Helioseismic Study of Large-Scale Flows and Emerging Active Regions

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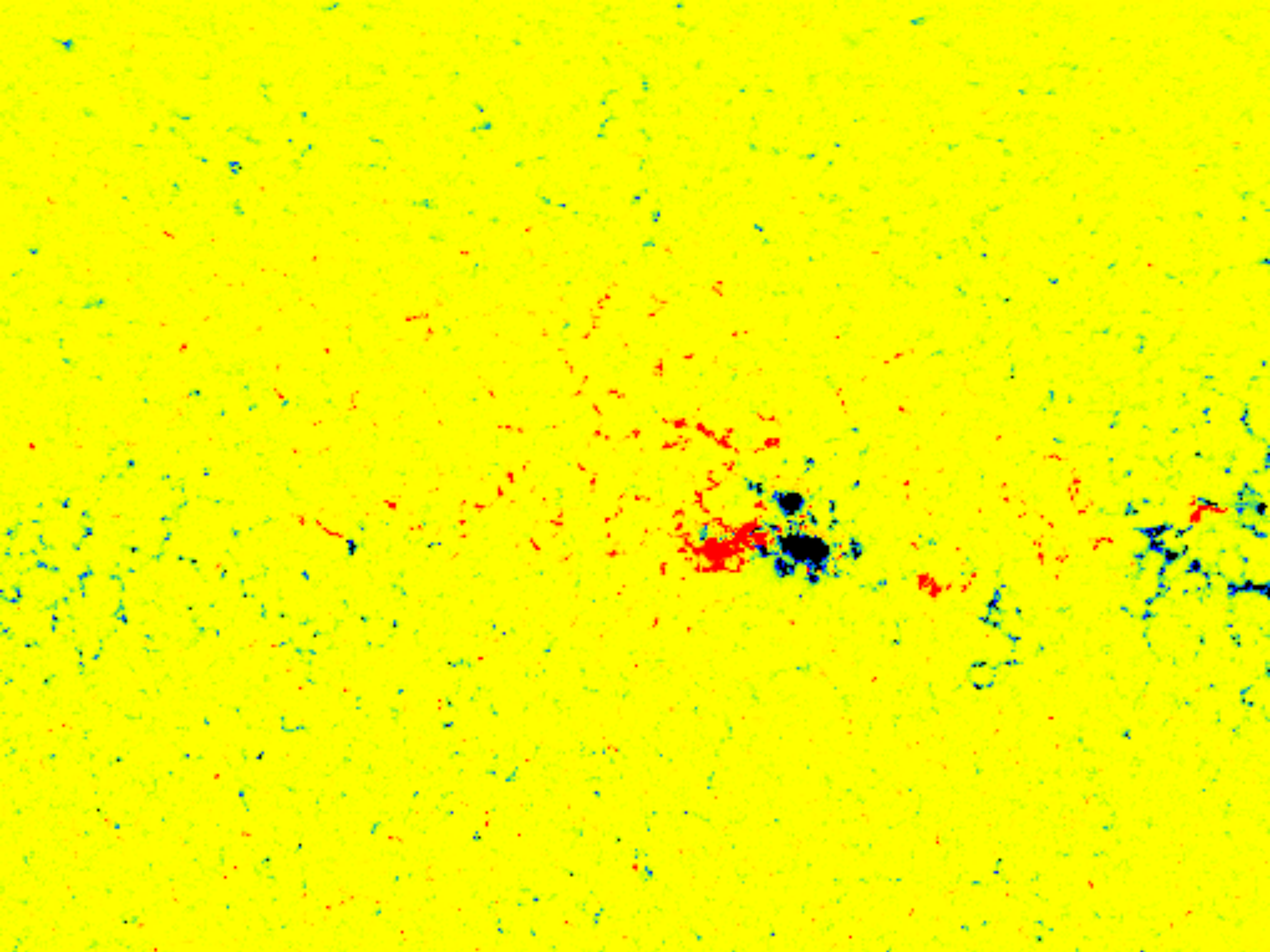
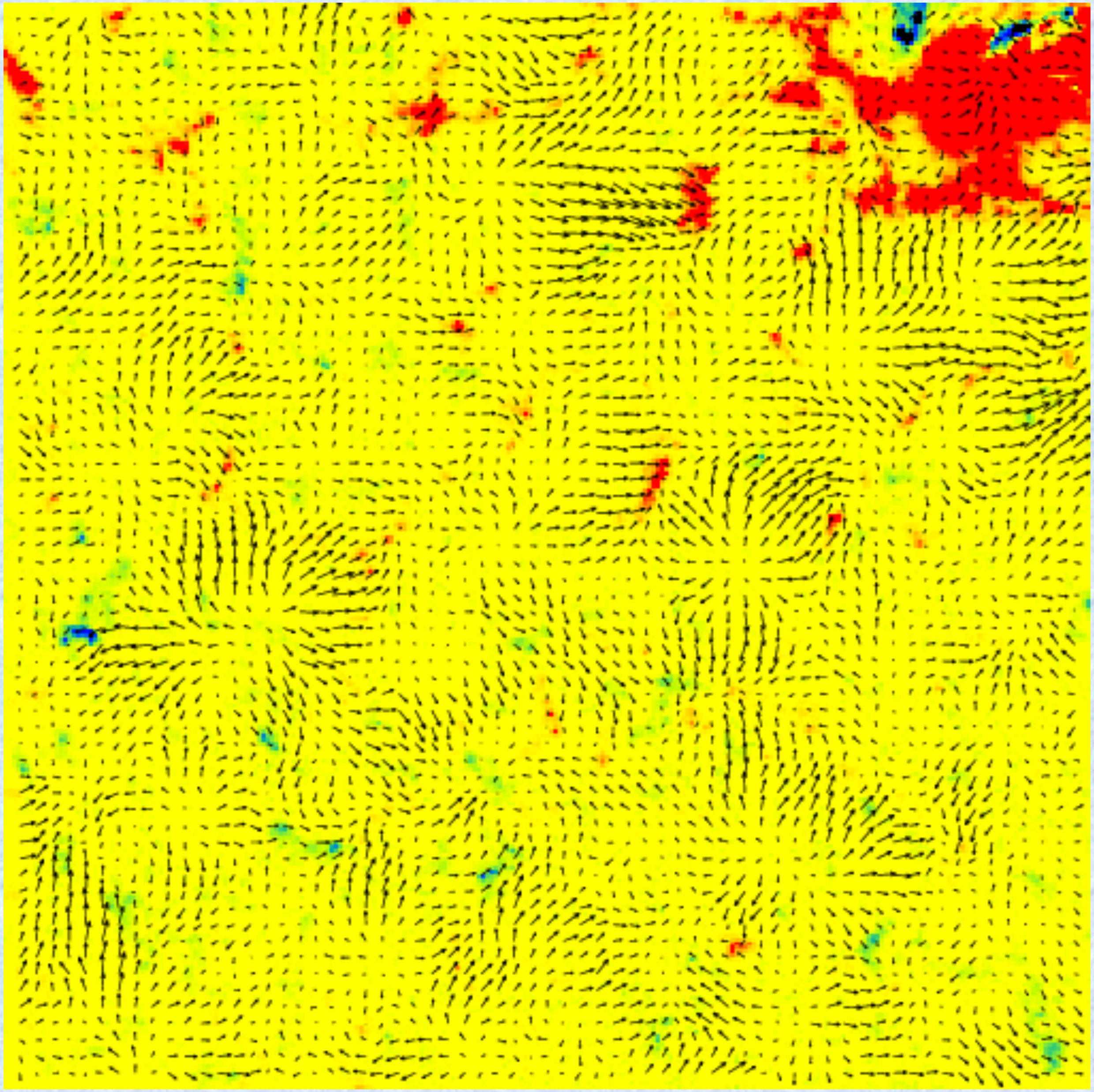
Large-Scale Subsurface Flow from HMI Time-Distance Data-Analysis Pipeline

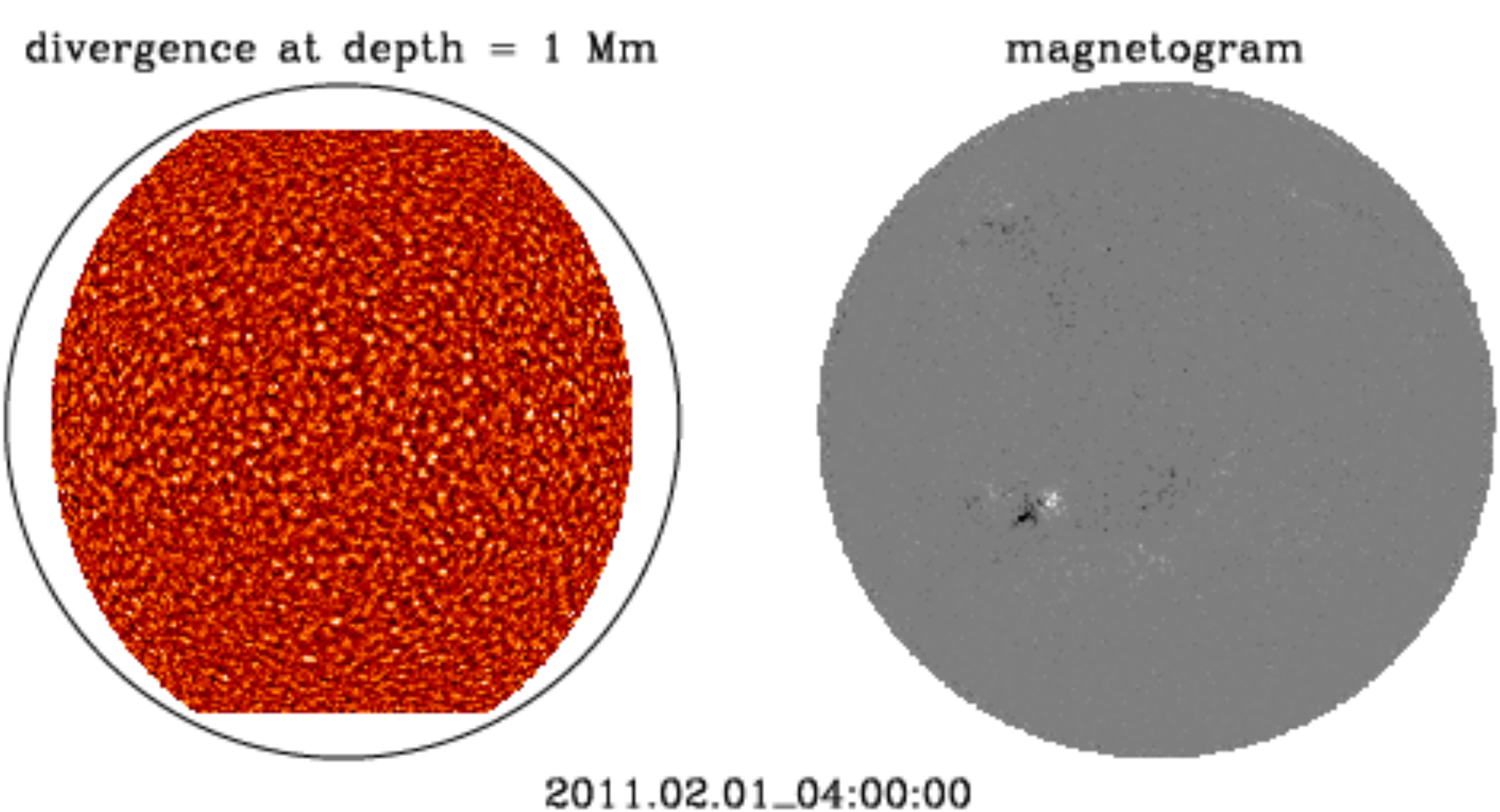


Subsurface Flow Field

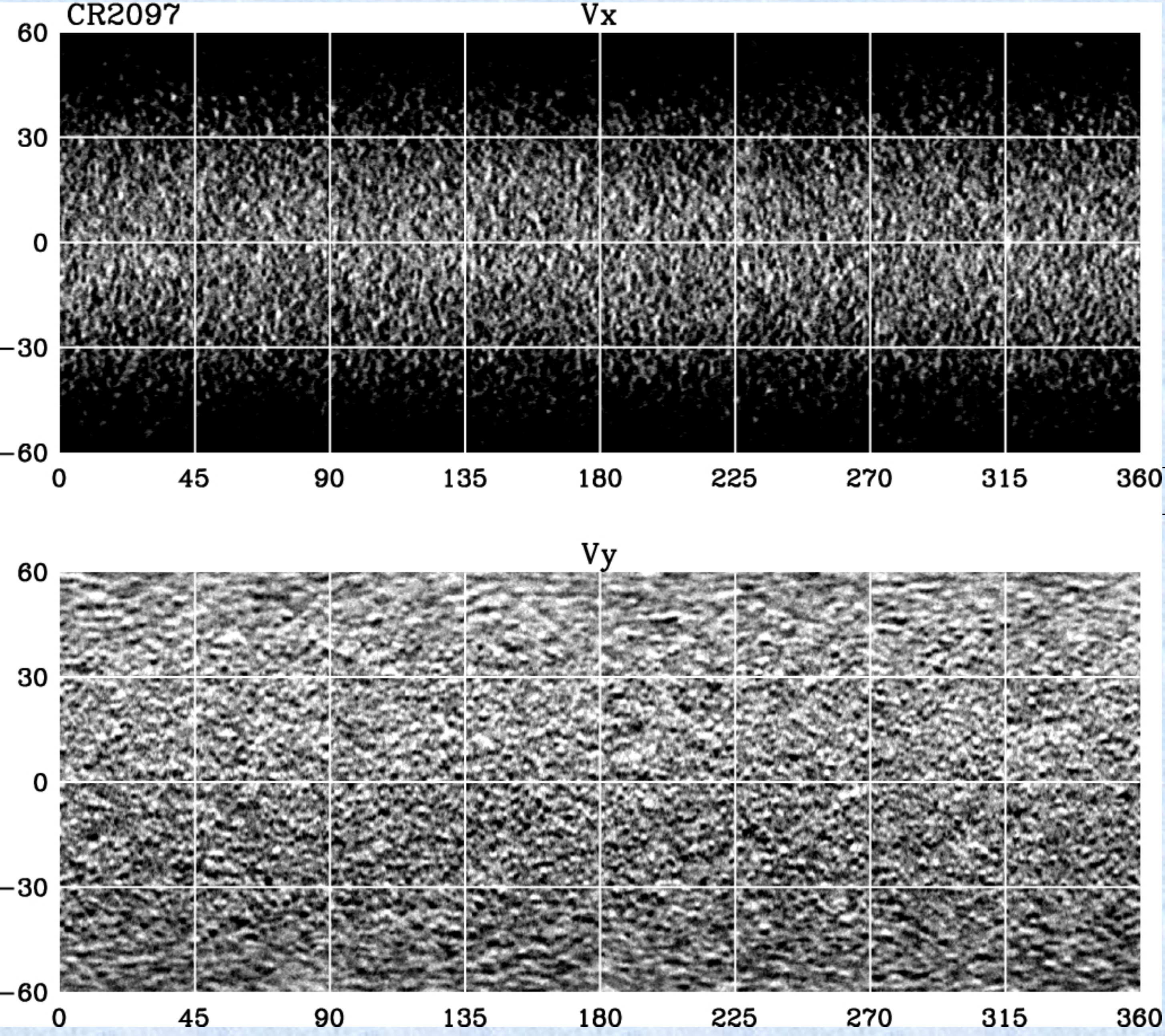


The shown is an area of $15^o x 15^o$ area at the depth of 0 – 1 Mm.

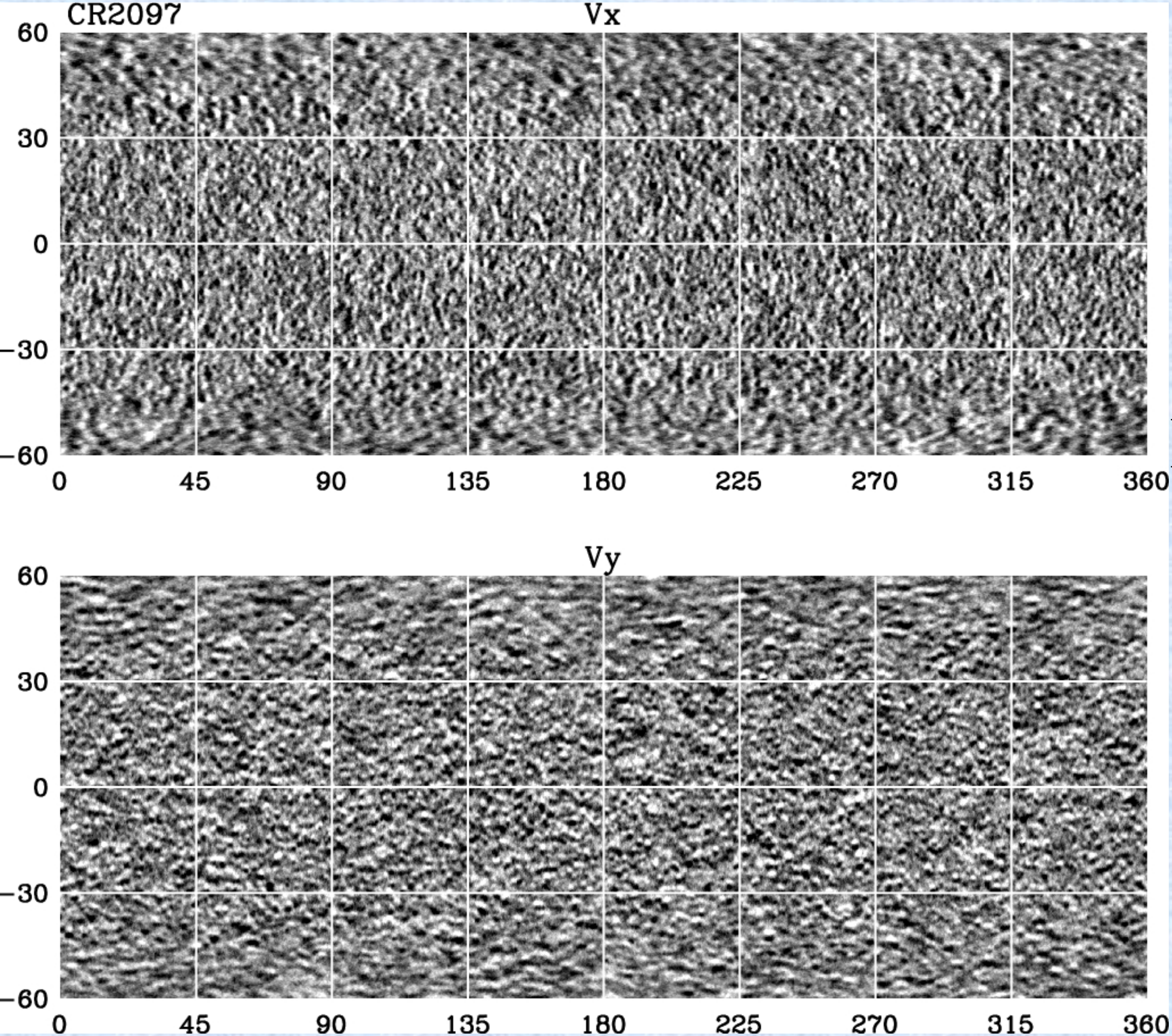
Full-Disk Subsurface Flow Field



Full-disk subsurface flow fields can be used to study together with other observables, like magnetograms.

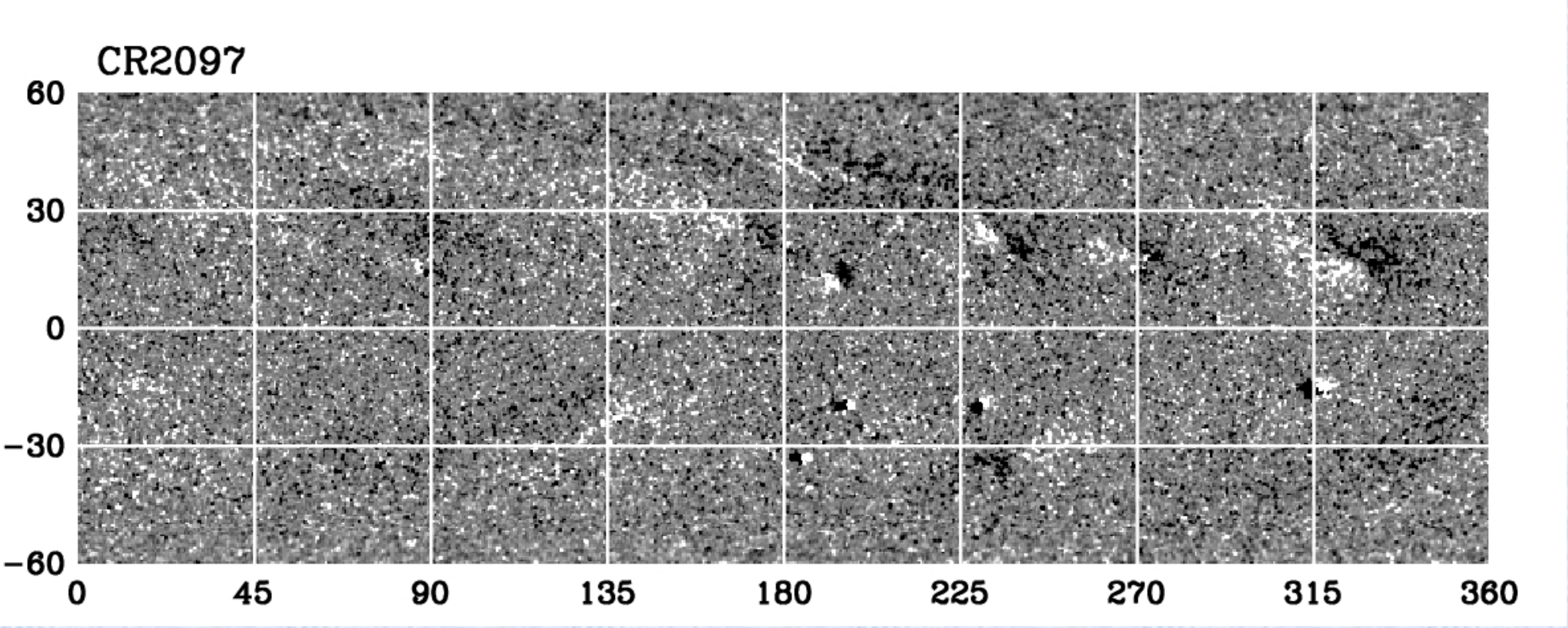


Synoptic Flow Chart from Time-Distance Pipeline

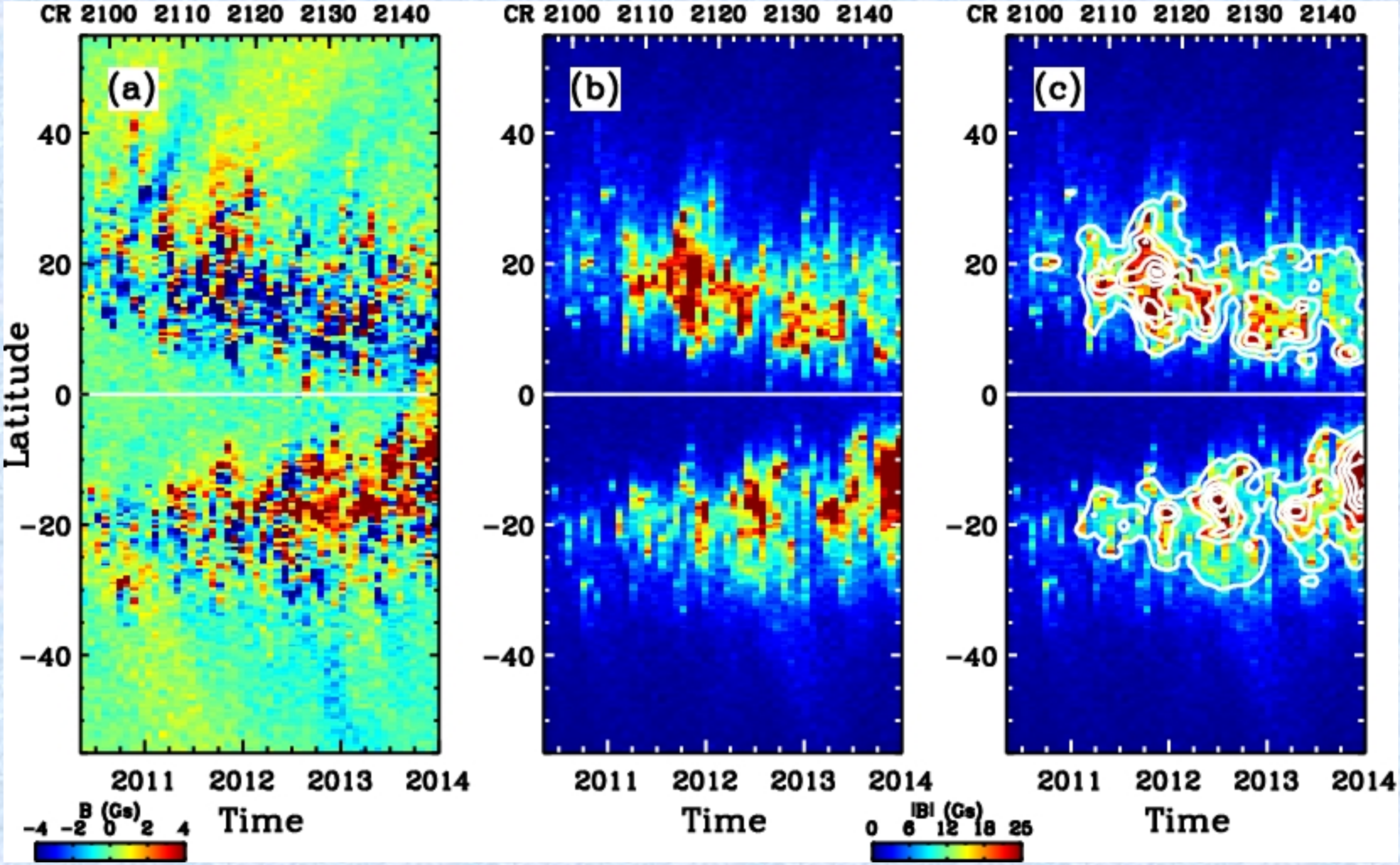


Synoptic Flow Chart from Time-Distance Pipeline

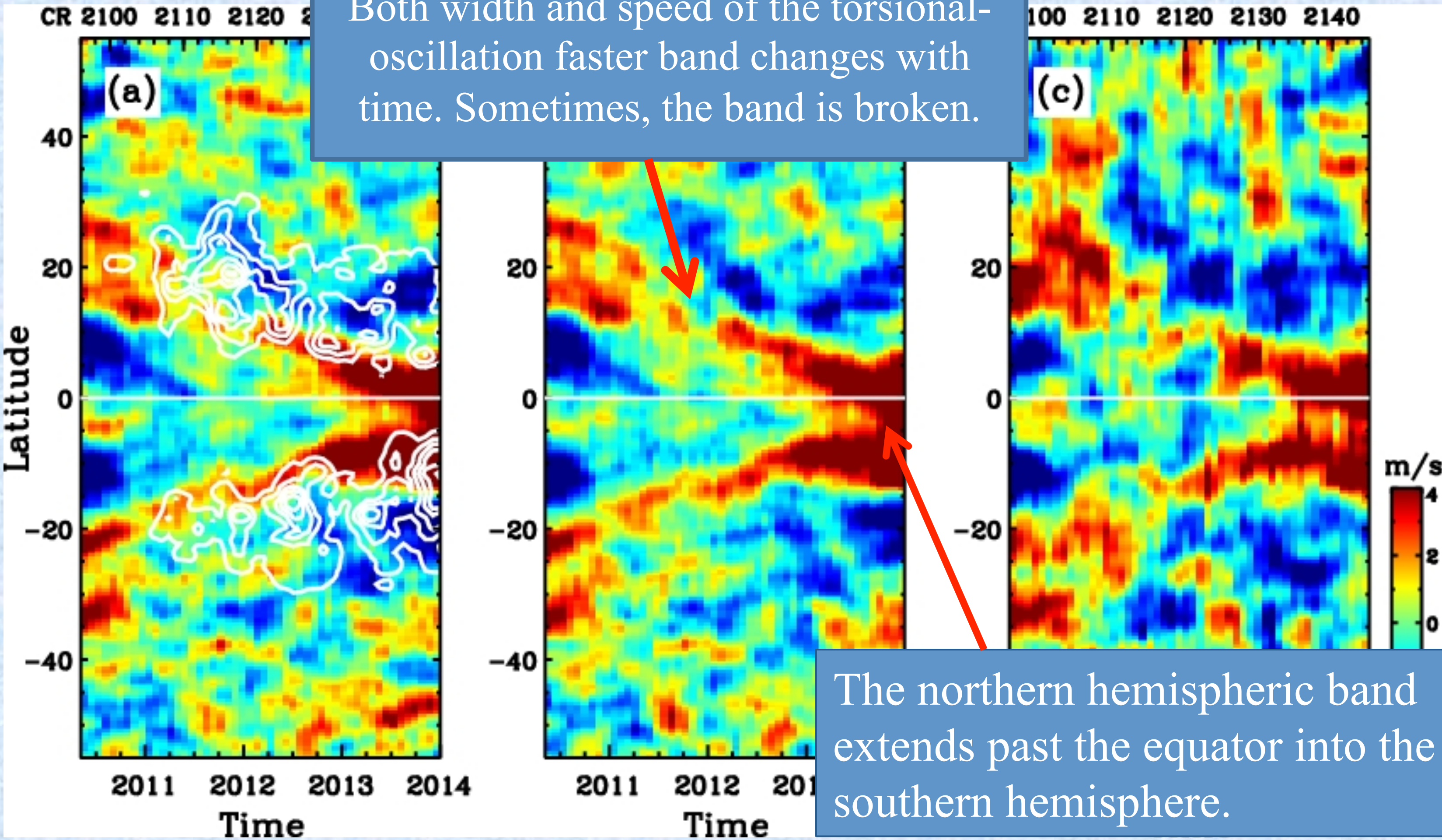
Line-of-Sight Magnetic Field Synoptic Chart



Magnetic Field Butterfly Diagram



(a) Magnetic field averaged over all longitude for each Carrington rotation, displayed as a function of time. (b) Unsigned magnetic field averaged over all longitude for each Carrington rotation. (c) Same as (b) but with contours of 10, 15, 20, 25, and 30 Gs overplotted.

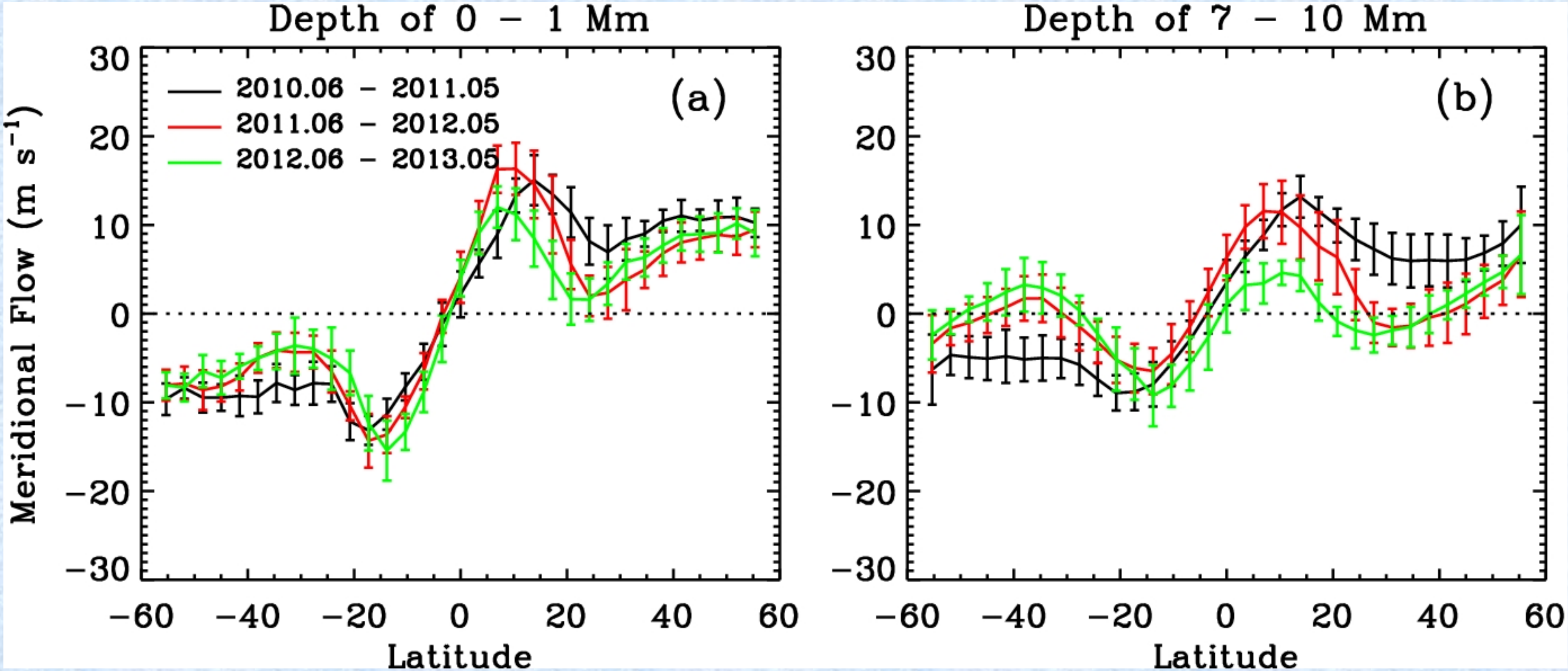


Both width and speed of the torsional-oscillation faster band changes with time. Sometimes, the band is broken.

The northern hemispheric band extends past the equator into the southern hemisphere.

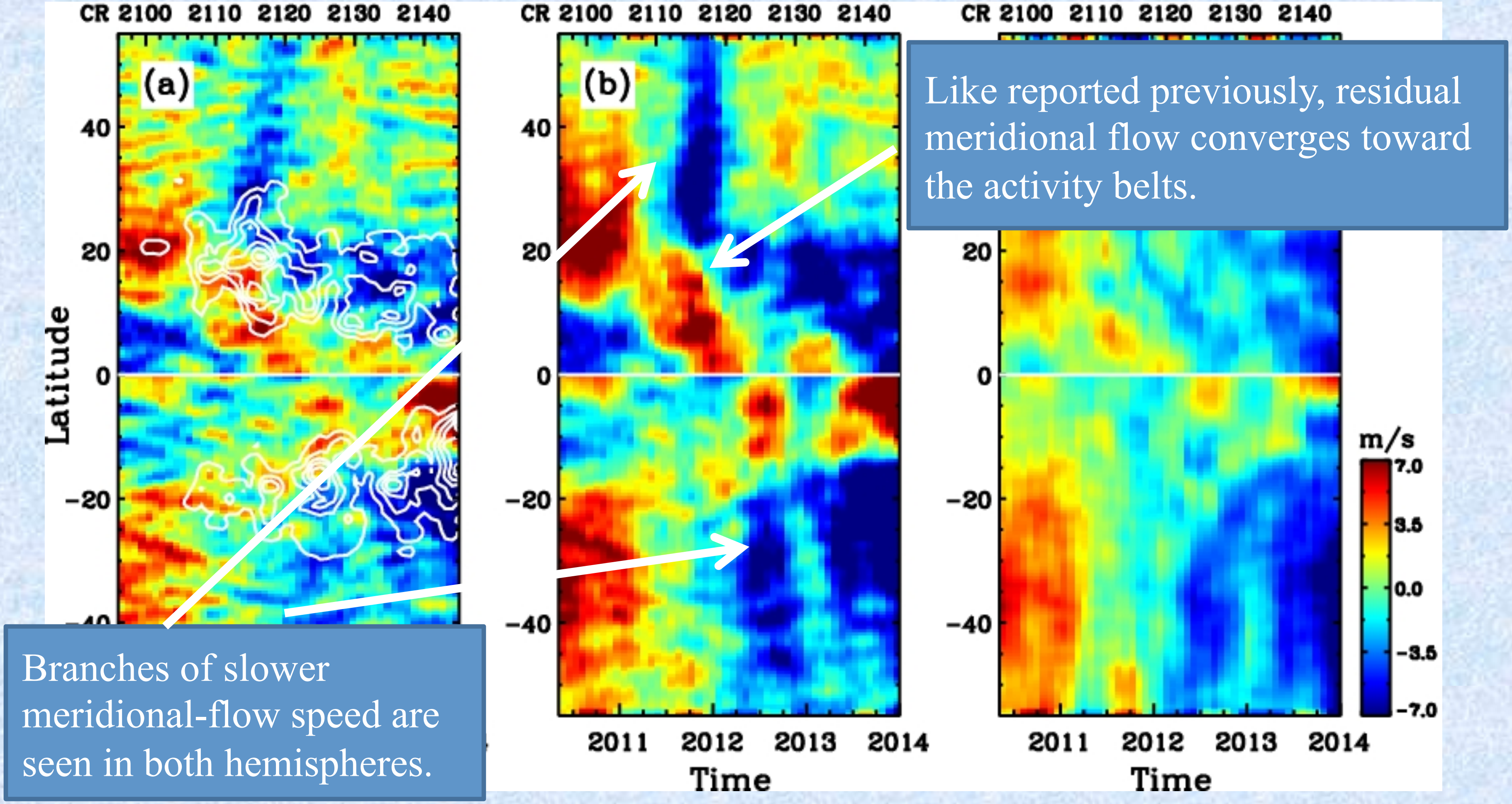
Torsional oscillations showing zonal flows after removing the mean rotational flow profile for the depths of (a) 0 – 1 Mm , (b) 3 – 5 Mm, and (c) 7 – 10 Mm. The white contours showing locations of activity belts are the same as shown in the previous slide.

Decrease of Meridional Flow Speed

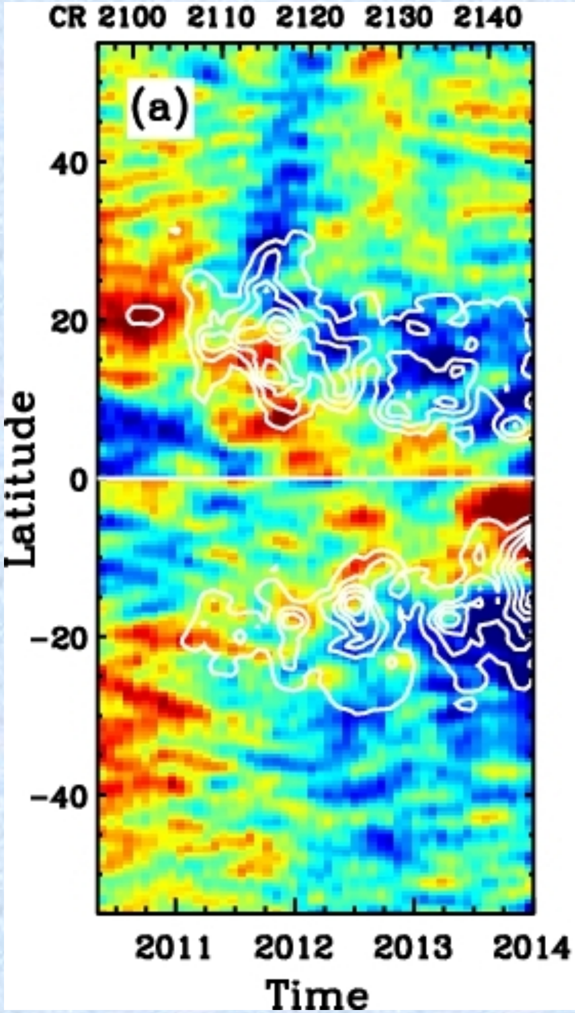


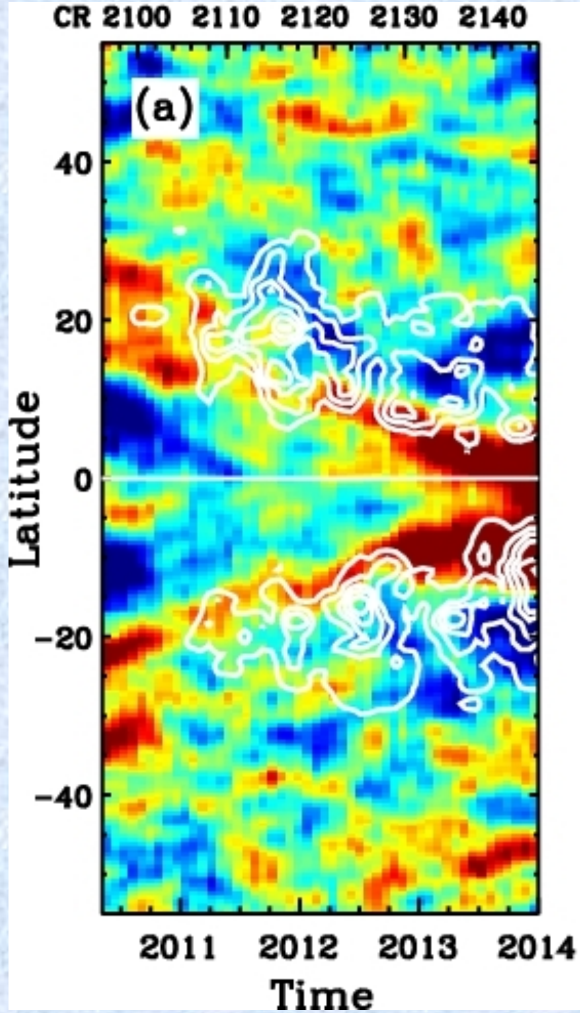
Mean meridional flow profiles averaged from three consecutive years and displayed for two selected depths: (a) 0 – 1 Mm and (b) 7 – 10 Mm.

Meridional Flow



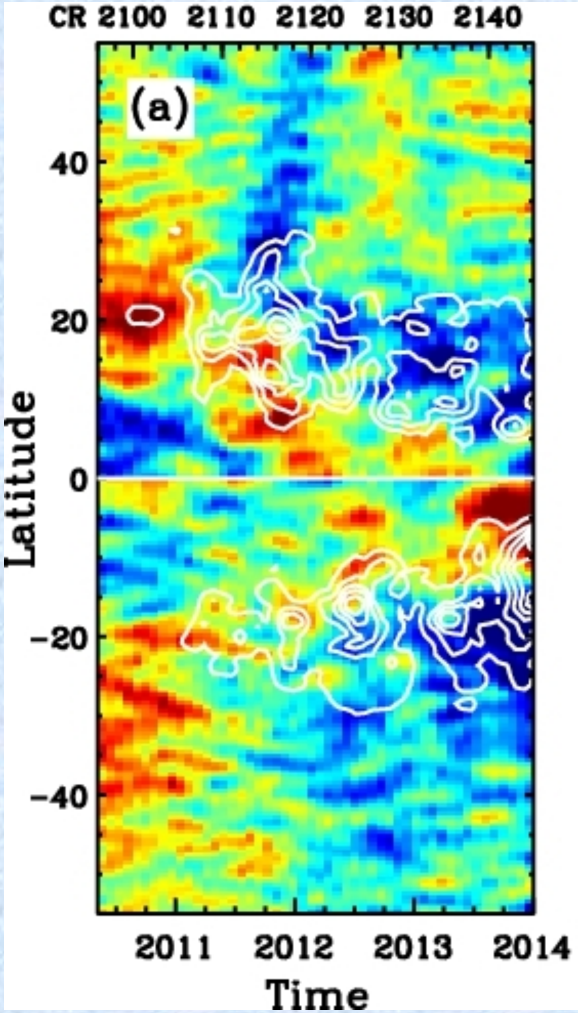
Residual meridional flows showing the meridional flow profiles after removing the mean meridional flow profiles for the depths (a) 0 – 1 Mm, (b) 3 – 5 Mm, and (c) 10 – 13 Mm. The signs of flow in the southern hemisphere are revered. Positive flow is poleward and negative is equatorward.

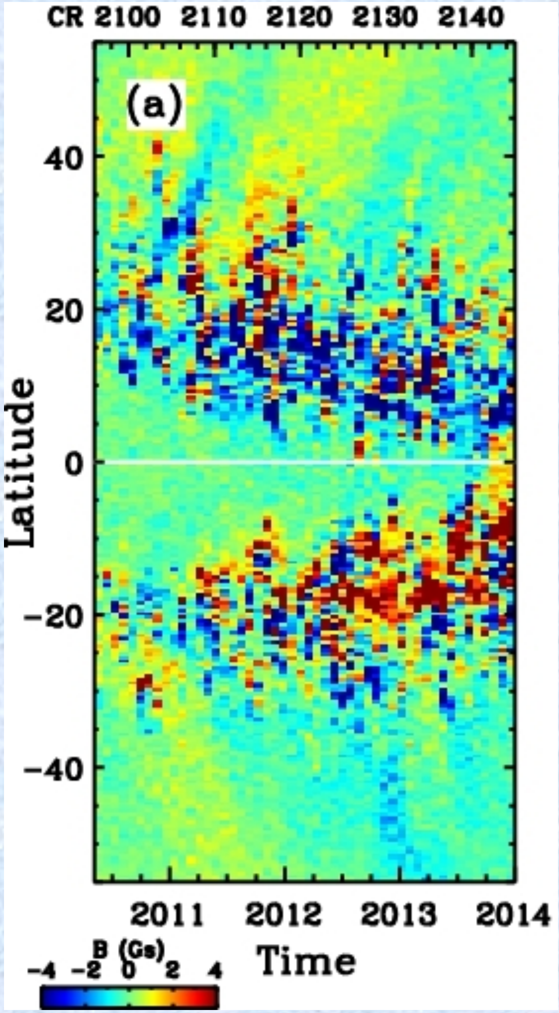




- The faster band in residual meridional flow is wider than the faster band in zonal flow.
- Faster band in residual meridional flow touches the equator earlier than that in zonal flow.
- Zonal flow is more well-organized and consistent than the residual meridional flow.

Comparing residual meridional flow with zonal flow (torsional oscillation).

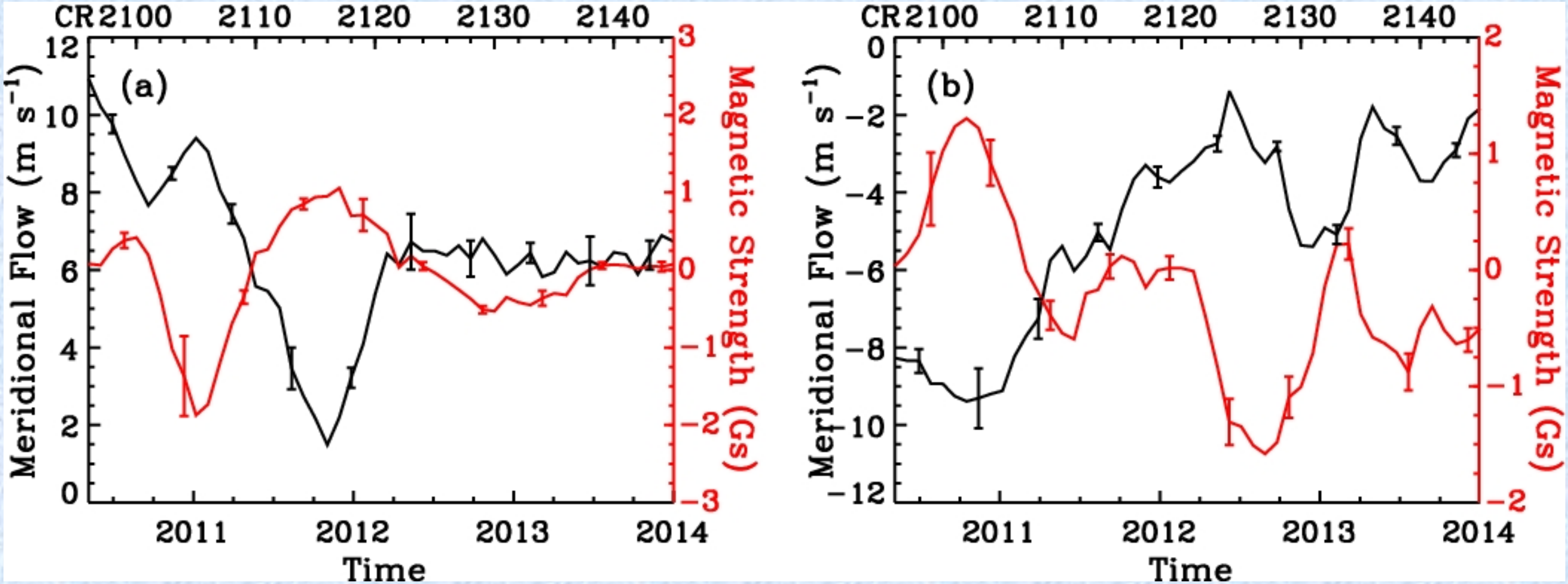




In each hemisphere, it seems that when leading-polarity magnetic flux is transported to the pole, the speed of meridional flow, which is poleward, is faster. When the following-polarity flux is transported, the meridional flow speed is slower. This process slows the polarity reversal in high latitude areas.

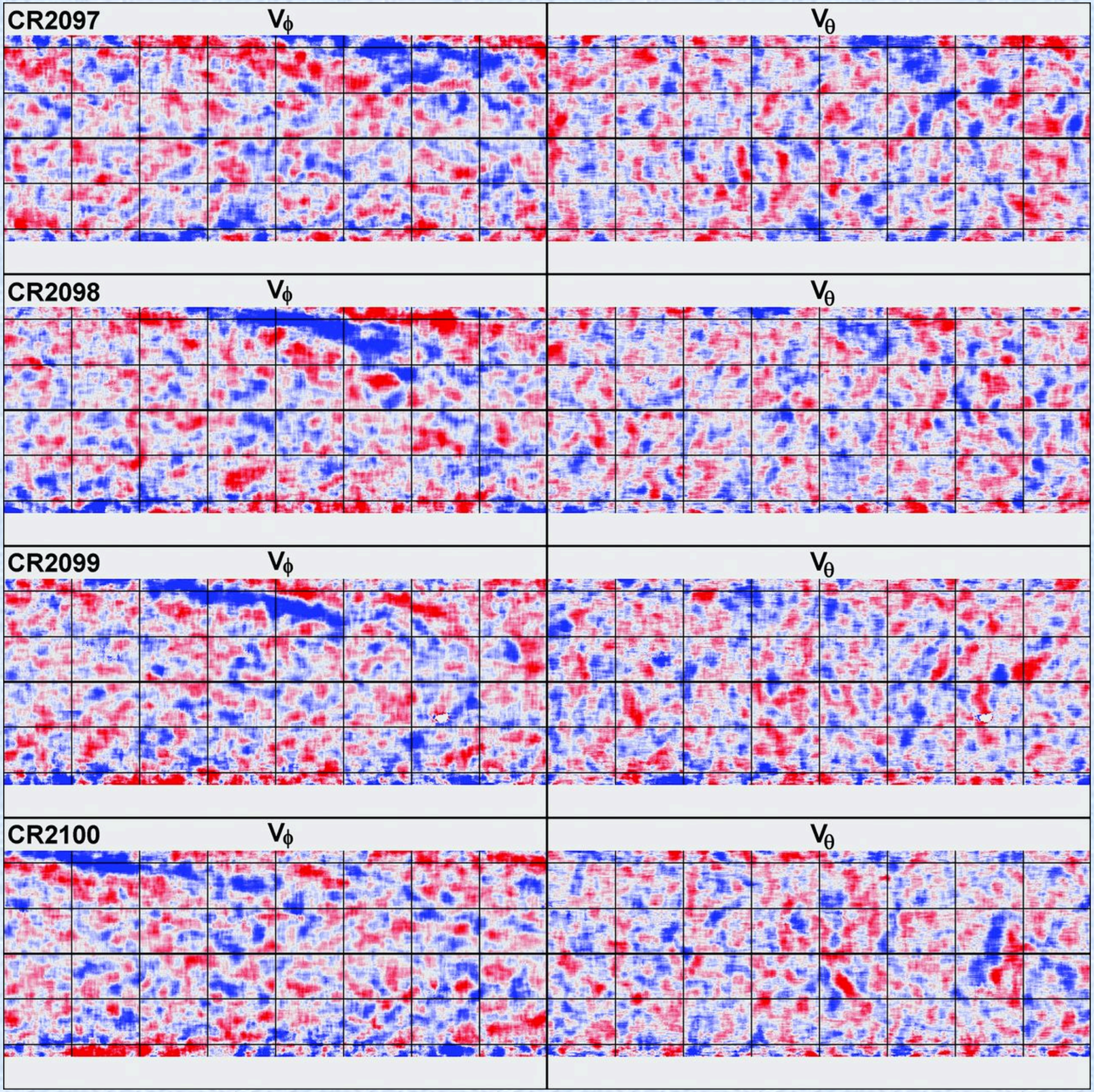
Comparing residual meridional flow with net magnetic flux.

Anti-Correlation between Poleward-Transporting Magnetic Flux and Meridional-Flow Speed



(a) Black curves are meridional flow velocity, as a function of time, averaged from the latitude of 35^{o}N – 40^{o}N. Red curves are magnetic field from the same latitude bands. (b) Same as in panel (a) but for the southern hemisphere. Note that the meridional flow speed increases with the vertical axis in panel (a) but decreases in panel (b).

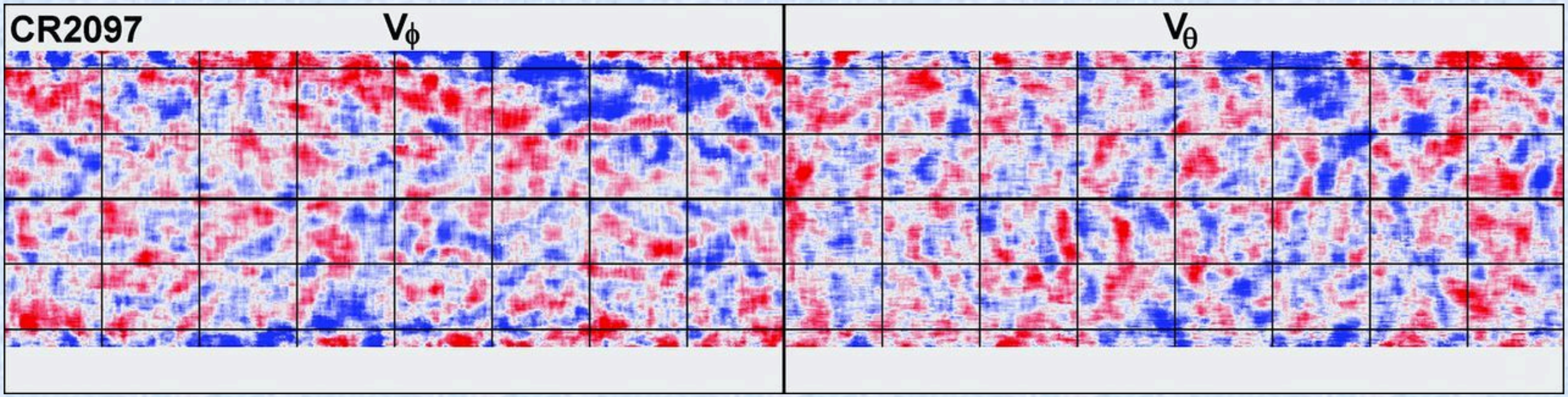
Detection of Solar Giant Cells?

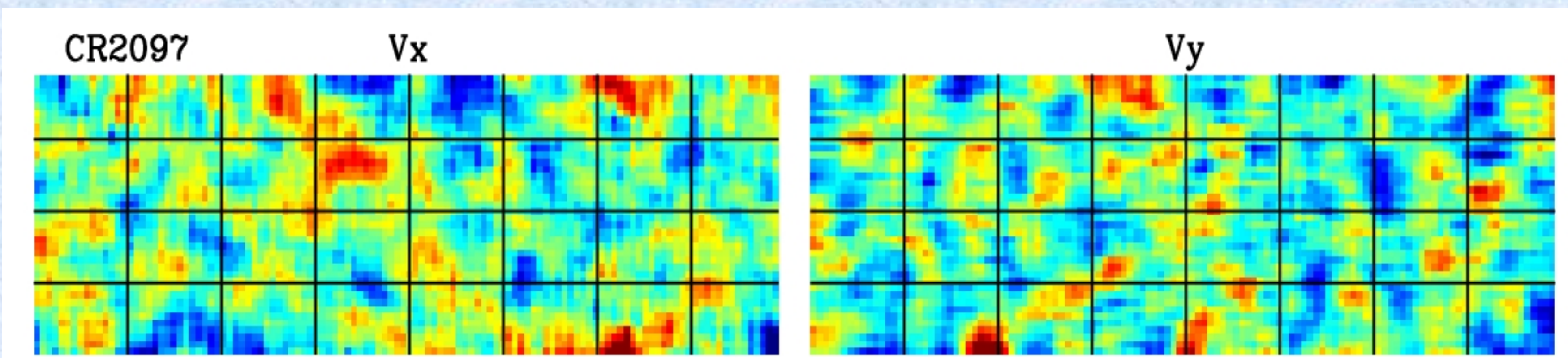


Left side of each panel shows longitudinal velocity, and the right side shows latitudinal velocity.

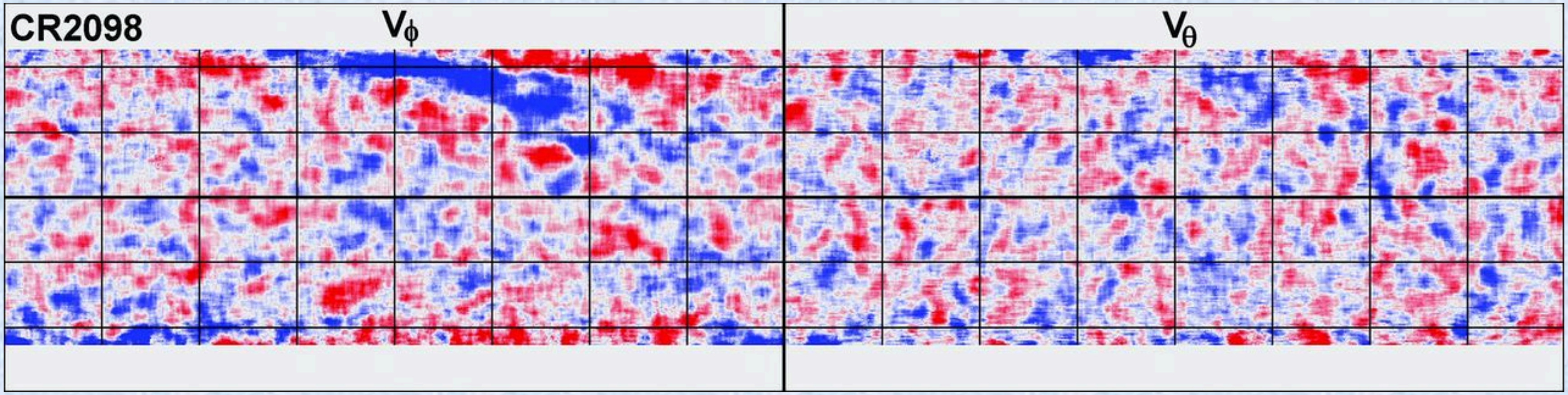
(Hathaway et al. 2013 Science)

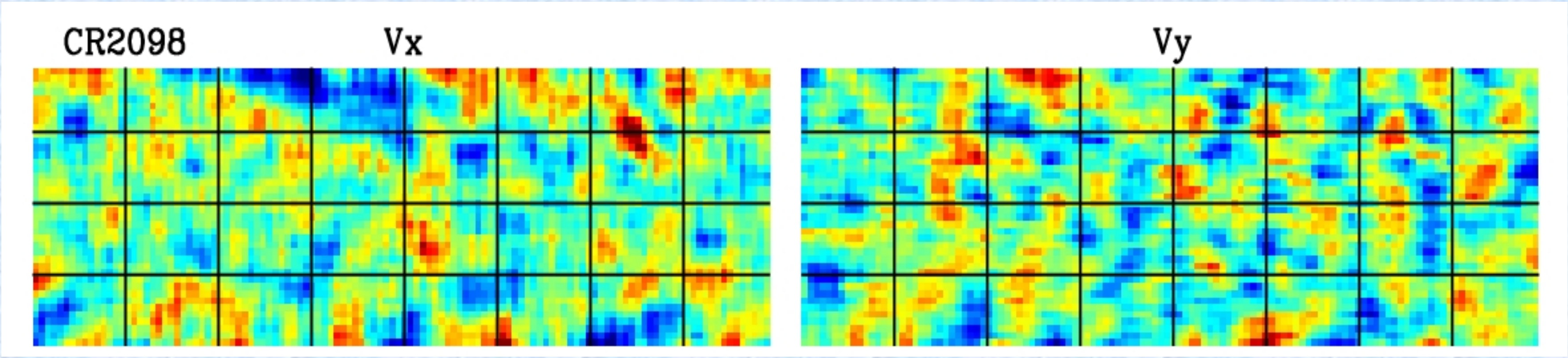
Giant Cells? Comparing Time-Distance Results with Hathaway et al.'s Results



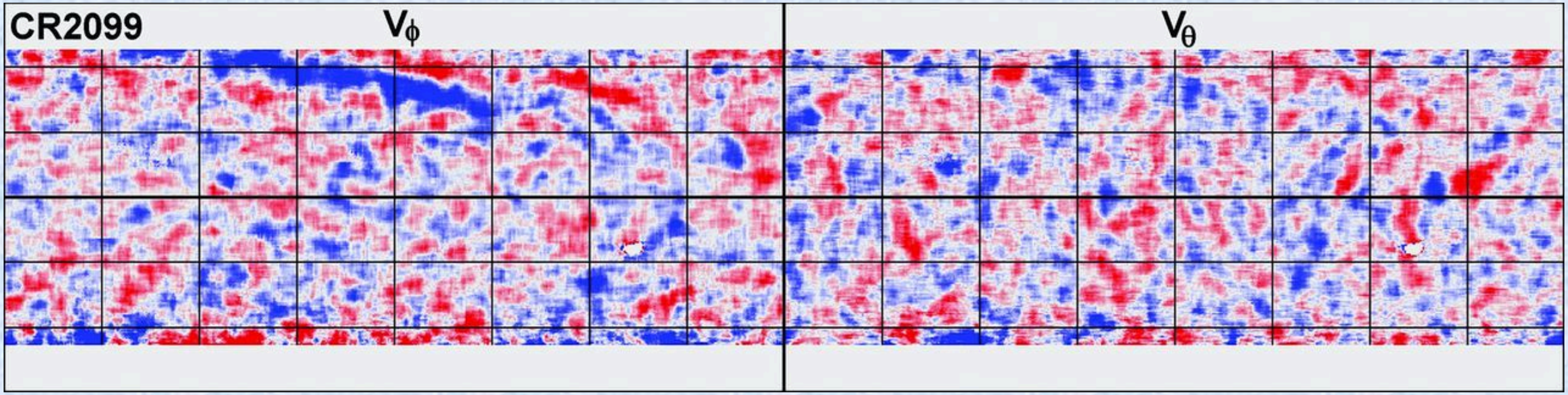


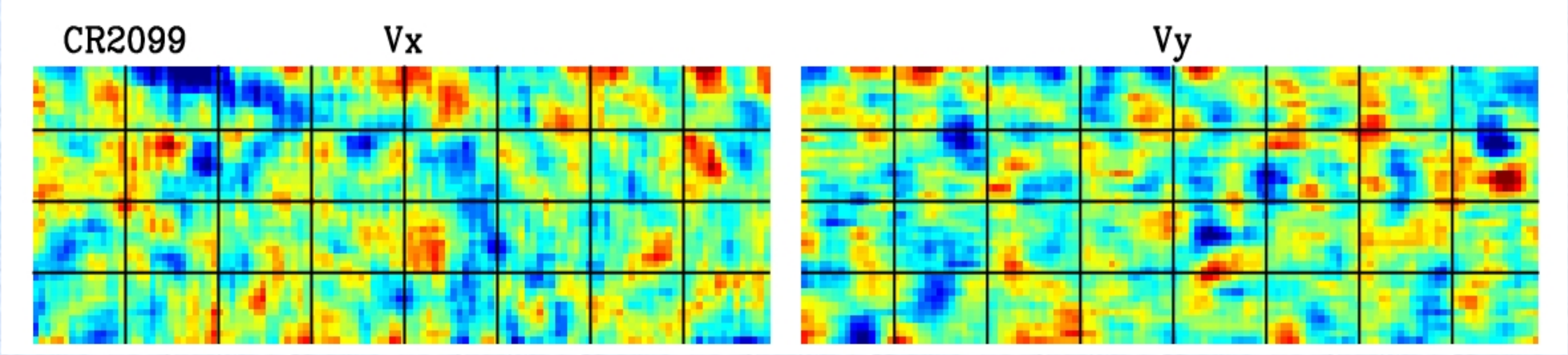
Giant Cells? Comparing Time-Distance Results with Hathaway et al.'s Results



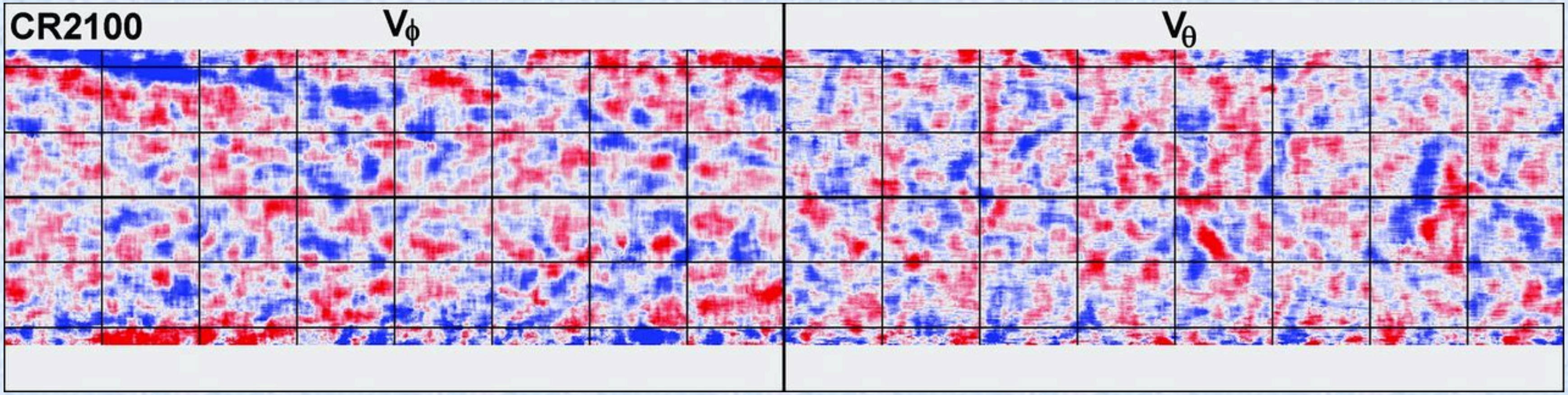


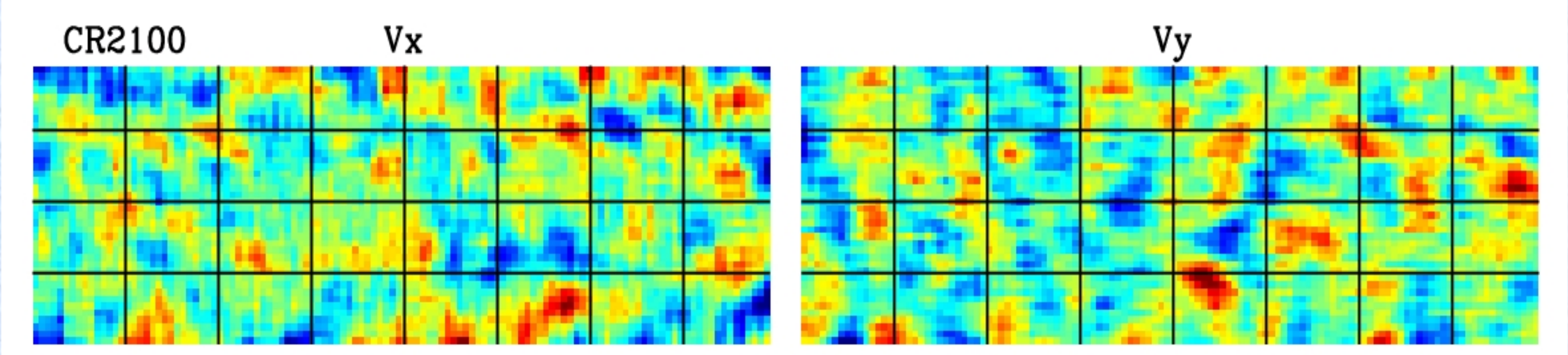
Giant Cells? Comparing Time-Distance Results with Hathaway et al.’s Results





Giant Cells? Comparing Time-Distance Results with Hathaway et al.'s Results





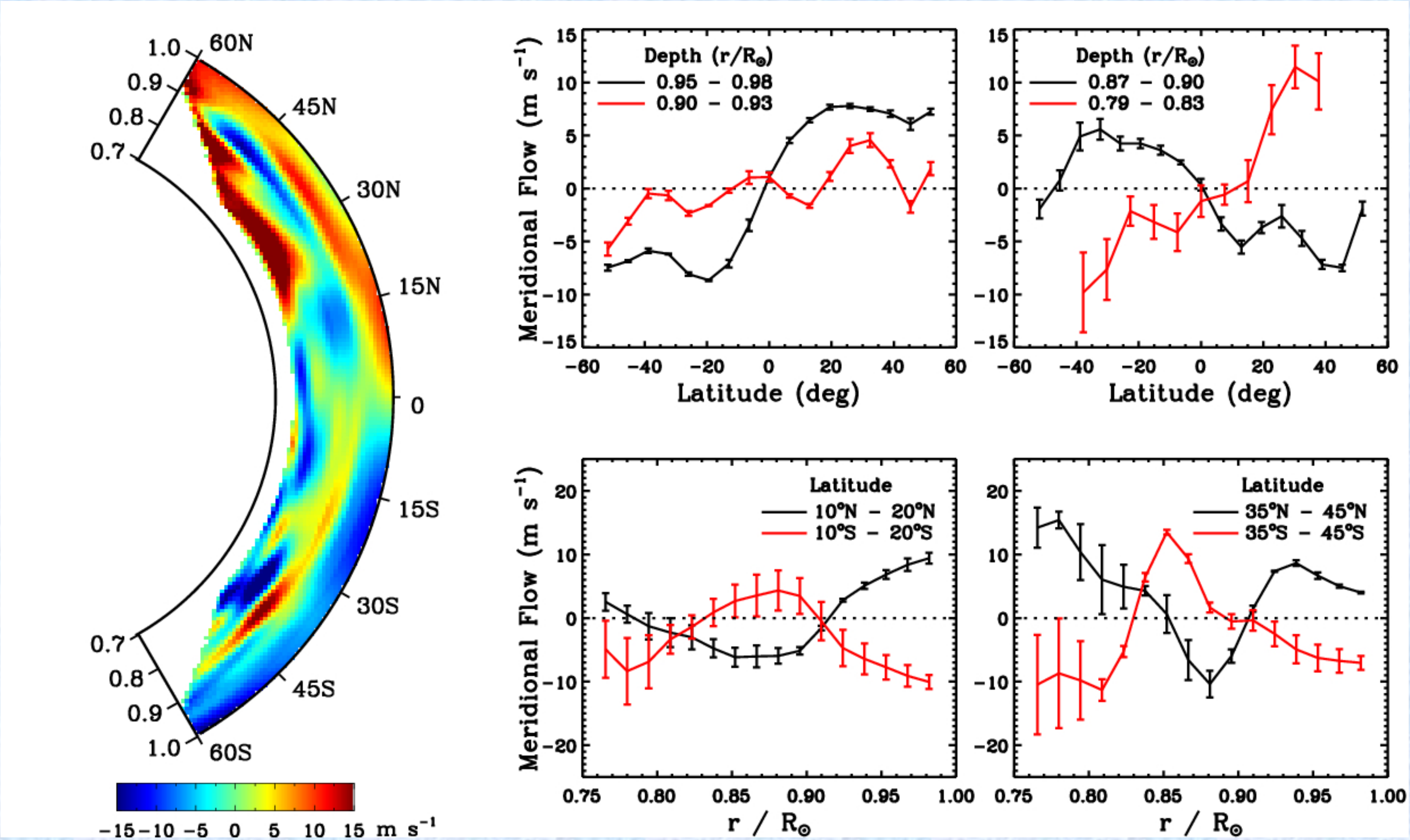
Giant Cells? Comparing Time-Distance Results with Hathaway et al.'s Results

It seems that both analyses show similar large-scale structures in high-latitude areas, but the locations of the large structures are shifted relatively.

It is not clear to us what causes these large-scale structures, and it's not clear either whether these structures are giant cells.

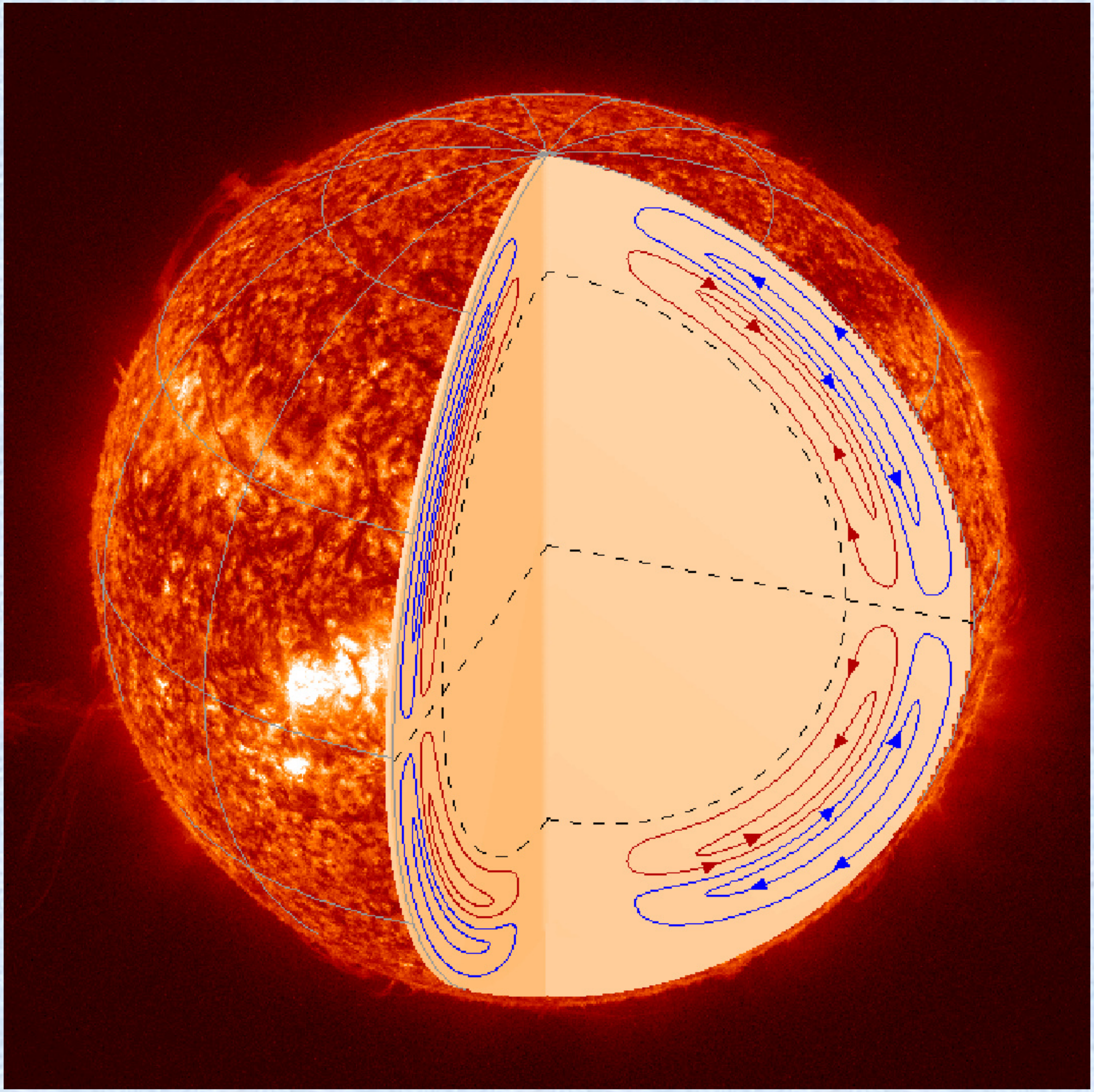
Detection of Equatorward Meridional Flow and Double-Cell Meridional Circulation

Detection of Equatorward Meridional Flow



Poleward flows extend from the surface to 0.91R. Equatorward flow is from 0.91R to about 0.82R, with the maximum equatorward speed of 8m/s. Below that, the flow changes to poleward again. (Zhao et al. 2013 ApJL)

Double-Cell Meridional Circulation

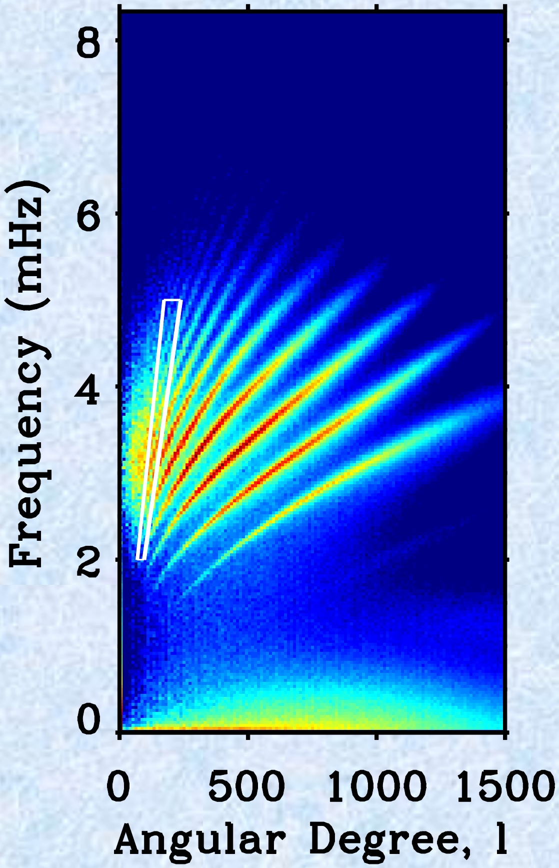


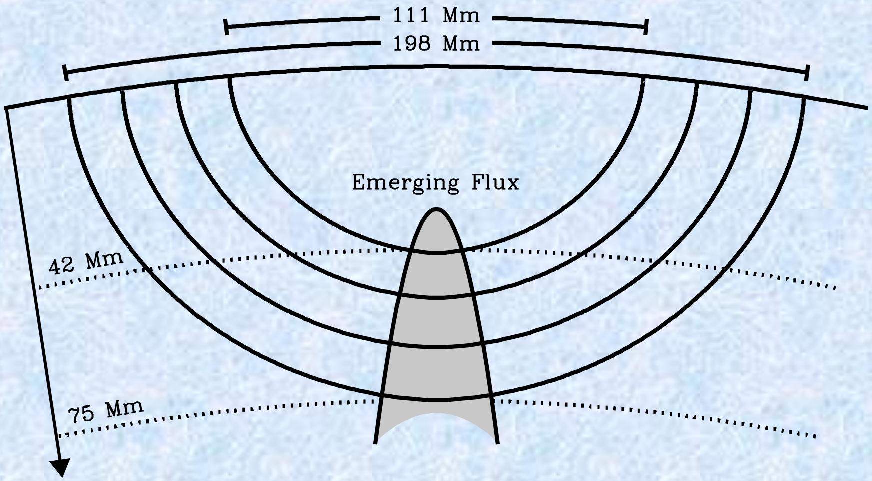
A schematic plot showing the double-cell meridional circulation inside the Sun. Our analysis does not exclude possible existence of more cells in both the radial and latitudinal directions.

Helioseismic Studies on Emerging Active Regions

Measurement Scheme

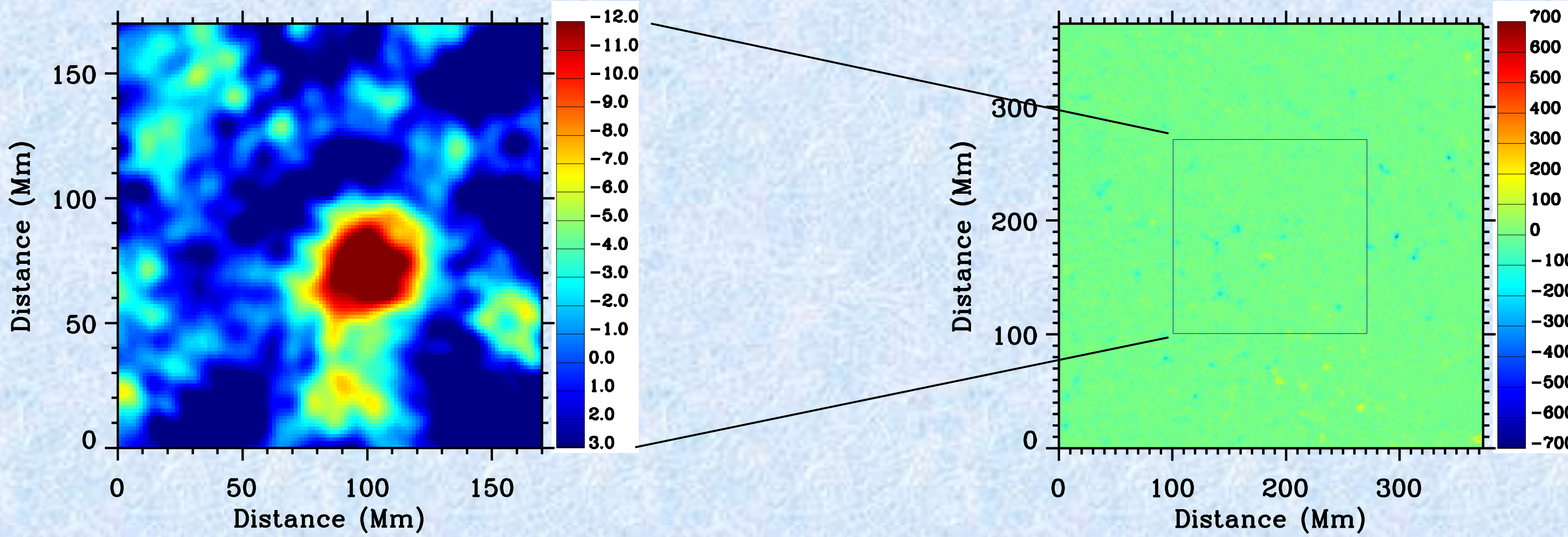
The phase-speed filter selects acoustic waves with similar phase speed. These waves have about the same penetration depth.





(Ilonidis et al., 2001, Science)

Results of AR10488



03:30 UT 26 Oct 2003

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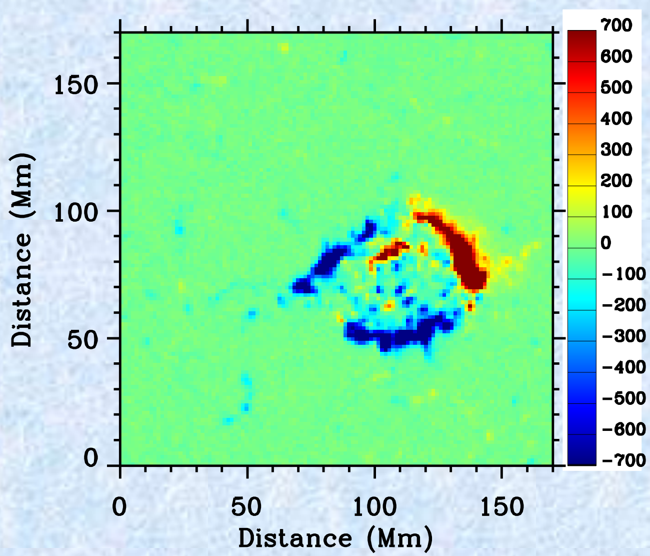

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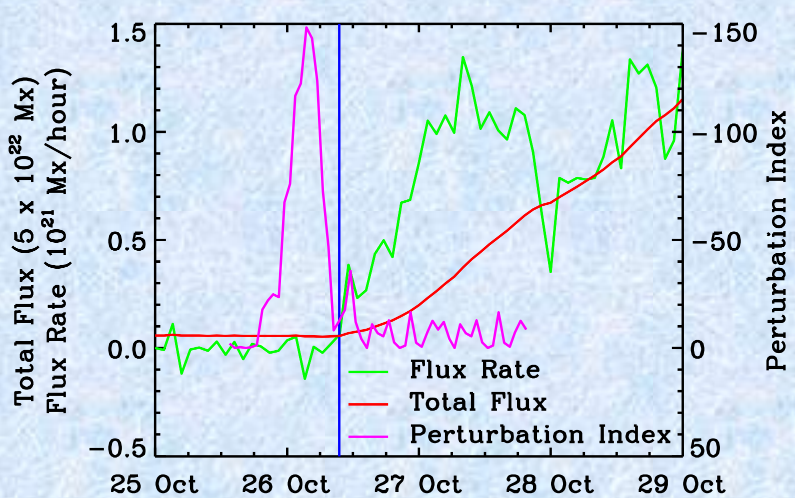
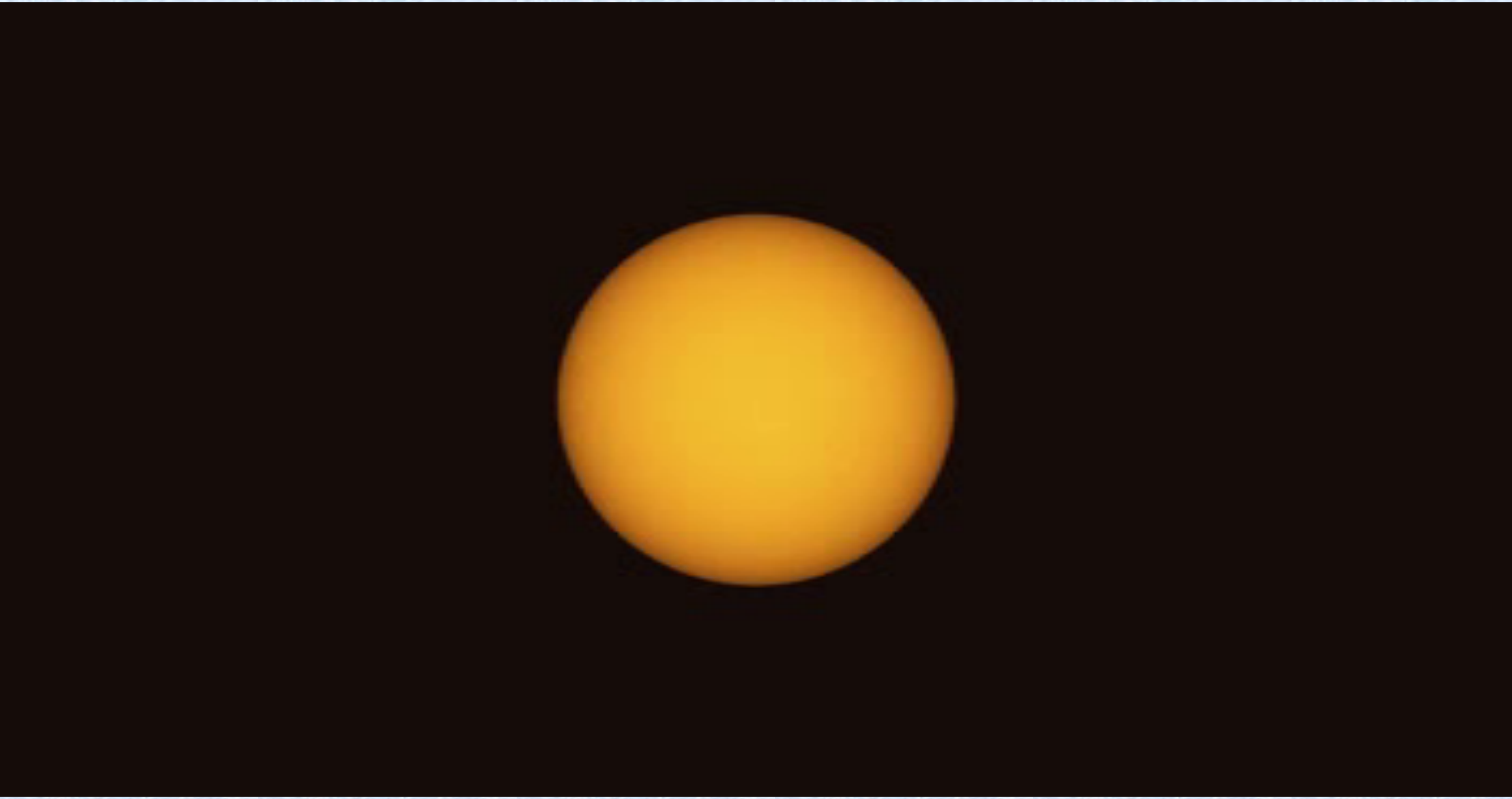
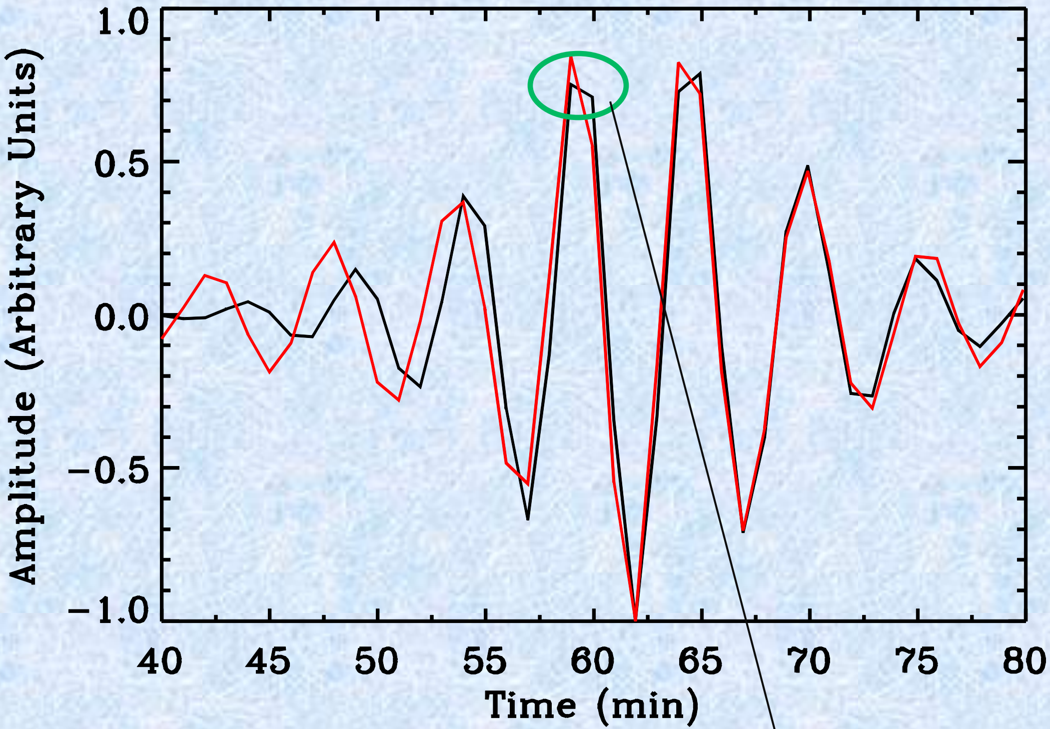




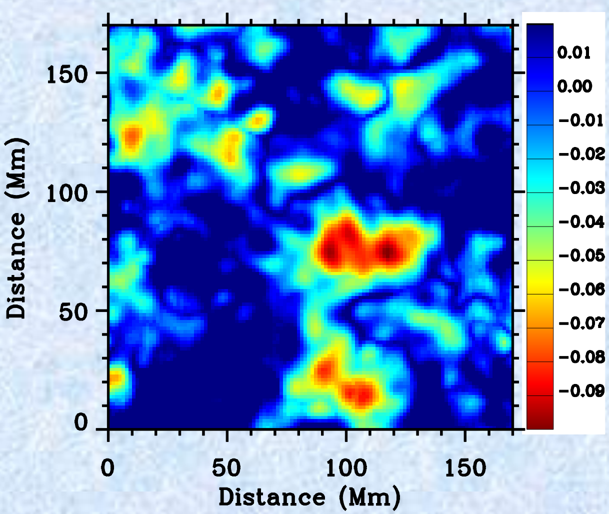


Cross-Correlation:
Black: Quiet Region
Red: AR 10488

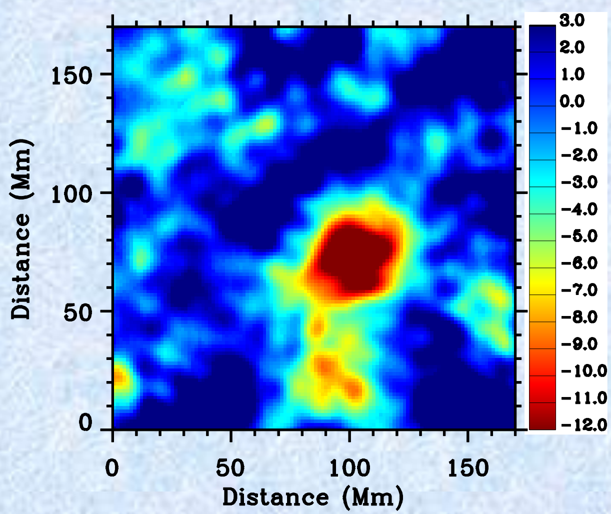
<u>Conclusion:</u>
Phase shifts are related with frequency shifts.

Asymmetric shifts of cross-correlation

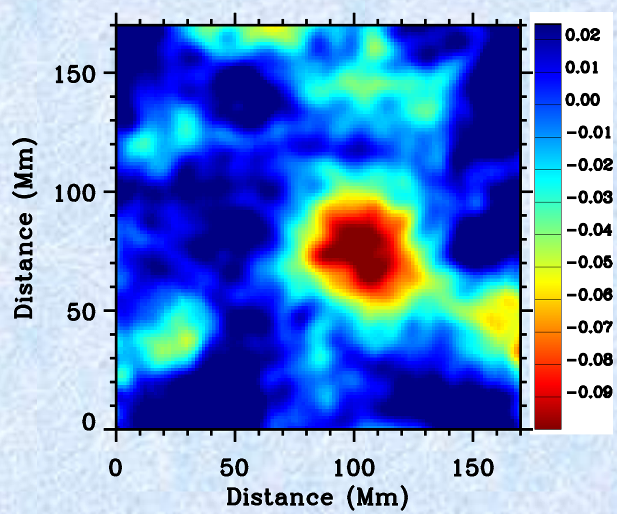
(Ilonidis et al. 2013, ApJ)



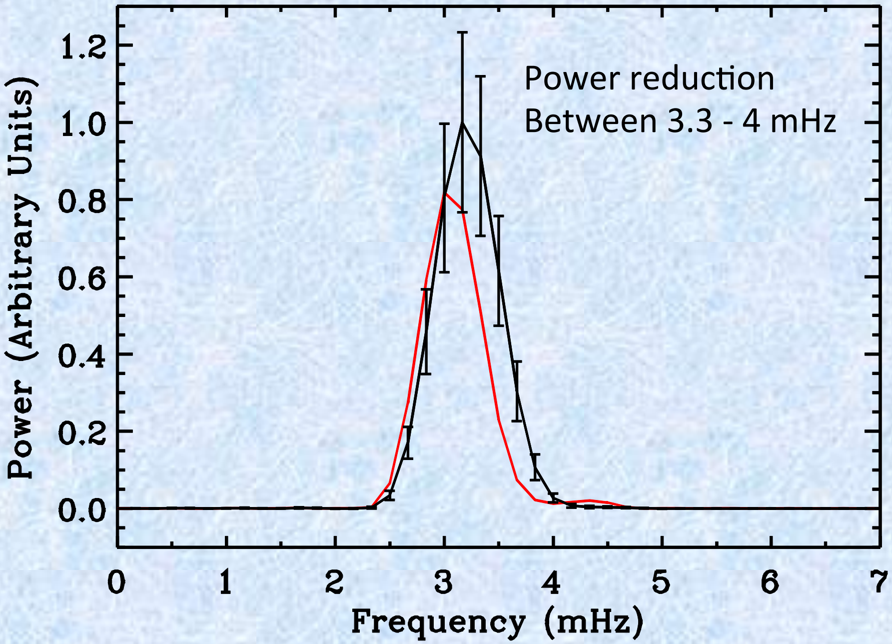
Amplitude perturbation



Travel-time perturbation

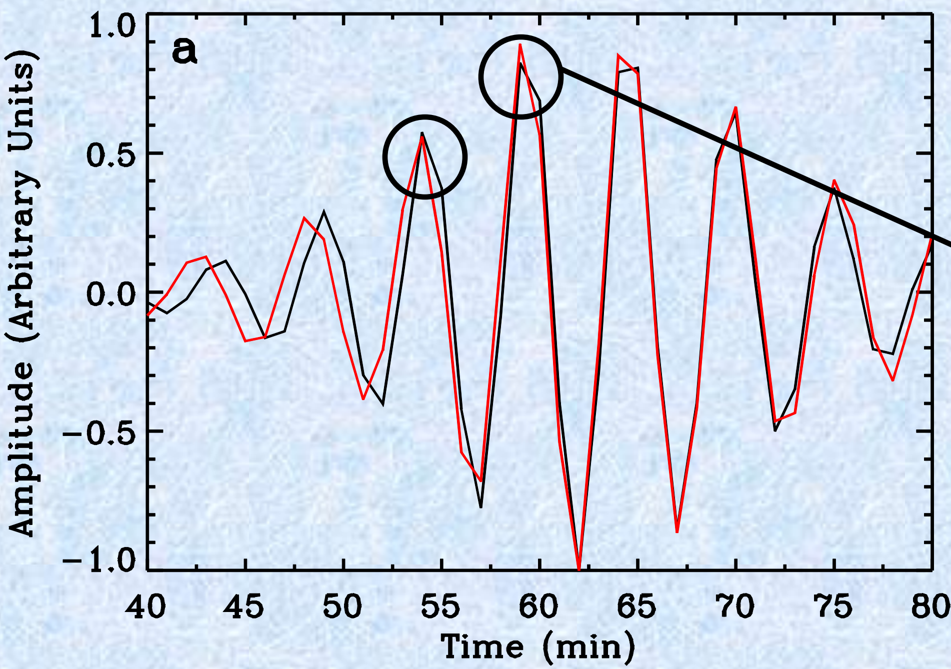


Frequency perturbation



Black line: quiet region
Red line: emerging-flux region

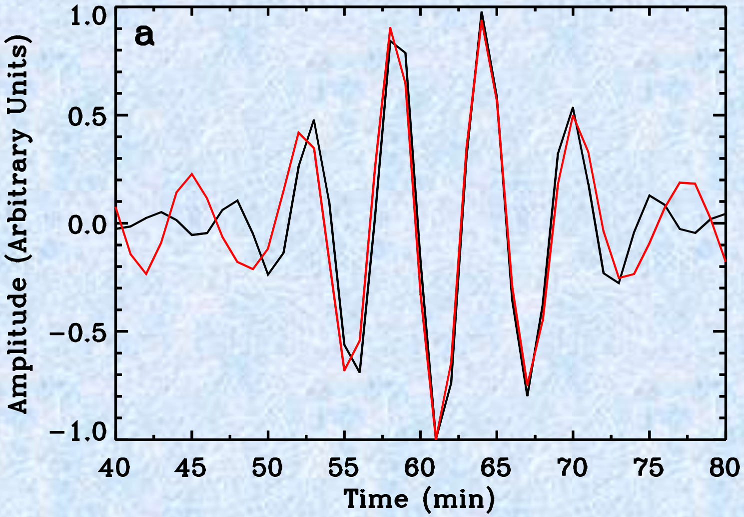
A power reduction between 3.3 and 4 mHz in emerging-flux region reduces the mean frequency of oscillations.



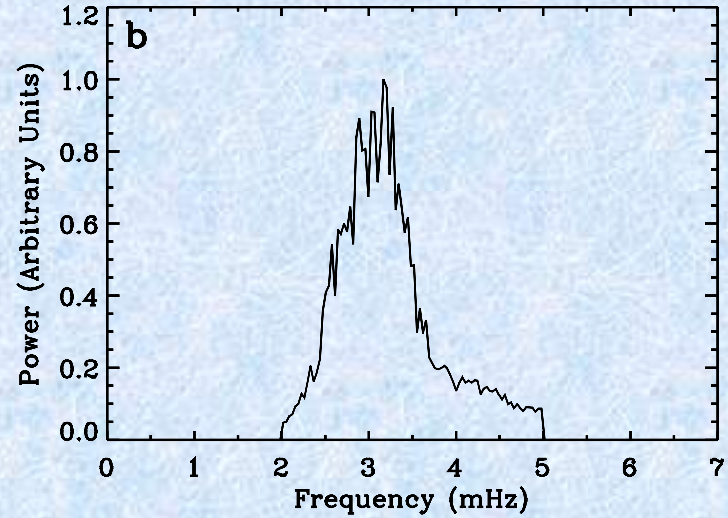
The frequency of cross-covariance is shifted down in emerging-flux region.

Large phase travel-time shifts for specific cross-covariance peaks.

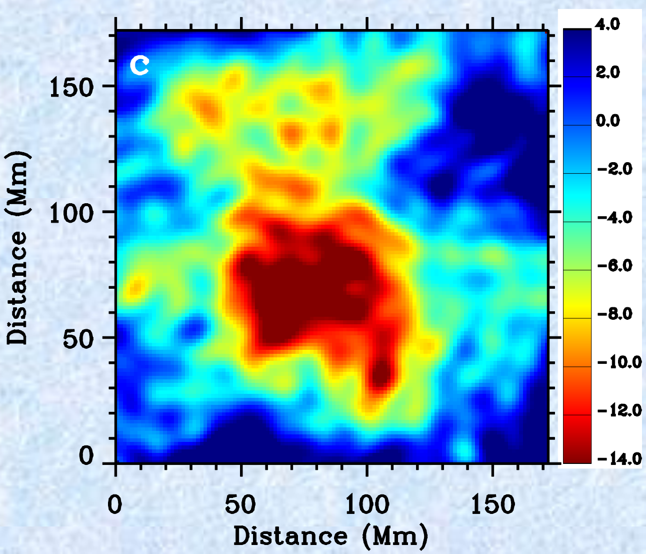
Simulation data: 10% sound-speed perturbation at -60 Mm



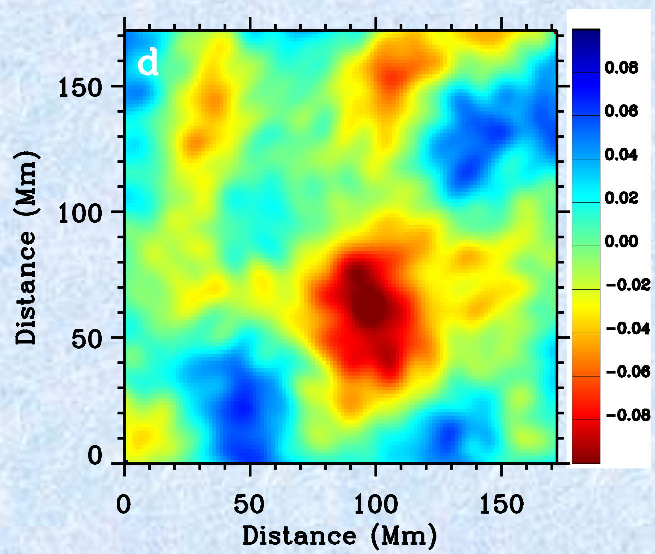
Cross-correlation function
Red: perturbation region, Black: quiet region



Acoustic power distribution



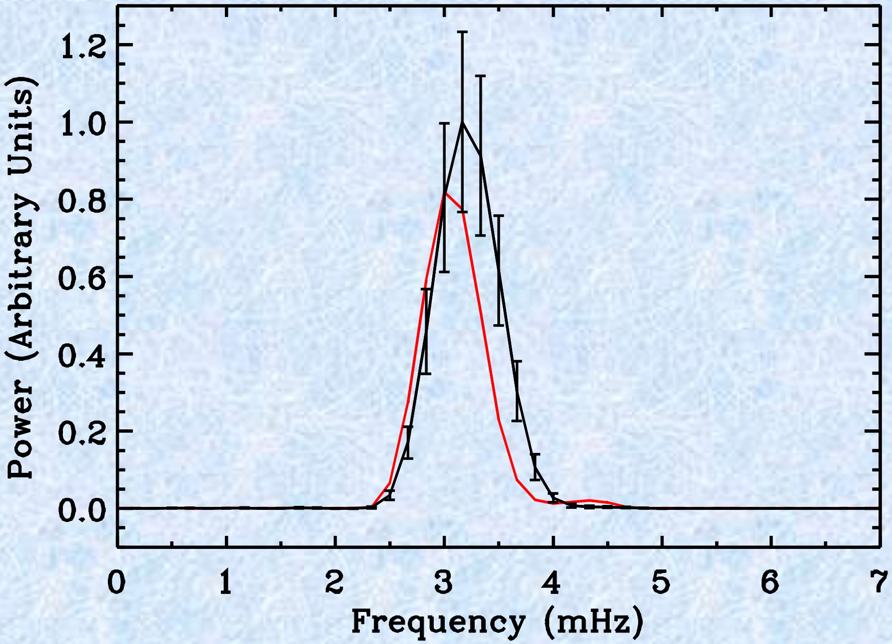
Phase travel-time perturbation map



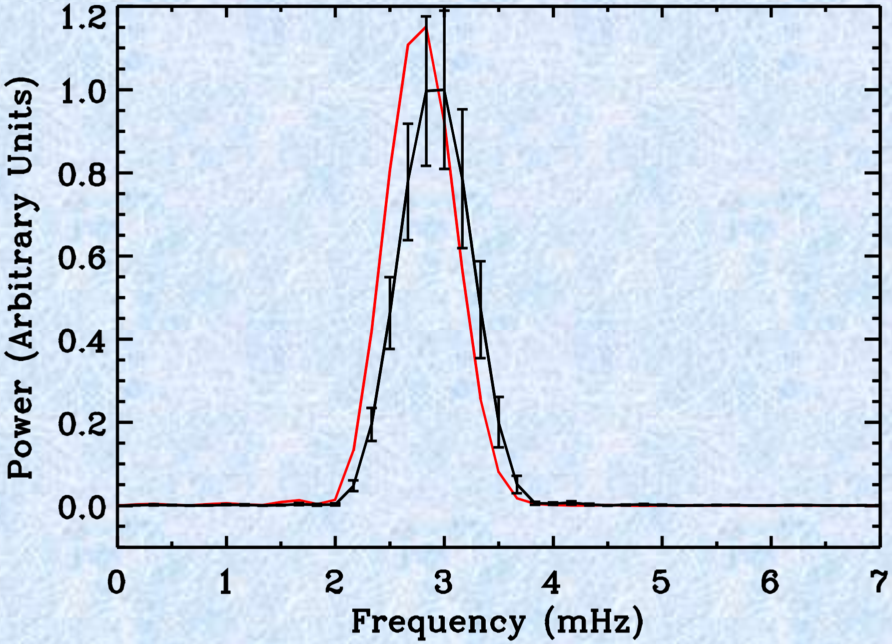
Frequency perturbation map

Comparison of Power Variations from Observations and Simulations

Observation



Simulation



Power reduction 3.3 – 4.0 mHz
Power enhancement 4.0 – 4.7 mHz

Power enhancement 2.0 – 3.0 mHz

The analysis of simulation data also shows power variations for very large perturbations but cannot reproduce all the properties of power variations derived from observations.

Numerical simulations of solar interior magnetic structures helped us better understand our helioseismic measurements, and will potentially help us to design better measurement method.

Conclusions

- Some breakthroughs were achieved in meridional circulation studies using HMI data. These results will greatly help us better understand solar dynamo and solar cycles.
- With the help of numerical simulations, we are better understanding our measurements of emerging active regions.
- Some large-scale structures are seen in high-latitude areas, but what causes them and whether these structures are giant cells remain to be studied.