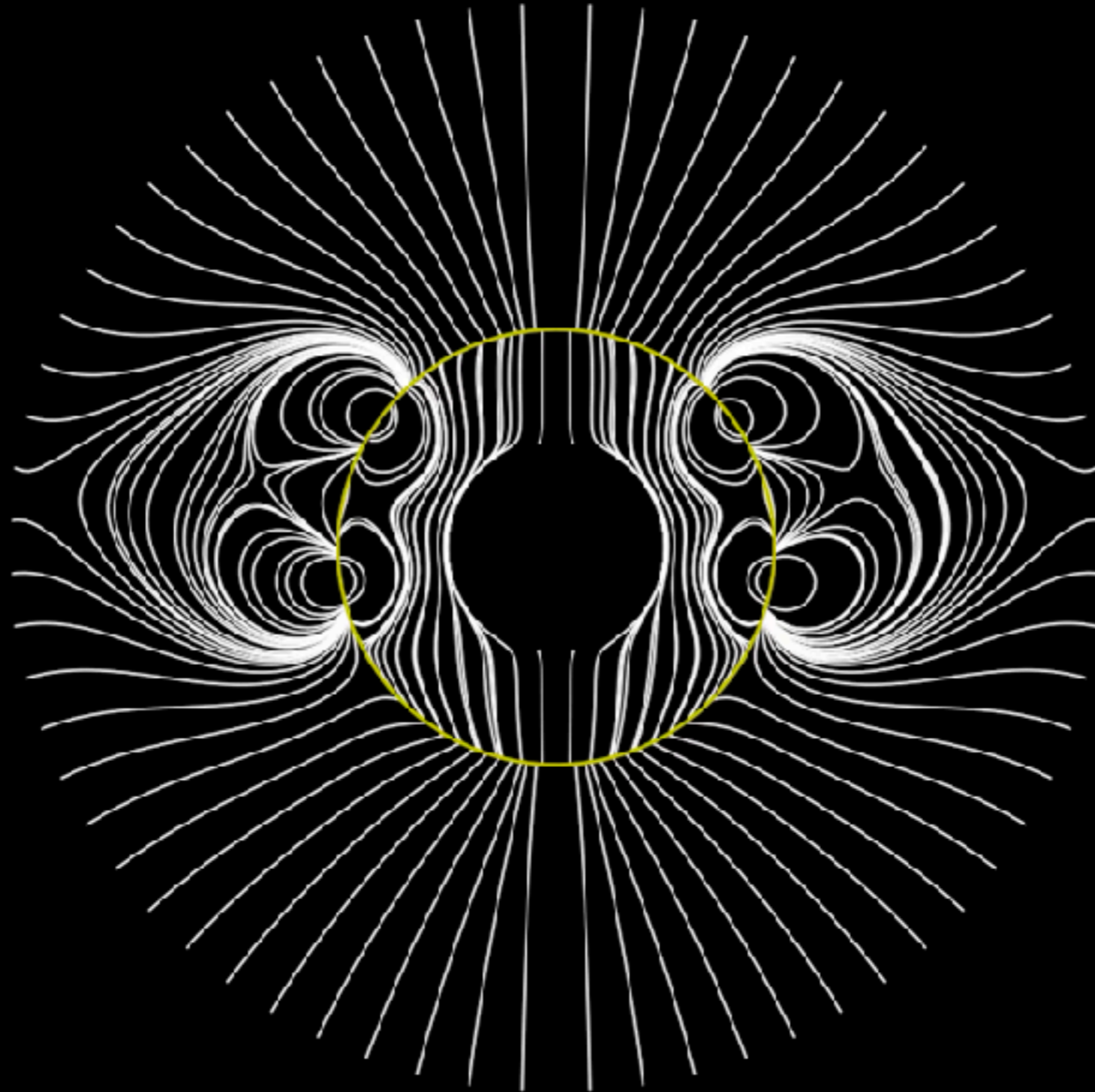


H. Alfvén, Nobel Prize for Physics, 1970

So magnetic helicity must be injected from the boundary.

Relative helicity - magnetic helicity of the coronal field closed with no external source currents.

Berger & Field, *J. Fluid Mech.* [1984]



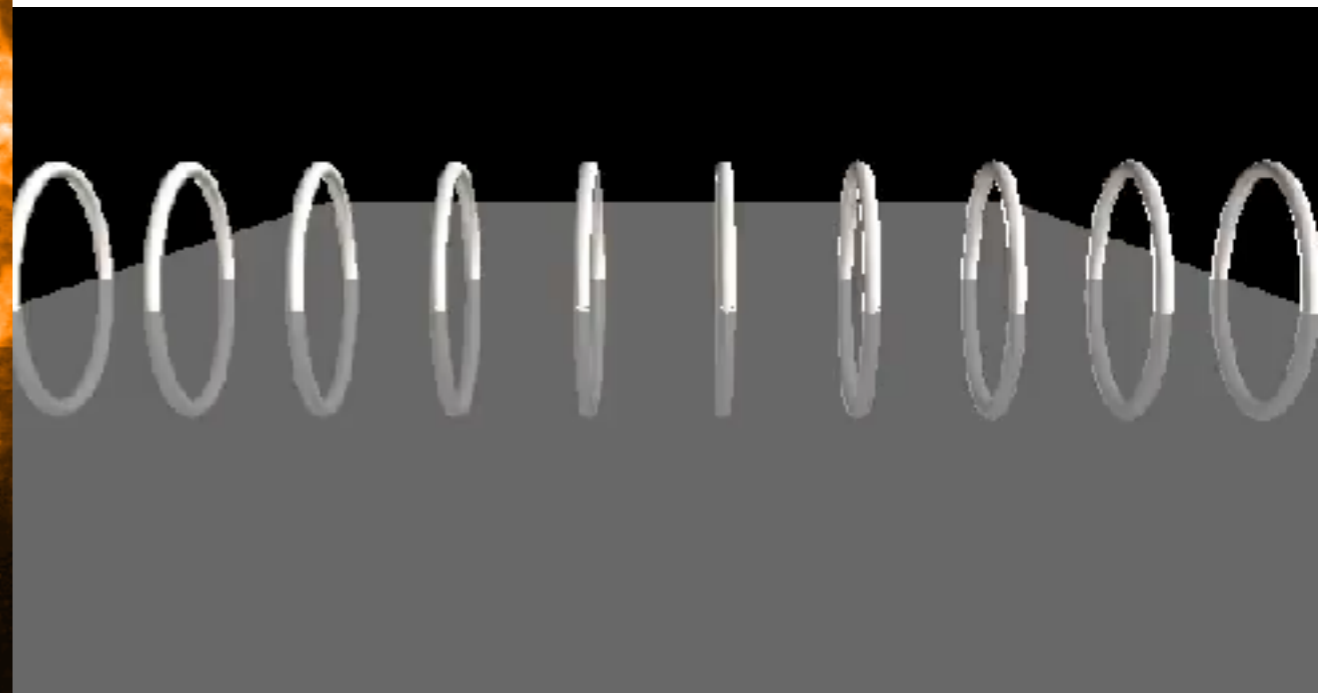
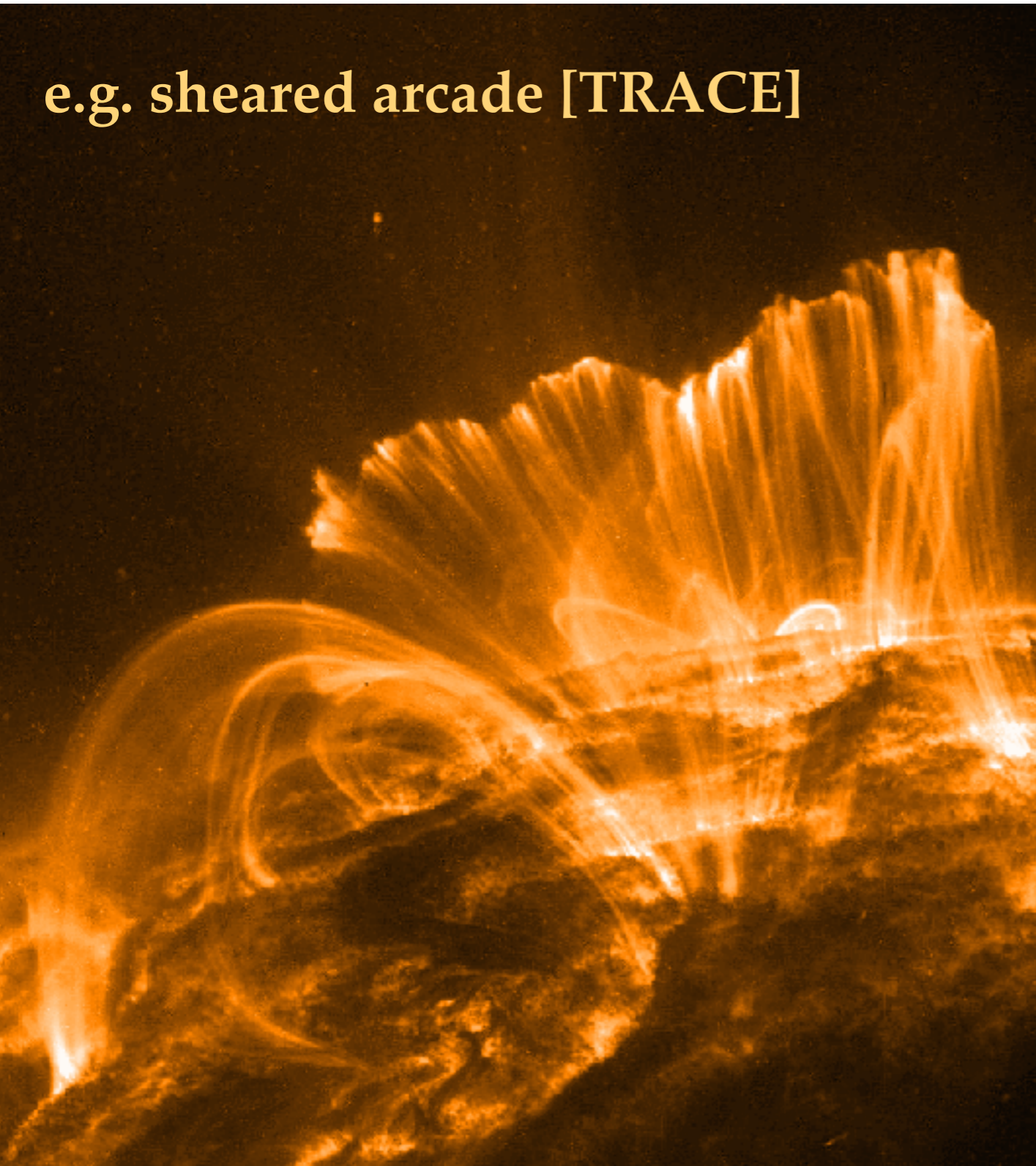
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- 1. Magnetic helicity is injected by surface motions.**
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Footpoint motions can inject relative helicity.

Berger & Field, *J. Fluid Mech.* [1984]
Démoulin & Berger, *Solar Phys.* [2003]

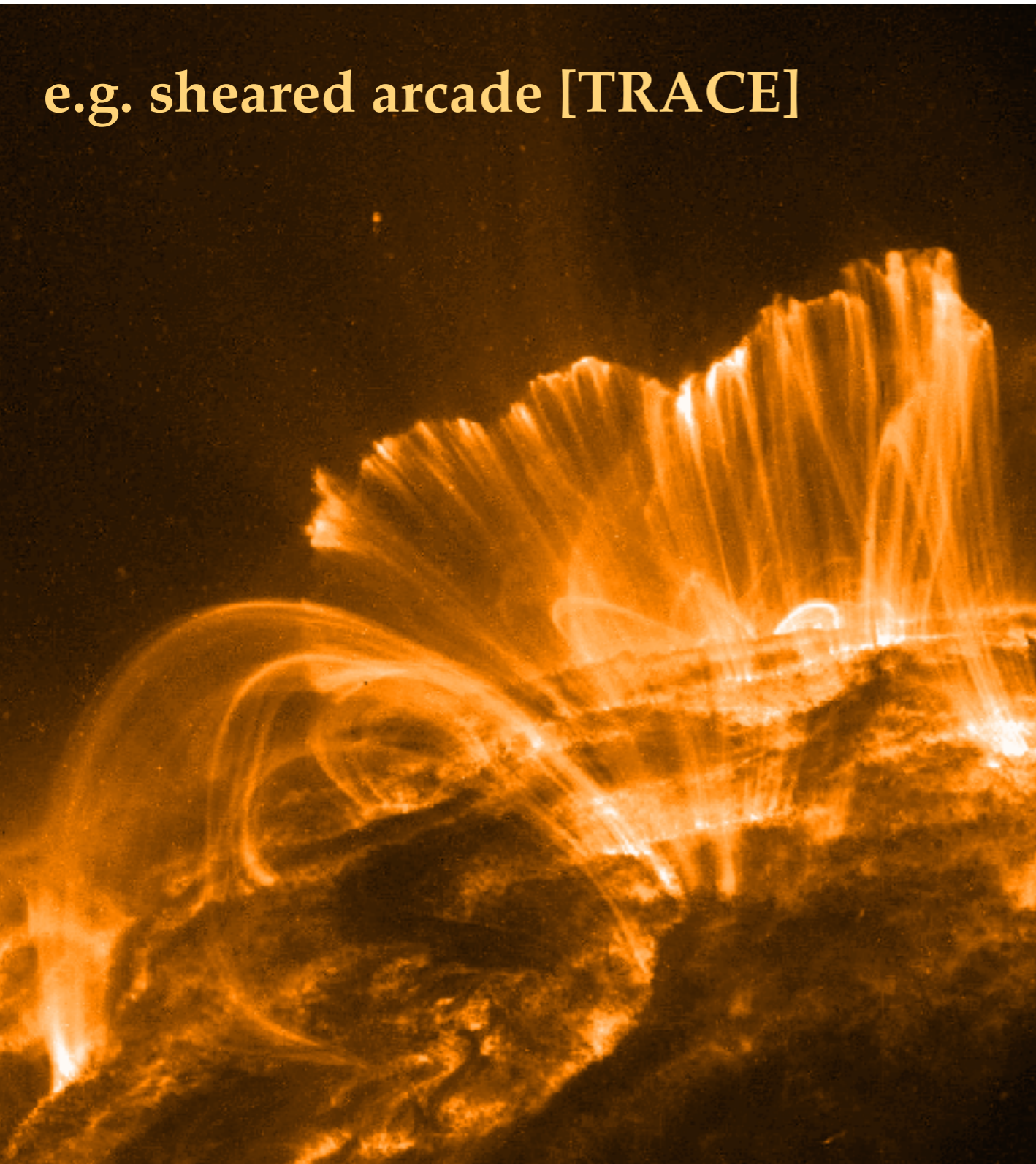
e.g. sheared arcade [TRACE]



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Berger & Field, *J. Fluid Mech.* [1984]
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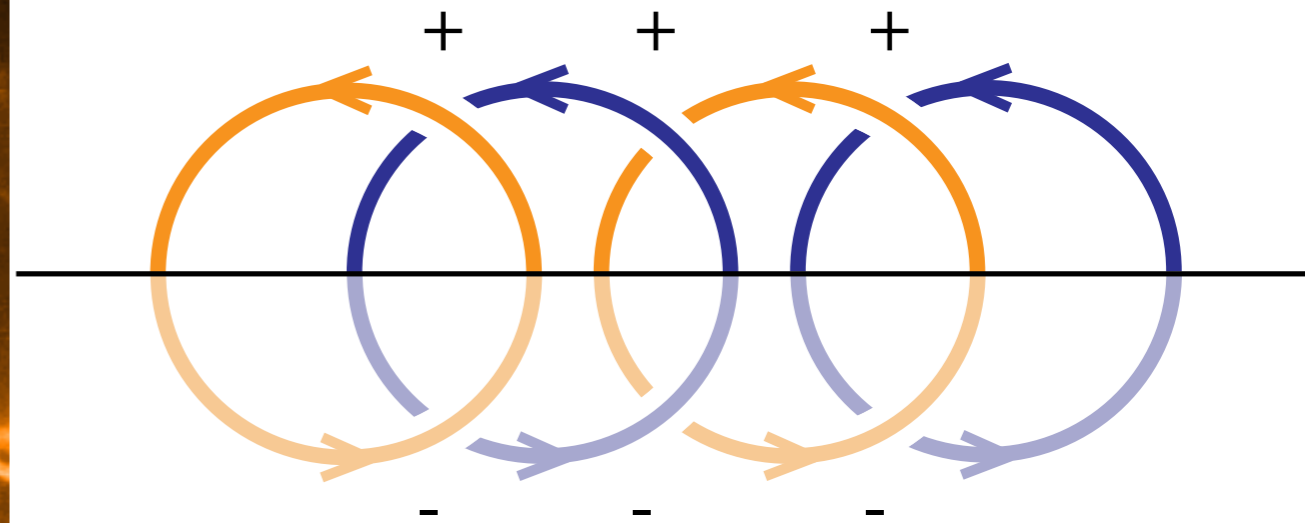
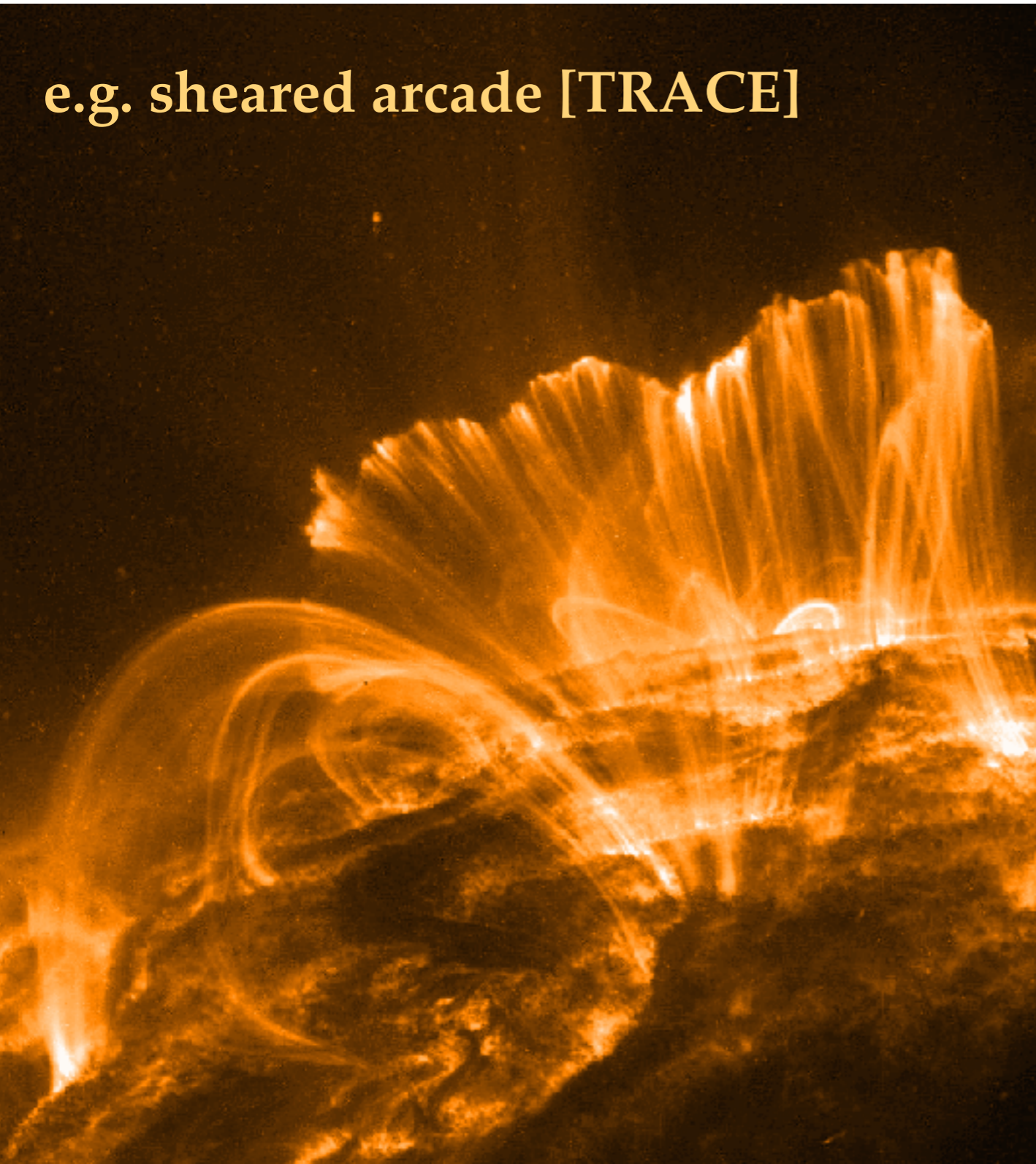
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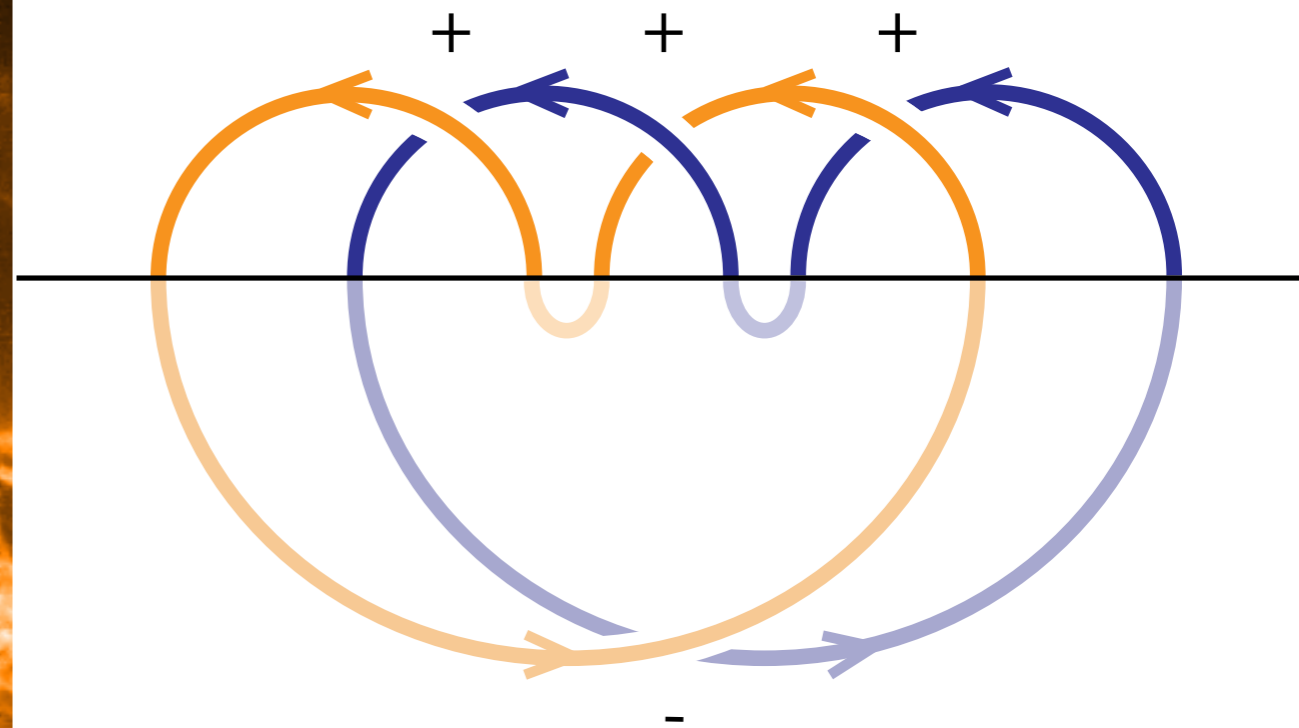
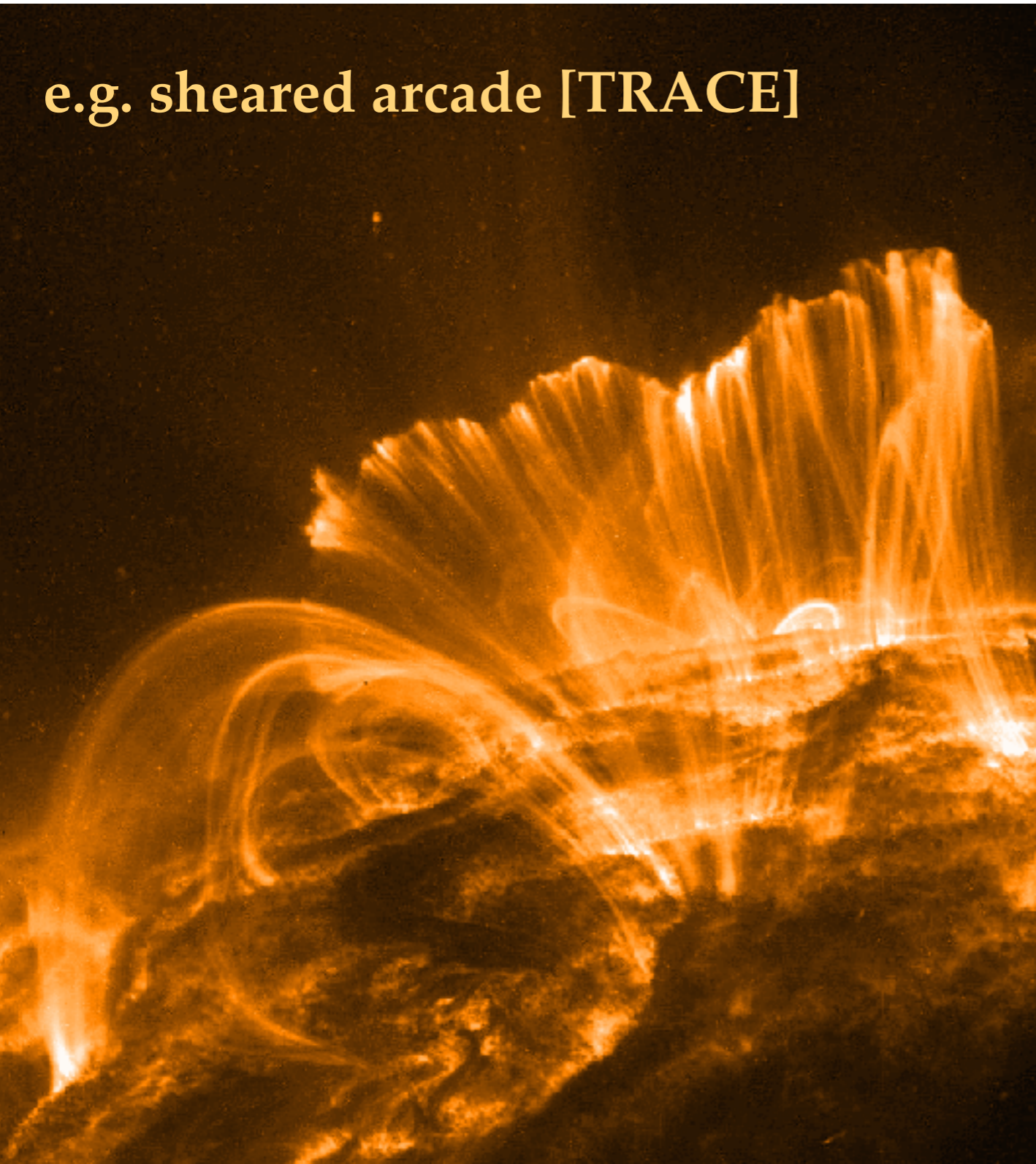


currents

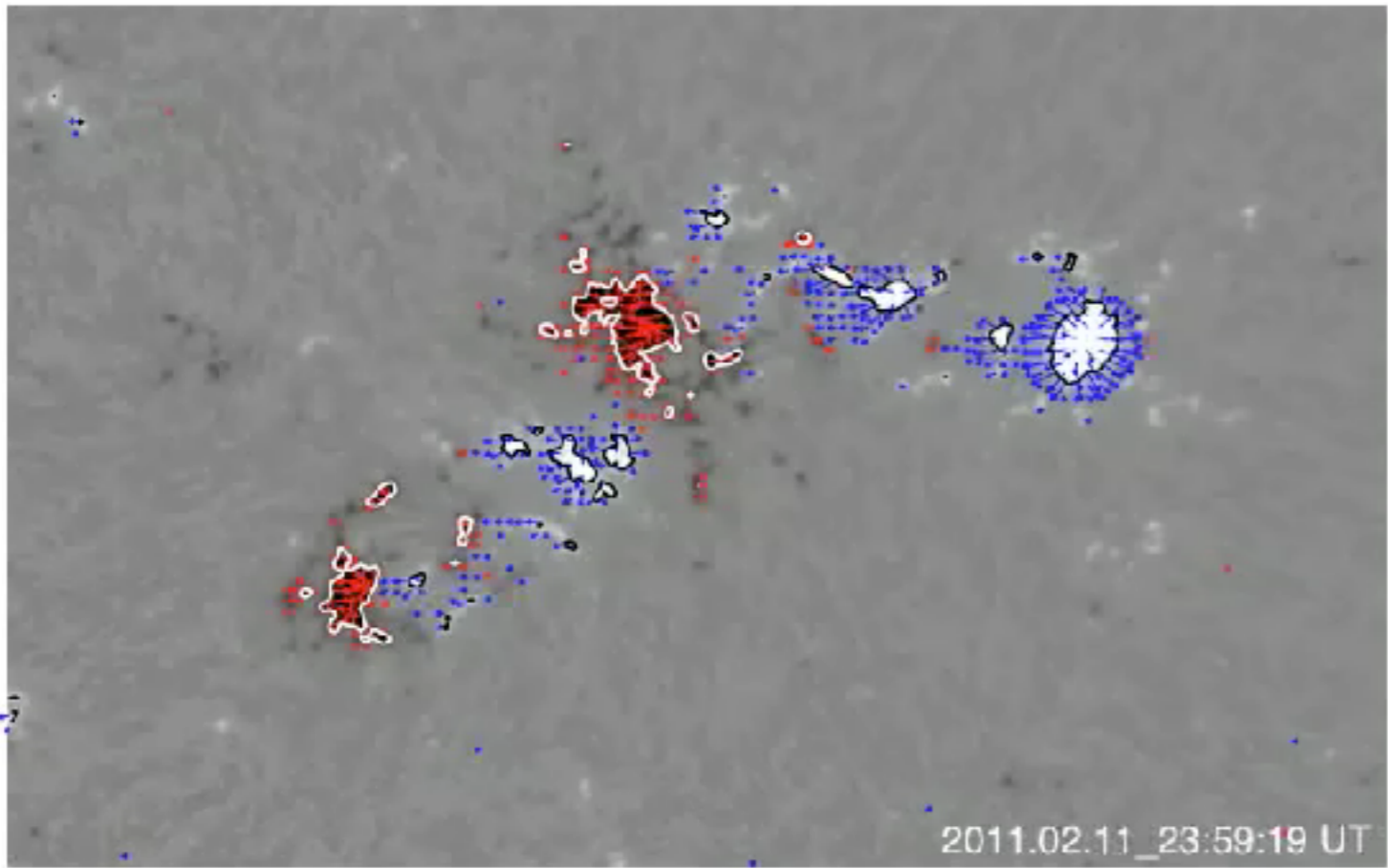
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Berger & Field, *J. Fluid Mech.* [1984]
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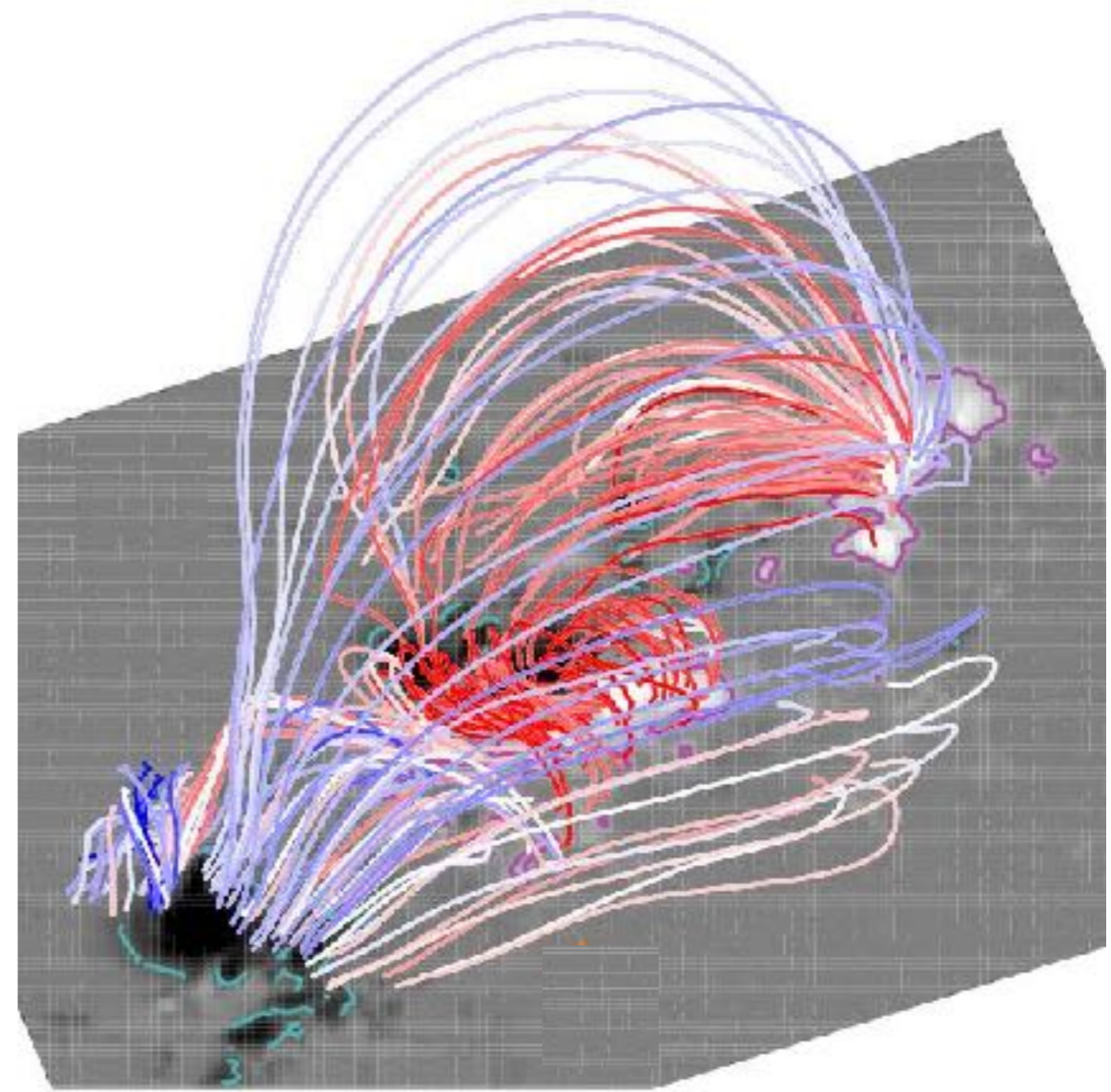
e.g. sheared arcade [TRACE]



no currents in extension



e.g. Sun et al., *ApJ* [2012]



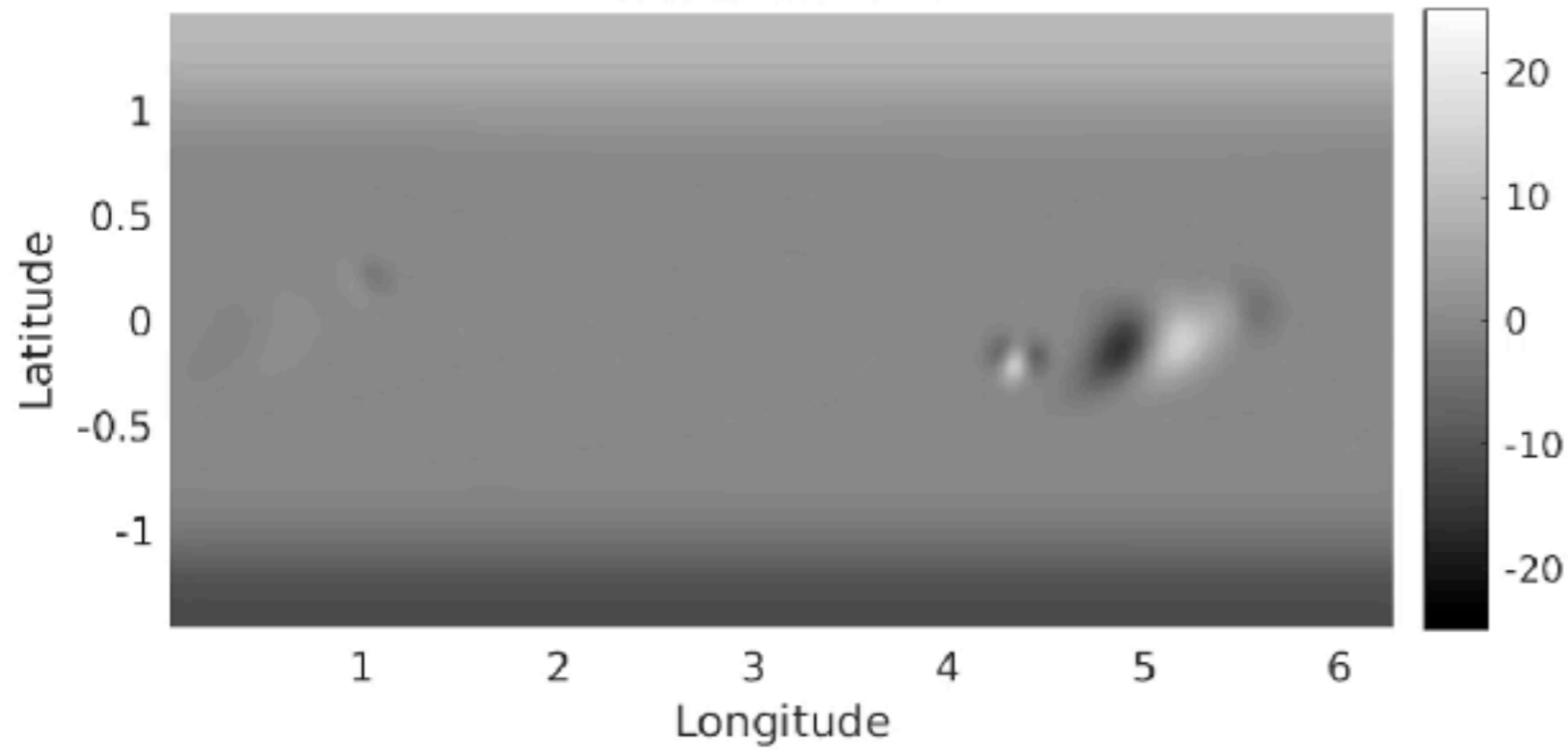
e.g. Dalmasse et al., *A&A* [2013]

Observation 1:

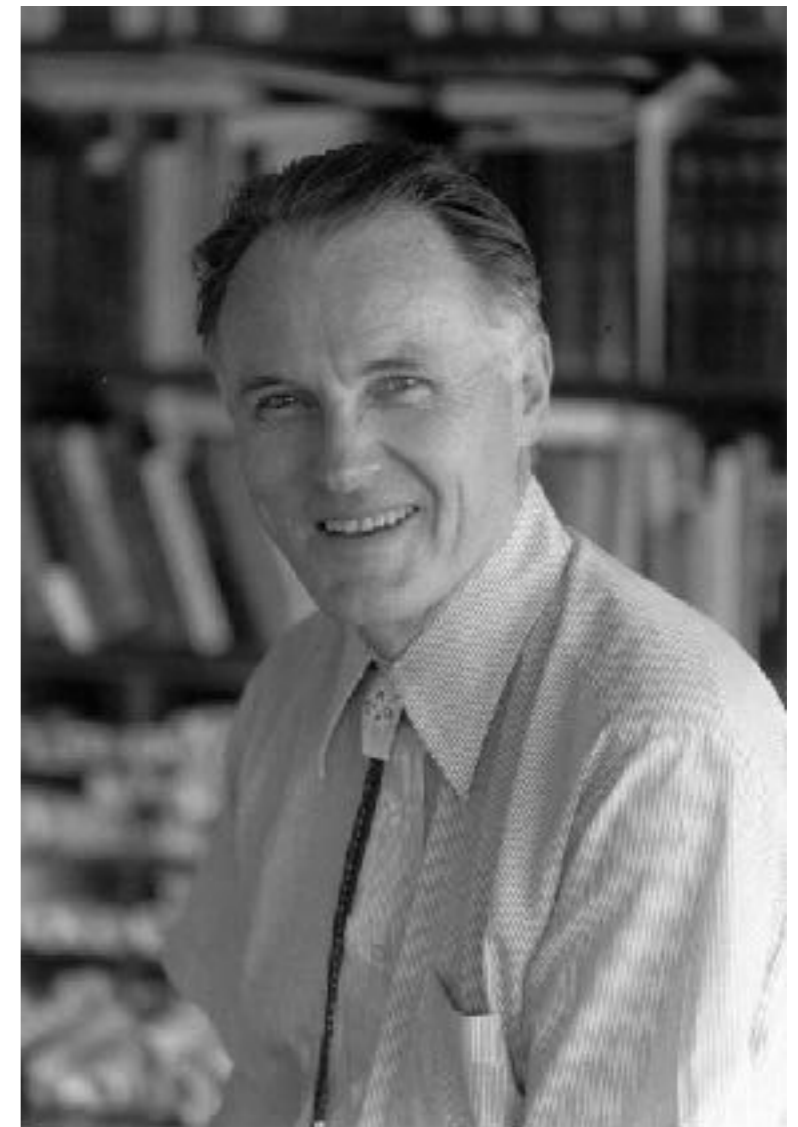
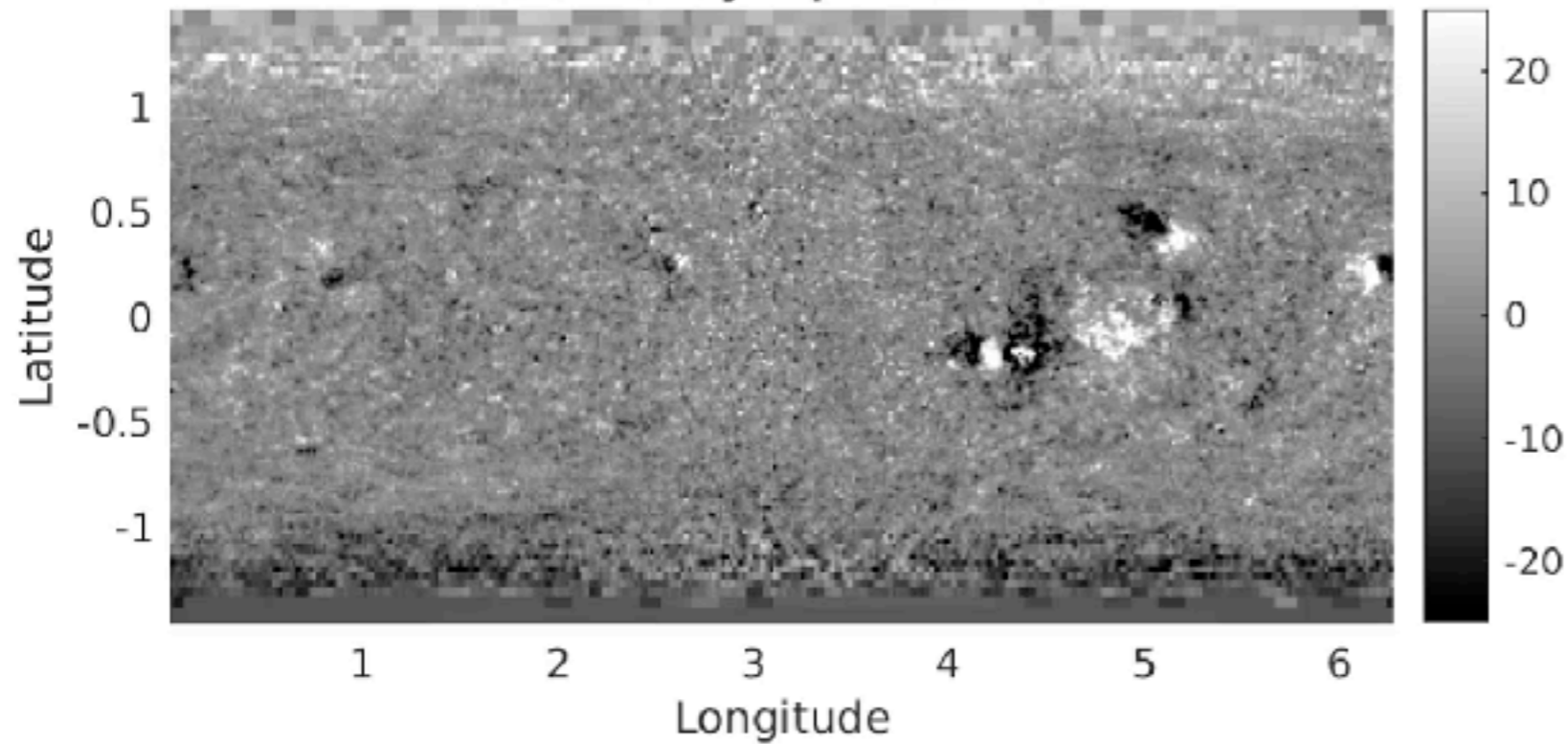
Active region emergence generates $\sim 10^{46}$ Mx² per cycle.

LaBonte et al., *ApJ* [2007]
Georgoulis et al., *ApJL* [2009]

End of CR 1911

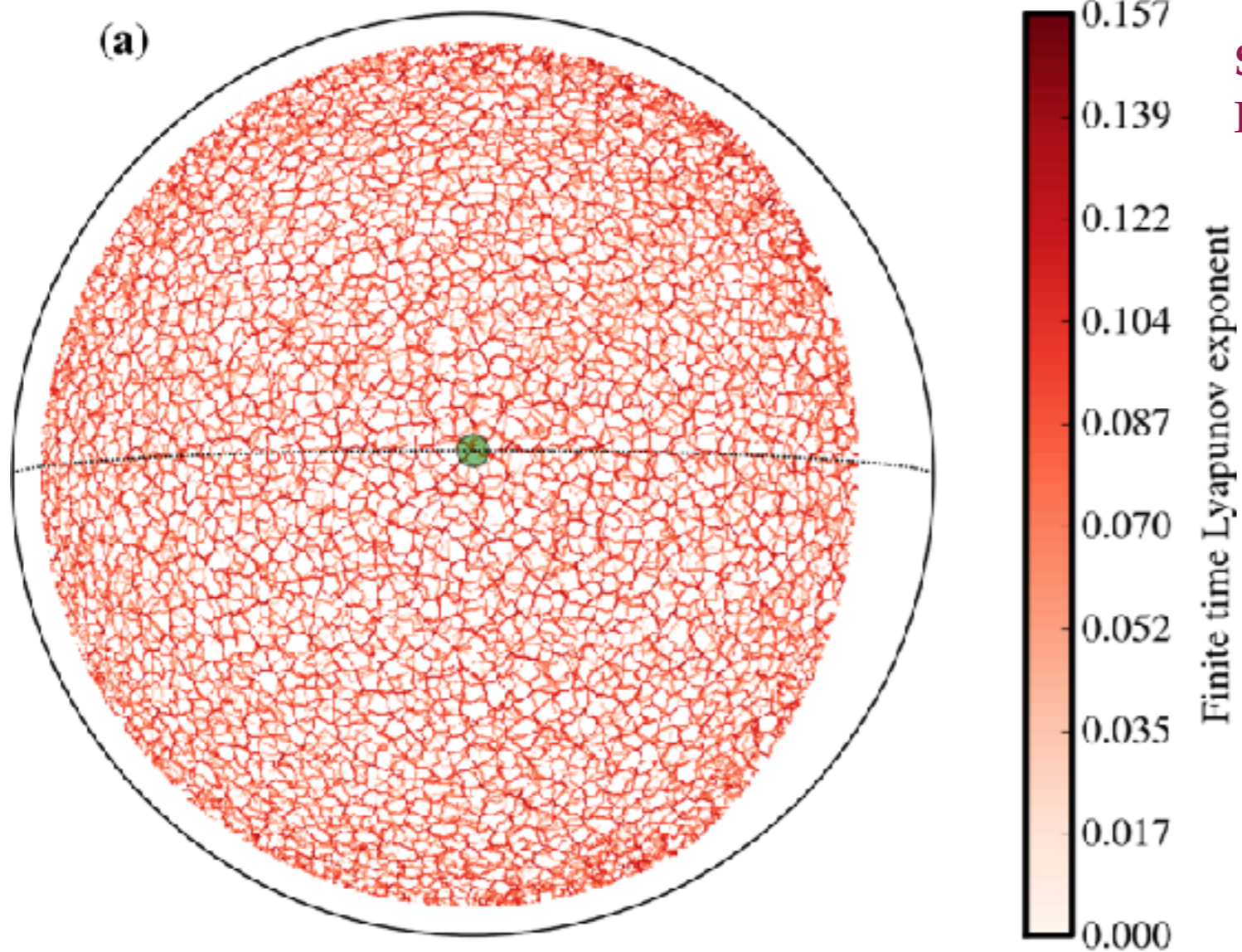


Observed synoptic CR 1911



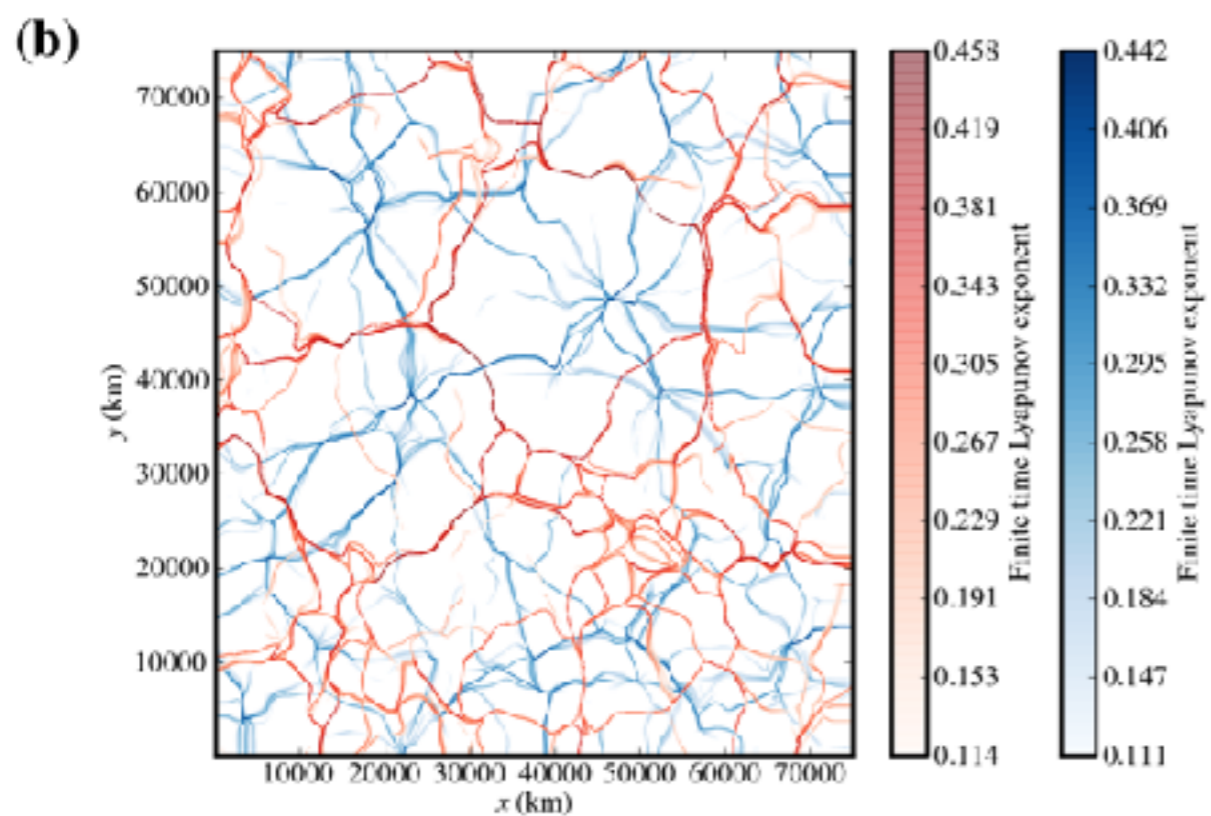
Leighton, *ApJ* [1964]

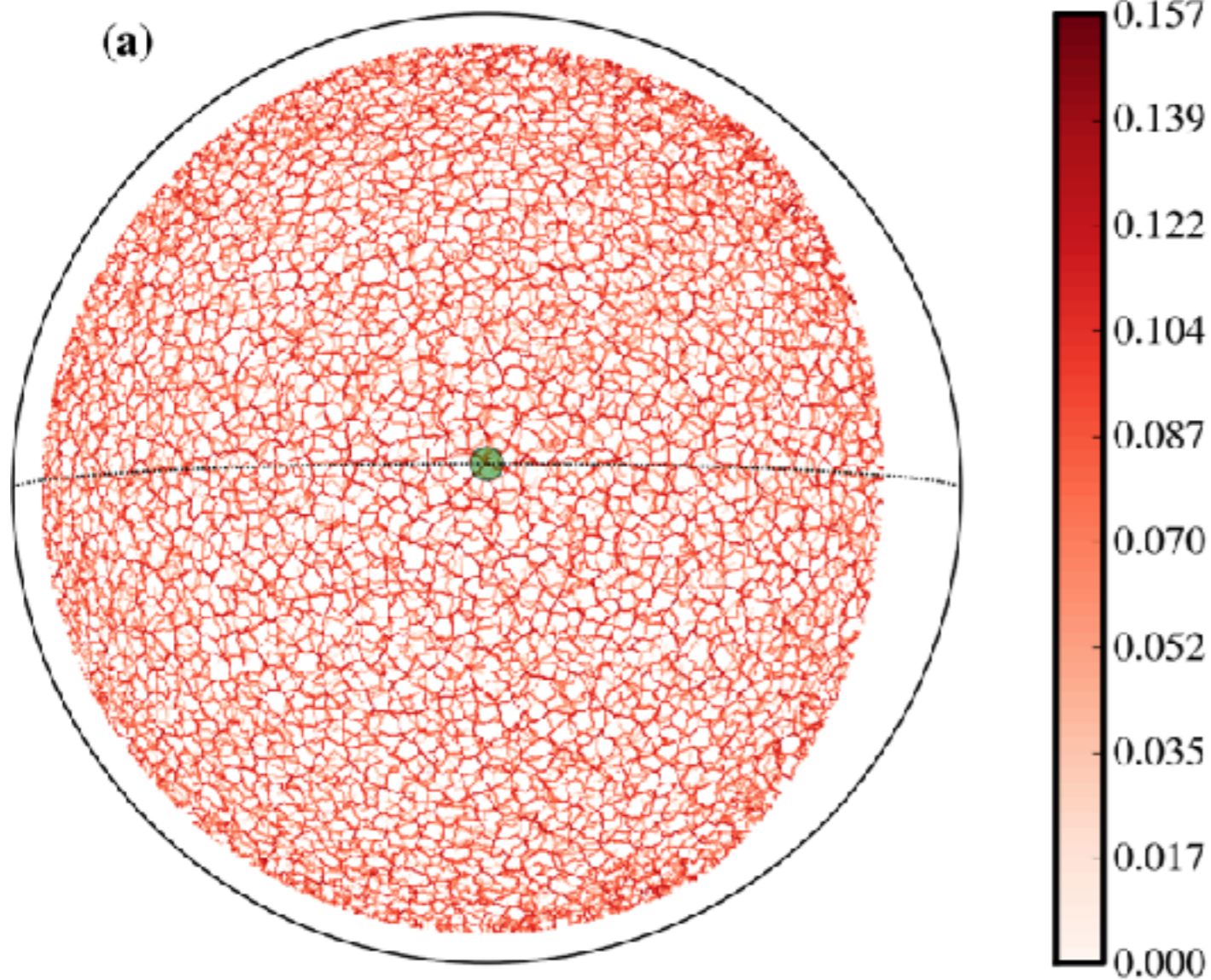
DeVore et al, *Solar Phys.* [1984]



SDO data:

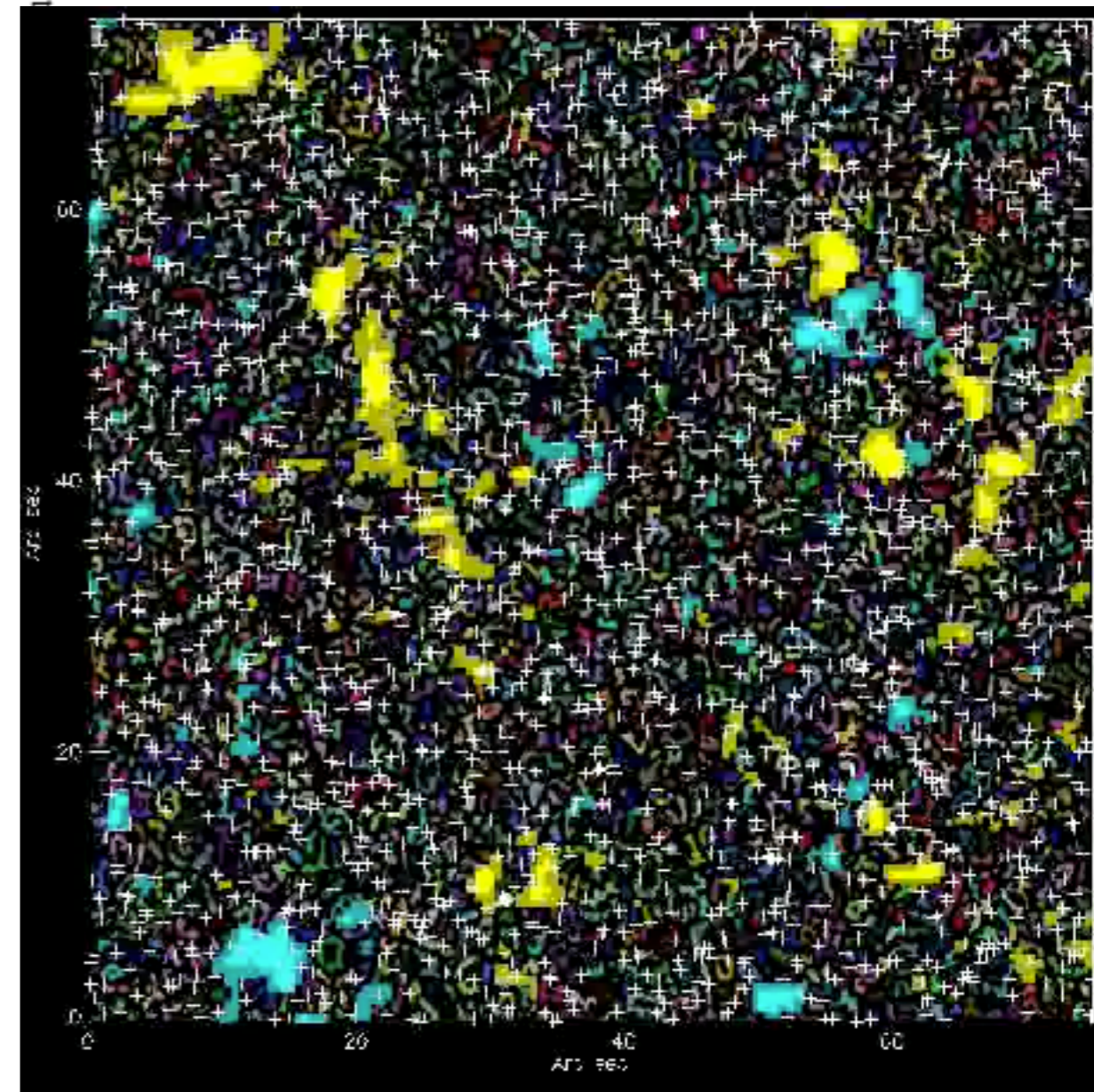
Rincon & Rieutord, *Living Rev. Solar Phys.* [2018]





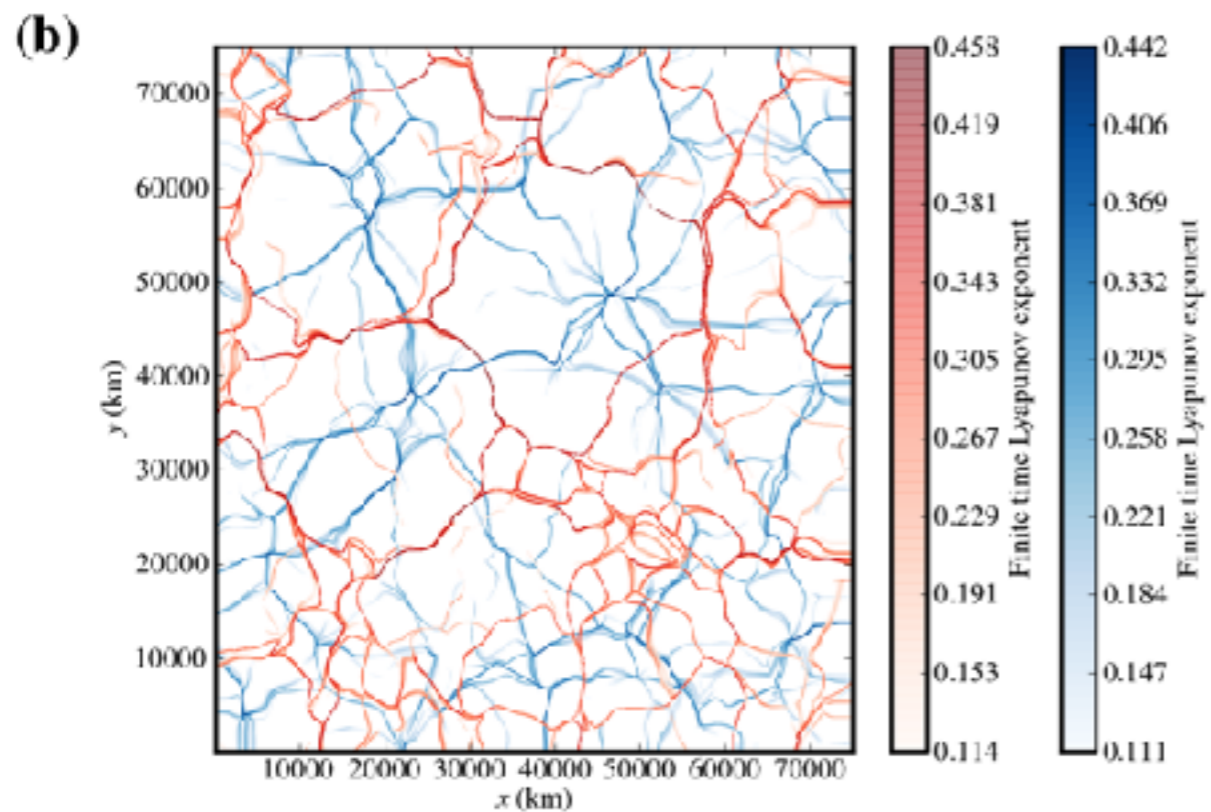
SDO data:

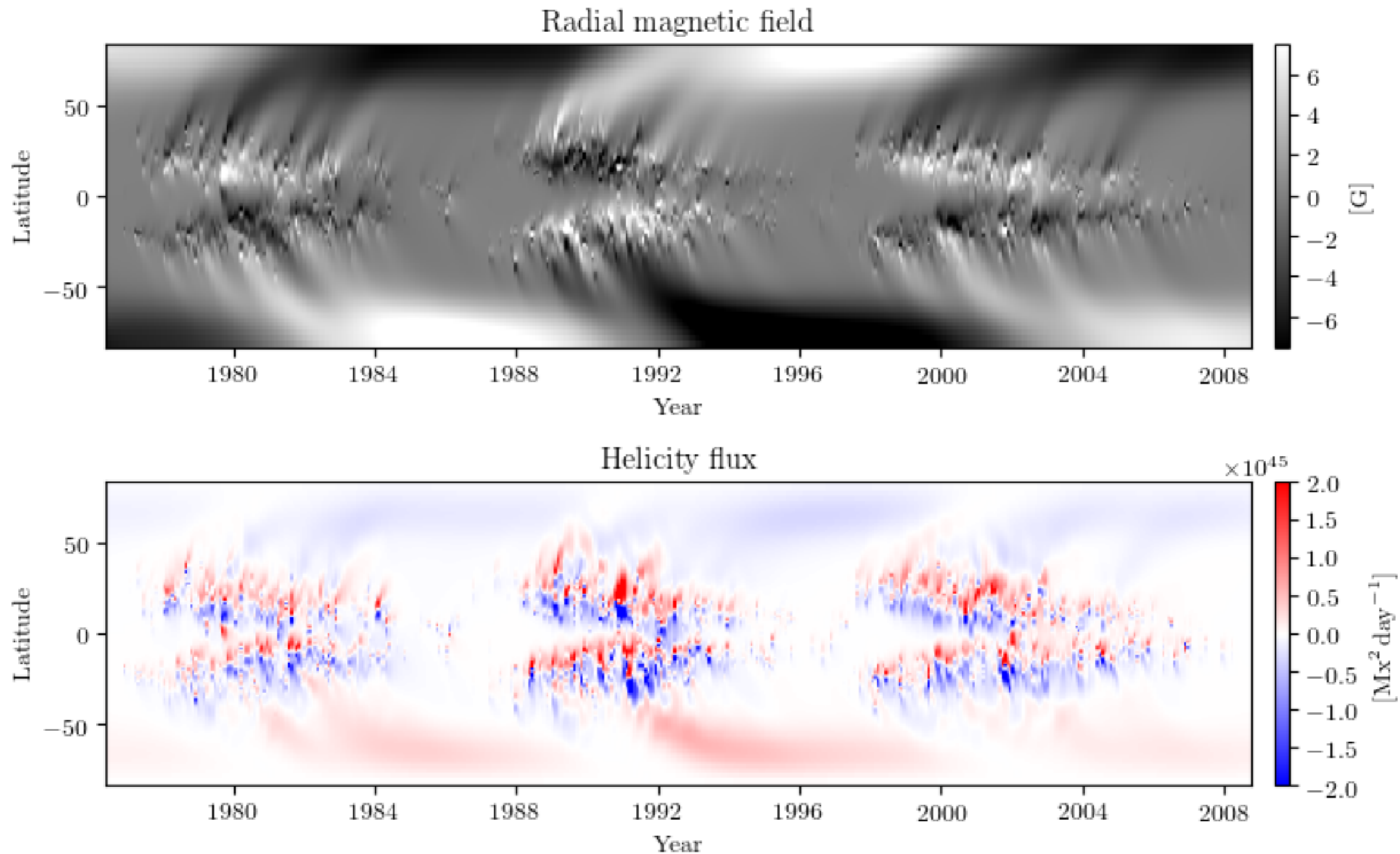
Rincon & Rieutord, *Living Rev. Solar Phys.* [2018]



Hinode and SDO data (24 hrs):

Roudier, Malherbe, Rieutord & Frank, *A&A* [2016]





Berger & Ruzmaikin, *JGR* [2000]
 Hawkes & Berger, *Solar Phys.* [2018]
 Hawkes & Yeates, *A&A* [2019].

Observation 2:

Solar rotation generates $\sim 2 \times 10^{46} \text{ Mx}^2$ per hemisphere per cycle.

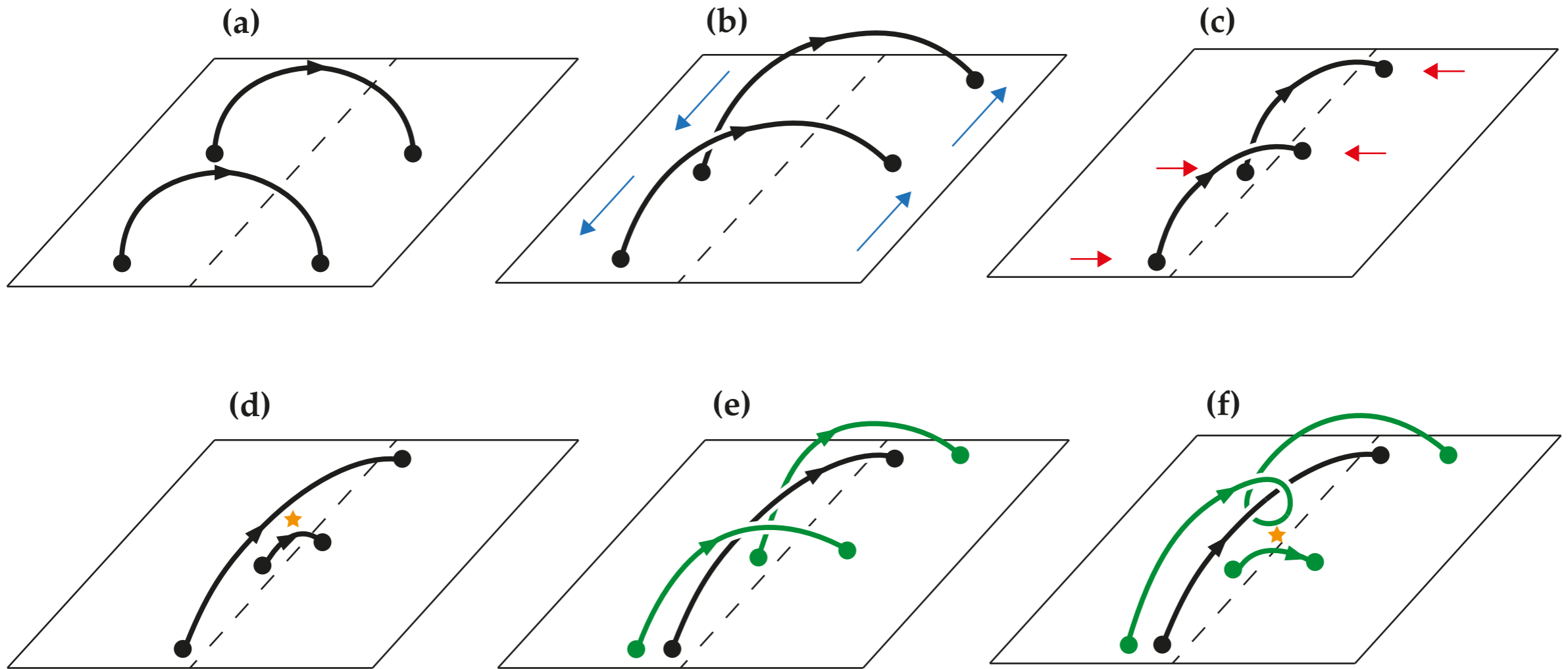
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****small-scale convection is critical!****

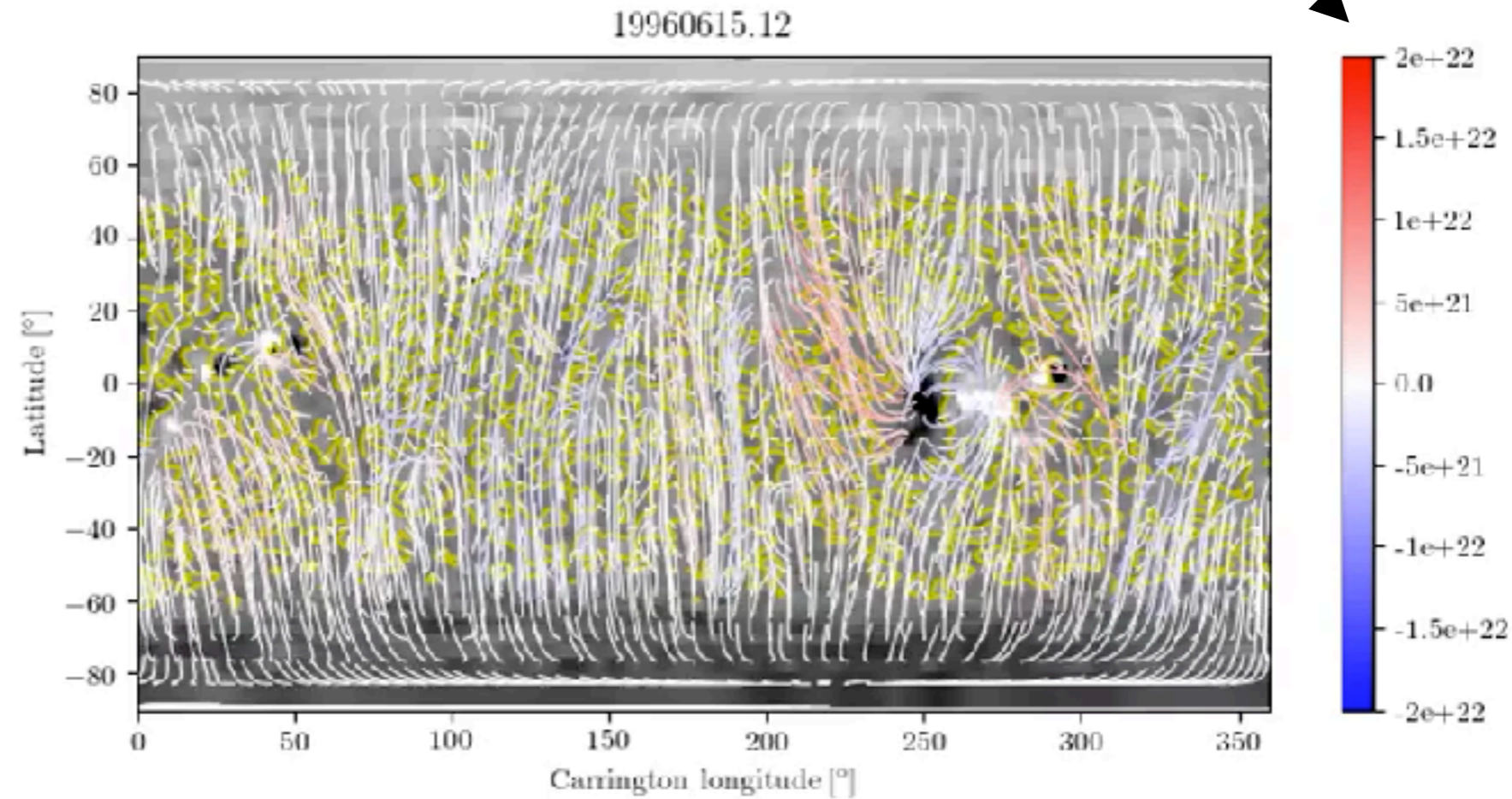
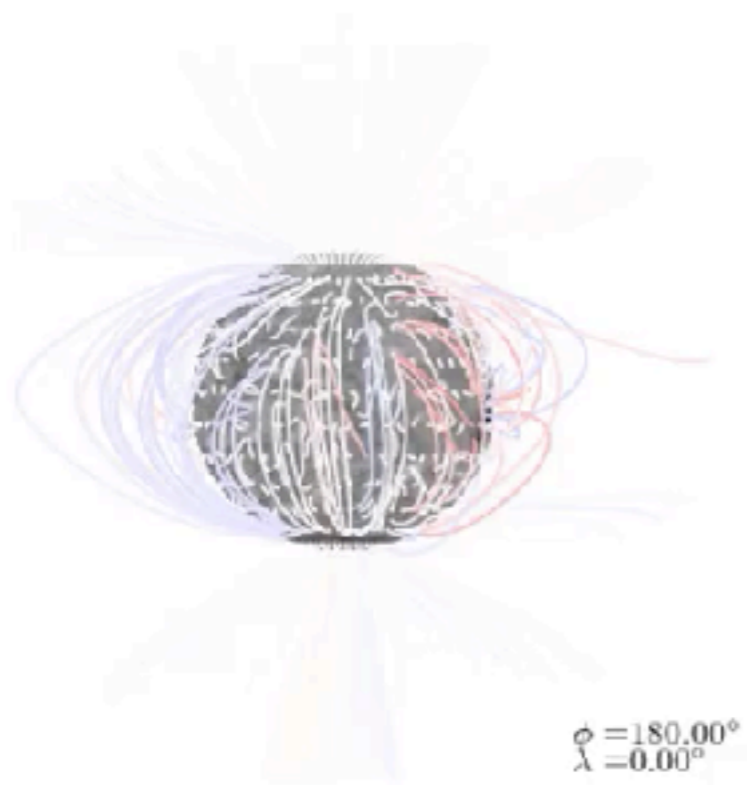
helicity
injection

diffusion



reconnection

field-line helicity

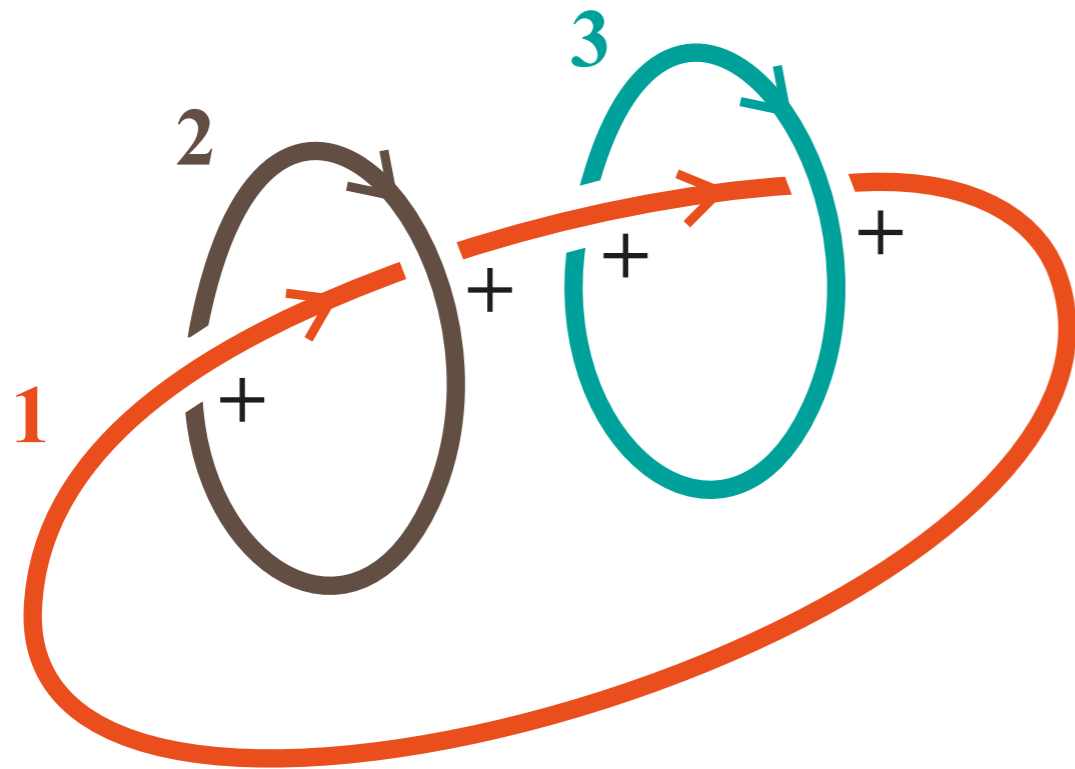


Magneto-frictional model: van Ballegooijen, Priest & Mackay, *ApJ* [2000]

Full solar cycle simulation: Yeates, *Solar Phys.* [2014]

Field line helicity - the net linkage of magnetic flux with one field line.

$$H = \frac{1}{2} \sum_i \mathcal{A}_i \Phi_i \quad \text{where} \quad \mathcal{A}_i = \sum_j L_{ij} \Phi_j$$

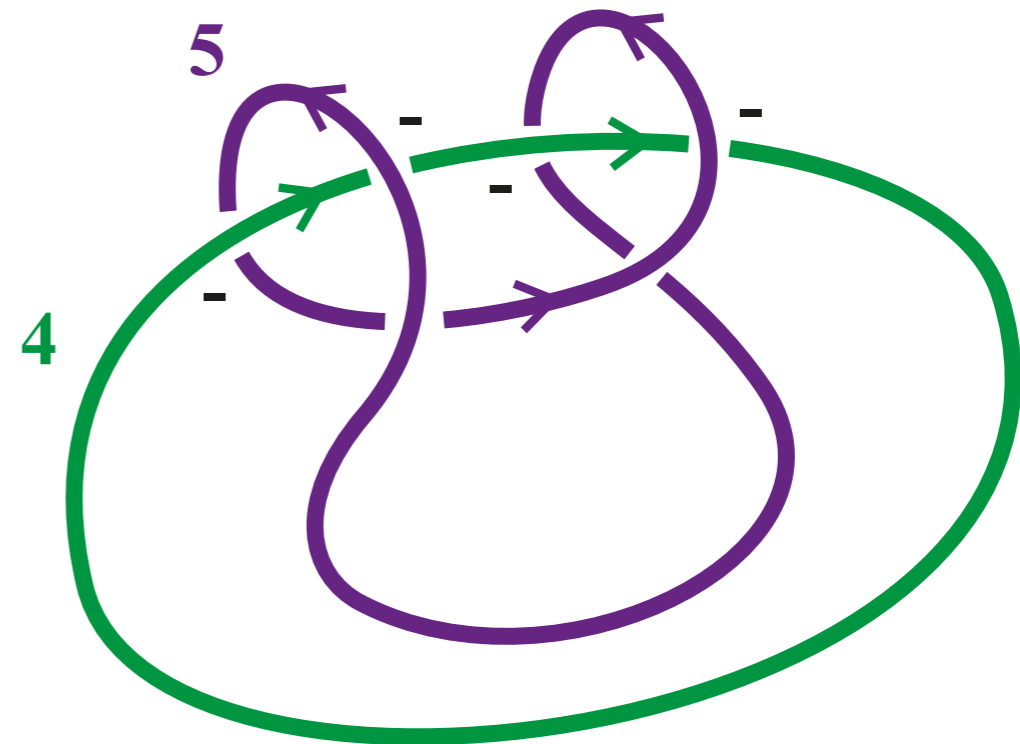


$$H = \Phi_1 \Phi_2 + \Phi_1 \Phi_3$$

$$\mathcal{A}_1 = \Phi_2 + \Phi_3$$

$$\mathcal{A}_2 = \Phi_1$$

$$\mathcal{A}_3 = \Phi_1$$



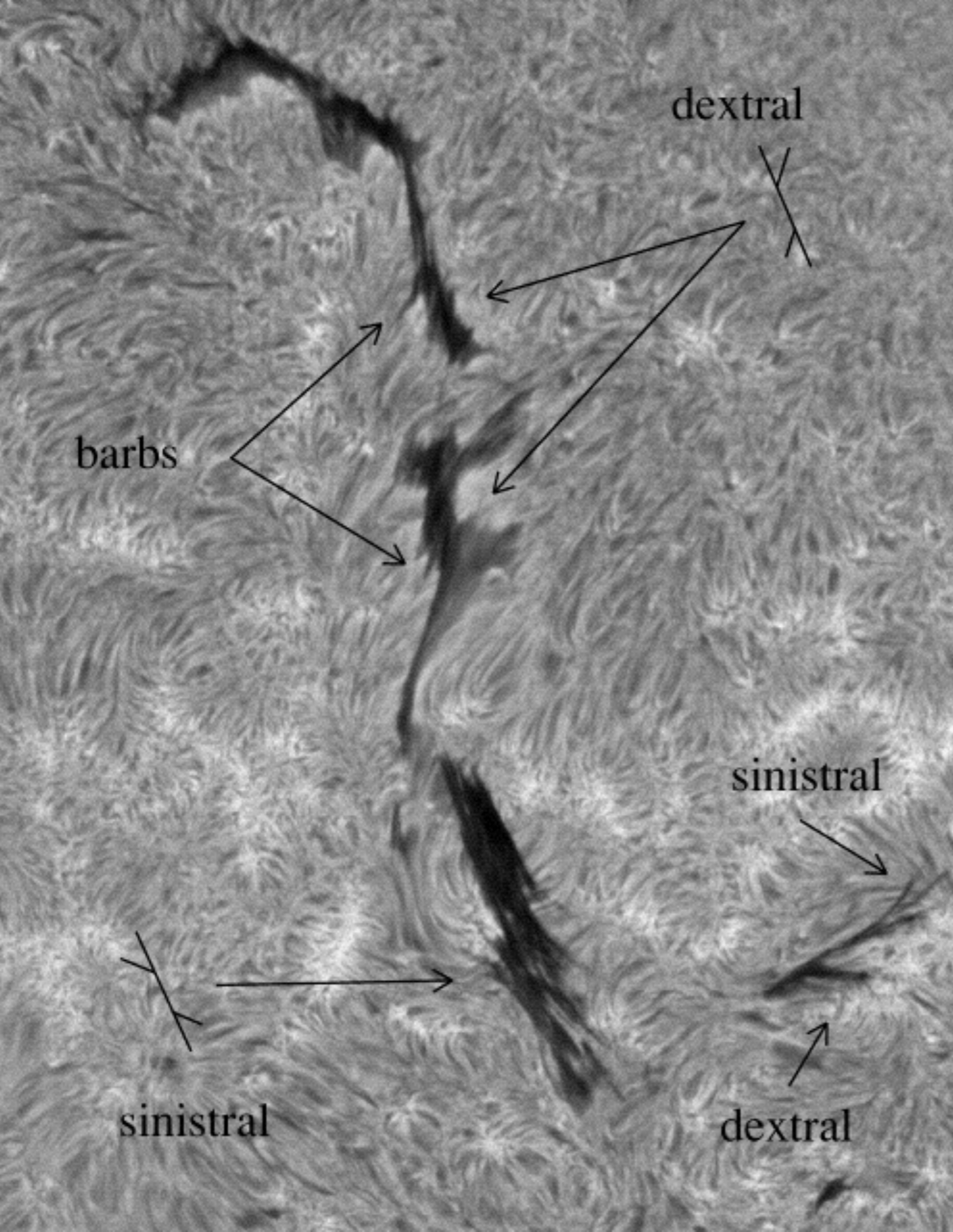
$$H = -2\Phi_4 \Phi_5$$

$$\mathcal{A}_4 = -2\Phi_5$$

$$\mathcal{A}_5 = -2\Phi_4$$

Berger, A&A [1988]

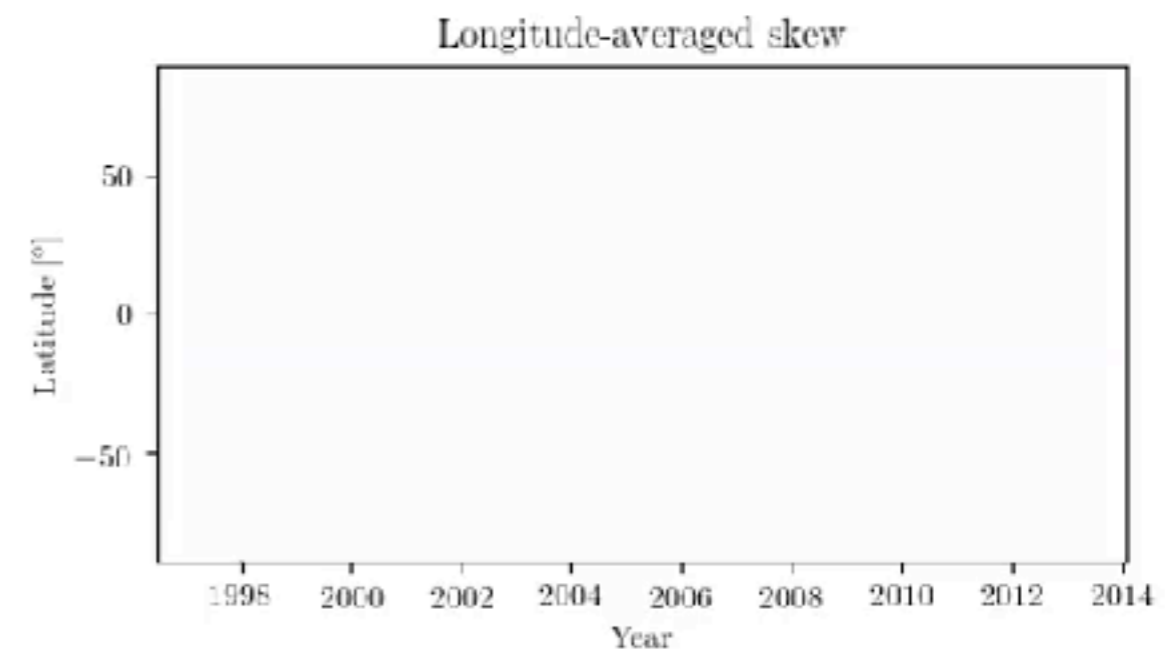
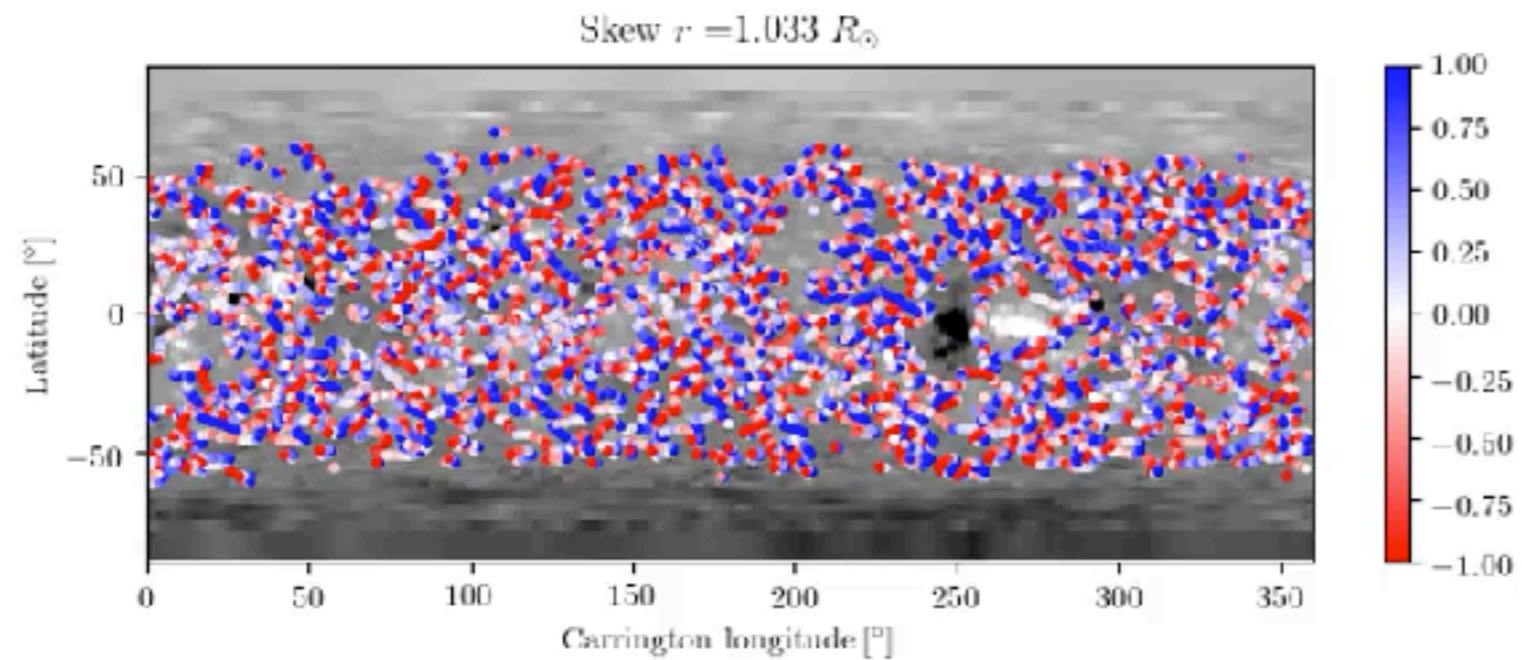
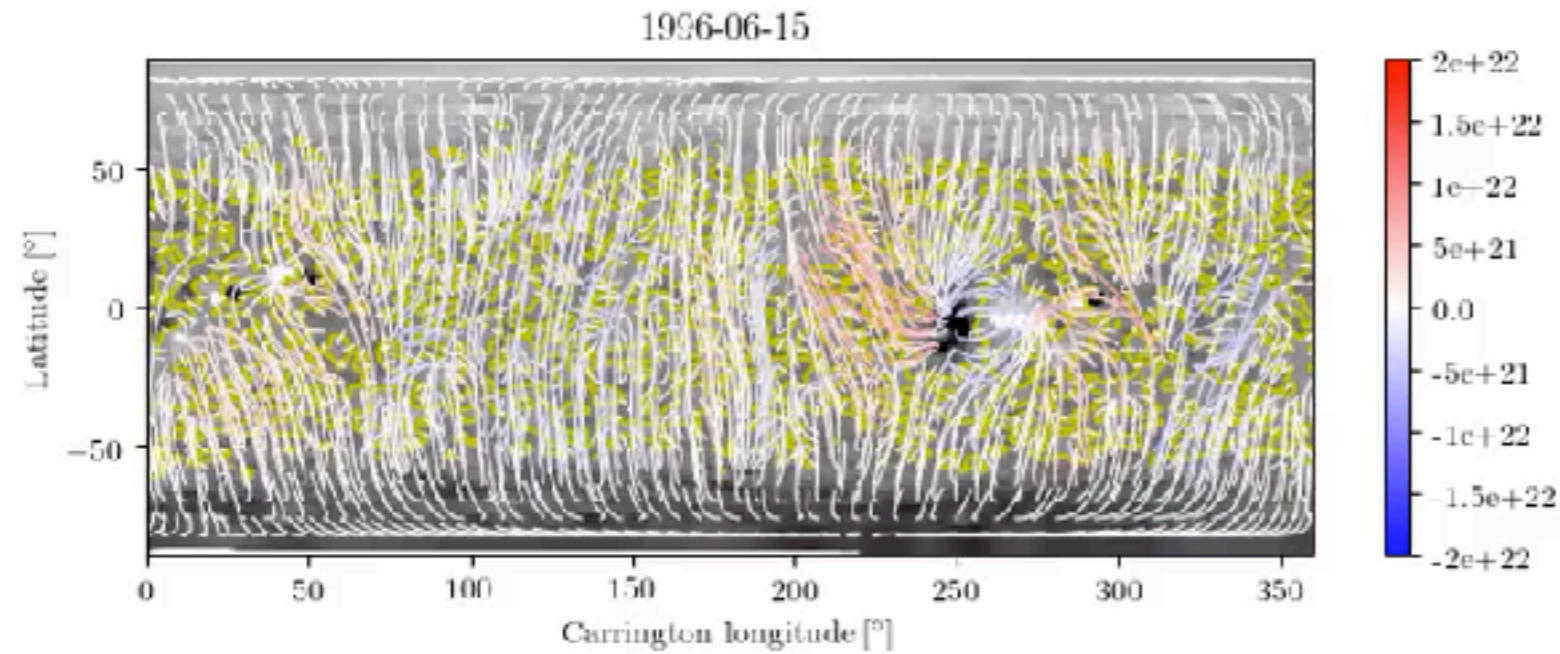
Yeates & Hornig, A&A [2016]



H α

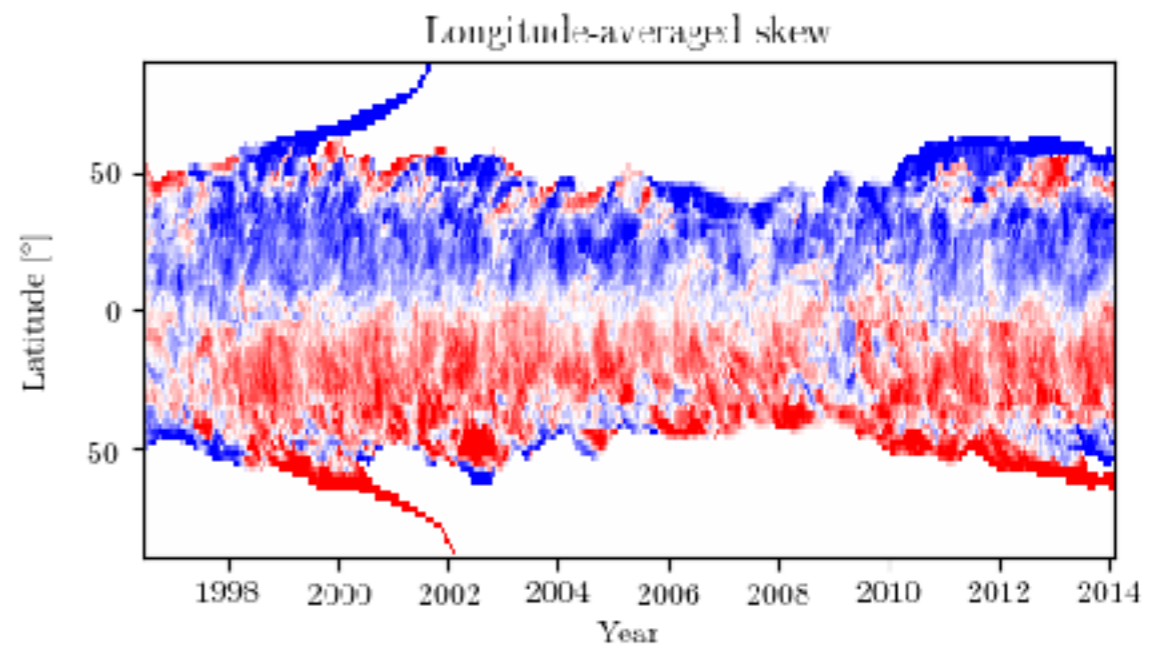
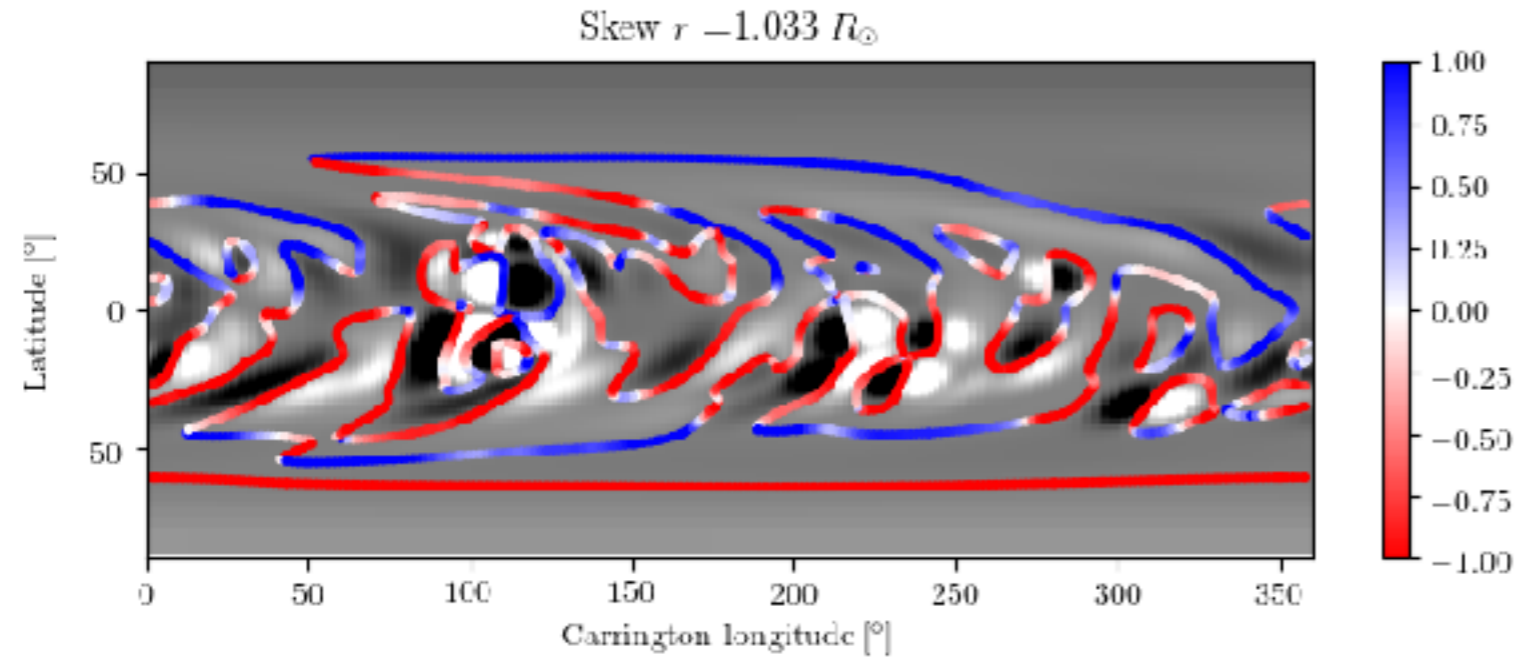
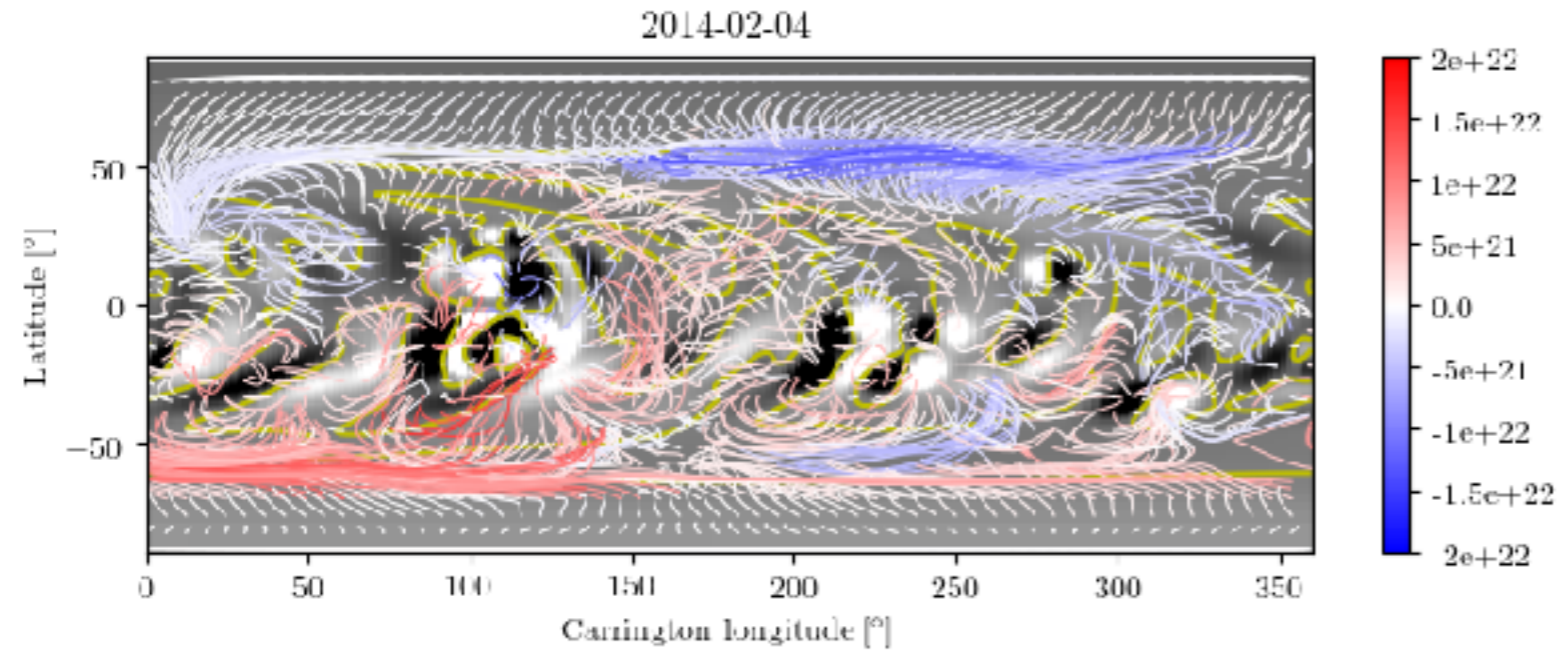
Martin, Bilimoria & Tracadas. [1994]

Pevtsov, Balasubramaniam & Rogers, *ApJ* [2003]

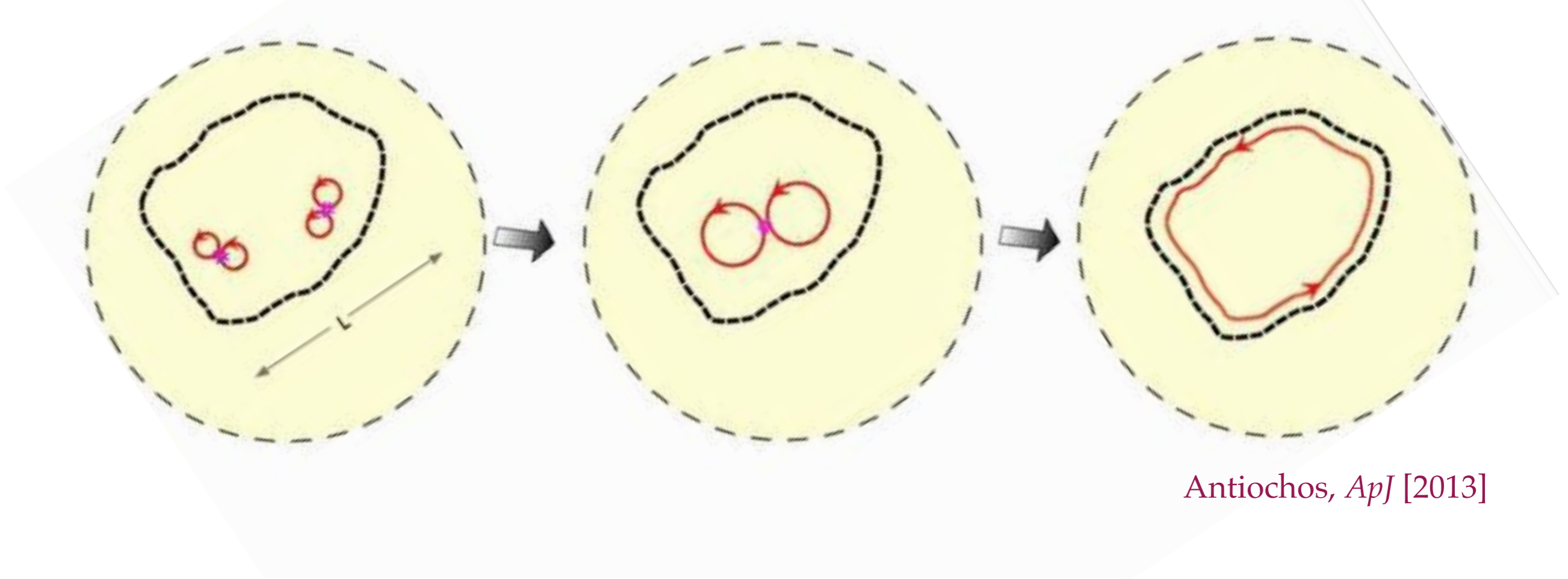


Yeates, Mackay & van Ballegooijen, *Solar Phys.* [2008, 2009]

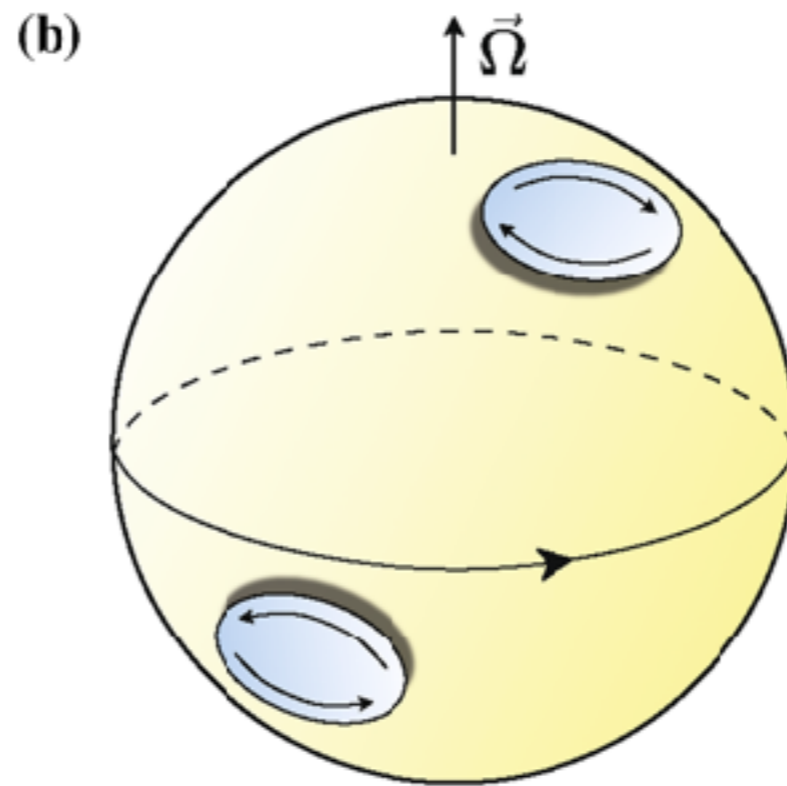
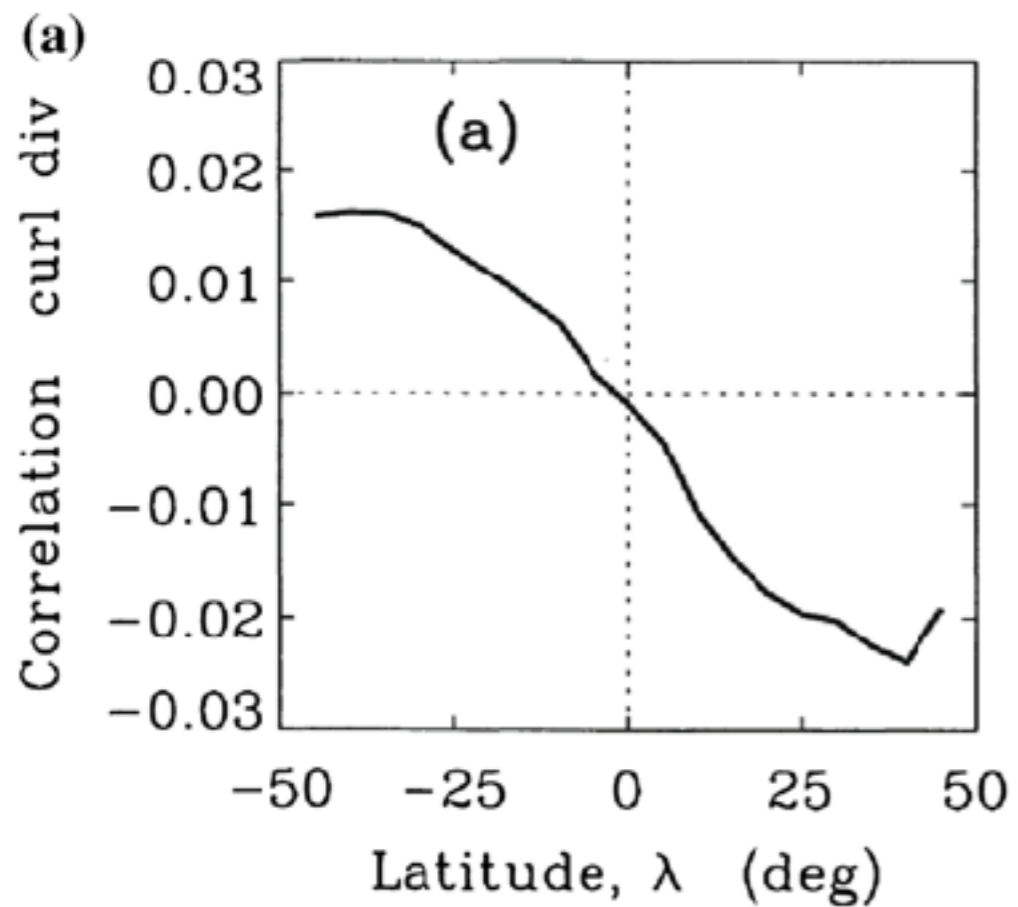
Yeates & Mackay, *ApJL* [2012]



Yeates, Mackay & van Ballegooijen, *Solar Phys.* [2008, 2009]
 Yeates & Mackay, *ApJL* [2012]

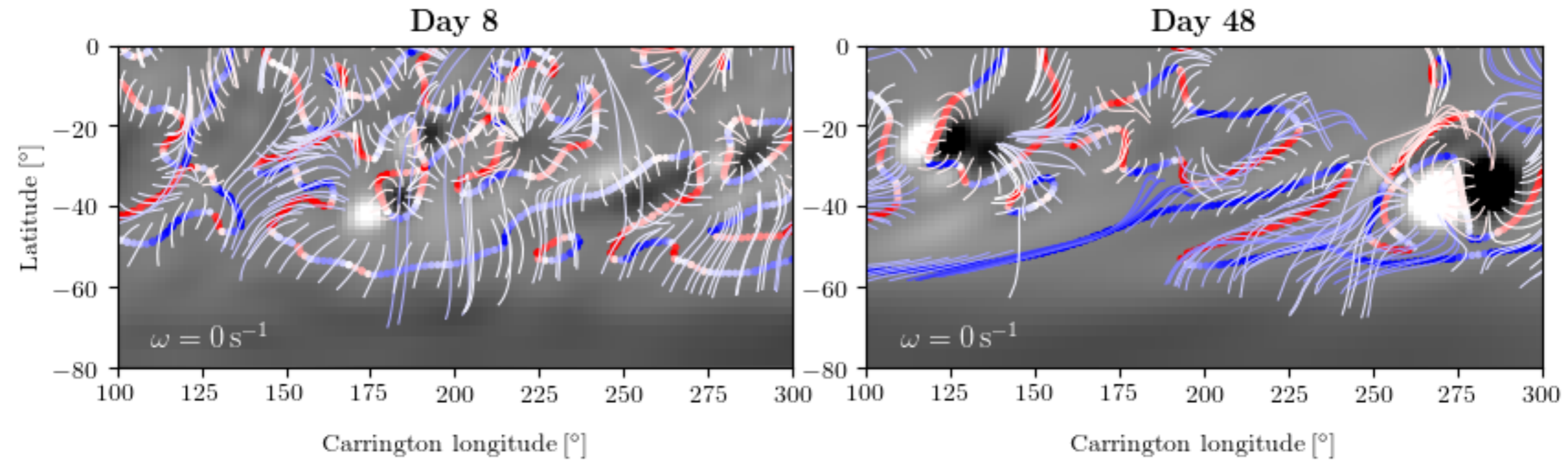


Antiochos, *ApJ* [2013]



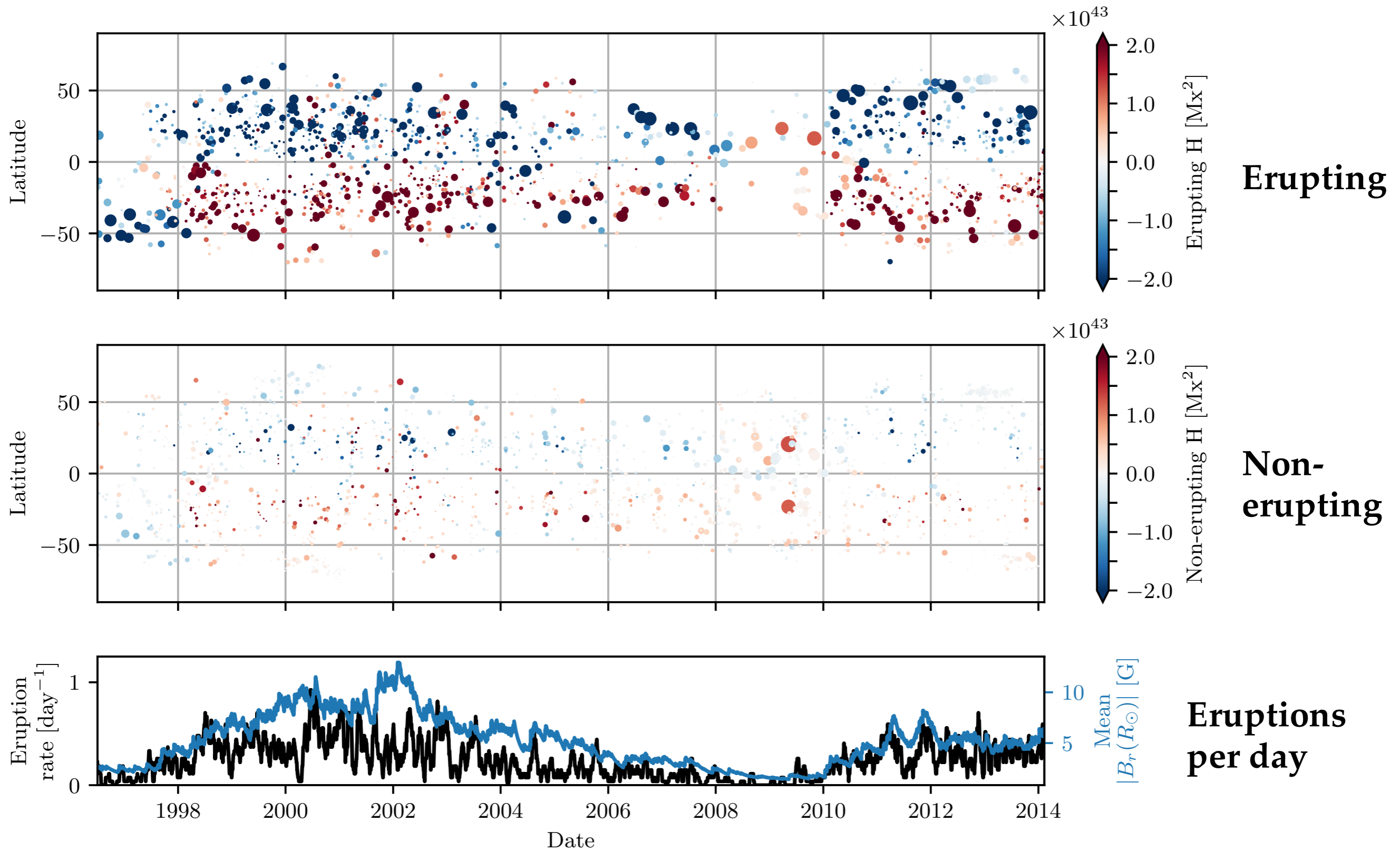
Observed
supergranular
vorticity
 $\sim 10^{-6} \text{ s}^{-1}$

Gizon & Duvall [2003]
Komm et al., *ApJ* [2007]



FUNDAMENTALS OF CORONAL EVOLUTION:

1. Magnetic helicity is injected by surface motions.
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Total helicity removed in eruptions $\sim 2.4 \times 10^{46} \text{ Mx}^2$

Conclusion

- 1. Magnetic helicity is injected by surface motions.**
- 2. It accumulates at polarity inversion lines.**
- 3. It is removed by coronal mass ejections.**

- **Progress this century so far:**
 - Observations and models —> general acceptance of this paradigm.
 - Quantitative measurements of helicity injected and ejected.
 - Improvement of helicity measures and computational methods.
- **In the rest of this century?**
 - Credible predictions of CME magnetic structure (and geo-effectiveness), and even advance warning of eruptions.
 - Better constraints on small-scale helicity injection.
 - Building detailed active-region models into global simulations.

<http://www.maths.dur.ac.uk/~bmjg46/>