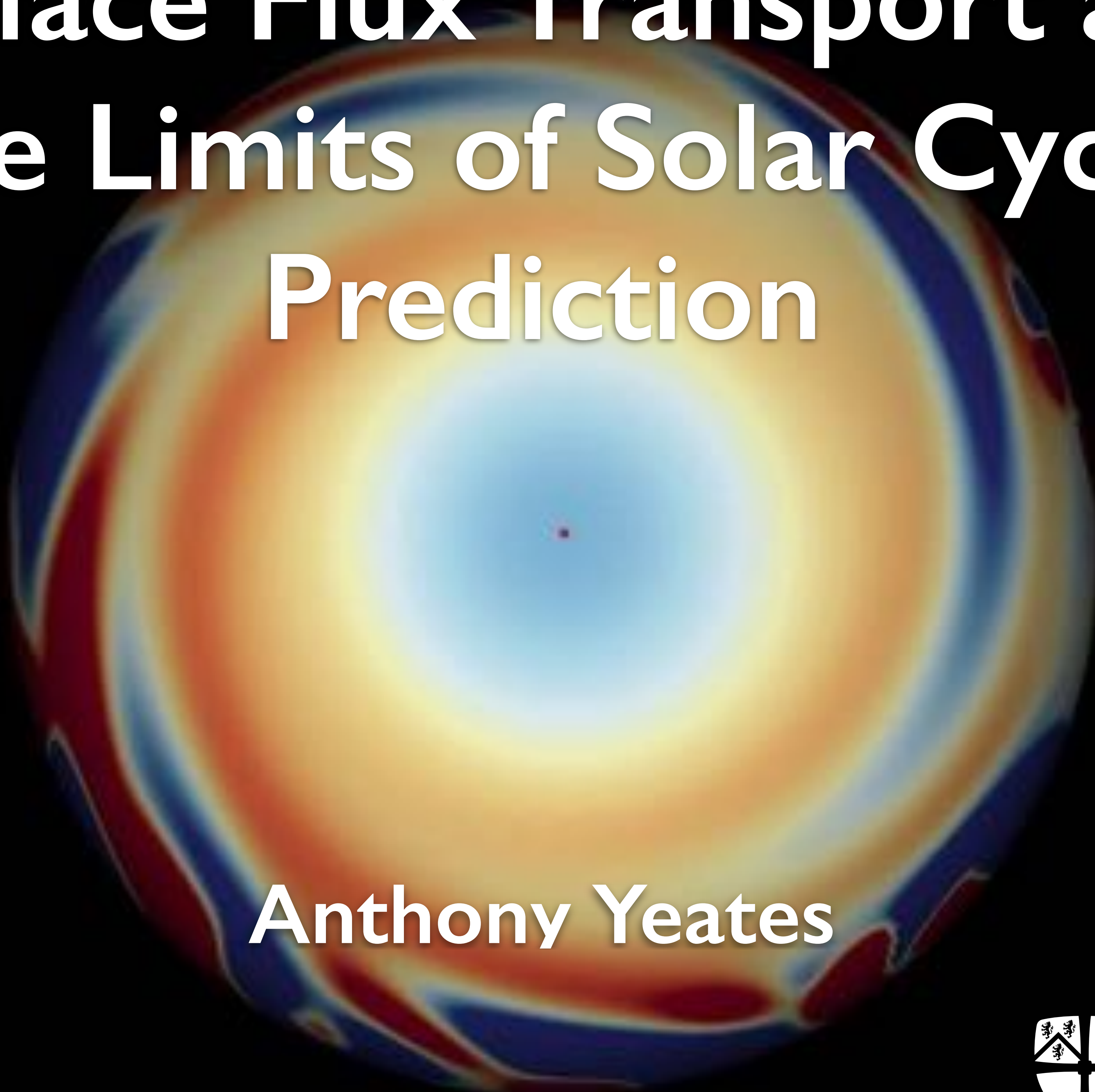
Surface Flux Transport and the Limits of Solar Cycle Prediction

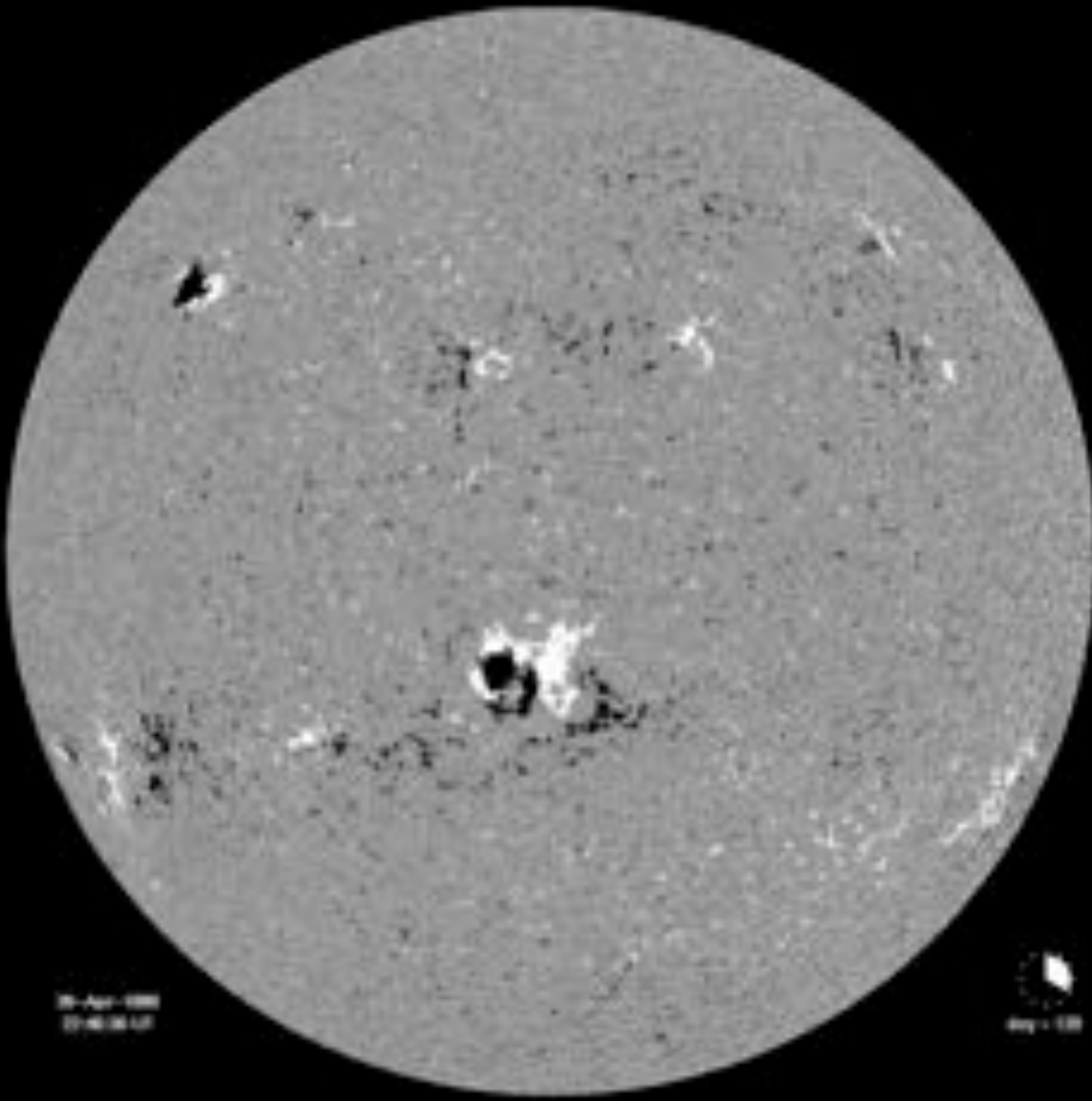


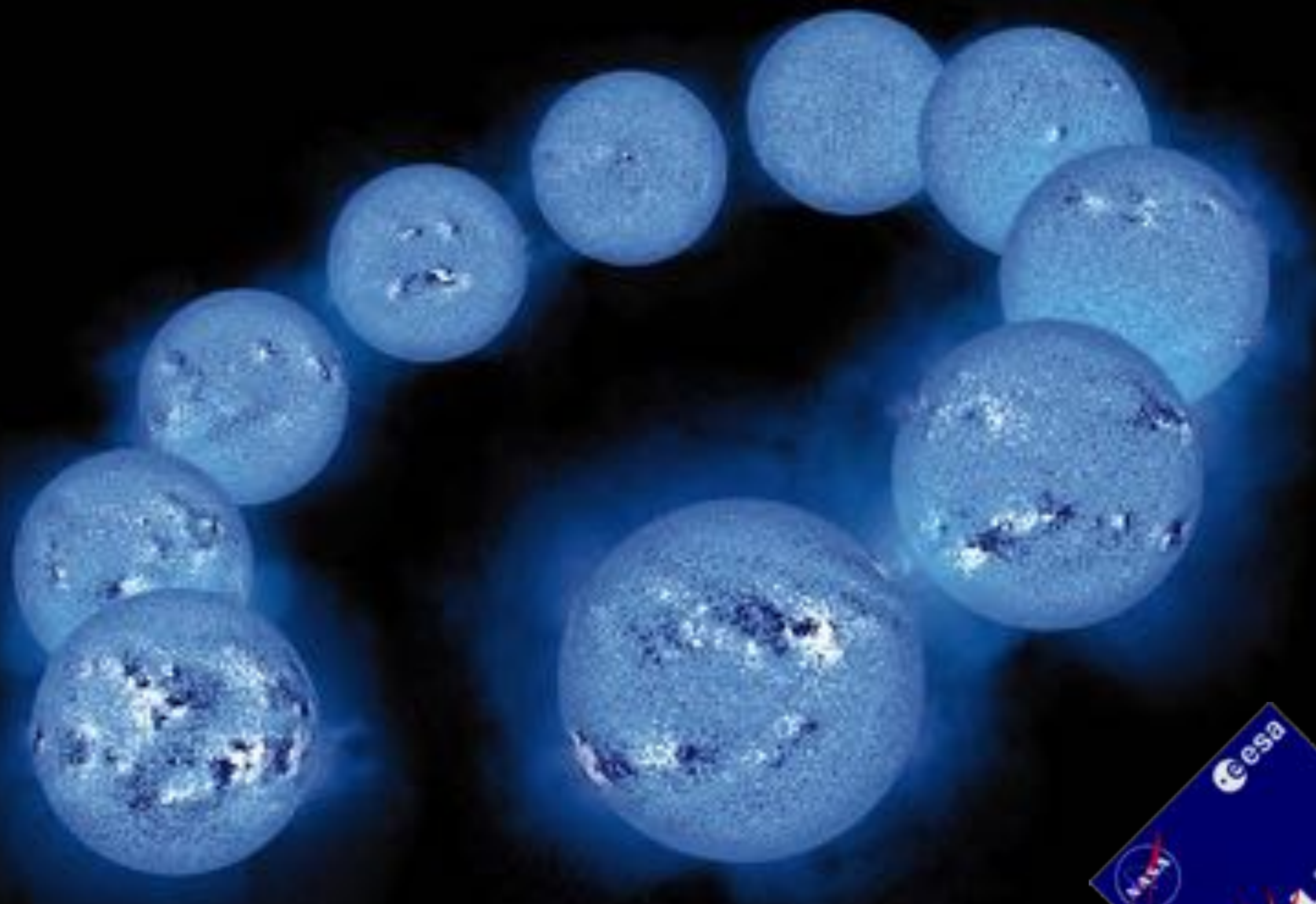
Anthony Yeates

Lockheed-Martin, California, 30-Mar-2015

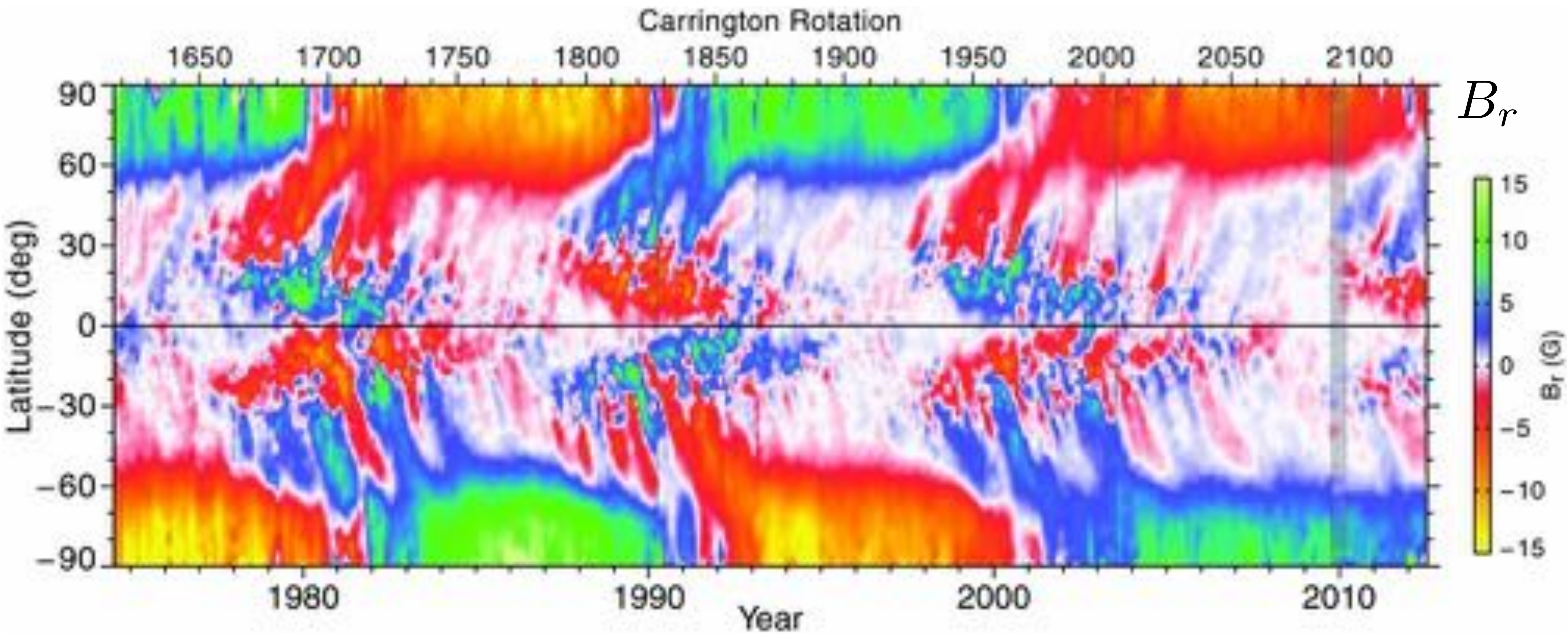
Durham University

INTRODUCTION

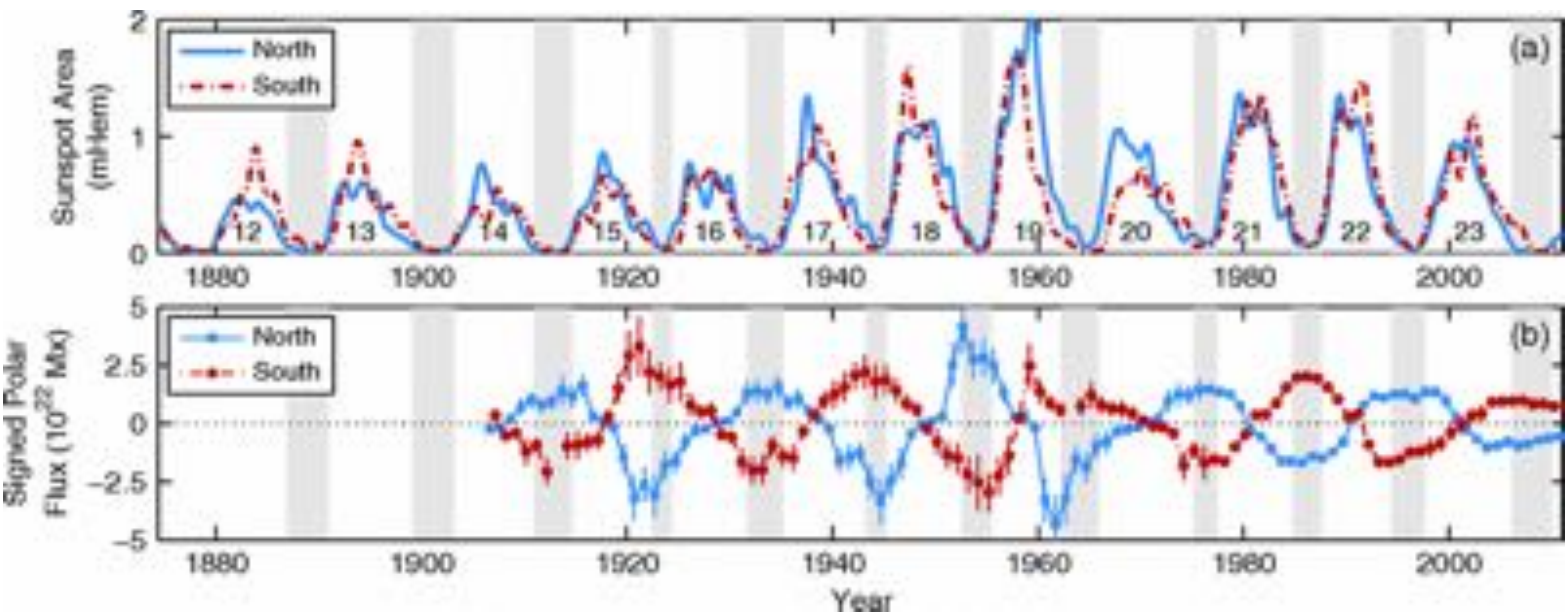



esa
SOHO

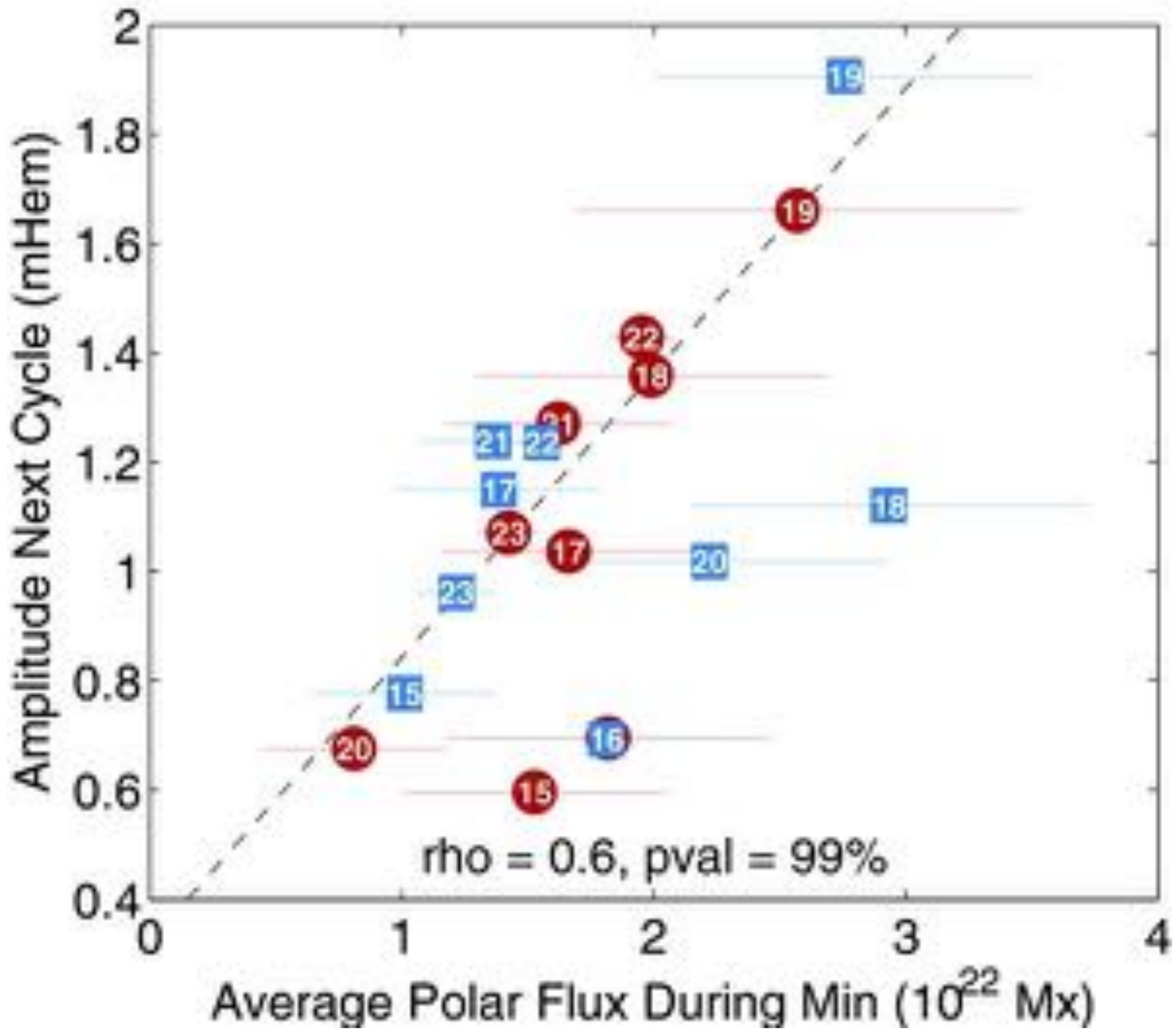
Ulrich & Tran, *ApJ* (2013) - **Mt Wilson data**



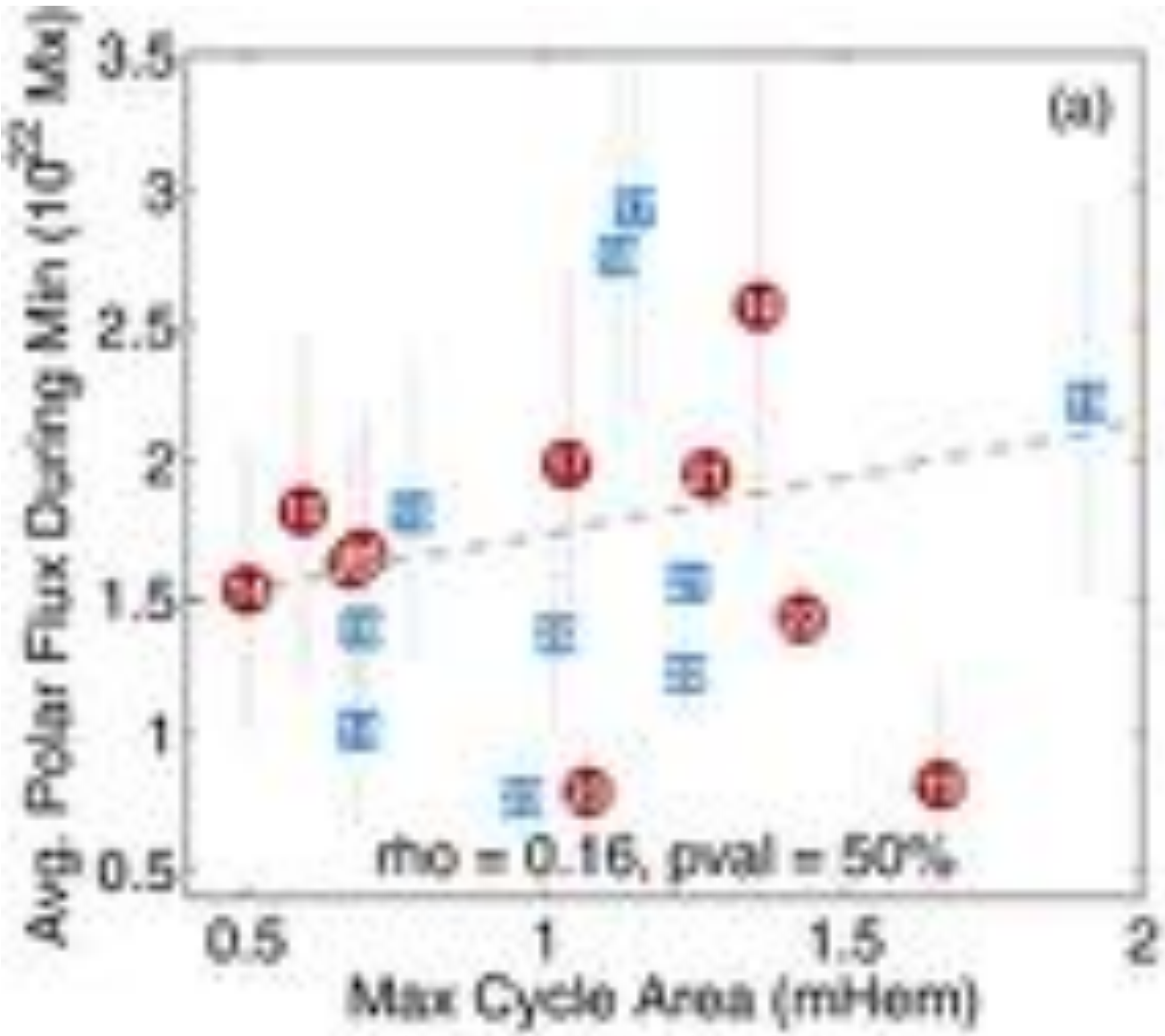
B_r

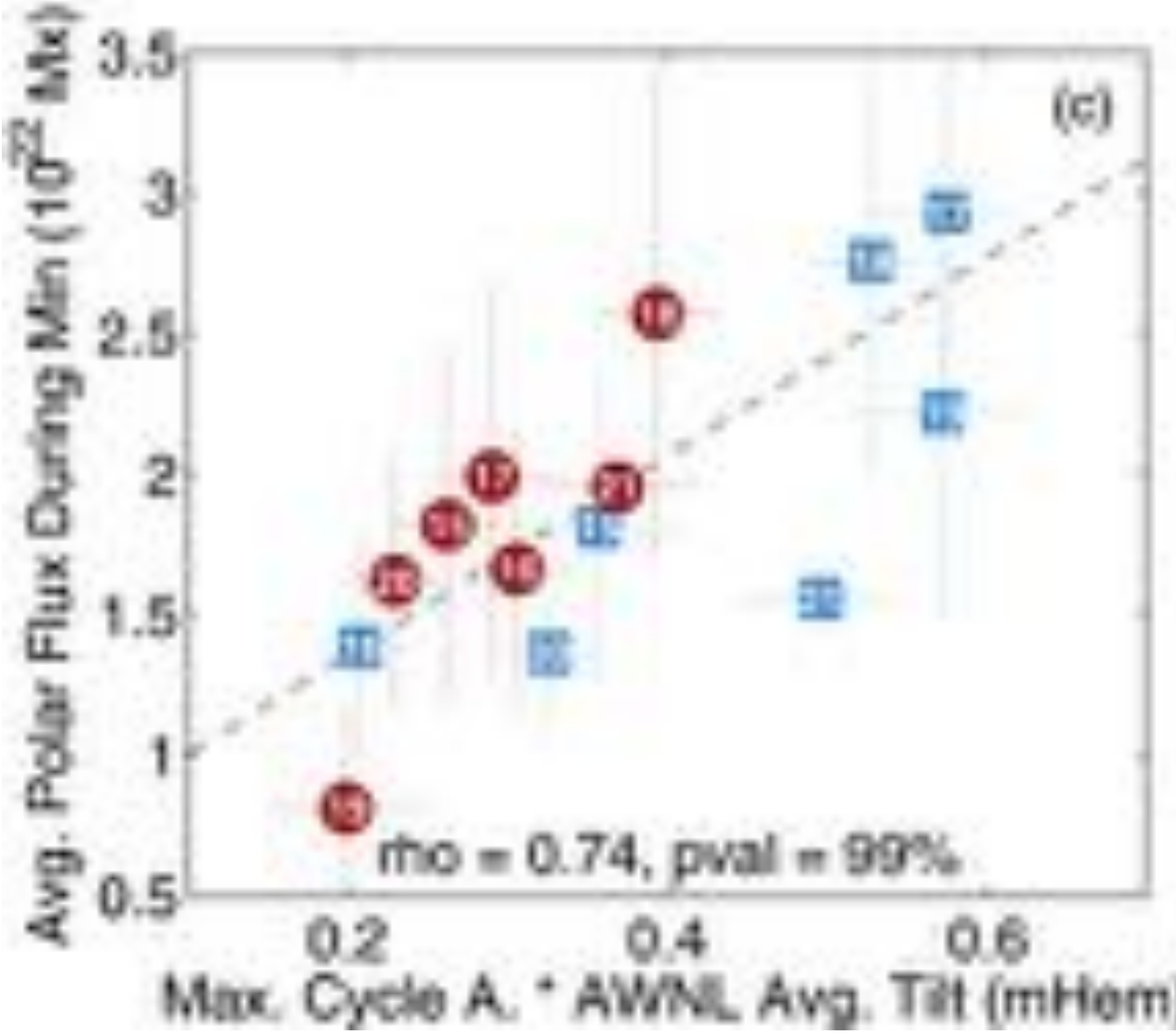


Muñoz-Jaramillo, Balmaceda & DeLuca, *PRL* (2013)



Muñoz-Jaramillo et al., *ApJ* (2013)





Muñoz-Jaramillo et al., *ApJ* (2013)

Leighton, *ApJ* (1964)

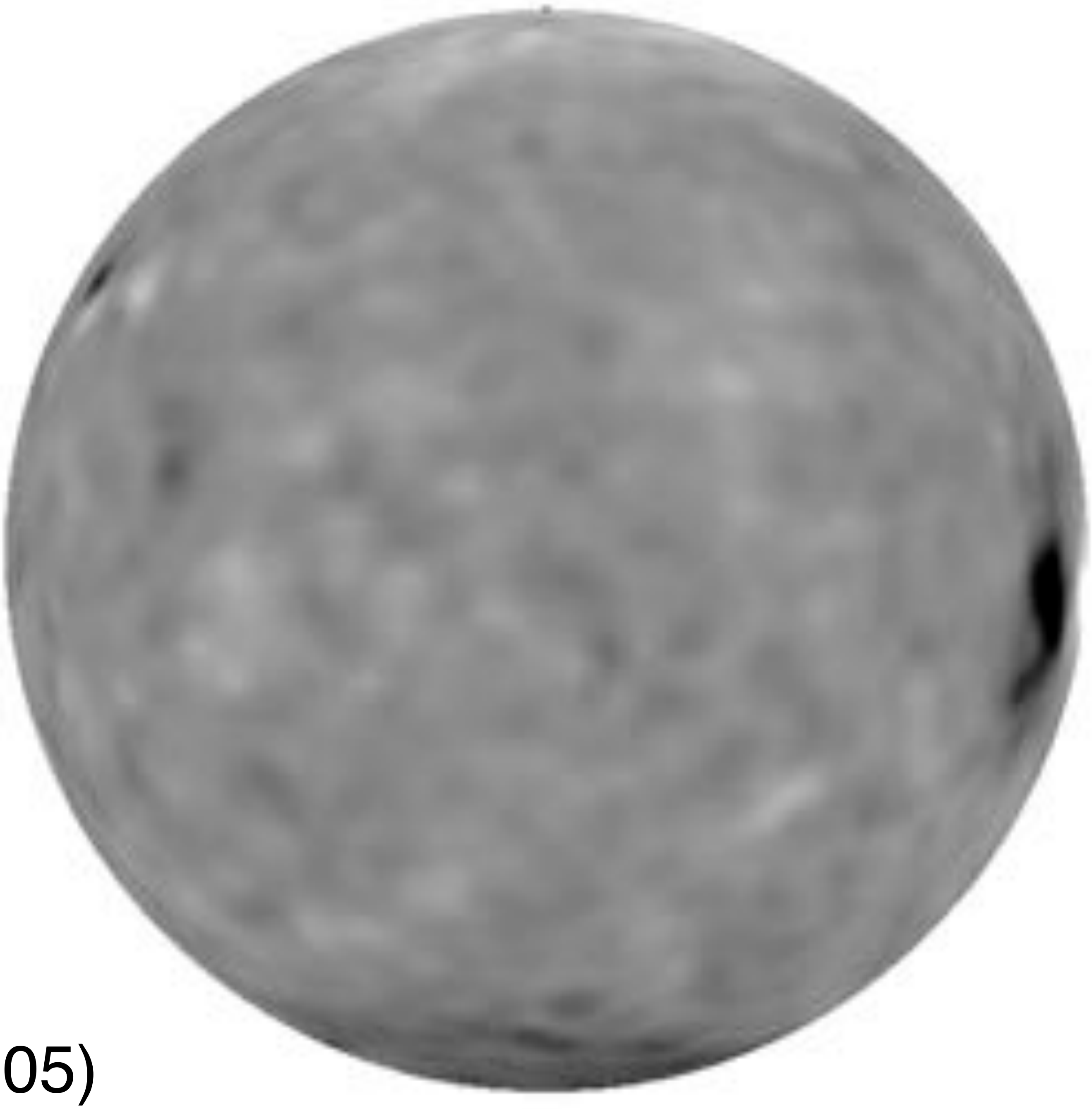
$$\frac{\partial B_r}{\partial t} = -(\nabla \cdot \mathbf{v})B_r - (\mathbf{v} \cdot \nabla)B_r + \eta\nabla^2 B_r$$

(1) Differential rotation

(2) Supergranular diffusion

(3) Meridional flow

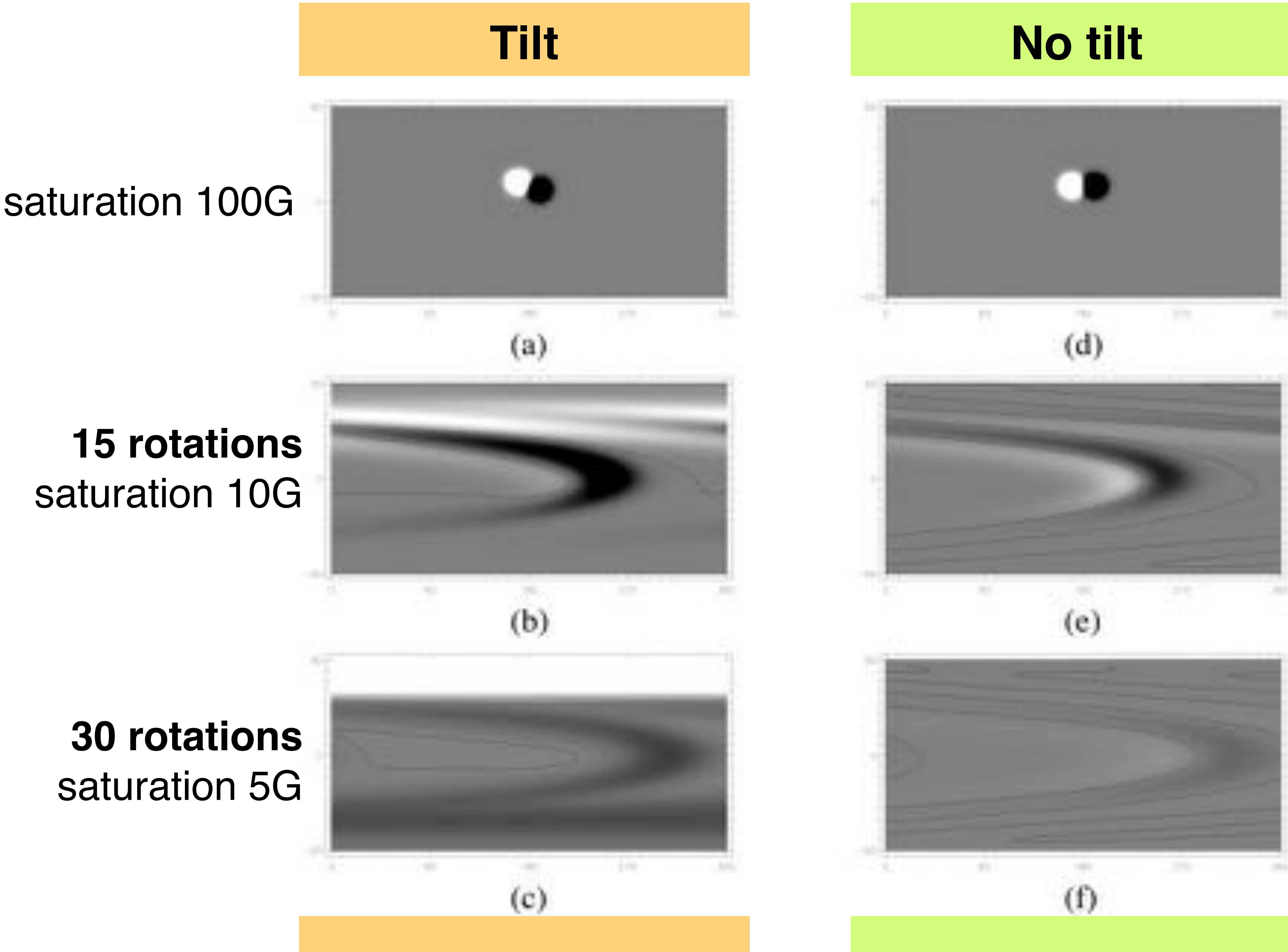
(4) Flux emergence



Sheeley, *Living Rev. Solar Phys.* (2005)

Mackay & Yeates, *Living Rev. Solar Phys.* (2012)

Jiang et al., *Space Sci. Rev.* (2014)



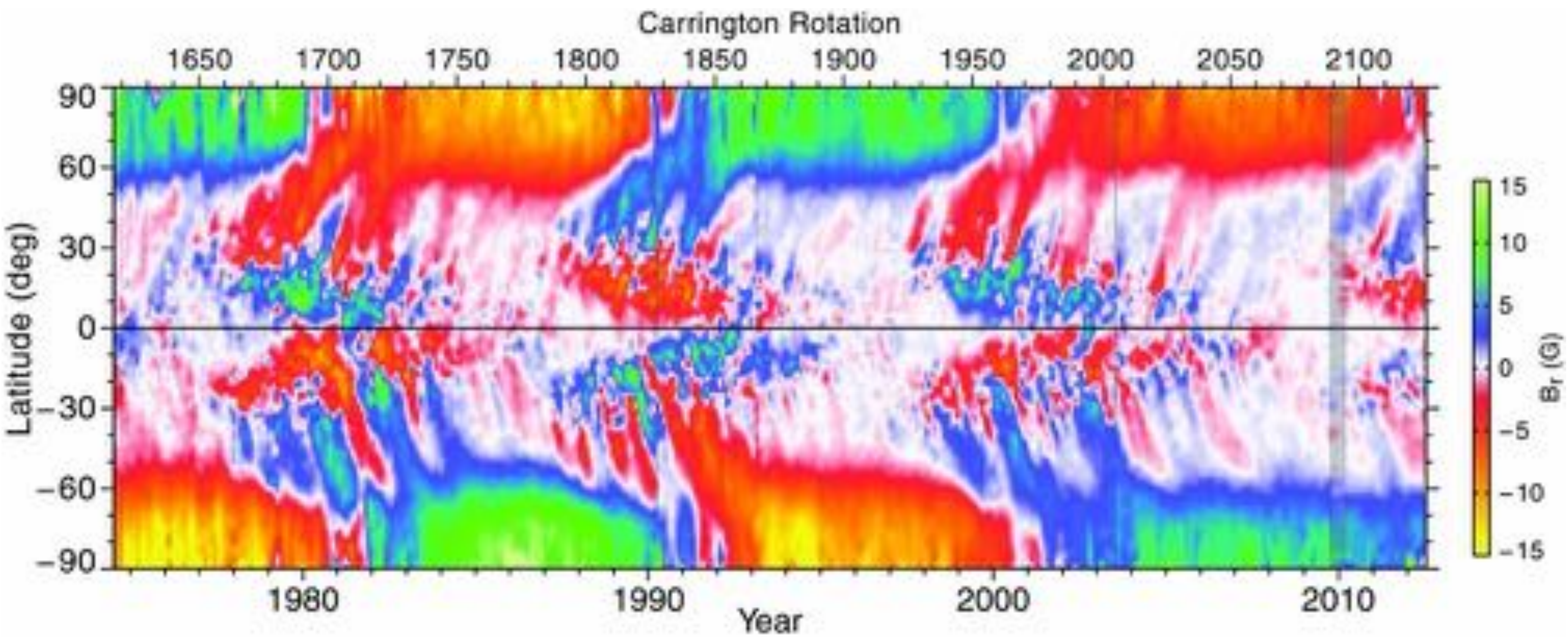
Tilt
No tilt
saturation 100G
15 rotations
saturation 10G
30 rotations
saturation 5G
(a)
(d)
(b)
(e)
(c)
(f)

CHALLENGE 1:

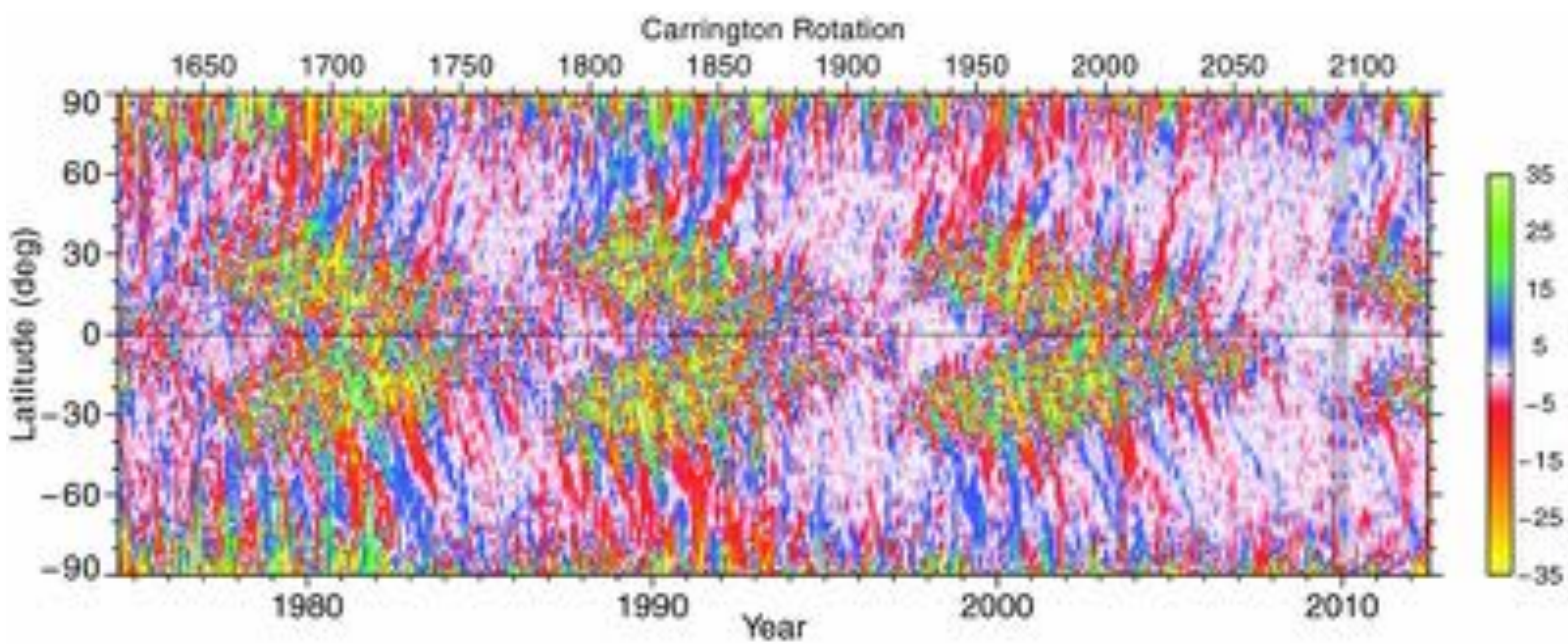
FLUCTUATIONS IN EMERGENCE MATTER!

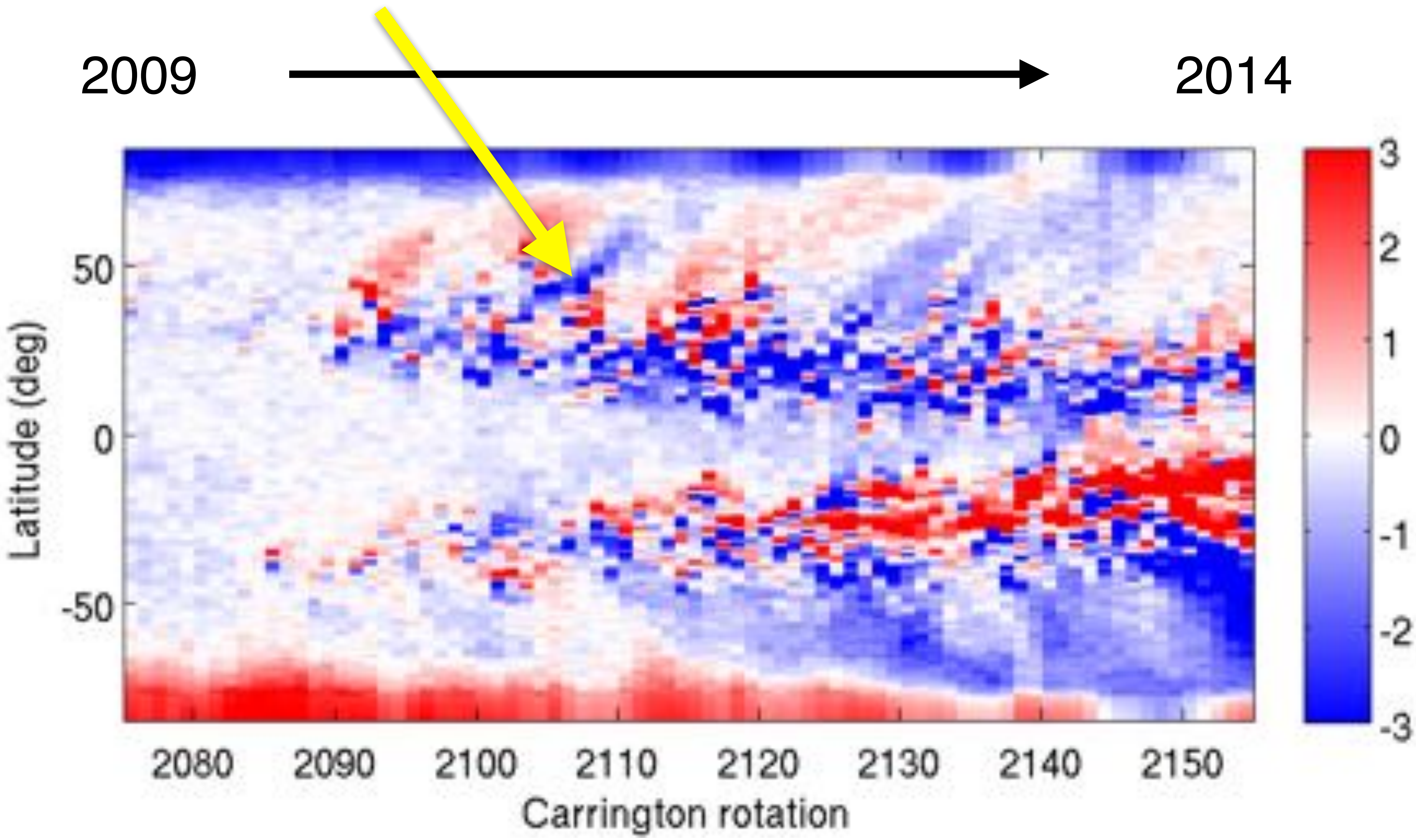
Ulrich & Tran, *ApJ* (2013) - **Mt Wilson data**

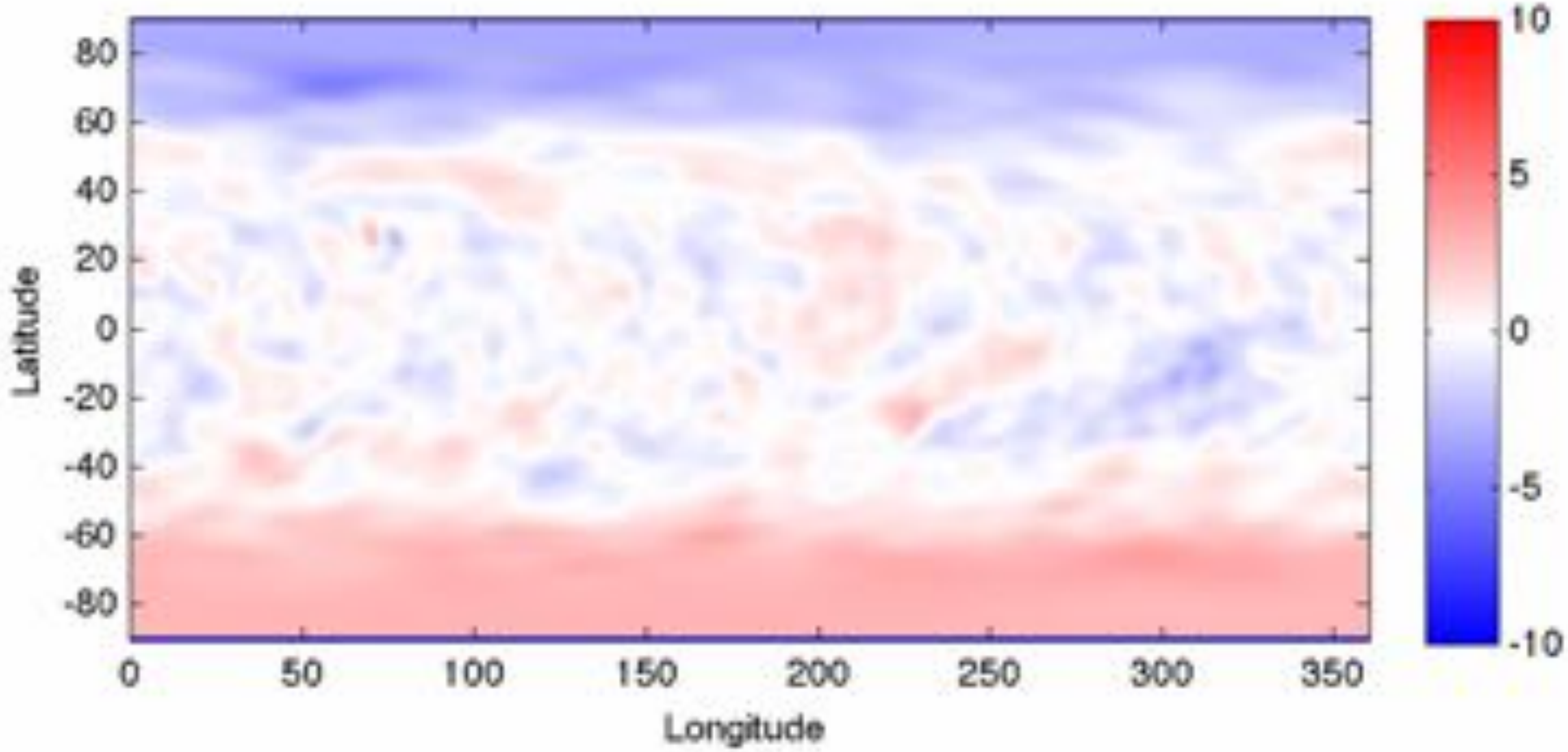
B_r

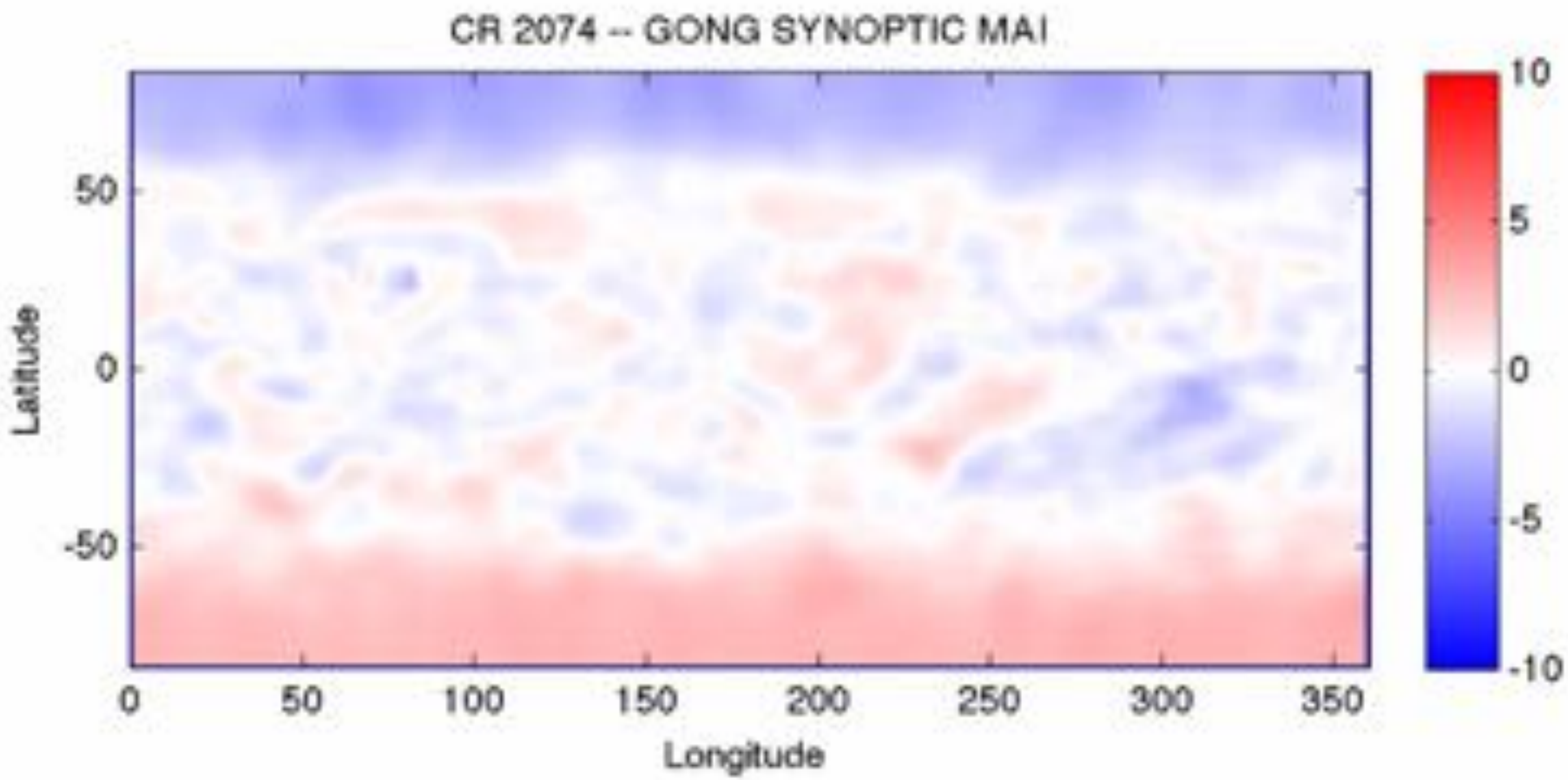


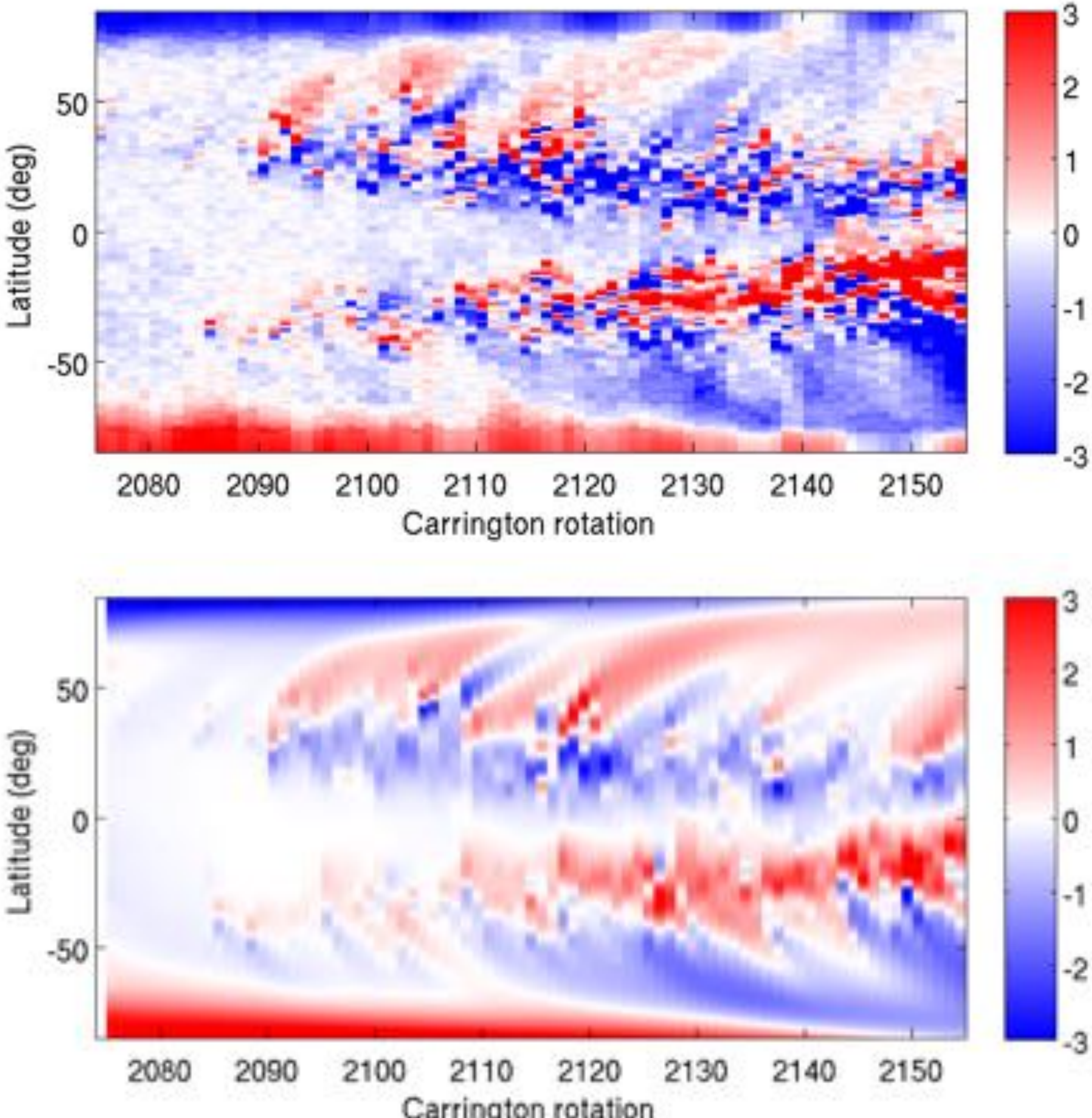
$$\frac{\partial B_r}{\partial t}$$




2009
2014
Latitude (deg)
50
0
-50
2080
2090
2100
2110
2120
2130
2140
2150
Carrington rotation
3
2
1
0
-1
-2
-3

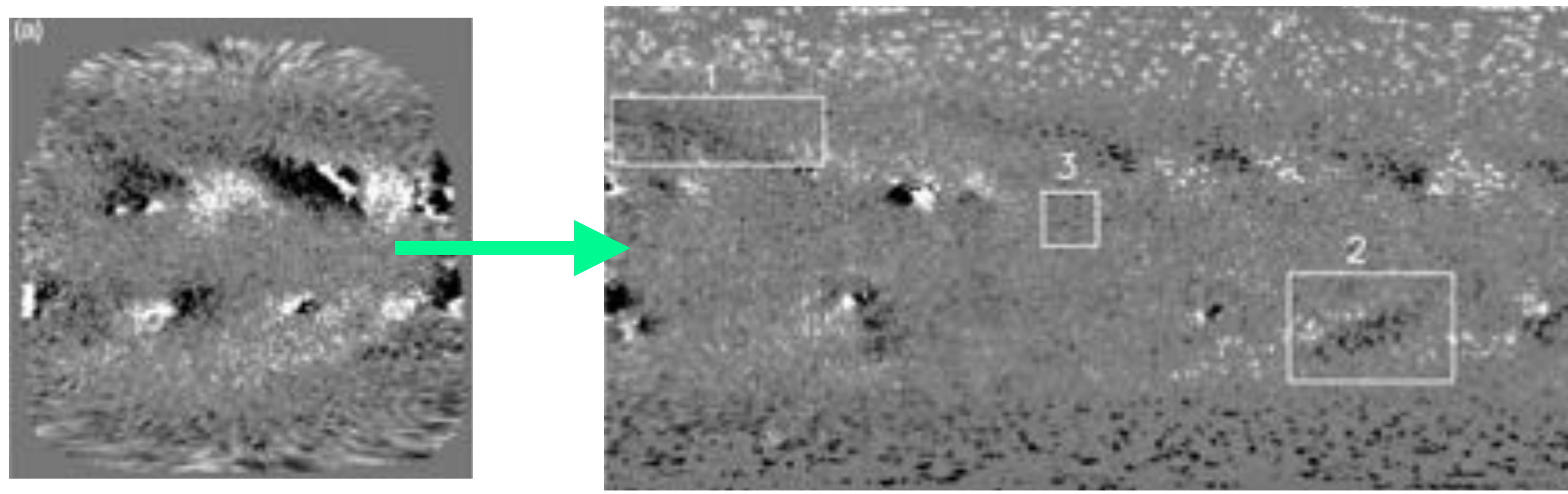

Latitude
Longitude
80
60
40
20
0
-20
-40
-60
-80
0
50
100
150
200
250
300
350
10
5
0
-5
-10


CR 2074 -- GONG SYNOPTIC MAI
Latitude
Longitude
50
0
-50
0
50
100
150
200
250
300
350
10
5
0
-5
-10

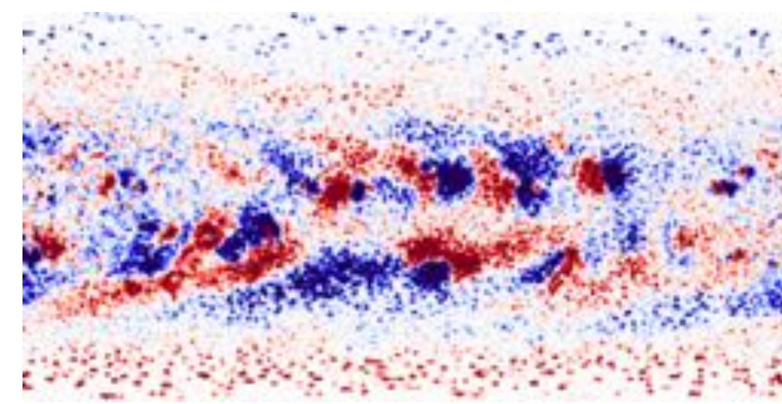

Latitude (deg)
Carrington rotation
50
0
-50
2080
2090
2100
2110
2120
2130
2140
2150
3
2
1
0
-1
-2
-3
Latitude (deg)
Carrington rotation

Magnetogram assimilation…

- Worden & Harvey, *Solar Phys.* (2000)

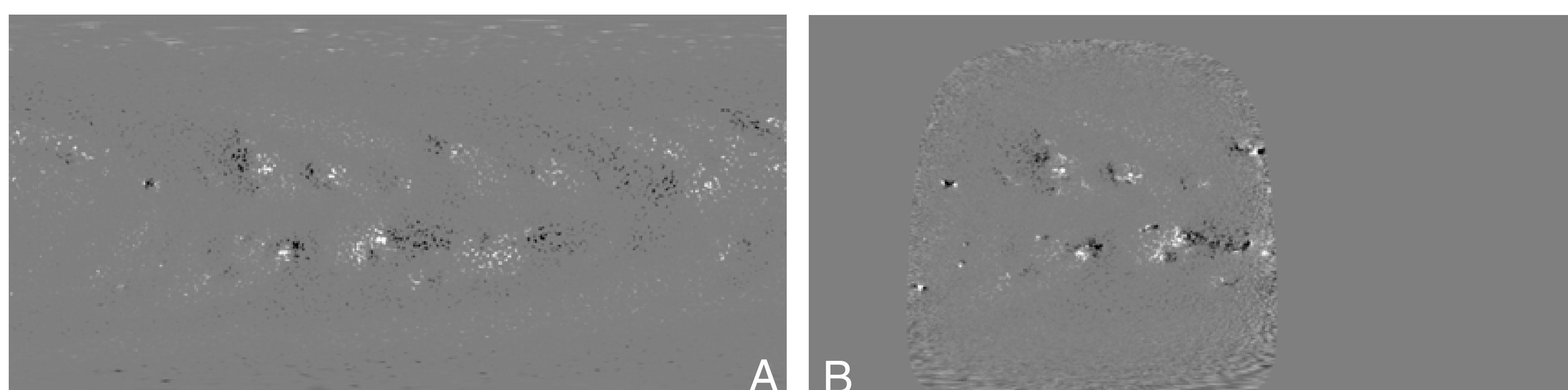


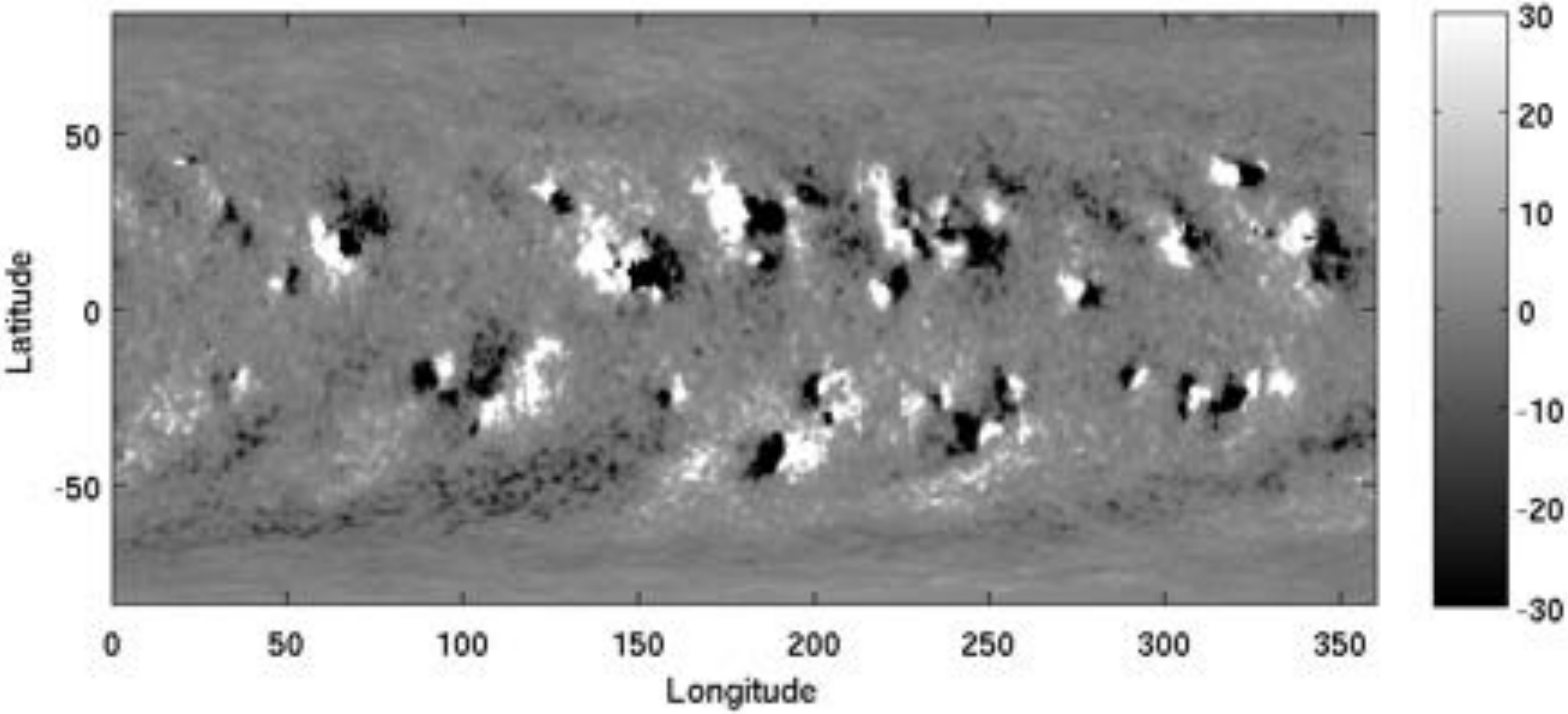
- Schrijver & DeRosa, *Solar Phys.* (2003)



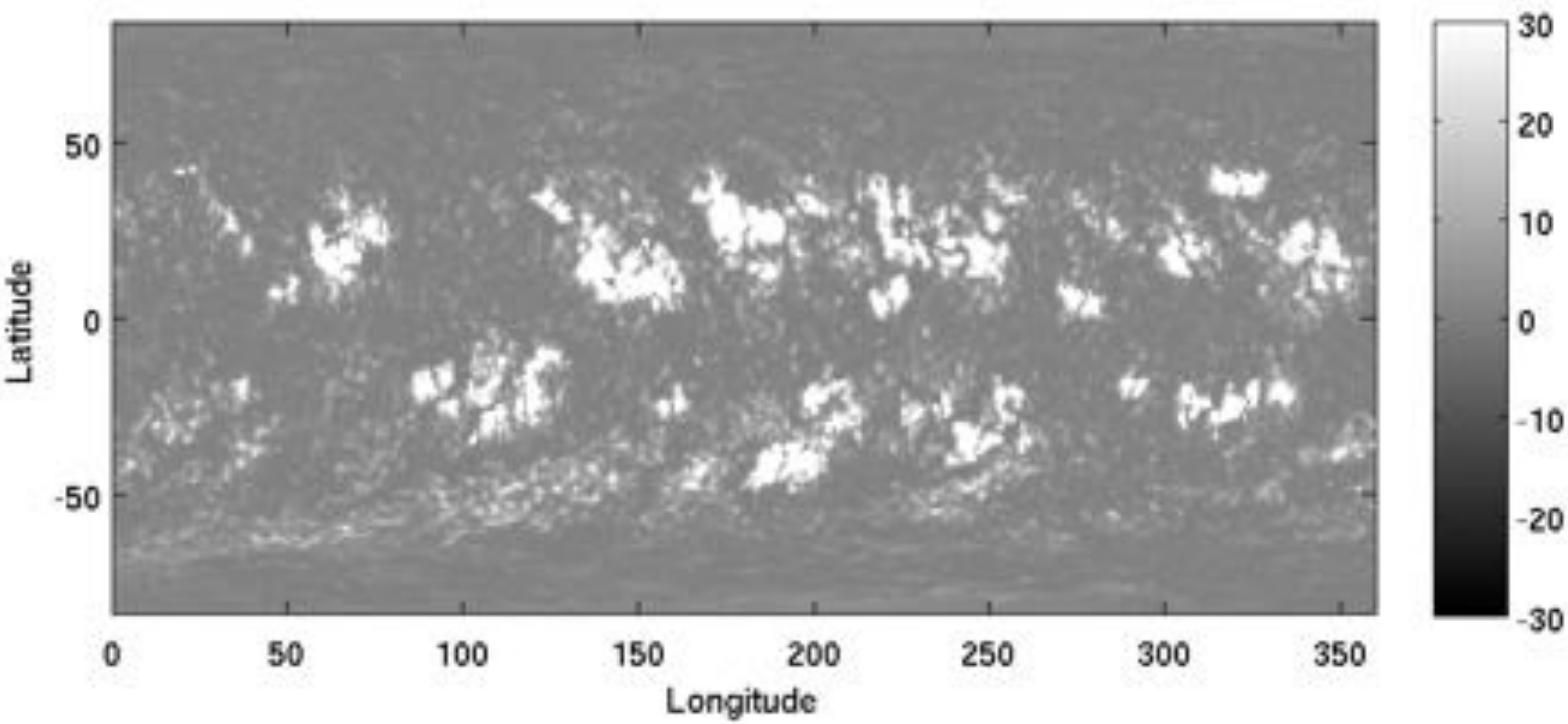
- ADAPT (Arge, Henney, et al.)

- Upton & Hathaway, *ApJ* (2014)

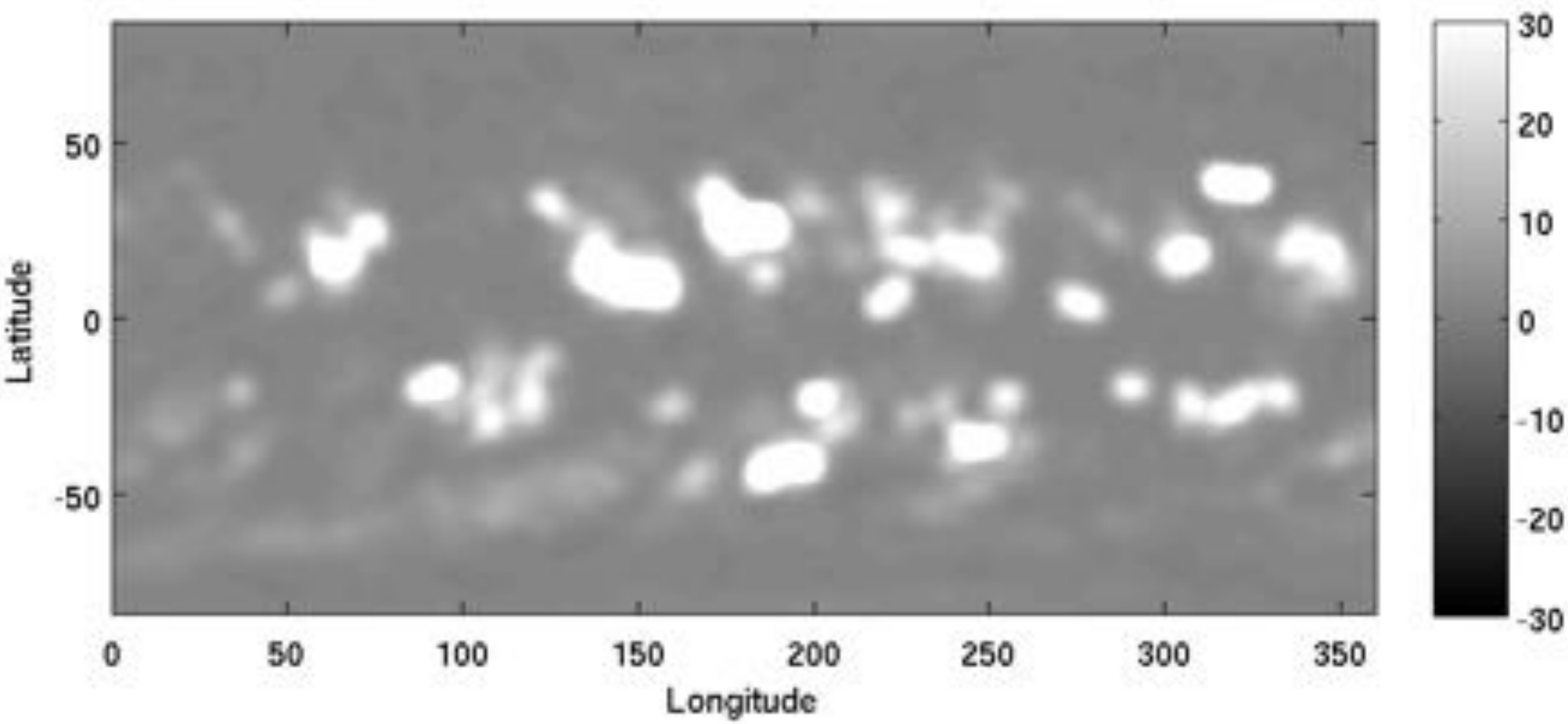




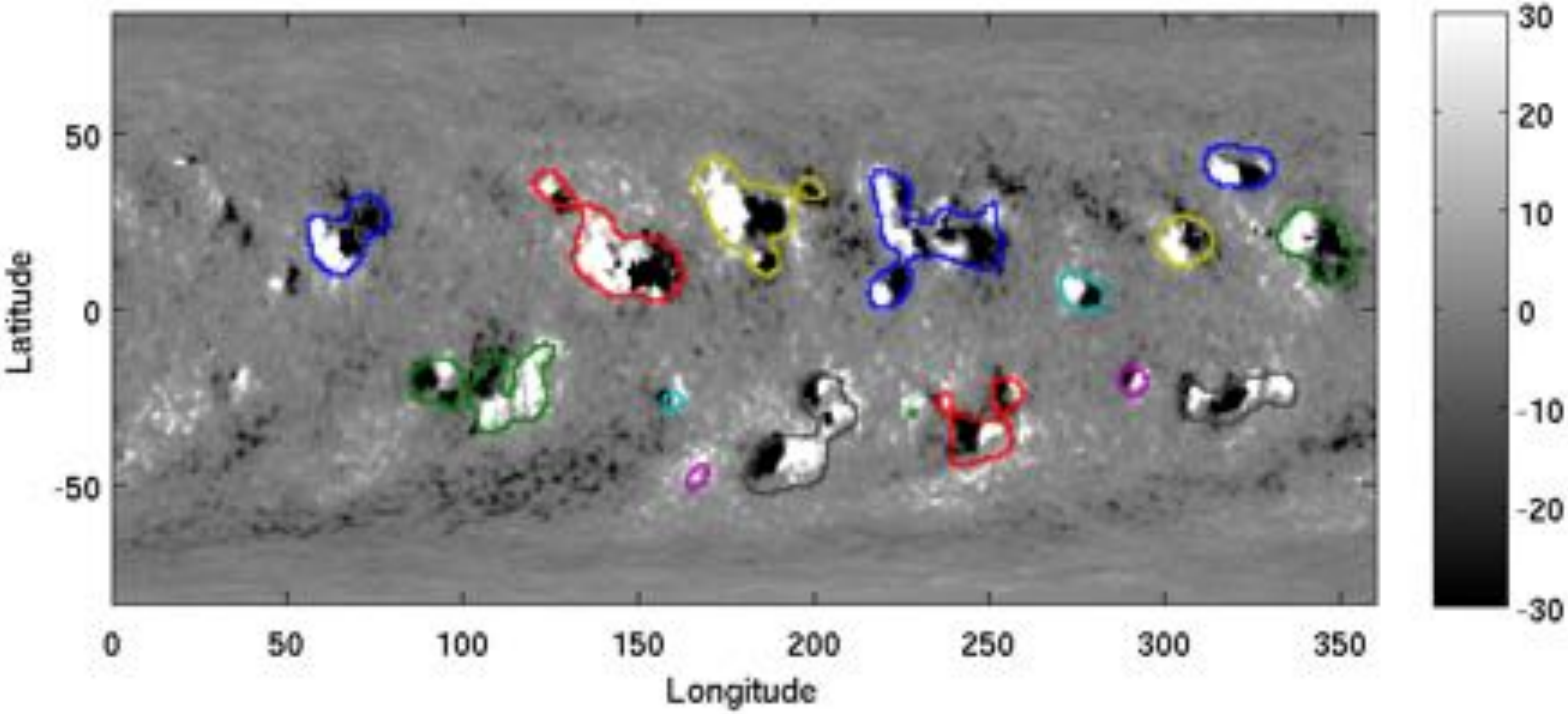
Latitude
Longitude
50
0
-50
0
50
100
150
200
250
300
350
30
20
10
0
-10
-20
-30



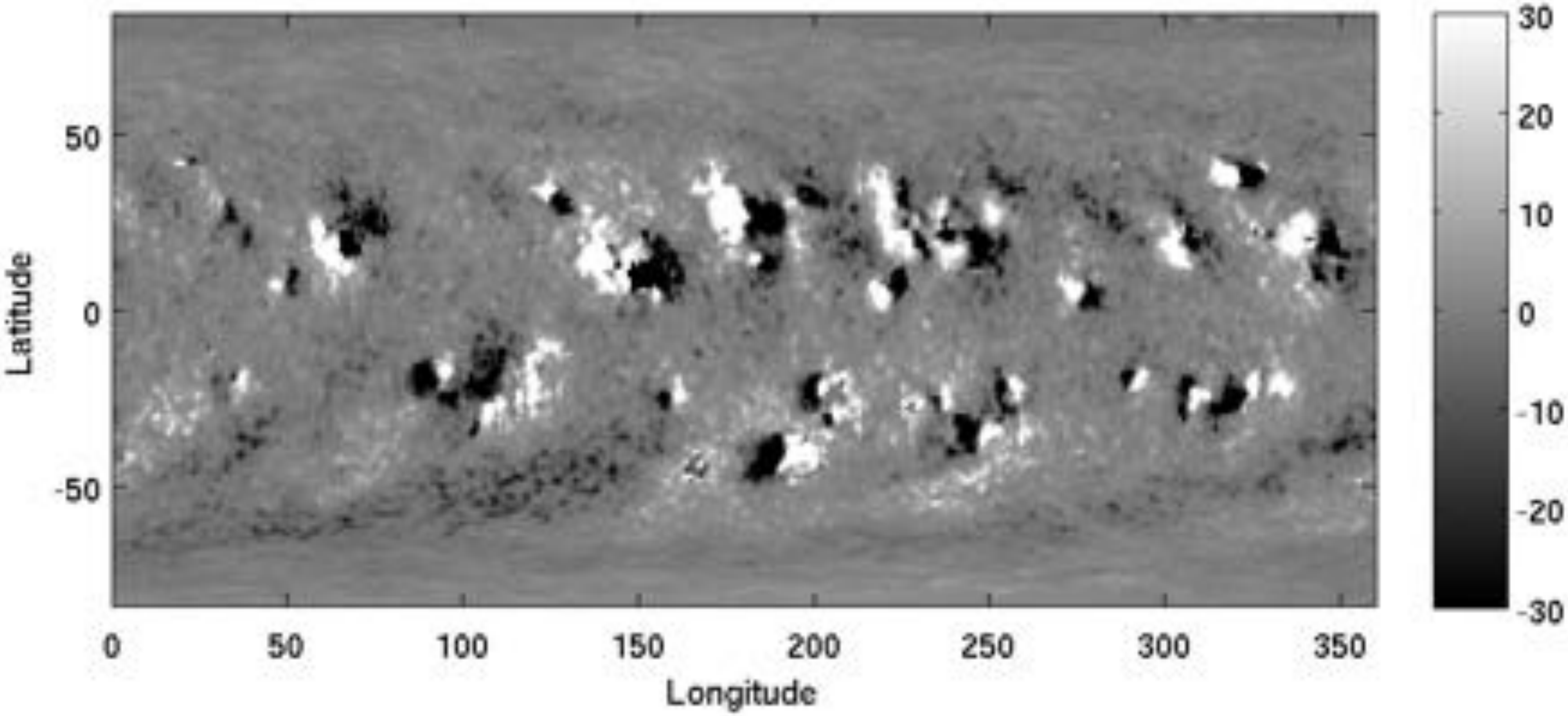
Latitude
50
0
-50
0
50
100
150
200
250
300
350
Longitude
30
20
10
0
-10
-20
-30



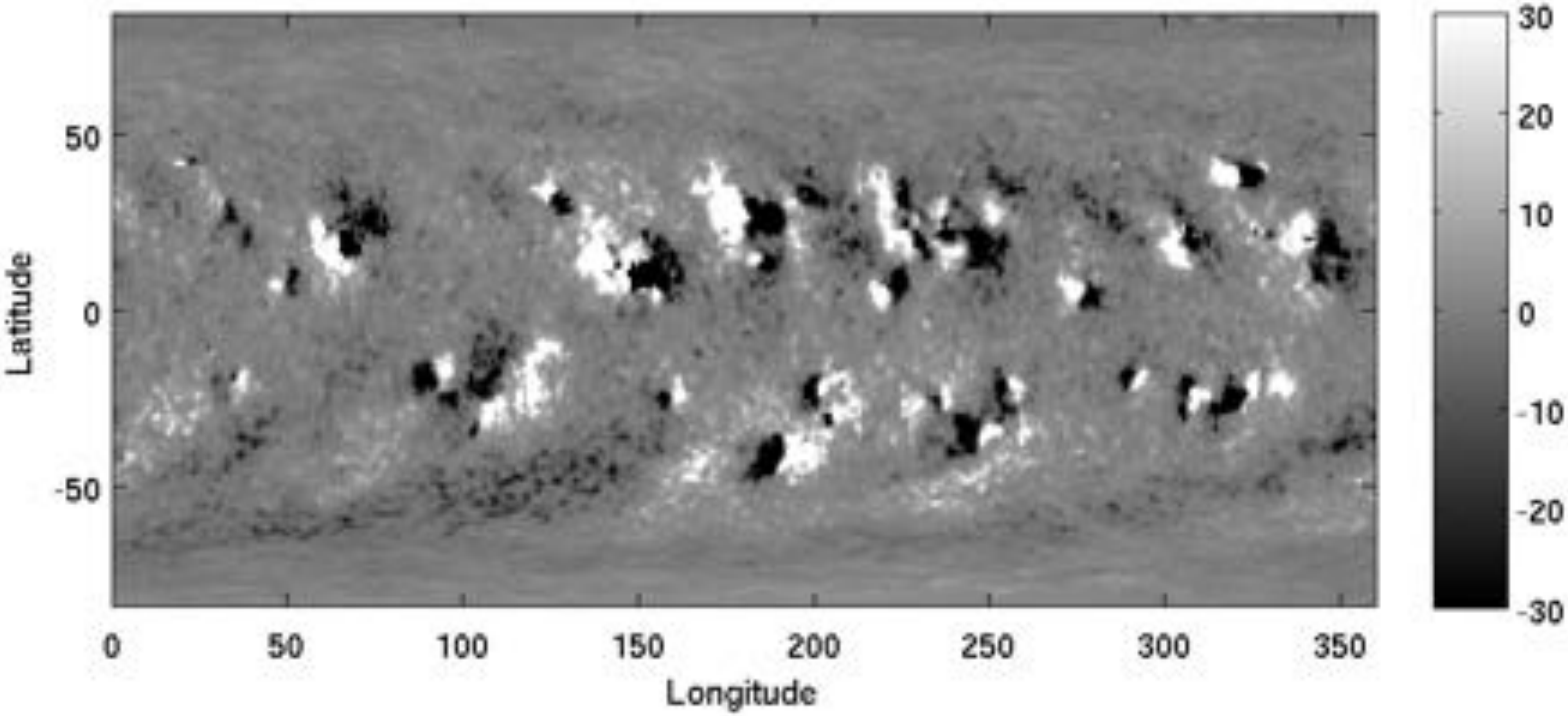
50
0
-50
Latitude
0
50
100
150
200
250
300
350
Longitude
30
20
10
0
-10
-20
-30



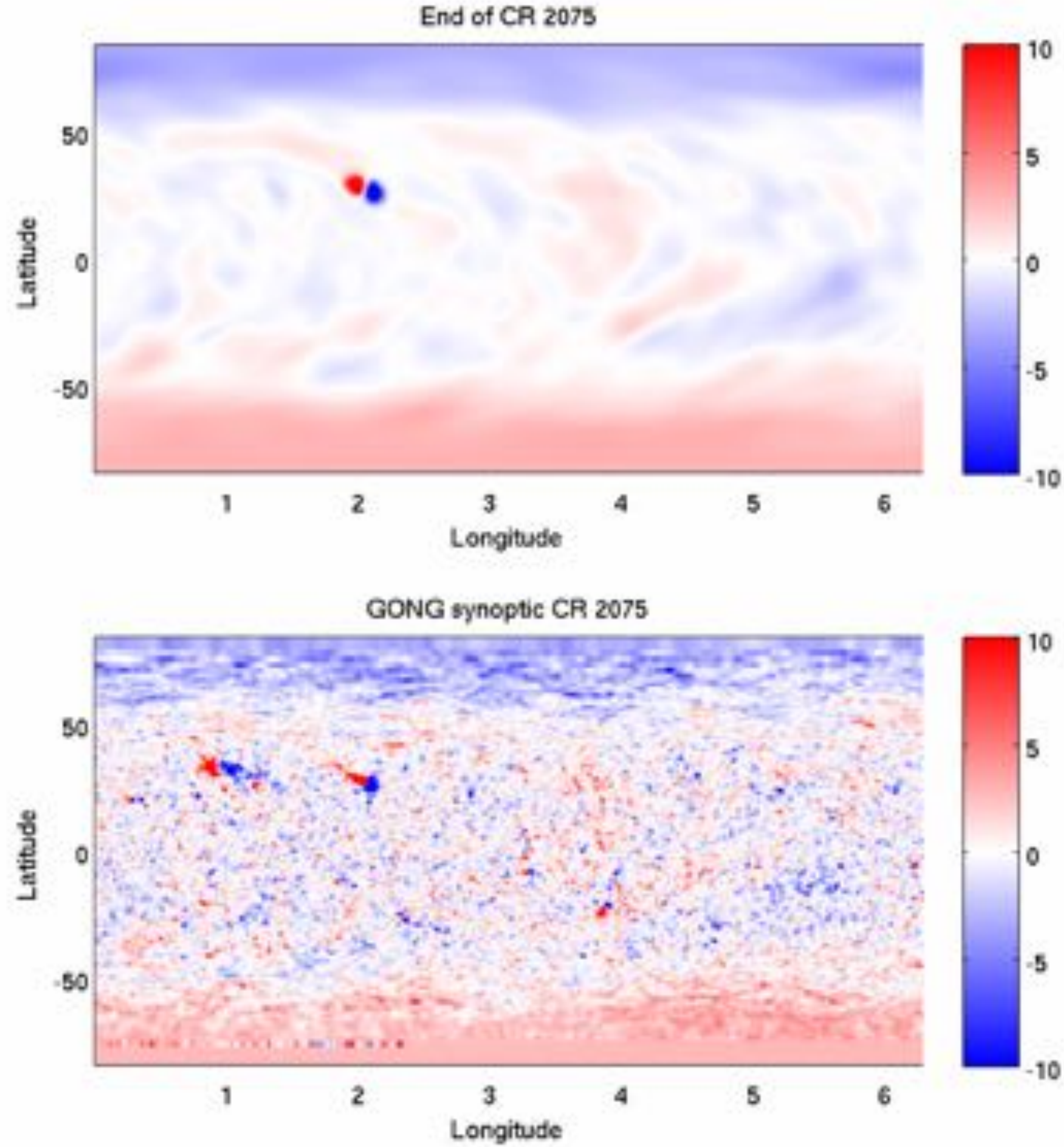
Latitude
Longitude
50
0
-50
0
50
100
150
200
250
300
350
30
20
10
0
-10
-20
-30

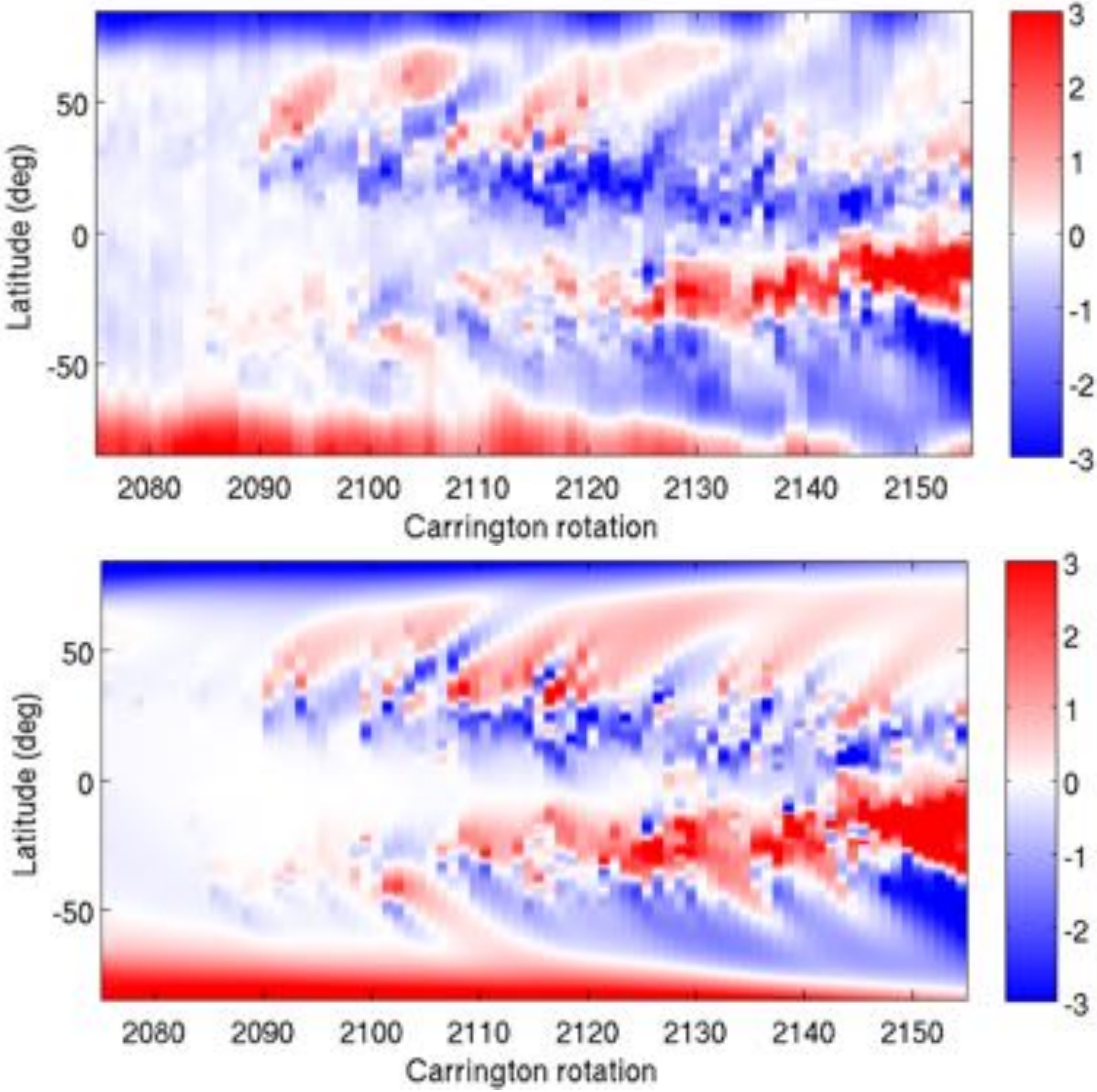


Latitude
Longitude
50
0
-50
0
50
100
150
200
250
300
350
30
20
10
0
-10
-20
-30

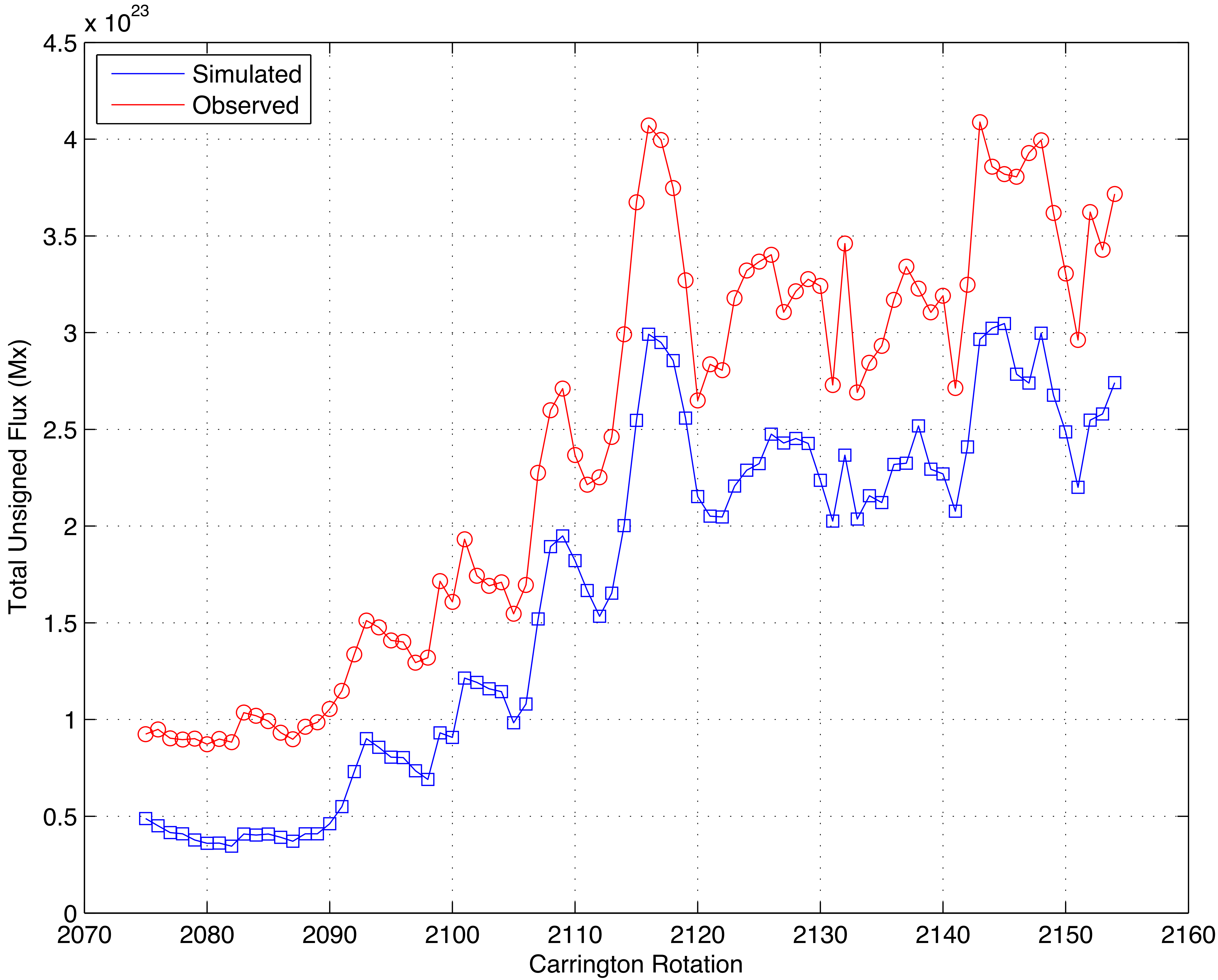


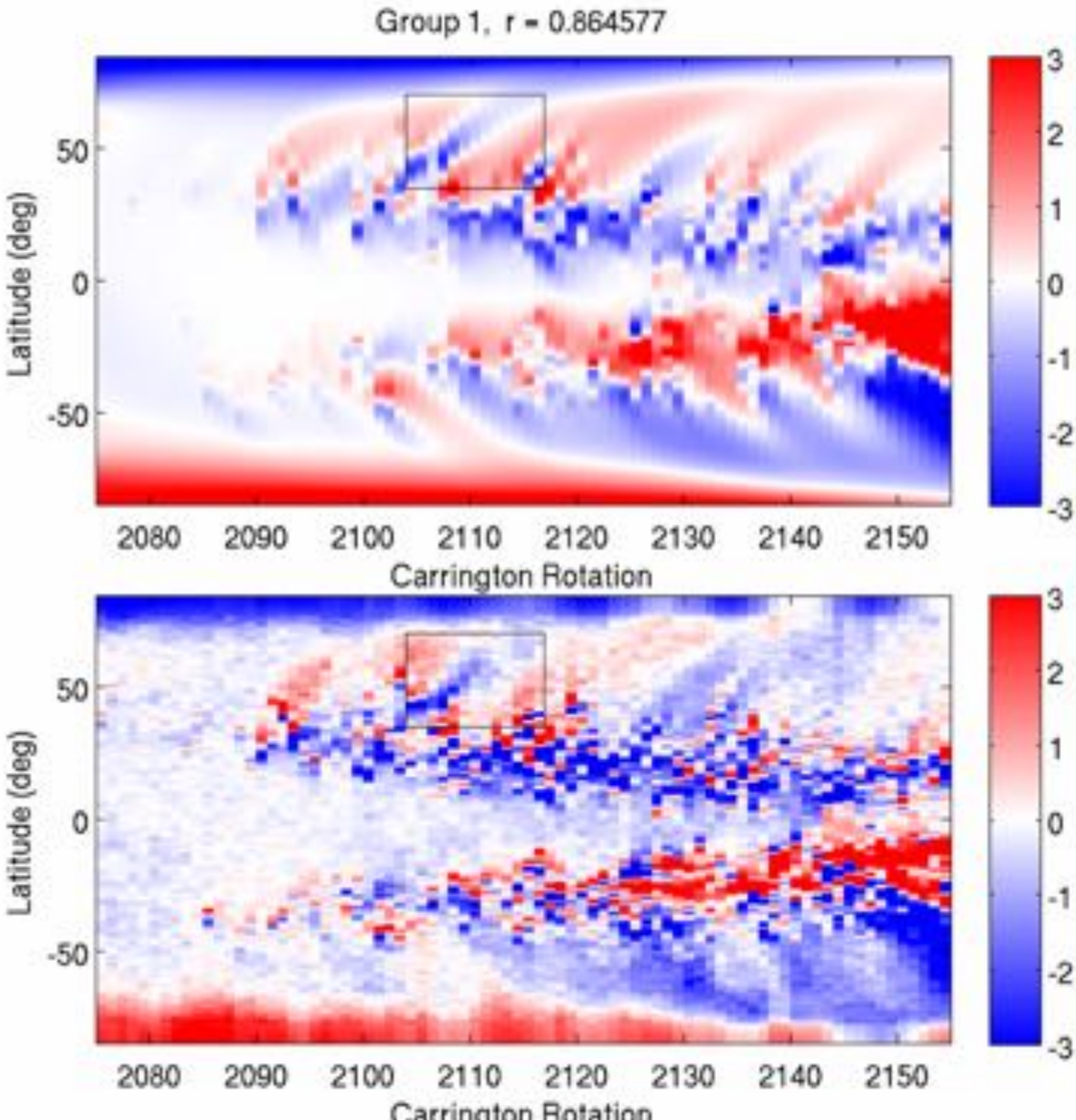
Latitude
50
0
-50
0
50
100
150
200
250
300
350
Longitude
30
20
10
0
-10
-20
-30

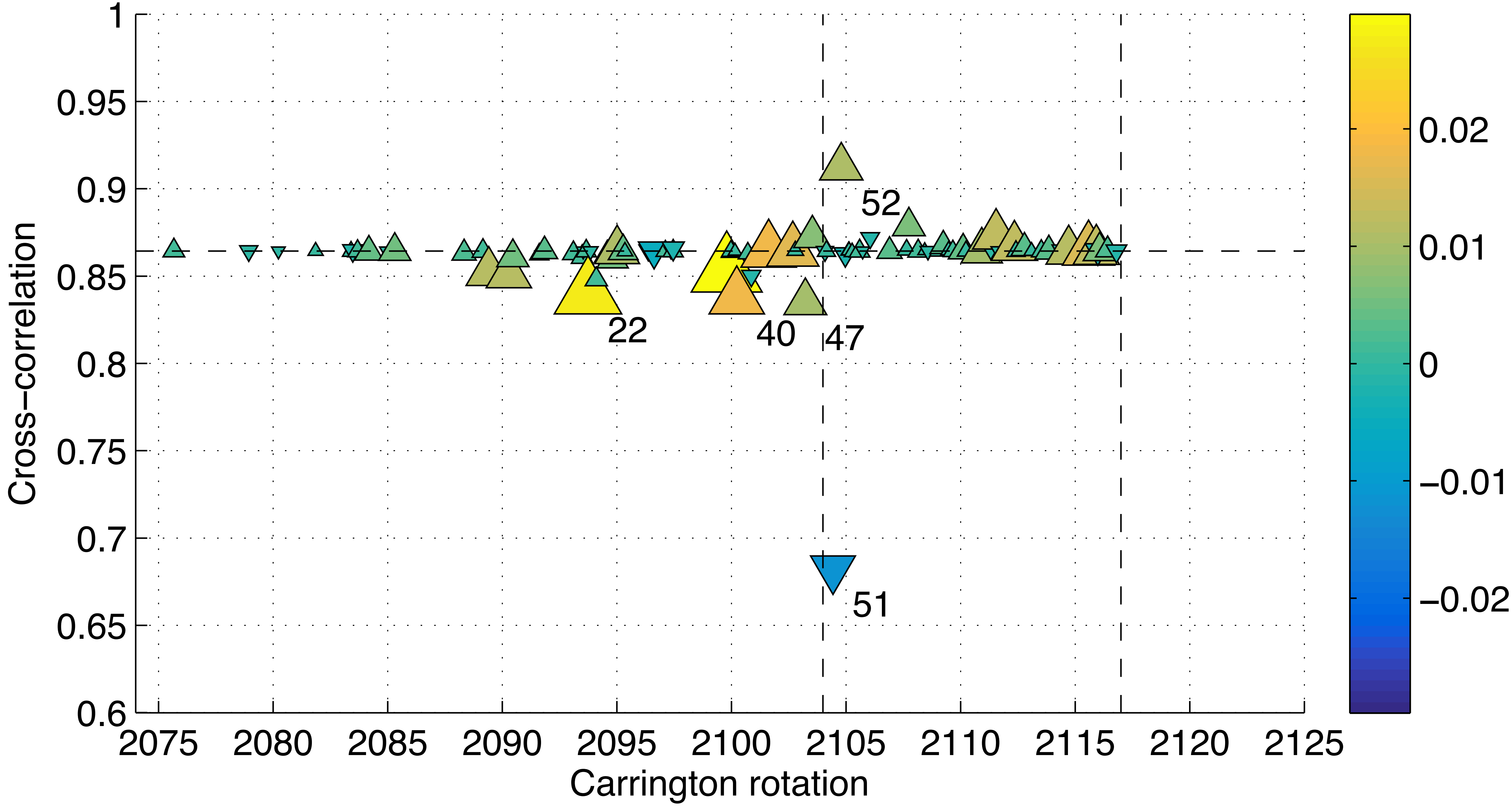

End of CR 2075
Latitude
Longitude
GONG synoptic CR 2075
Latitude
Longitude



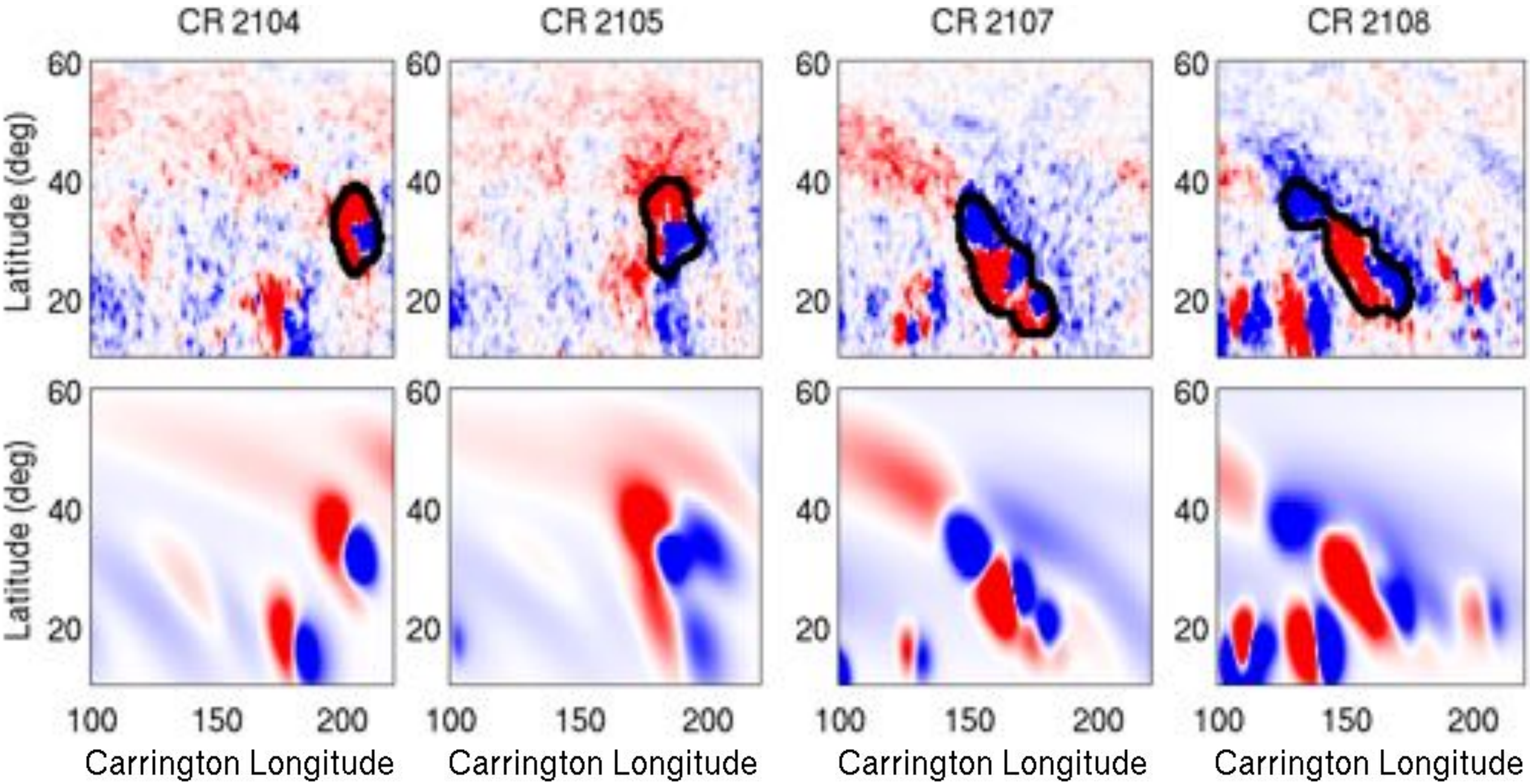
Latitude (deg)
50
0
-50
2080
2090
2100
2110
2120
2130
2140
2150
Carrington rotation
3
2
1
0
-1
-2
-3
Latitude (deg)
50
0
-50
2080
2090
2100
2110
2120
2130
2140
2150
Carrington rotation
3
2
1
0
-1
-2
-3


x 10^23
Simulated
Observed
Total Unsigned Flux (Mx)
Carrington Rotation
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
2070
2080
2090
2100
2110
2120
2130
2140
2150
2160


Group 1, r = 0.864577
Latitude (deg)
50
0
-50
3
2
1
0
-1
-2
-3
2080
2090
2100
2110
2120
2130
2140
2150
Carrington Rotation
Latitude (deg)
50
0
-50
3
2
1
0
-1
-2
-3
2080
2090
2100
2110
2120
2130
2140
2150
Carrington Rotation



Yeates, Baker & van Driel-Gesztelyi, *Solar Phys.* (2015)



CR 2104
CR 2105
CR 2107
CR 2108
Latitude (deg)
60
40
20
100
150
200
Carrington Longitude

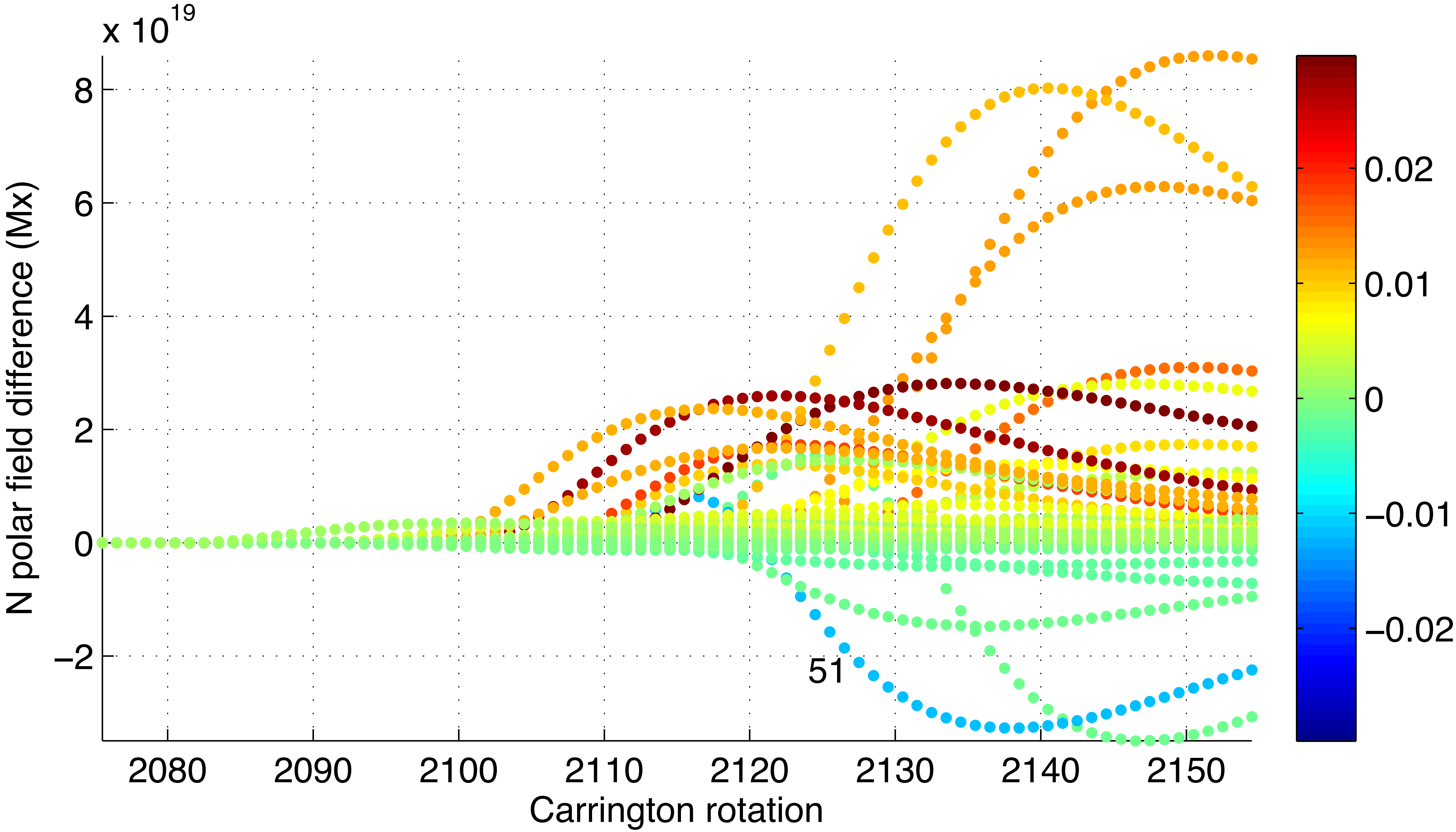
This region must make a large contribution to the polar field, right?

WRONG!

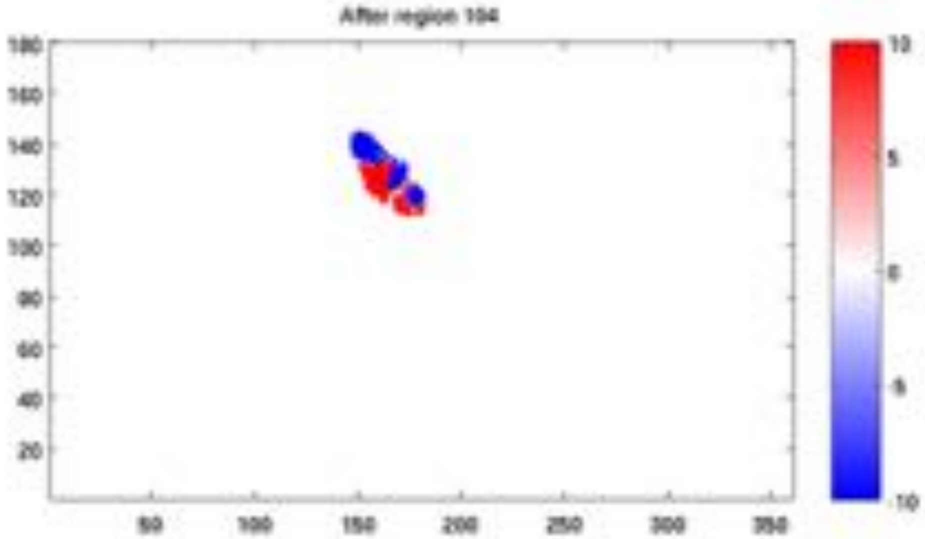
Giovanelli, *Aust. J. Phys.* (1985)

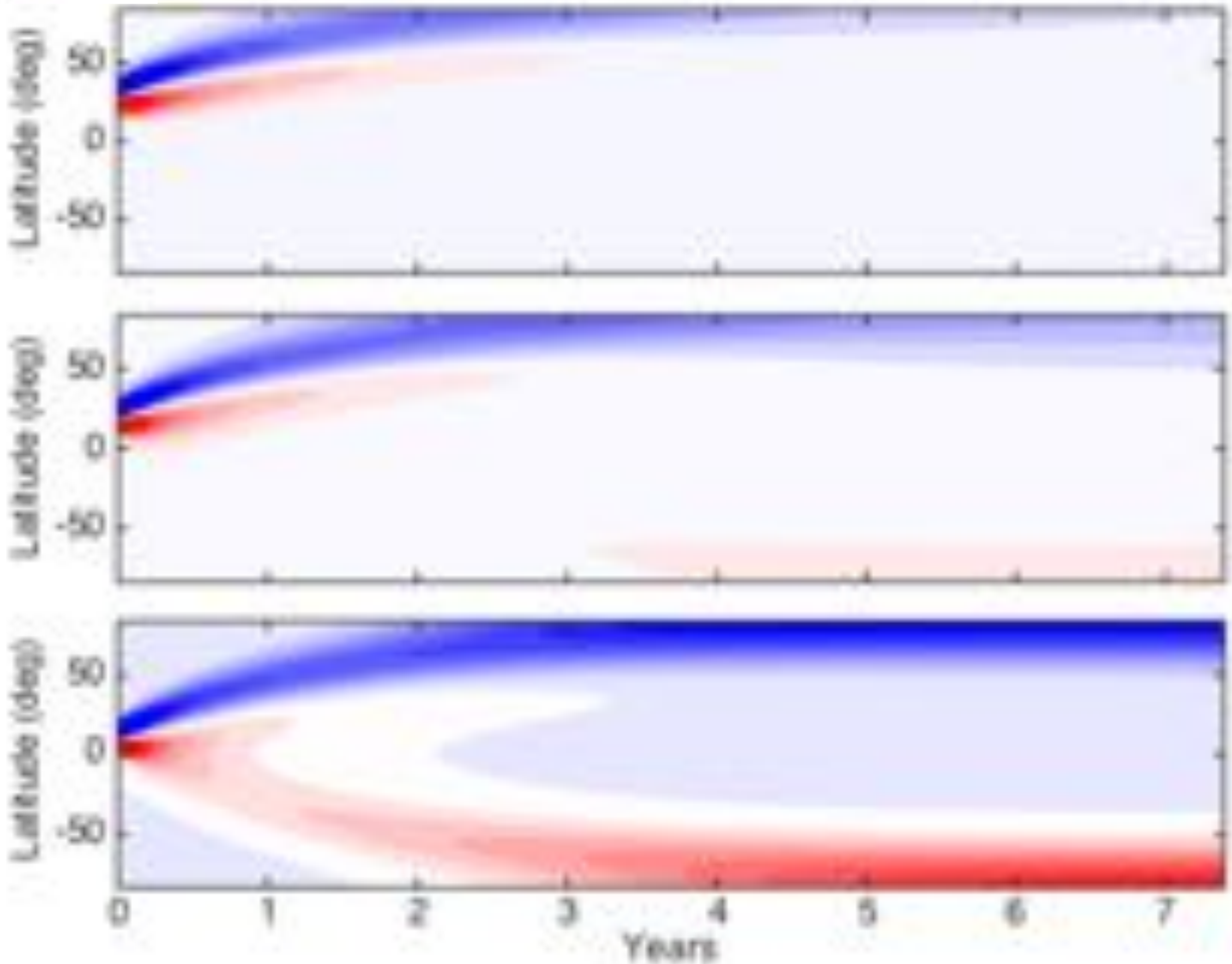
DeVore, *PhD thesis* (1986)

Cameron et al., *A&A* (2013)

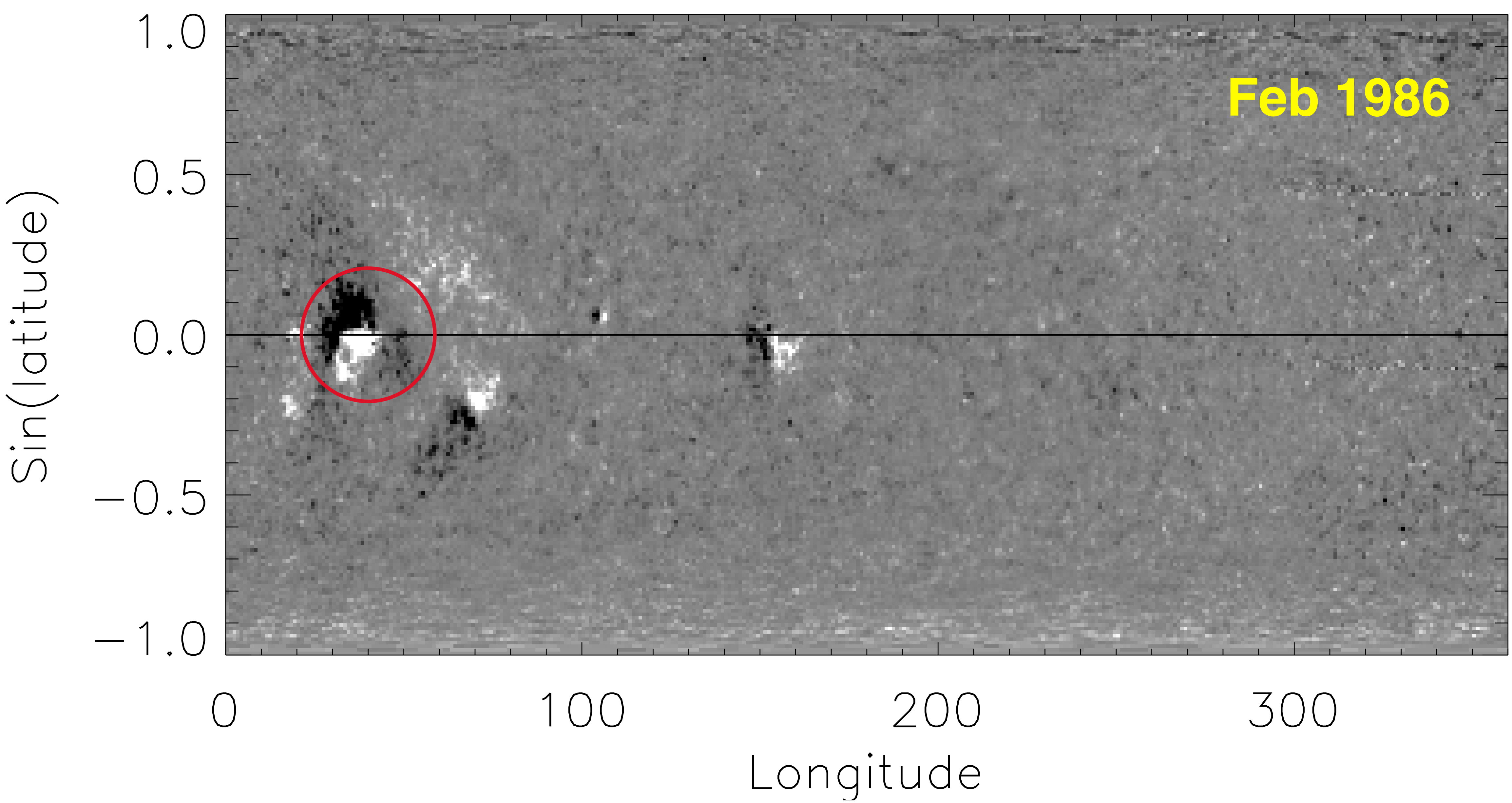


x 10^19
N polar field difference (Mx)
8
6
4
2
0
−2
51
2080
2090
2100
2110
2120
2130
2140
2150
Carrington rotation
0.02
0.01
0
−0.01
−0.02


After region 104


Latitude (deg)
Latitude (deg)
Latitude (deg)
Years

Cameron, *et al.*, *A&A* (2013)



A single cross-equatorial flux plume can affect the net hemispheric flux of the following minima by up to 60%.

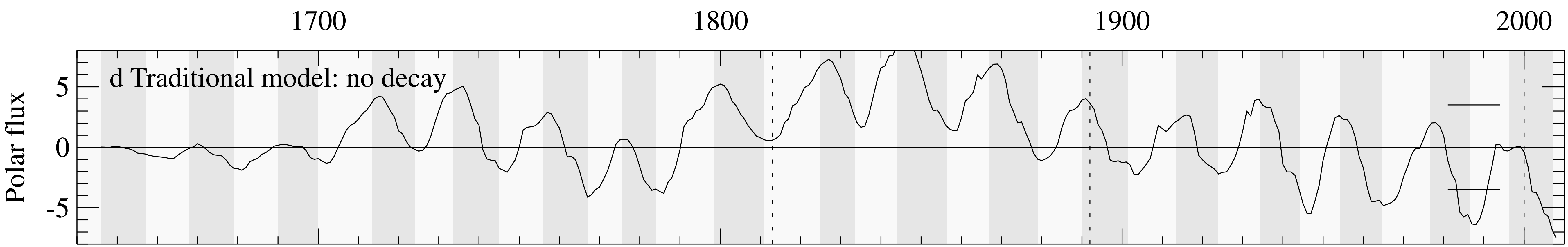
CHALLENGE 1:

FLUCTUATIONS IN EMERGENCE MATTER!

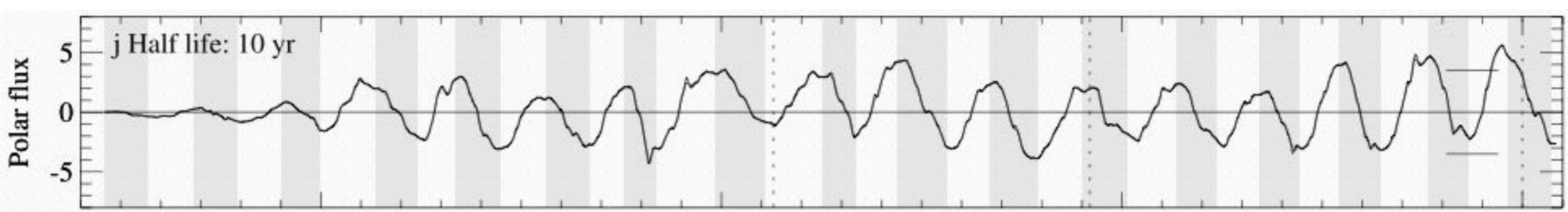
CHALLENGE 2:

SUBTLETIES IN DECAY MATTER!

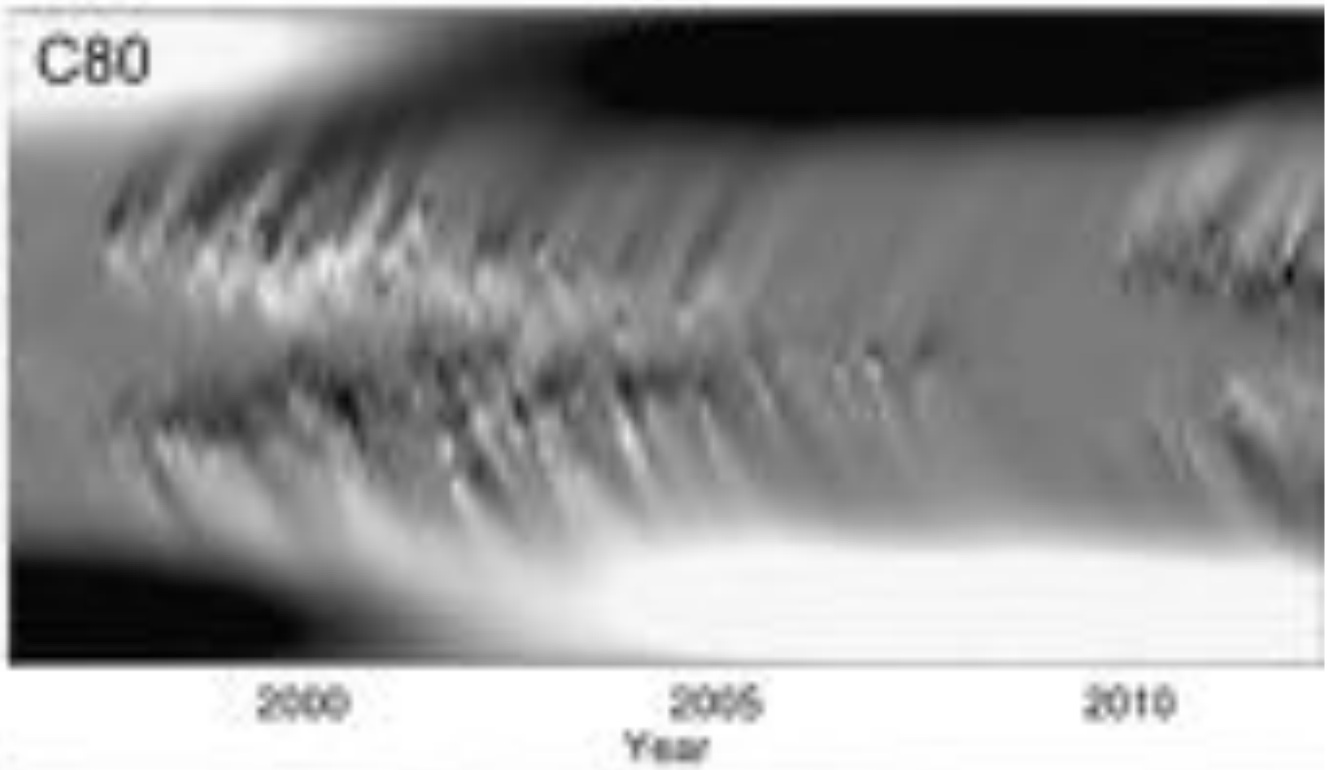
Schrijver, DeRosa & Title, *ApJ* (2002)



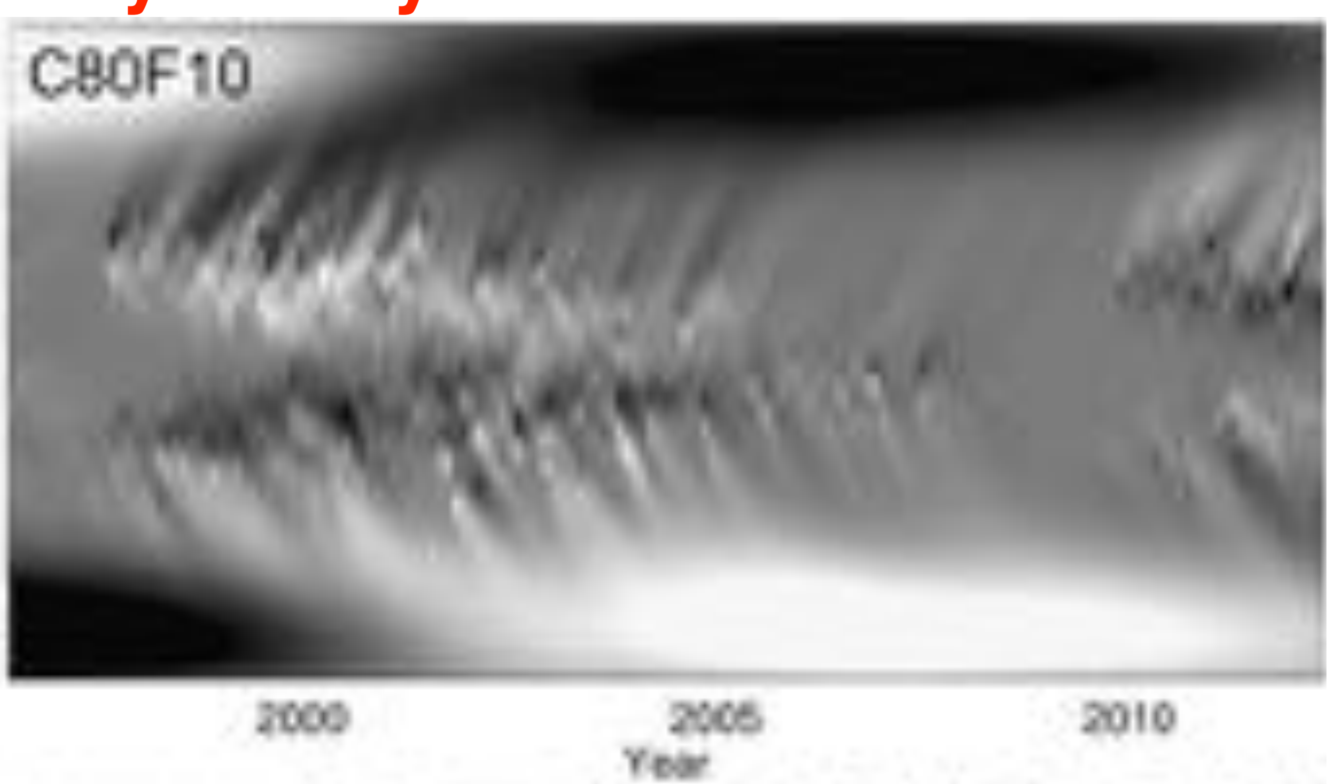
$$\frac{\partial B_r}{\partial t} = -(\nabla \cdot \mathbf{v})B_r - (\mathbf{v} \cdot \nabla)B_r + \eta \nabla^2 B_r - \frac{1}{\tau} B_r$$

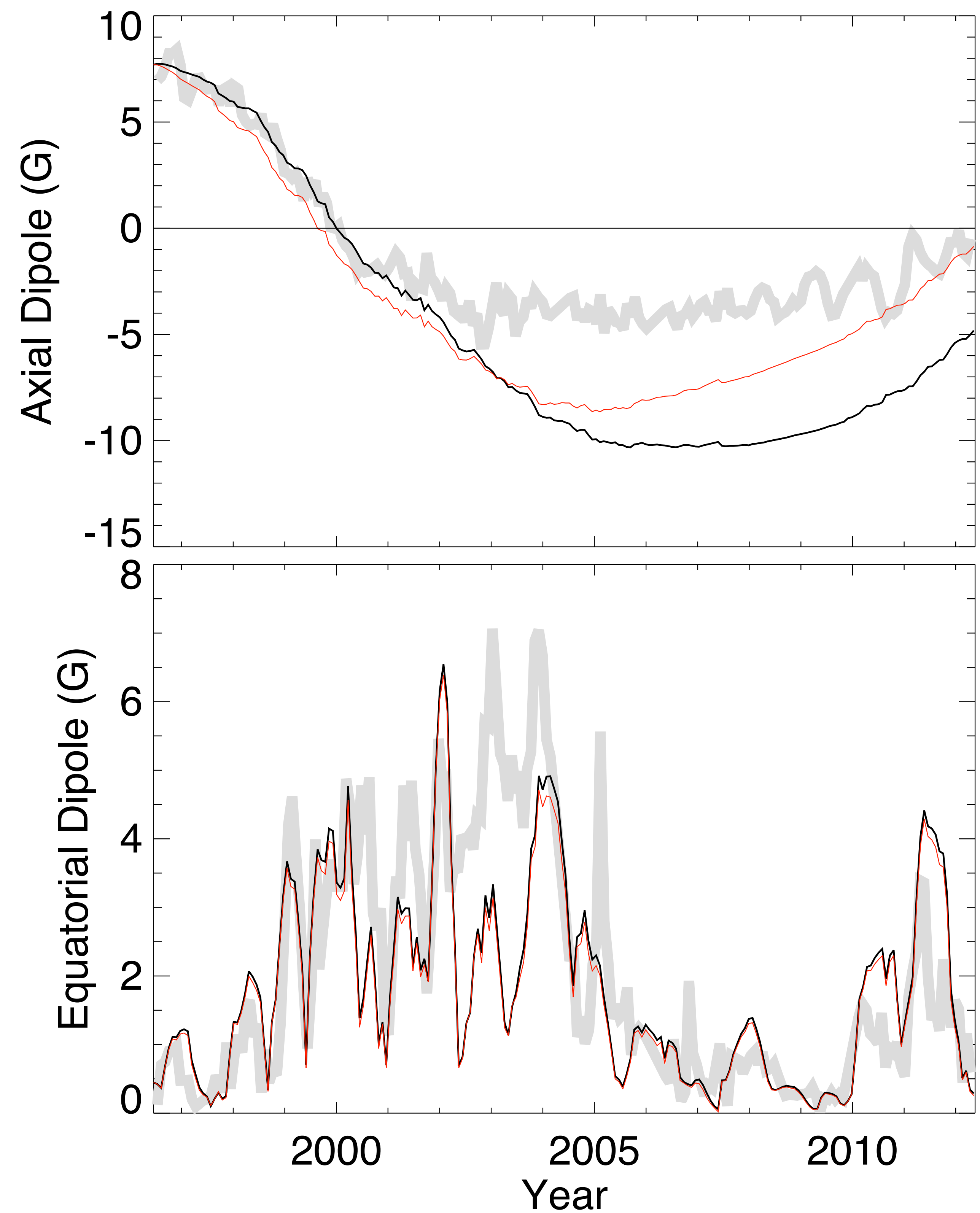


original



10 yr decay





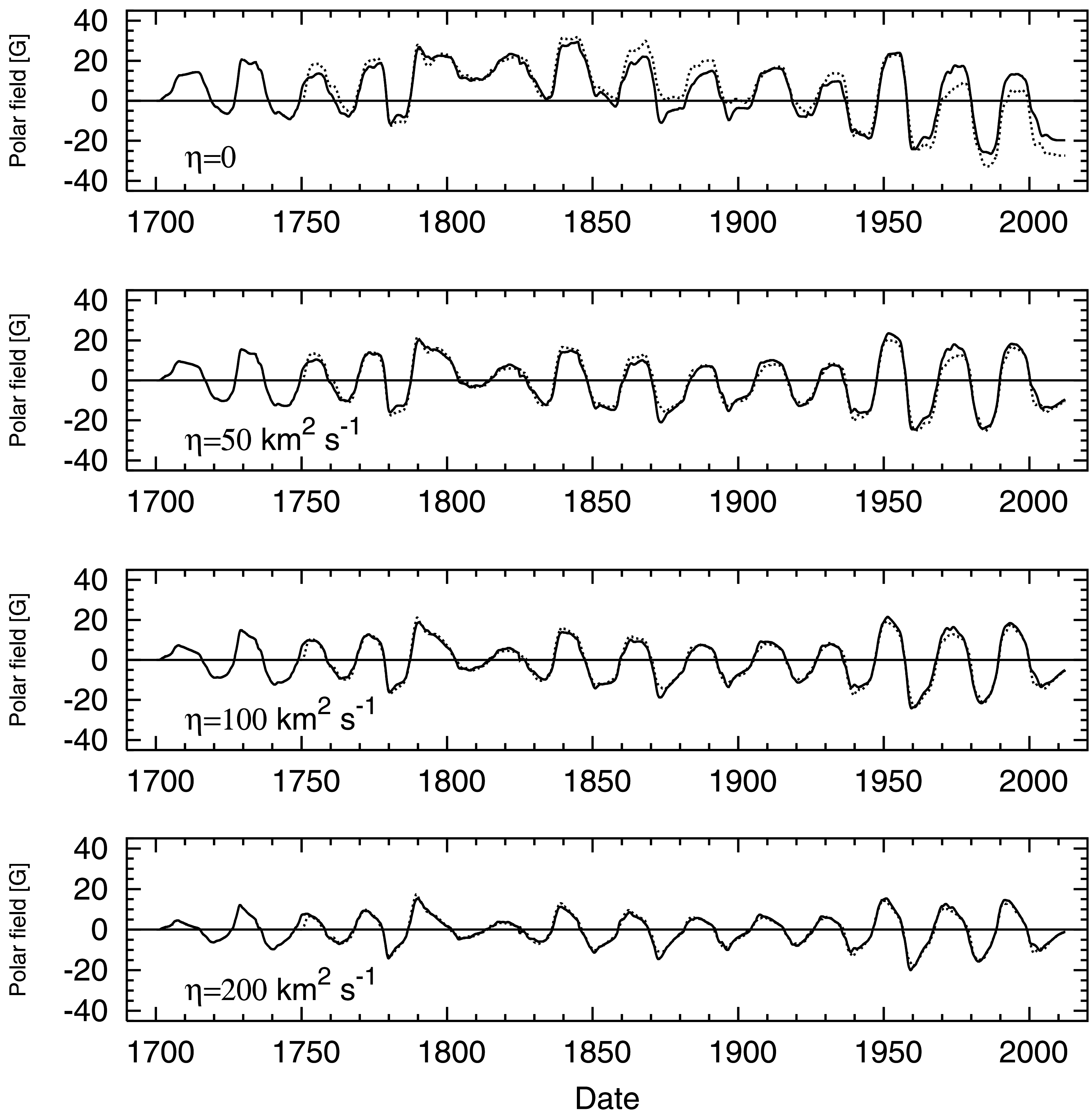
Yeates, *Solar Phys.* (2014)

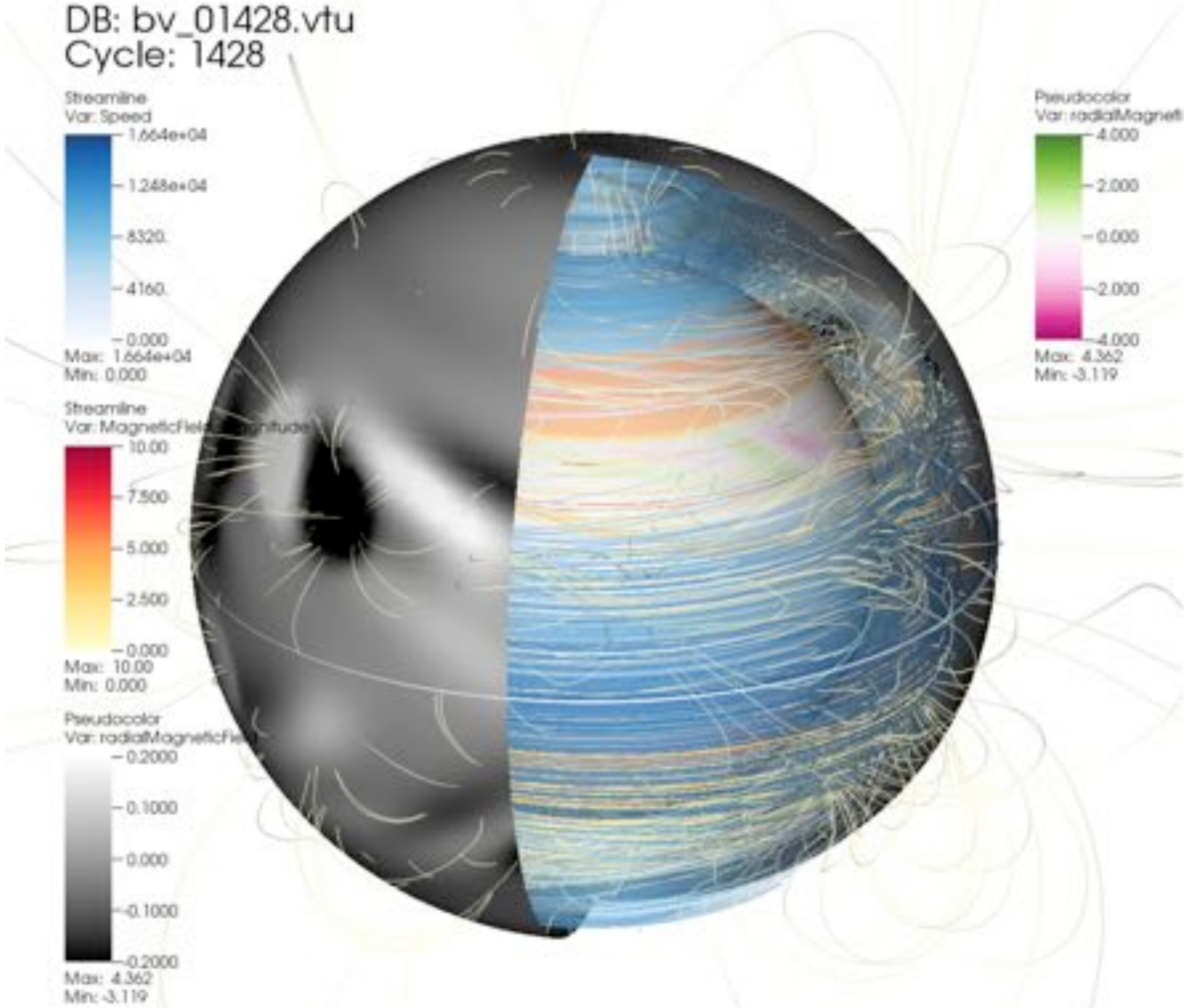
Baumann, Schmitt & Schüssler, *A&A* (2006)

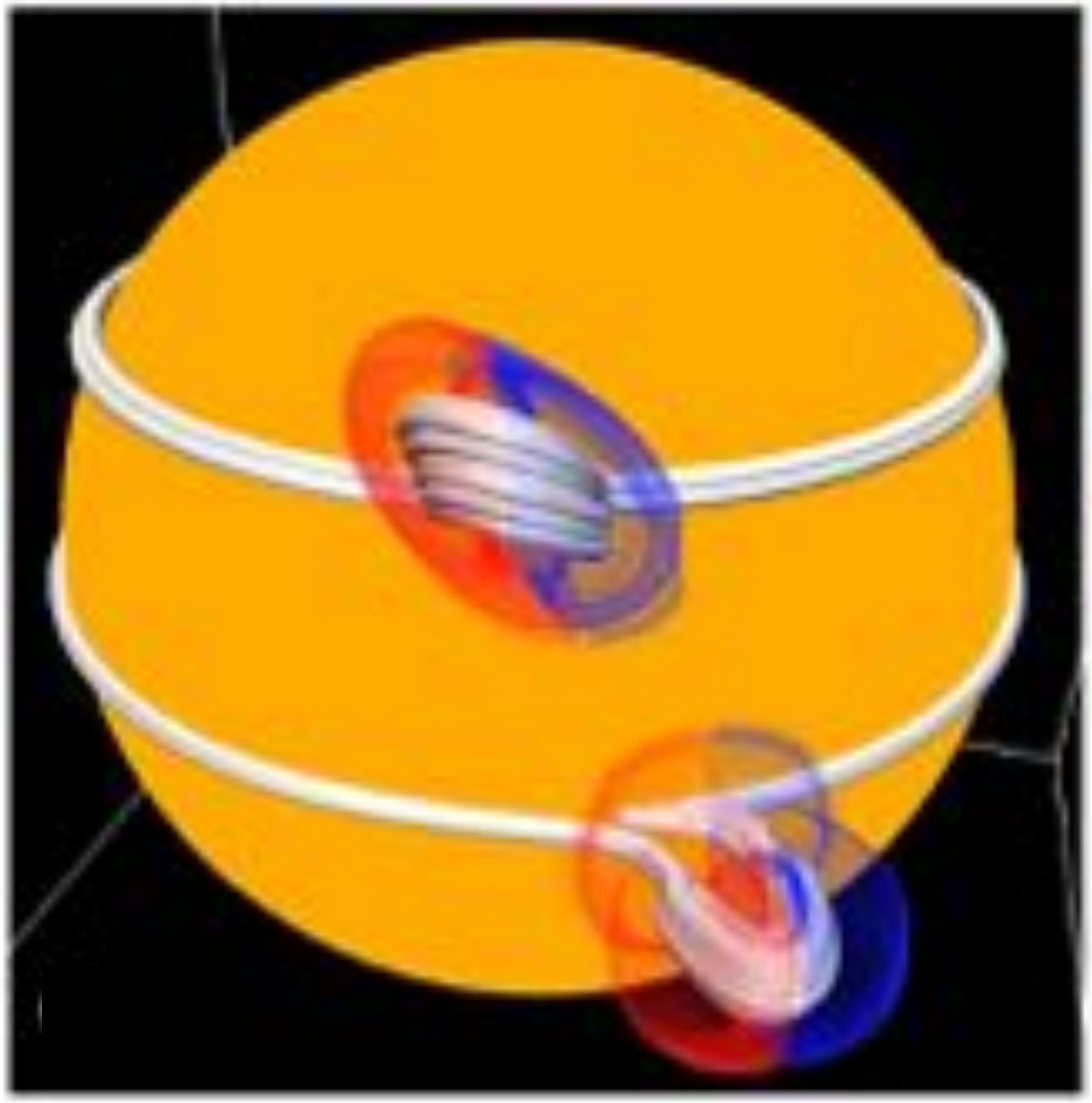
Explanation: decay comes from radial diffusion.

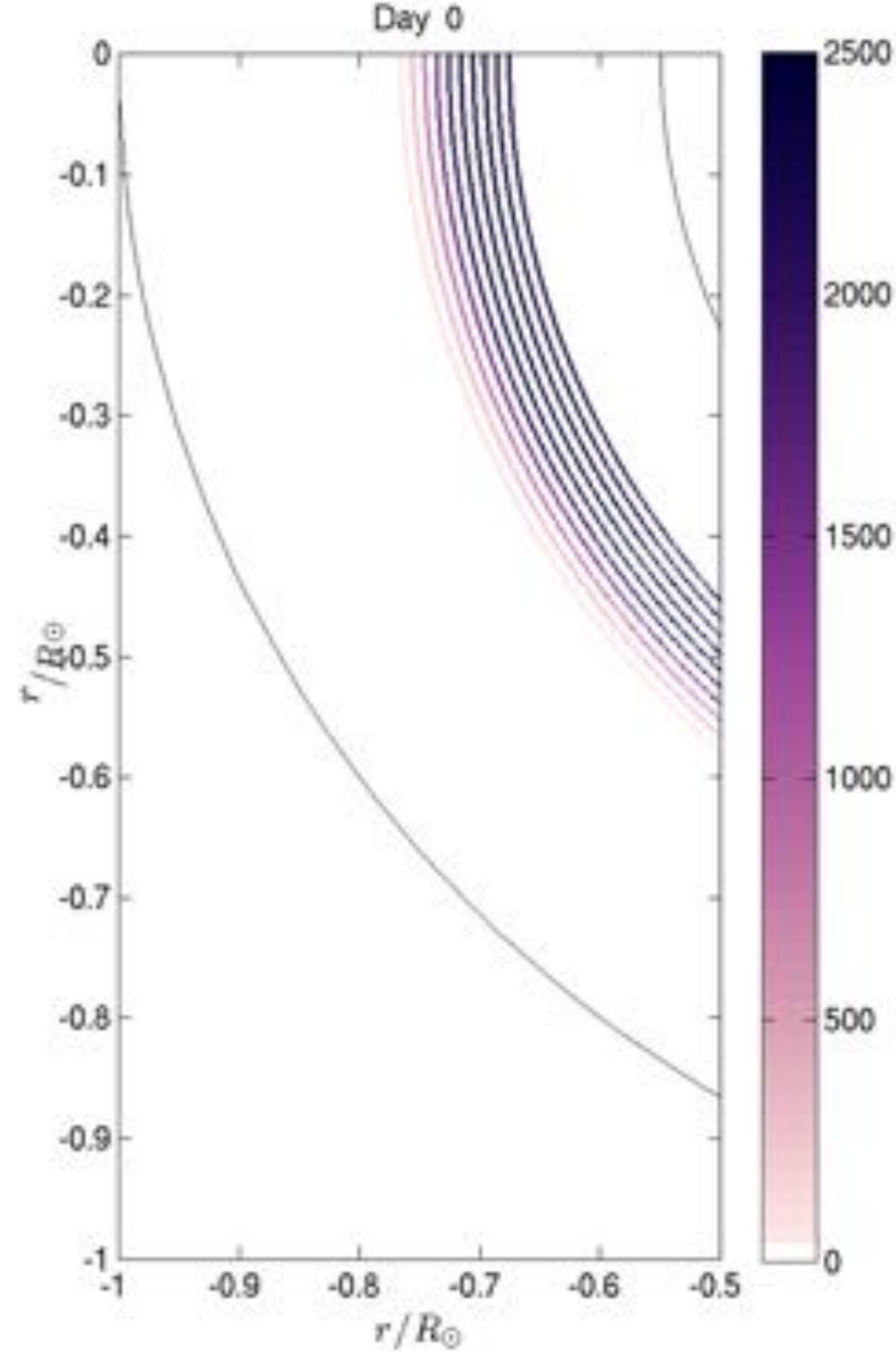
Parametrisation: based on decay modes for uniform diffusion in a spherical shell.

Higher degree harmonics decay faster.

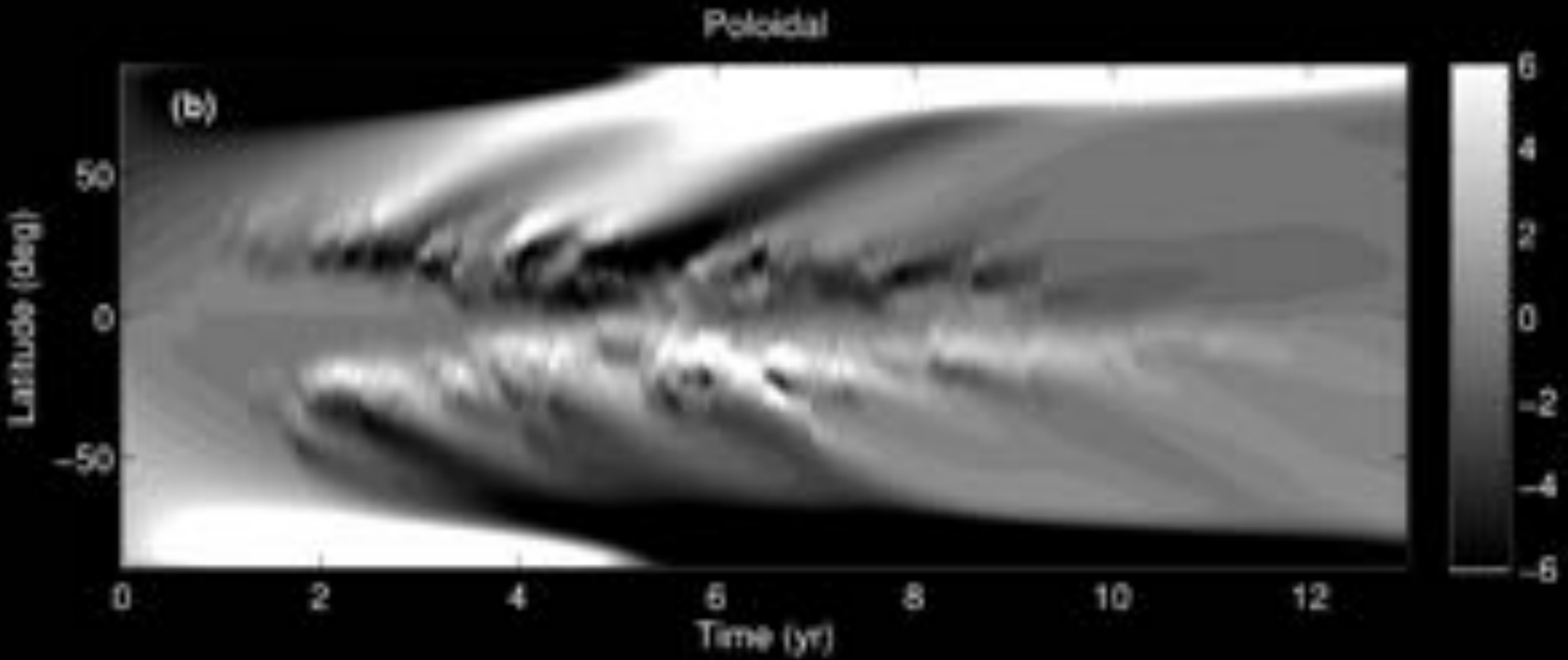



DB: bv_01428.vtu
Cycle: 1428
Streamline
Var: Speed
1.664e+04
1.248e+04
8320.
4160.
0.000
Max: 1.664e+04
Min: 0.000
Streamline
10.00
7.500
5.000
2.500
0.000
Max: 10.00
Min: 0.000
Pseudocolor
0.2000
0.1000
0.000
-0.1000
-0.2000
Max: 4.362
Min: -3.119
Pseudocolor
4.000
2.000
0.000
-2.000
-4.000
Max: 4.362
Min: -3.119

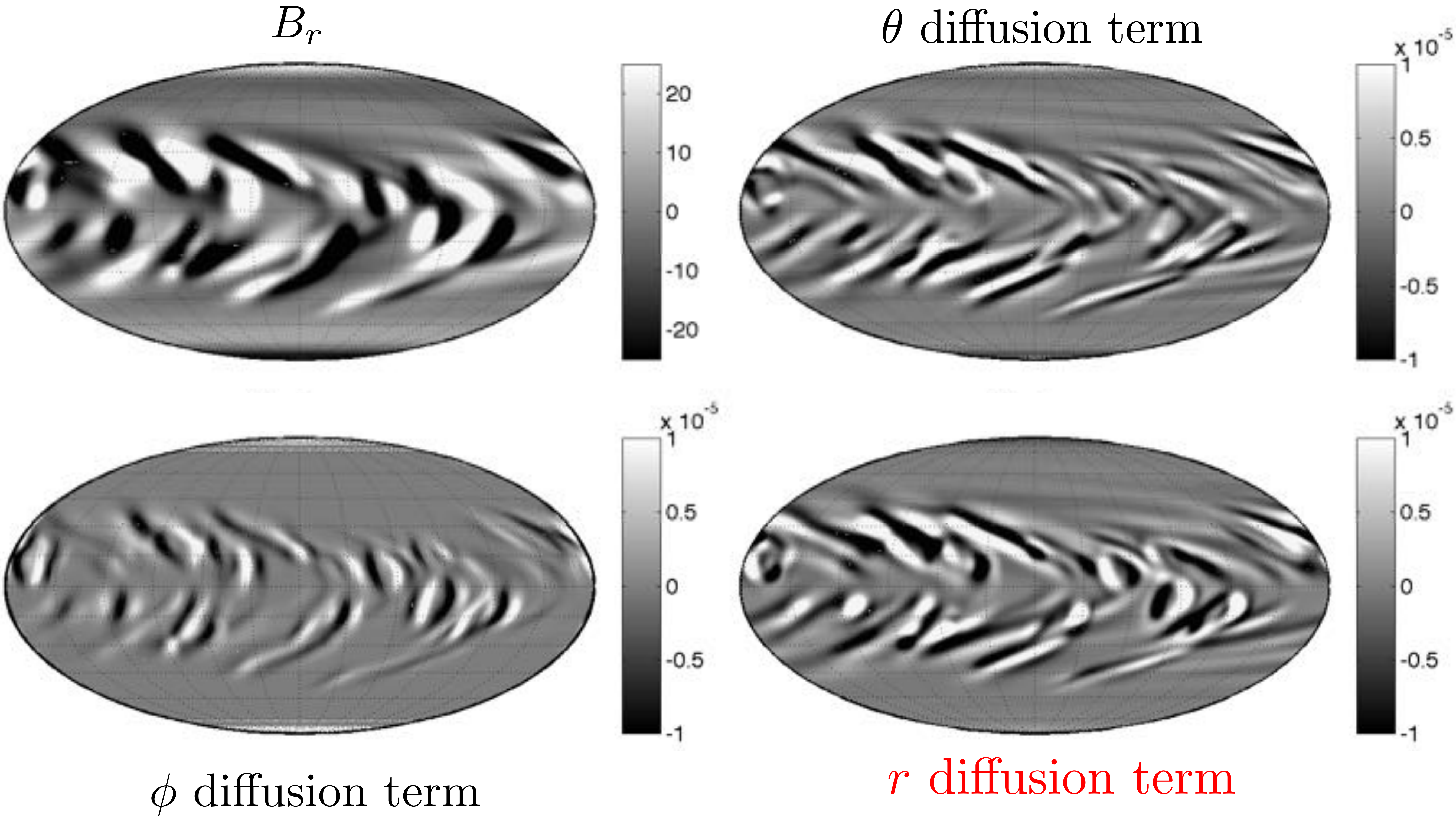


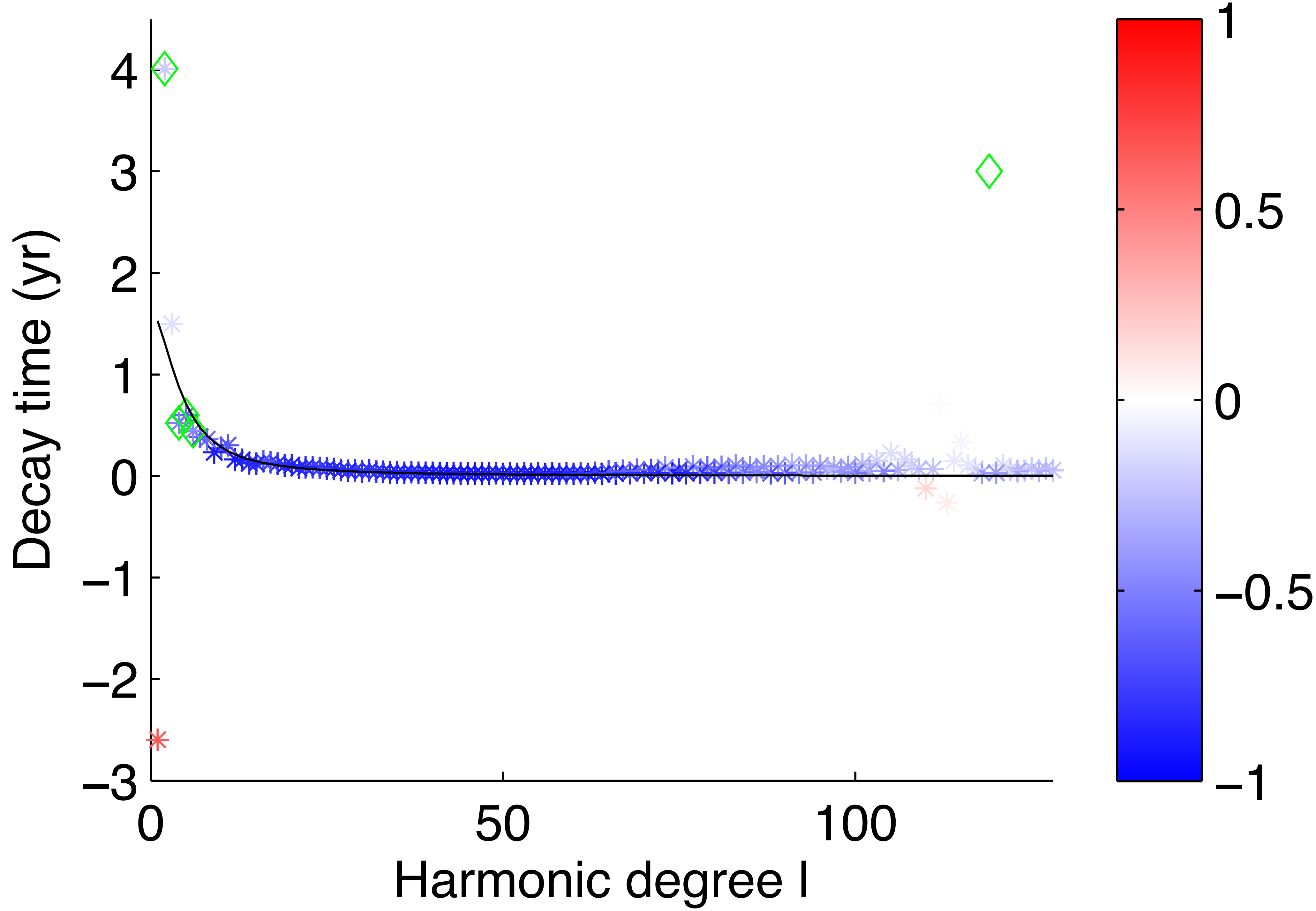


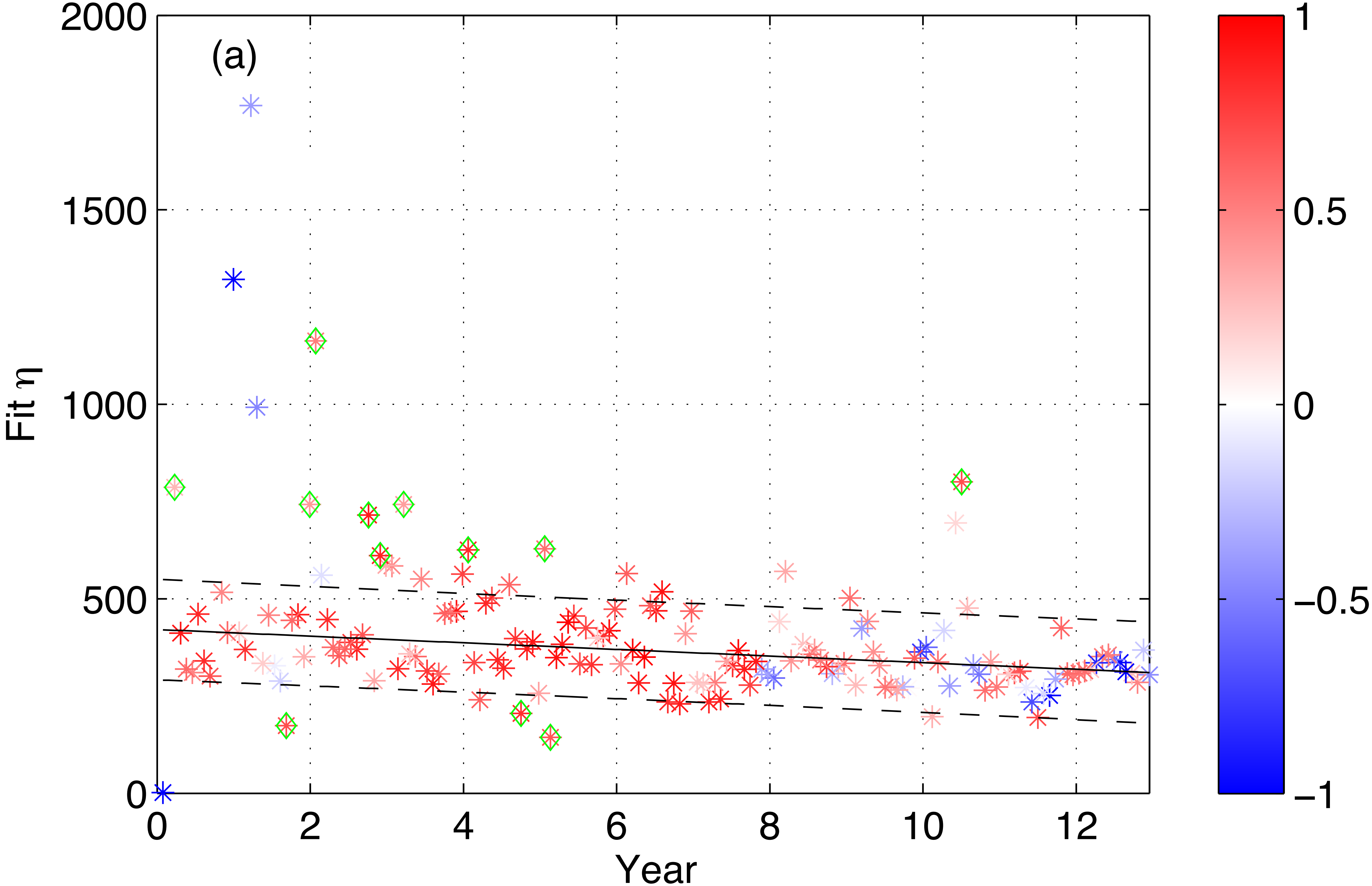
Yeates & Muñoz-Jaramillo,
MNRAS (2013)



Poloidal
(b)
Latitude (deg)
50
0
−50
0
2
4
6
8
10
12
Time (yr)
6
4
2
0
−2
−4
−6


B_r
θ diffusion term
ϕ diffusion term
r diffusion term
20
10
0
-10
-20
x 10^-5
1
0.5
0
-0.5
-1


Decay time (yr)
Harmonic degree l
4
3
2
1
0
−1
−2
−3
0
50
100
1
0.5
0
−0.5
−1



Support for the idea of radial decay, but best parametrisation remains to be determined.

Making solar cycle predictions *before* Minimum requires surface flux transport modelling.

May ultimately prove impossible to predict specific cycles due to sensitivity to fluctuations in active region emergence.

Best possible predictions need to incorporate
(1) accurate active regions
(2) appropriate flux decay mechanisms and rates.

Further reading

Mackay & Yeates, *Living Rev. Solar Phys.* **9**, 6 (2012)
Yeates & Muñoz-Jaramillo, *MNRAS* **436**, 3366 (2013)
Yeates, *Solar Phys.* **289**, 631 (2014)
Yeates, Baker & van Driel-Gesztelyi, *Solar Phys.* (2015)

Baumann, Schmitt & Schüssler, *A&A* (2006)

$$\frac{\partial B_r}{\partial t} = \hat{\mathbf{r}} \cdot \nabla \times \left(\mathbf{v} \times \mathbf{B}\right) - \hat{\mathbf{r}} \cdot \nabla \times \left(\eta \nabla \times \mathbf{B}\right)$$

$$B_\theta(R_\odot) = B_\phi(R_\odot) = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\eta = \eta(r)$$

$$\frac{\partial B_r}{\partial t} = -\frac{1}{r \sin\theta}\left[\frac{\partial}{\partial \theta}\left(\sin\theta v_\theta B_r\right) + \frac{\partial}{\partial \phi}\left(v_\phi B_r\right)\right]$$

$$+ \frac{\eta}{r^2 \sin\theta}\frac{\partial}{\partial \theta}\left(\sin\theta \frac{\partial B_r}{\partial \theta}\right) + \frac{\eta}{r^2 \sin^2\theta}\frac{\partial^2 B_r}{\partial \phi^2} + \frac{\eta}{r}\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r^2 B_r\right)\right)$$