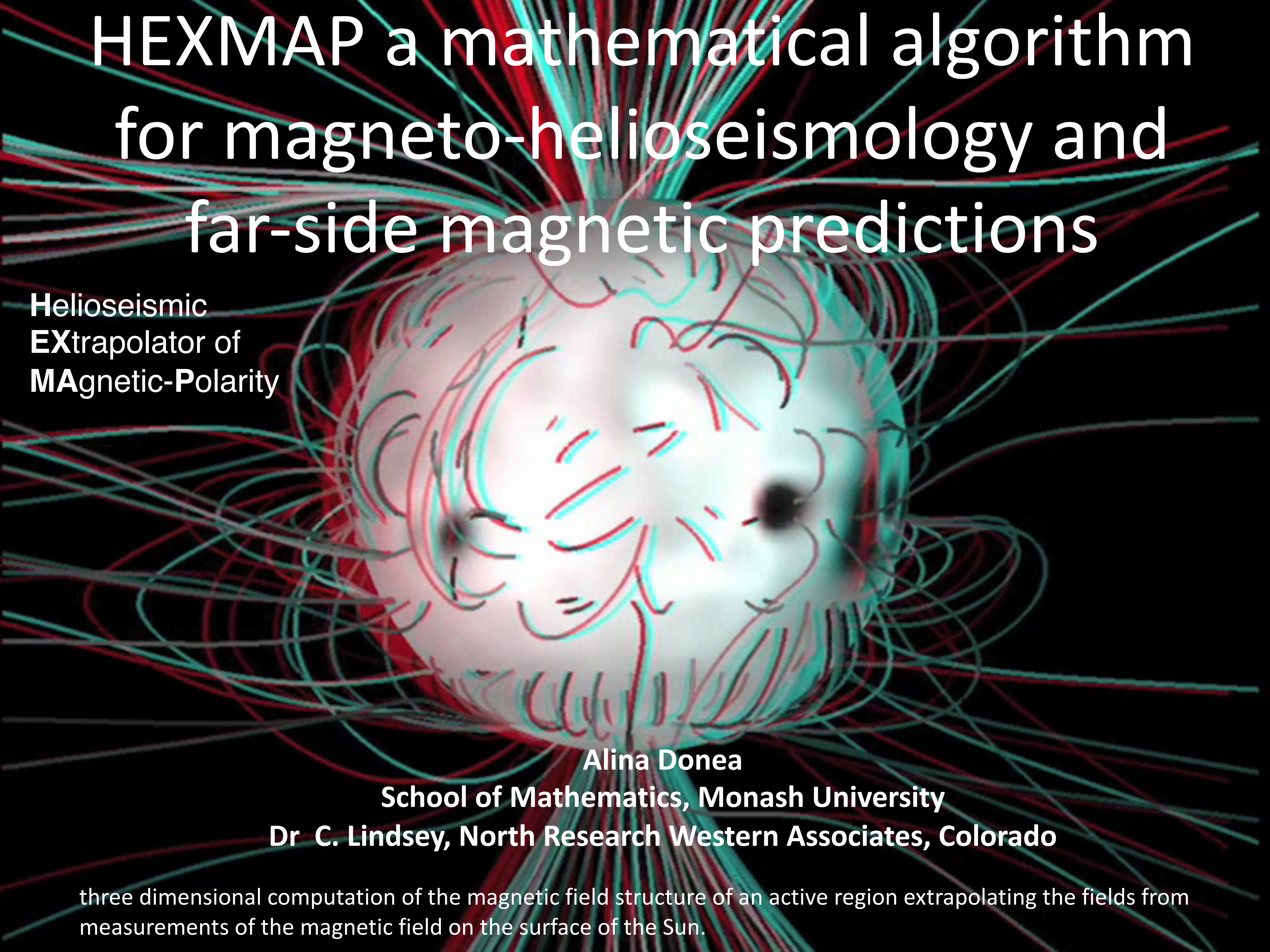
HEXMAP a mathematical algorithm for magneto-helioseismology and far-side magnetic predictions



Helioseismic
EXtrapolator of
MAgnetic-**P**olarity

Alina Donea
School of Mathematics, Monash University
Dr C. Lindsey, North Research Western Associates, Colorado

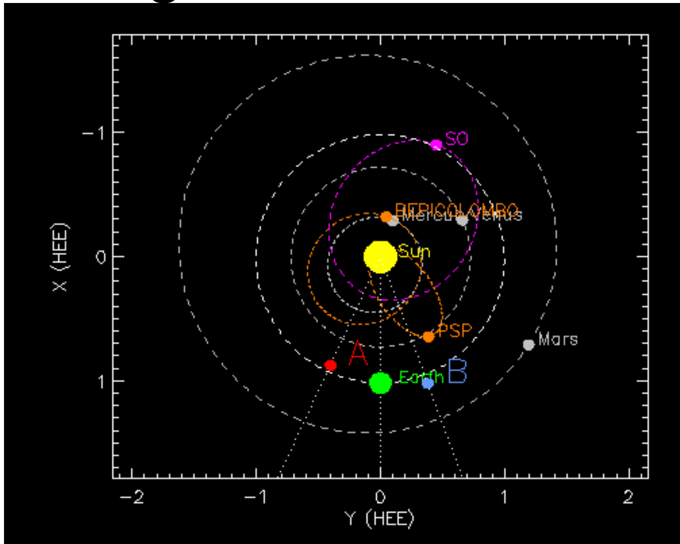
three dimensional computation of the magnetic field structure of an active region extrapolating the fields from measurements of the magnetic field on the surface of the Sun.

Plan of my talk

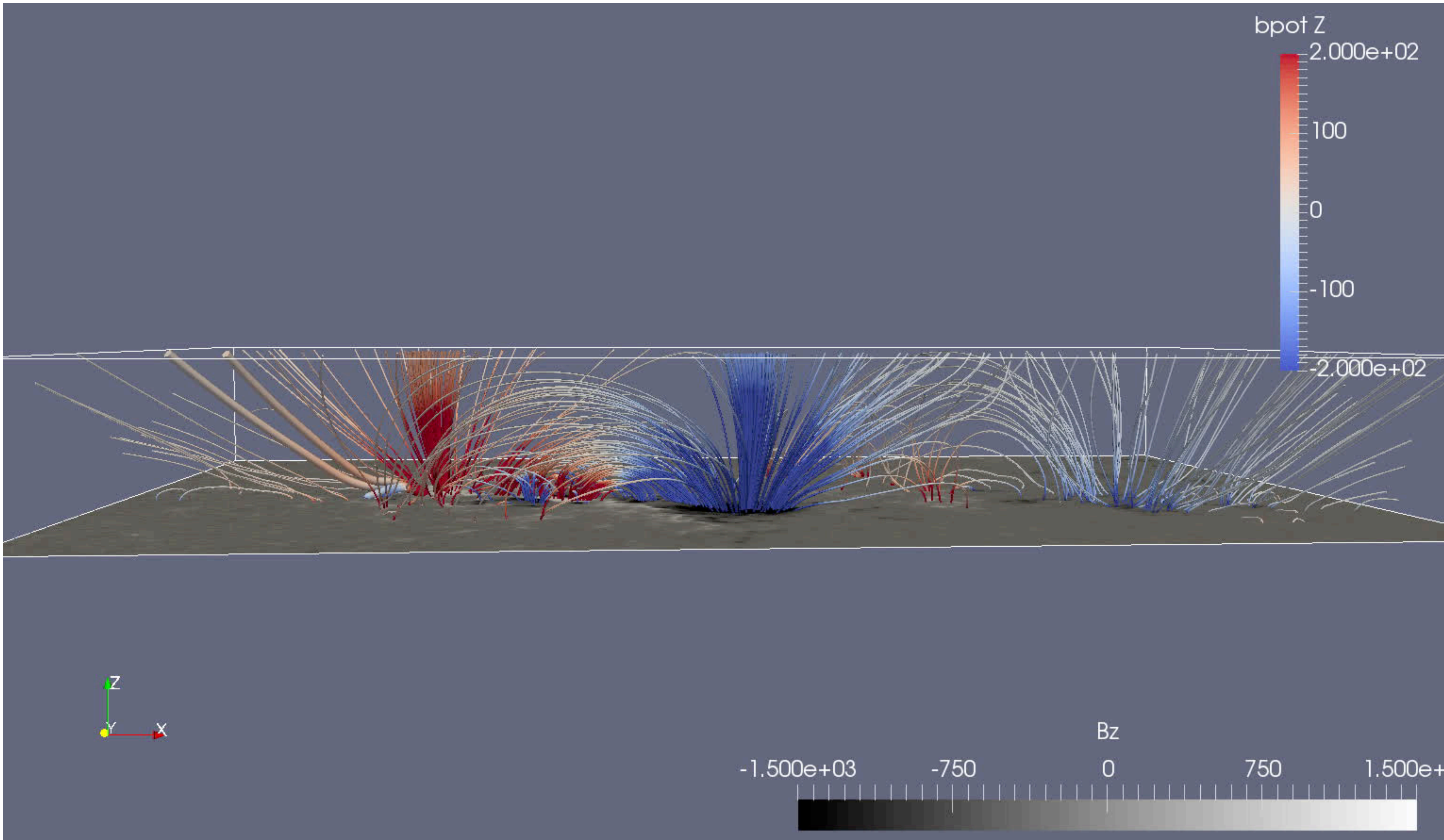
- Far Side Imaging of the Sun
- Magnetic maps and the link to seismology
- Helioseismic maps and phase shifts/time delay
- The prime HEXMAP algorithm
    1. *Basic concepts and tool components for the HEXMAP*:
    2. the Hale polarity law
    3. Advection
    4. The relative success of the algorithm in finding a travel time τ that gives a good "magnetic fit" (near an far sides)
    5. Difficulty: spatial resolution and sensitivity are much finer than for those of similar magnetic regions in the far hemisphere

Why is this important?
Connectivity of seismology with space weather research

- Monitoring of the Sun's far hemisphere: forecasting on time scales from a few days up to three weeks.
- NASA’s twin STEREO spacecraft : back to the Earth-side of the solar system, lost their far-side vantage in 2019.
- Solar seismology linked to magnetism => space weather apps
- Seismic monitoring of the Sun’s far hemisphere : heavily used (?)
- Basic research: Our present understanding of magnetic fields takes no account of flux emerging unseen in the far hemisphere.



Magnetic Fields of Active Regions: Prediction, Extrapolation by Alin Paraschiv



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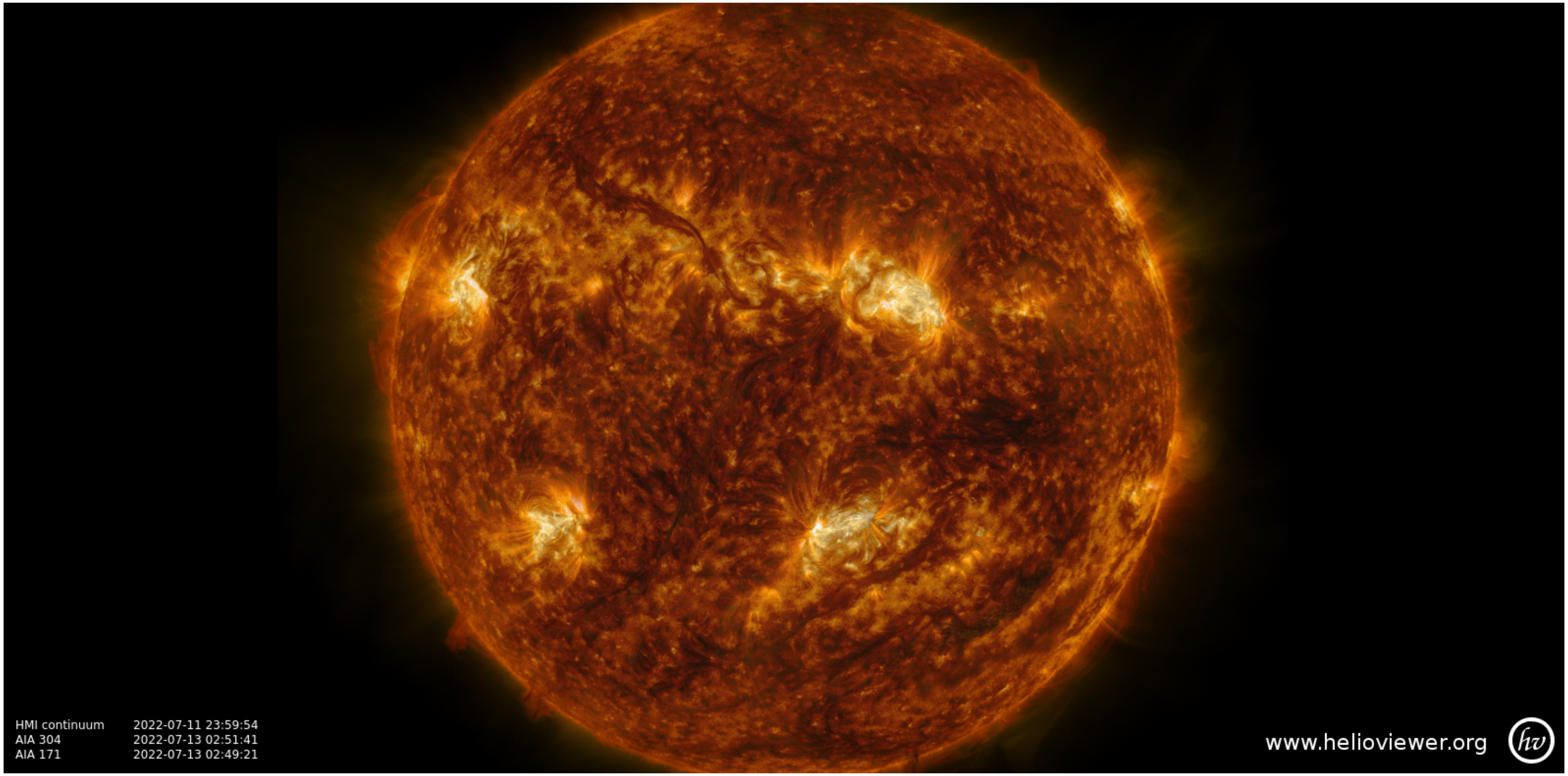
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www.helioviewer.org

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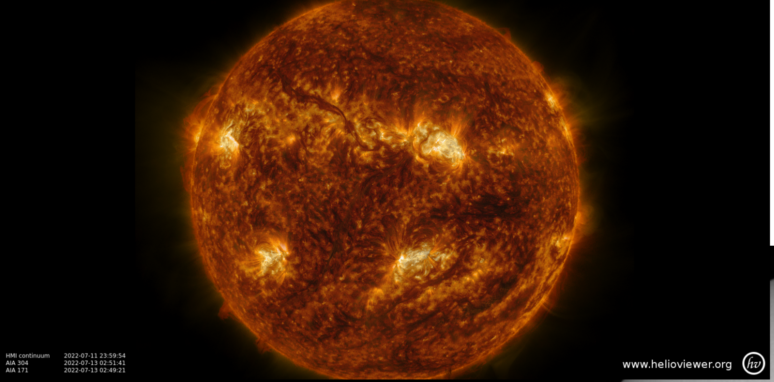
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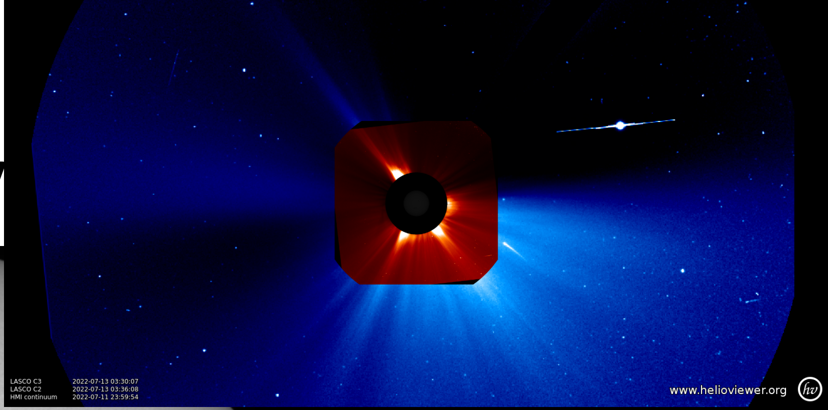
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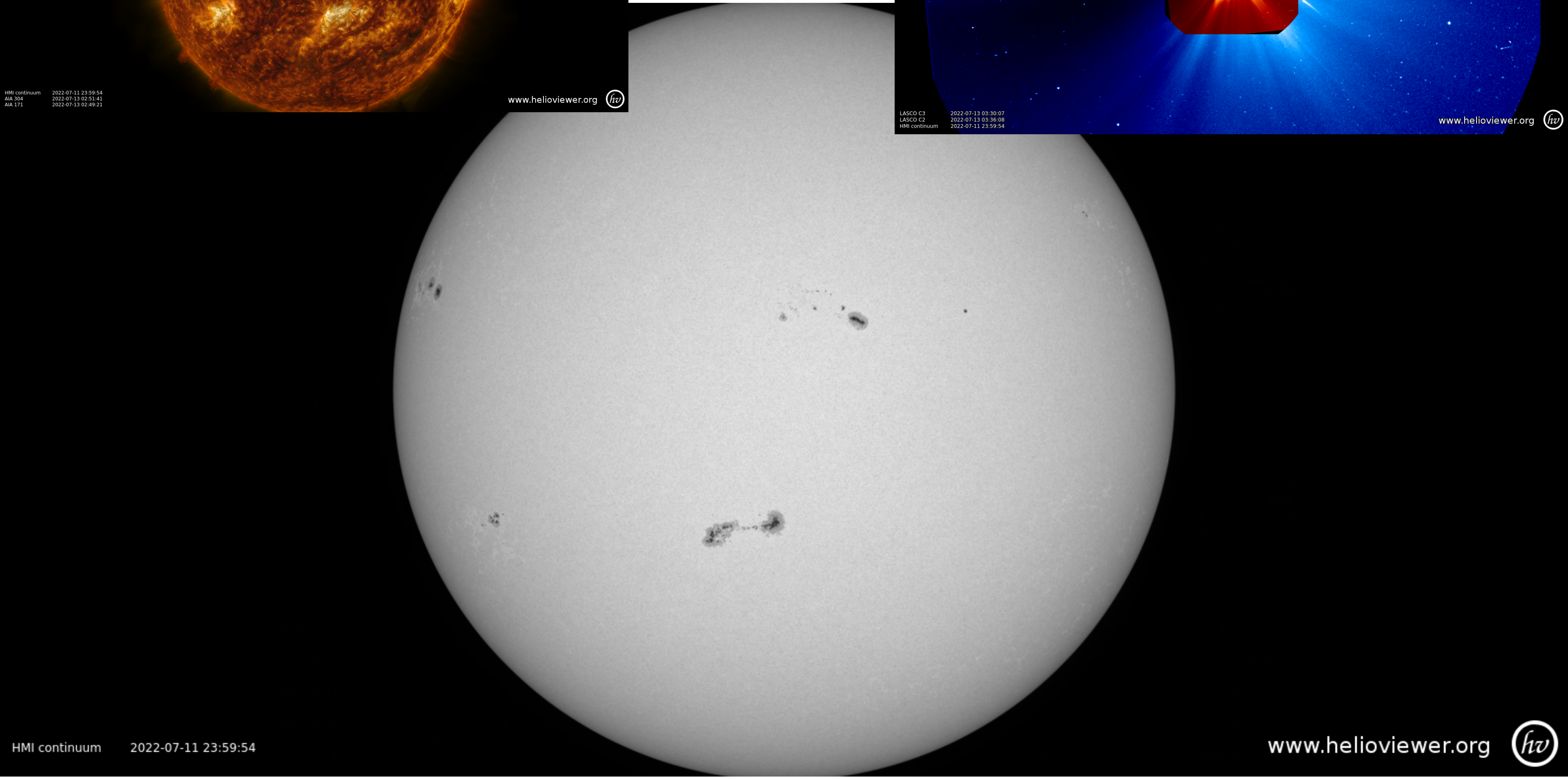
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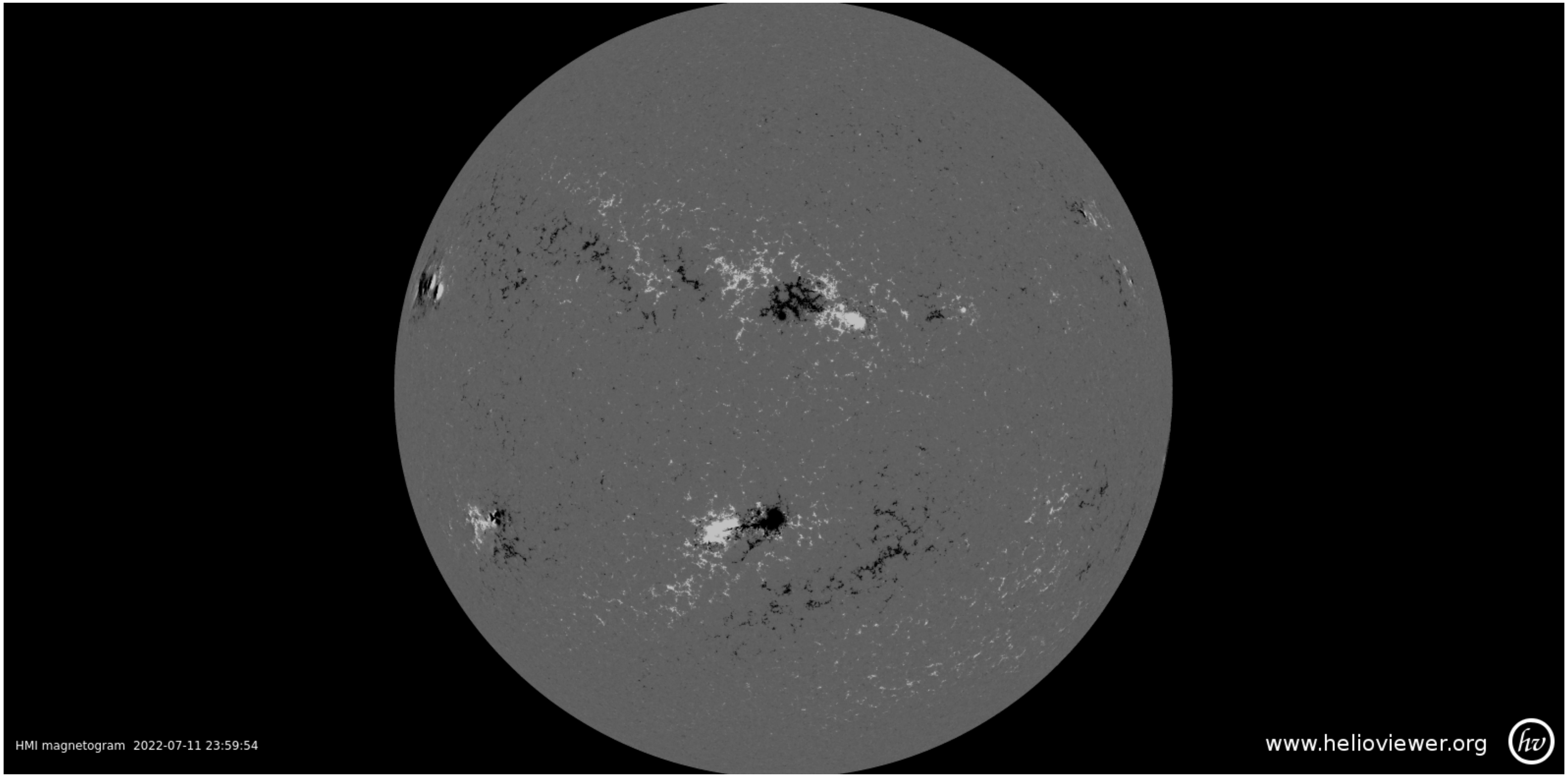
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www.helioviewer.org

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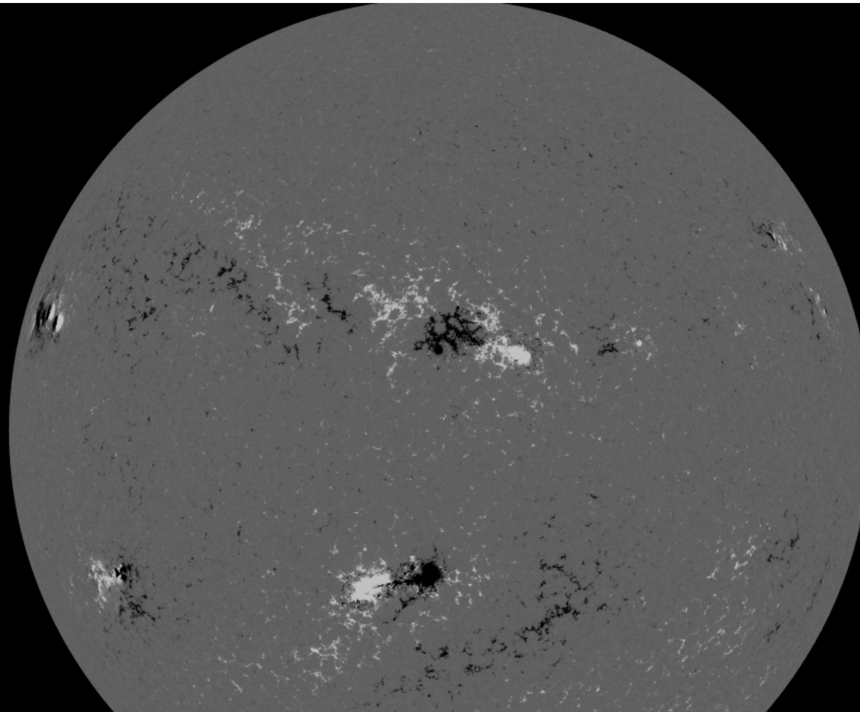
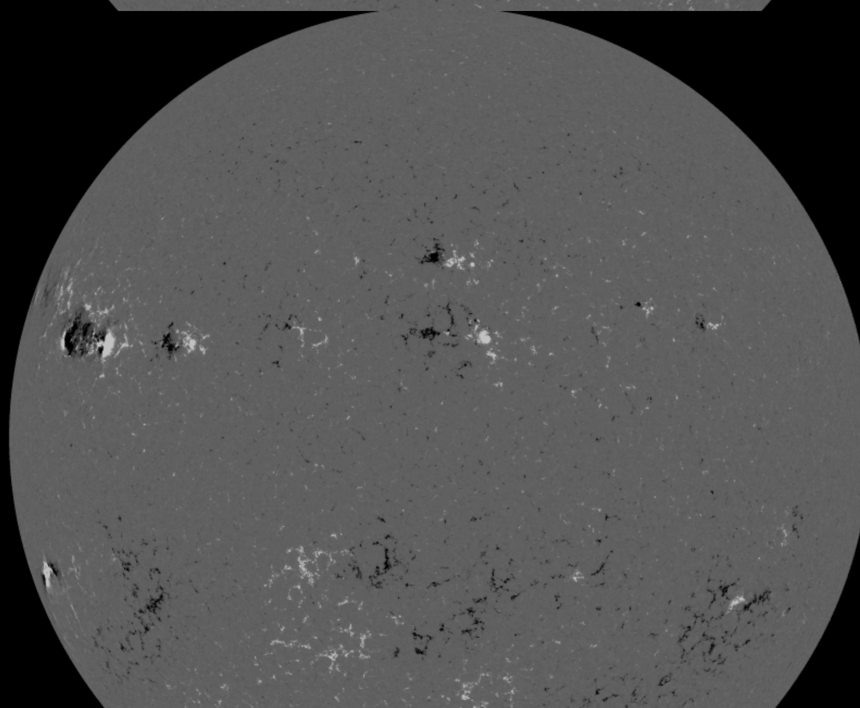


6-days ago



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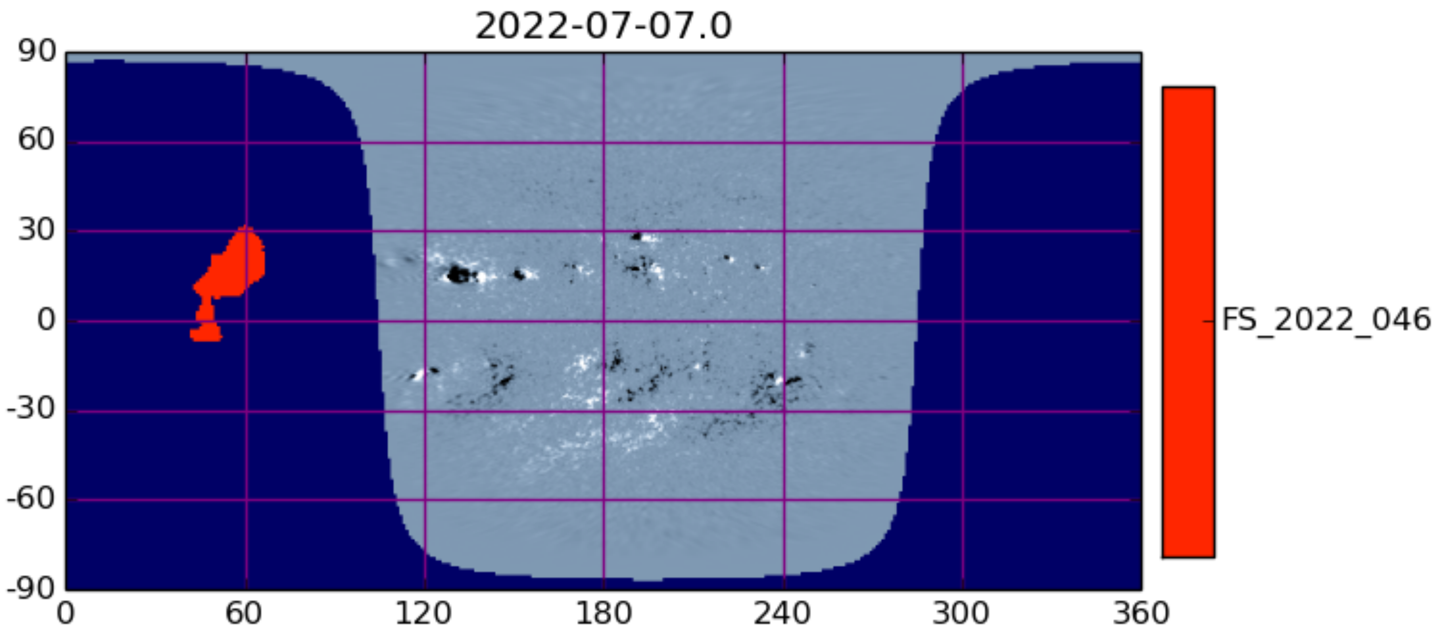
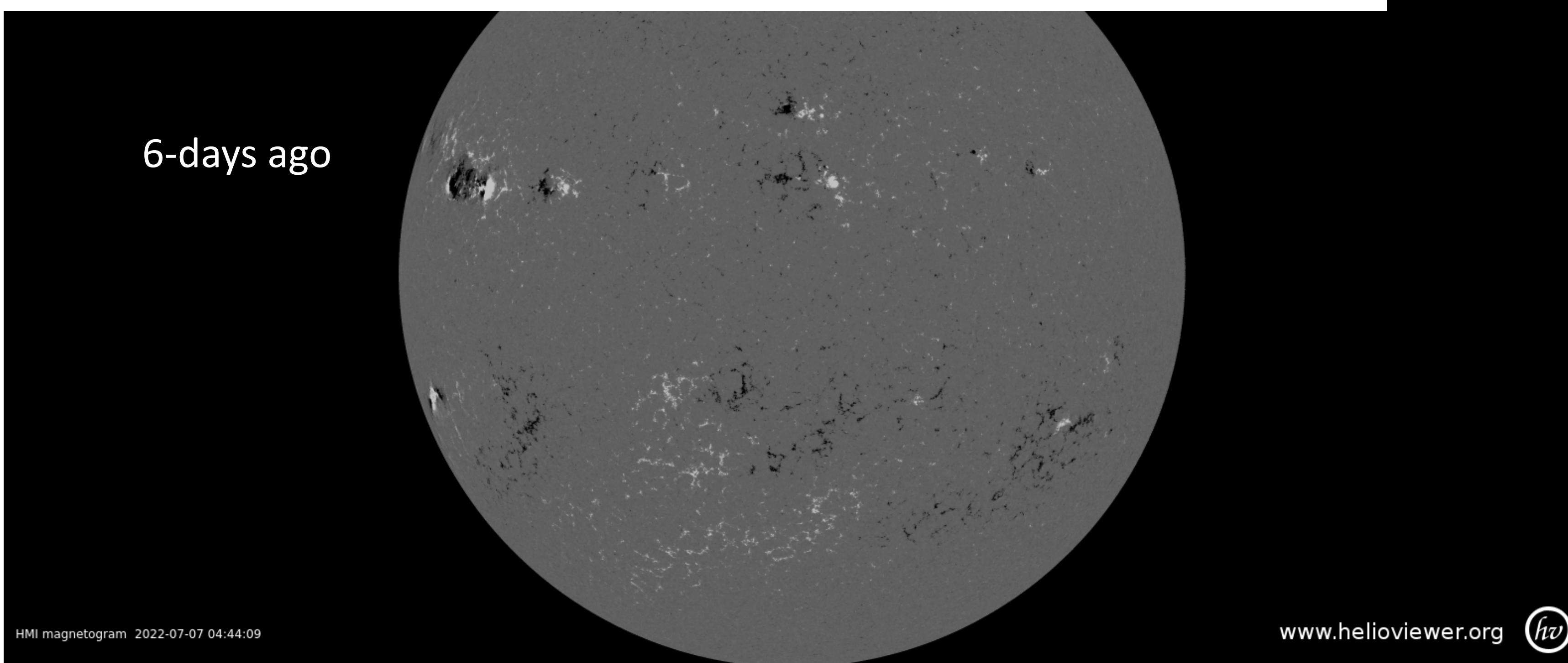
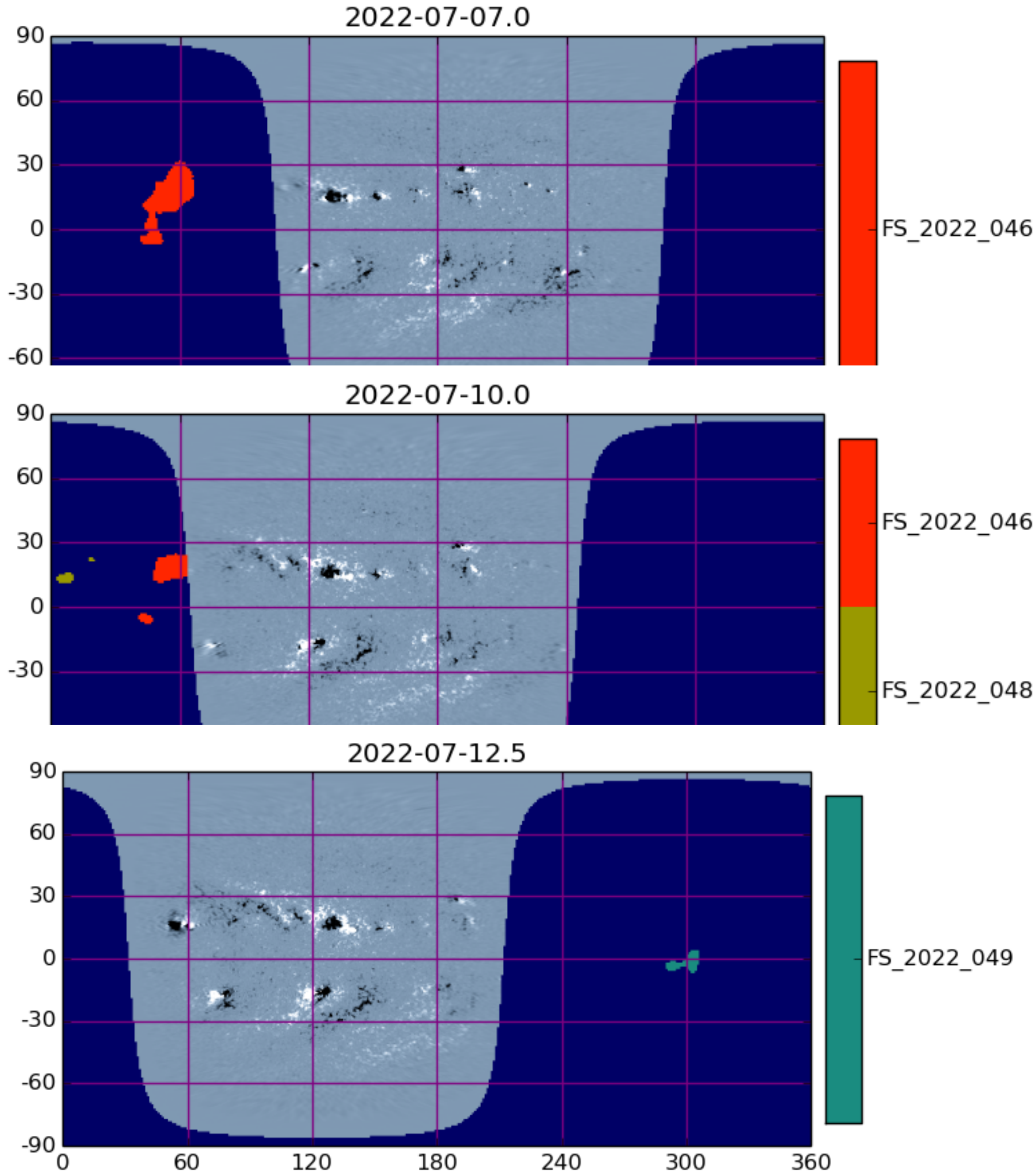


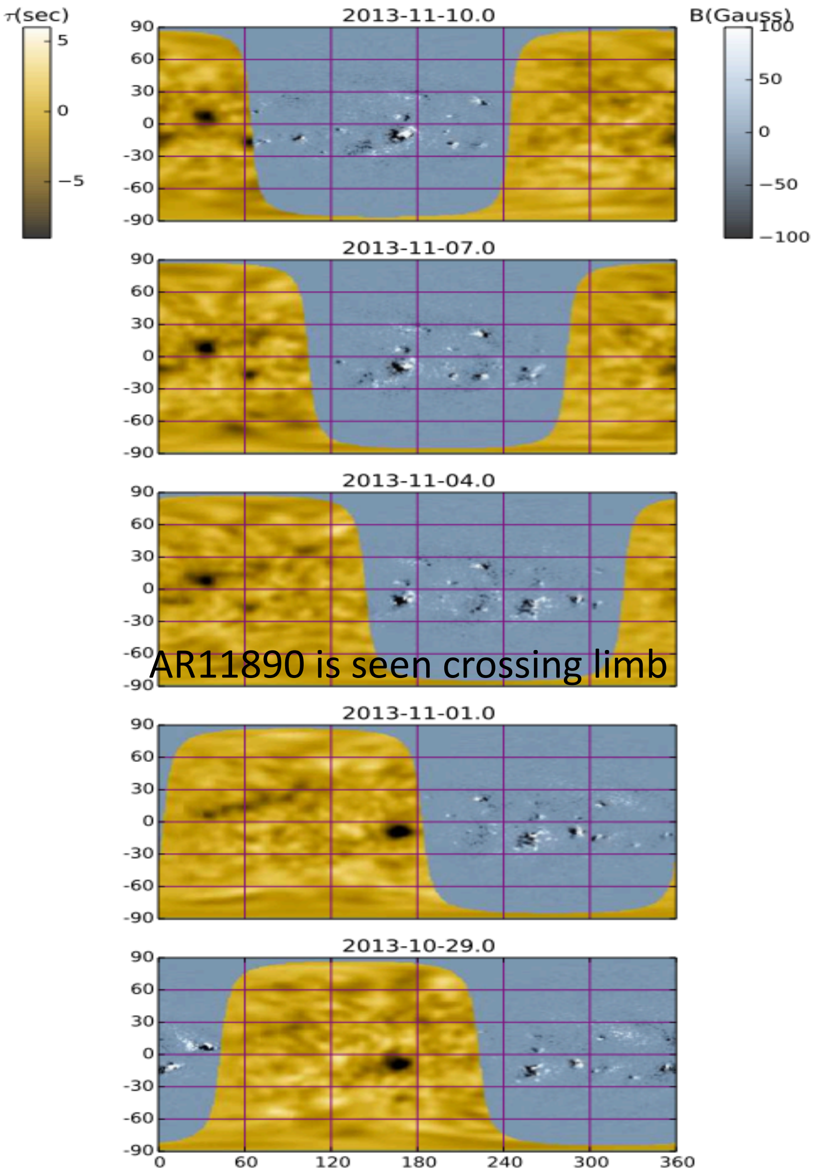


- [Strong Active Region Maps]() on Near and Far



the phase-sensitive seismic holography technique Lindsey and Braun [2000] Braun and Lindsey [2001].

Two-Skip Helioseismic Holography for Seismic Monitoring



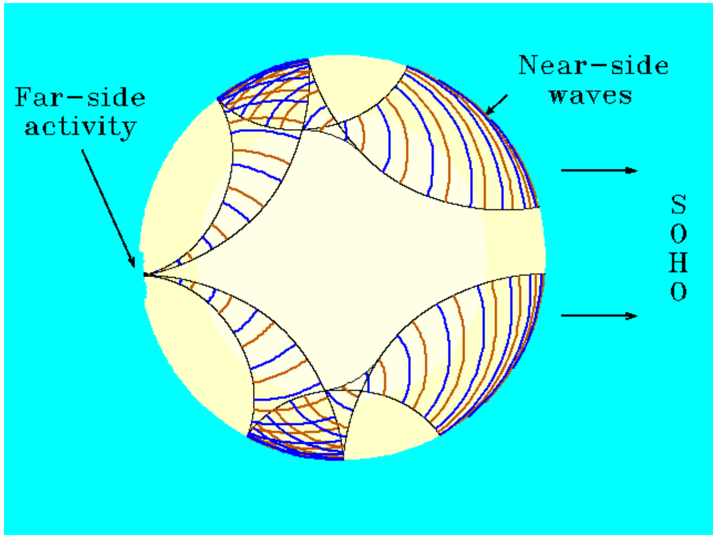
Five-day composite near-side magnetic and far-side 5-day cumulative seismic maps

- Calculated maps represent the phase shift between waves going into and out of a particular location (focus) on the Sun's far surface.
- Phase shift is expressed here as a travel-time of acoustic waves perturbation in seconds.

Phase Shift (Degree) $\phi = 360 \times freq \times \Delta t$

Phase Shift (radian) $\phi = 360 \times freq \times \Delta t \times Pi/180$

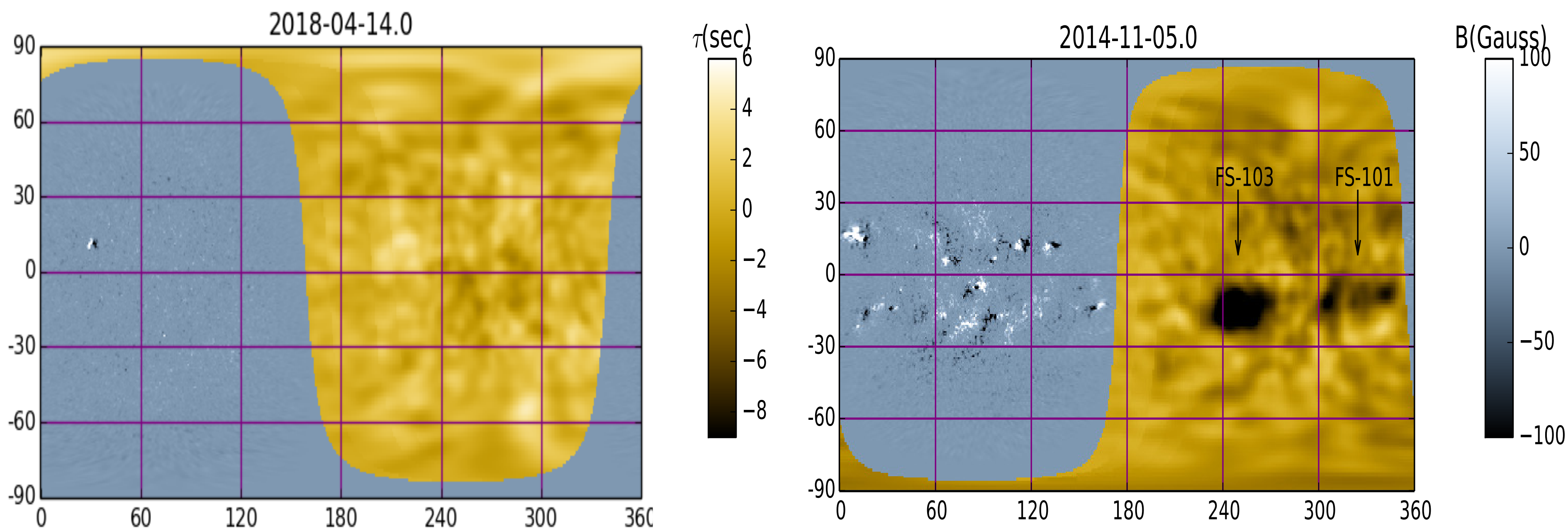
$$\text{Time Shift}(\Delta t) = \frac{\phi}{360 \times freq}$$



the phase-sensitive seismic holography technique

Lindsey and Braun [2000] Braun and Lindsey [2001].

My research focused question:



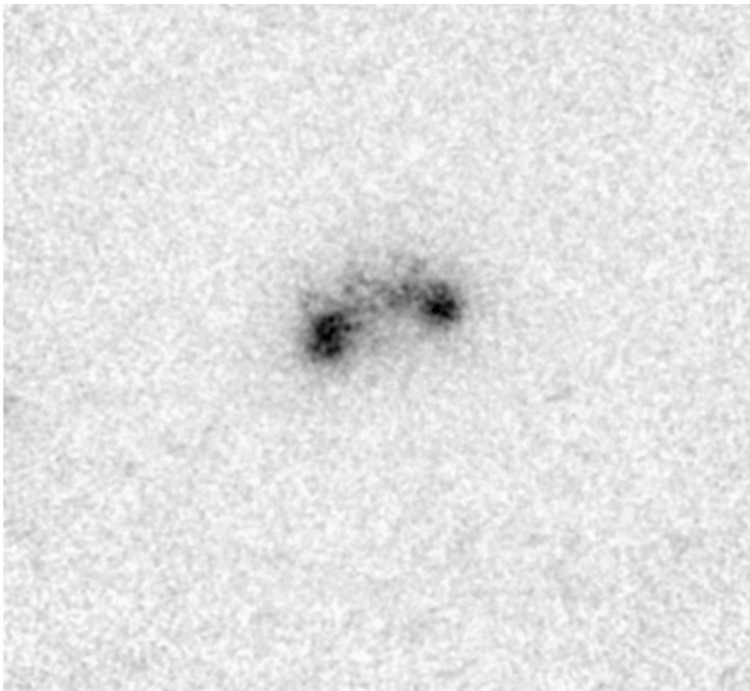
The ability of the far-side seismic monitor to detect and accurately locate the active regions in the far hemisphere, those that are of a major concern to space-weather forecasters, is well established.

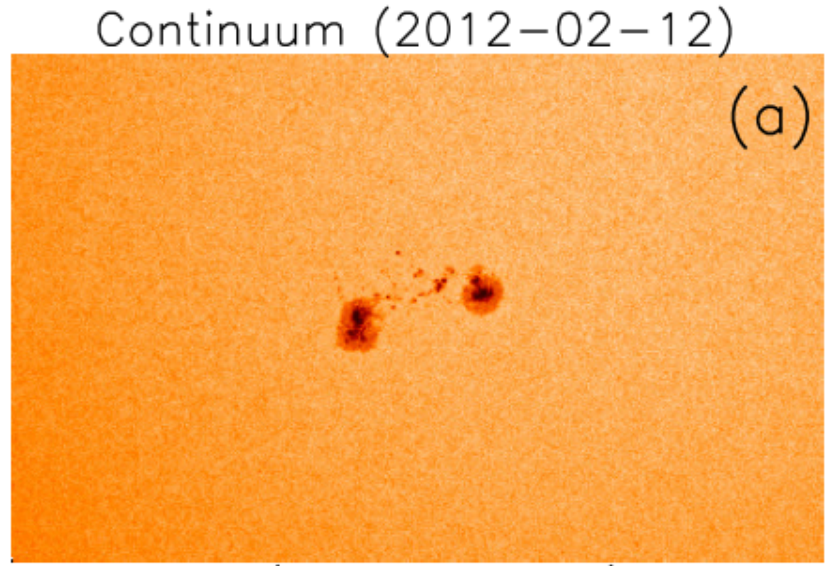
Somewhat unfortunately, helioseismic signatures are insensitive to: **magnetic polarity.**

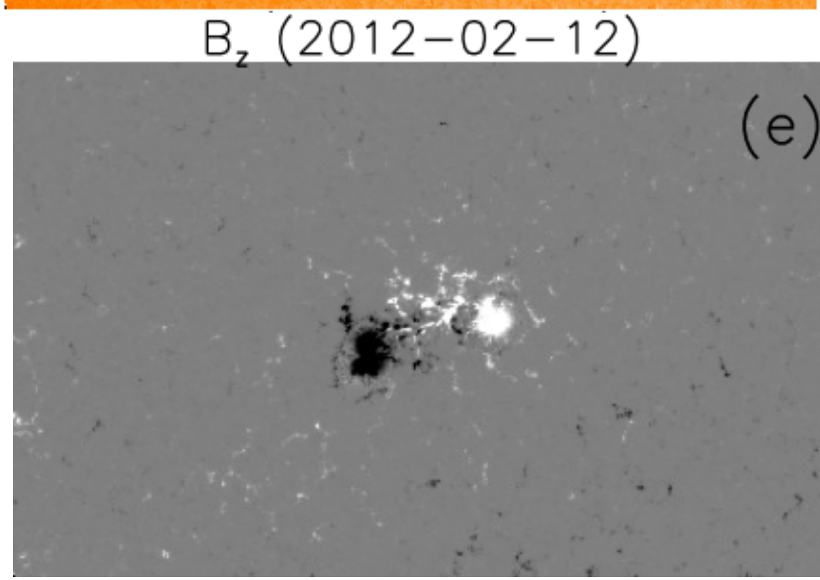
We want to fix this problem.

Seismic Phase Maps vs. Magnetic Maps on Near Side: Results

Phase map or Time delay map







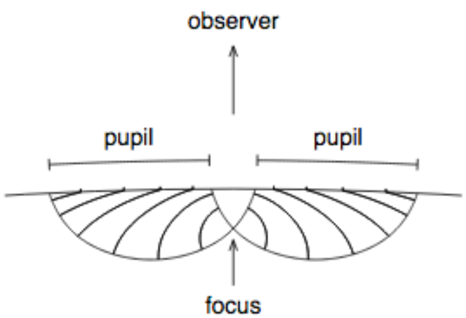
Magnetic Fields reduce Power in Local Acoustic Amplitude of Field Waves

Mathematics: Phase-Sensitive Helioseismic Holography

In a “space-frequency” context, the monochromatic egression and ingression are computed by integrals of the form:

$$H_{\pm}(\mathbf{r}, z, \nu) = \int_P d^2\mathbf{r}' \; G_{\pm}(\mathbf{r}, \mathbf{r}', z, \nu) \; \psi(\mathbf{r}', \nu)$$

In phase-correlation holography, we consider correlations between the egression and ingression



$$C(\mathbf{r}, z, \nu) = H_{+}(\mathbf{r}, z, \nu) H_{-}^{*}(\mathbf{r}, z, \nu),$$

The phase of the correlation [rad] is

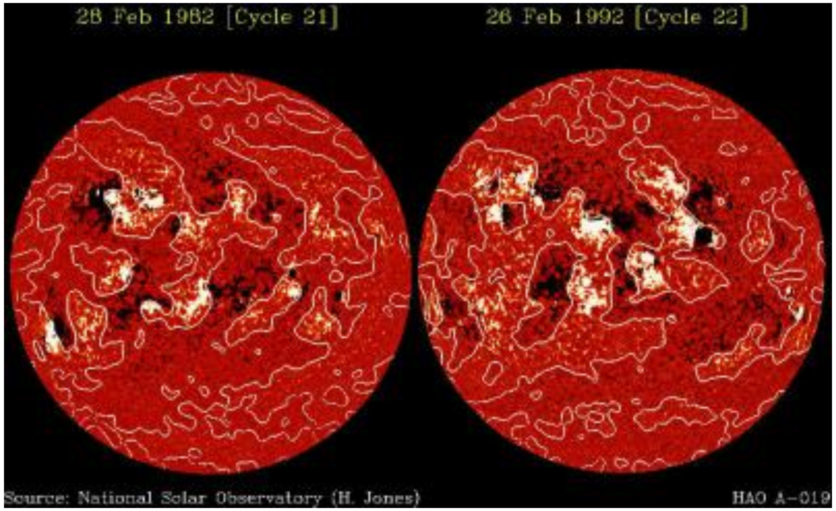
$$\phi(\mathbf{r}, z) = \arg\left(\left\langle C(\mathbf{r}, z, \nu)\right\rangle_{\Delta\nu}\right)$$

In the temporal domain, we may relate a mean travel-time difference, τ [sec], between the egression and ingression to the correlation phase above by

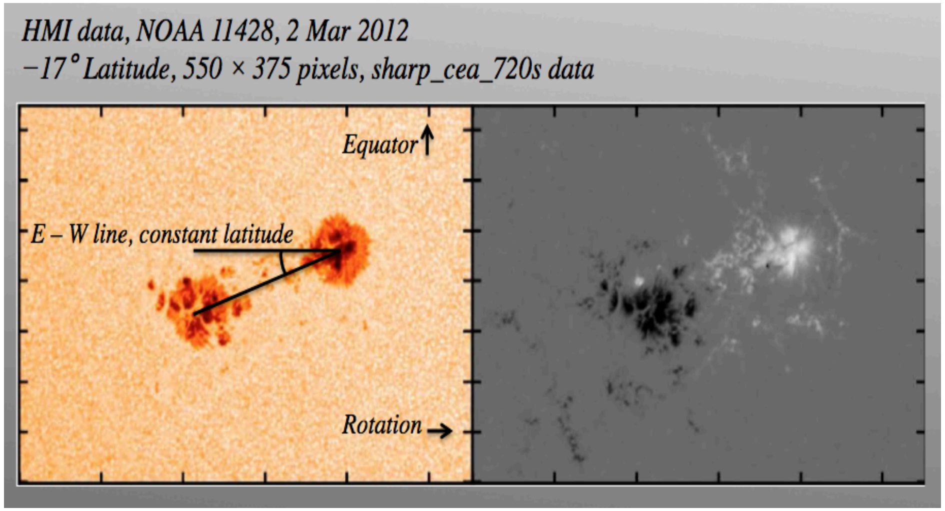
$$\phi(\mathbf{r}, z)/2\pi\nu_o$$

This is known:

The Hale Polarity Law as a Resource for Magnetic-Polarity Information

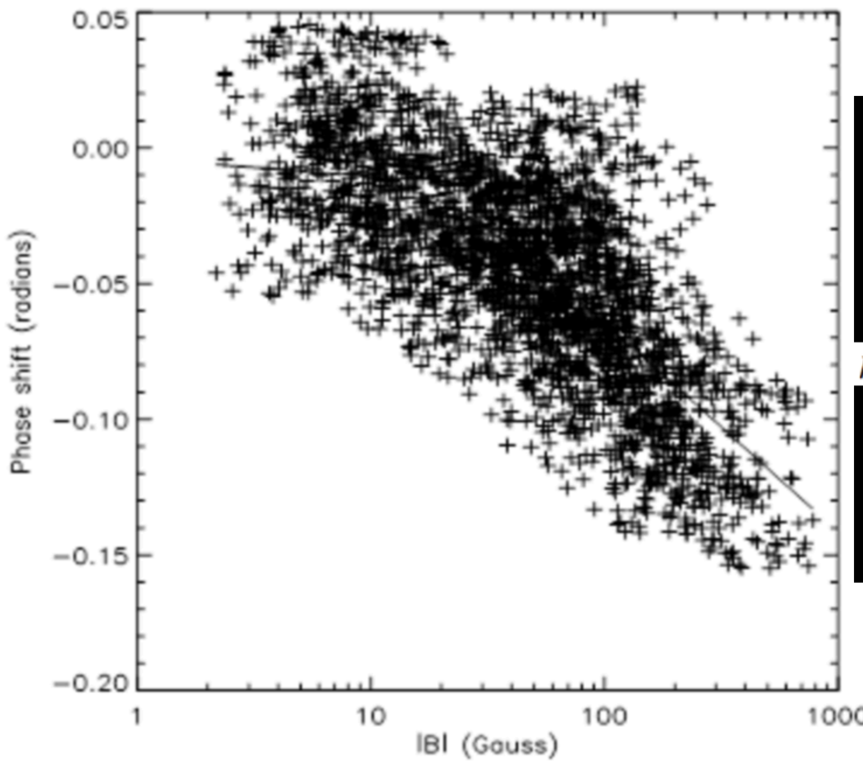


Joy's Law: Bipolar magnetic regions exhibit a tilt



This is now known:

Calibrating Helioseismic Signatures in Terms of Magnetic Field



$$\mathcal{J}(\langle B^2 \rangle) \equiv h_0 \ln\left(1 + \frac{\langle B^2 \rangle}{B_0^2}\right)$$

$h_0 = -15.0$ sec, and $B_0 = 75$ Gauss.

$$H = \mathcal{J}(\langle B^2 \rangle)$$

On the success rate of the farside seismic imaging of active regions (2010)

I. González Hernández,F. Hill,P. H. Scherrer,C. Lindsey, D. C. Braun

HEXMAP

Model needs to be simple enough to be easily understood, but accommodated with sufficient parameters to be conformable to what we observe

*H*elioseismic *EX*trapolator of *MA*gnetic-*P*olarity distribution (HEXMAP)

Individual North- and South-Polar Flux Densities and their Evolution

$$\langle B_z \rangle(\boldsymbol{\rho},\ t) \ = \ P_n(\boldsymbol{\rho},\ t) \ - \ P_s(\boldsymbol{\rho},\ t).$$

prescribe that the sum of Pn and Ps represent the mean square magnetic induction, i.e., the "magnetic pressure" except for the factor of 8π

$$\langle B^2 \rangle(\boldsymbol{\rho},\ t) \ = \ P_n^2(\boldsymbol{\rho},\ t) \ + \ P_s^2(\boldsymbol{\rho},\ t),$$

$$H(\mathbf{r},\ t) \ = \ \mathcal{H}(P_n^2(\mathbf{r},\ t) \ + \ P_s^2(\mathbf{r},\ t))$$

The key aspect is to consider that once a fully emerged contingent of bipolar magnetic flux has become
apparent on the Sun's surface it tends broadly to evolve primarily by the opposing polarities drifting apart in opposing directions, generally reinforcing the Hale polarity law

Mathematical Modelling of Evolution

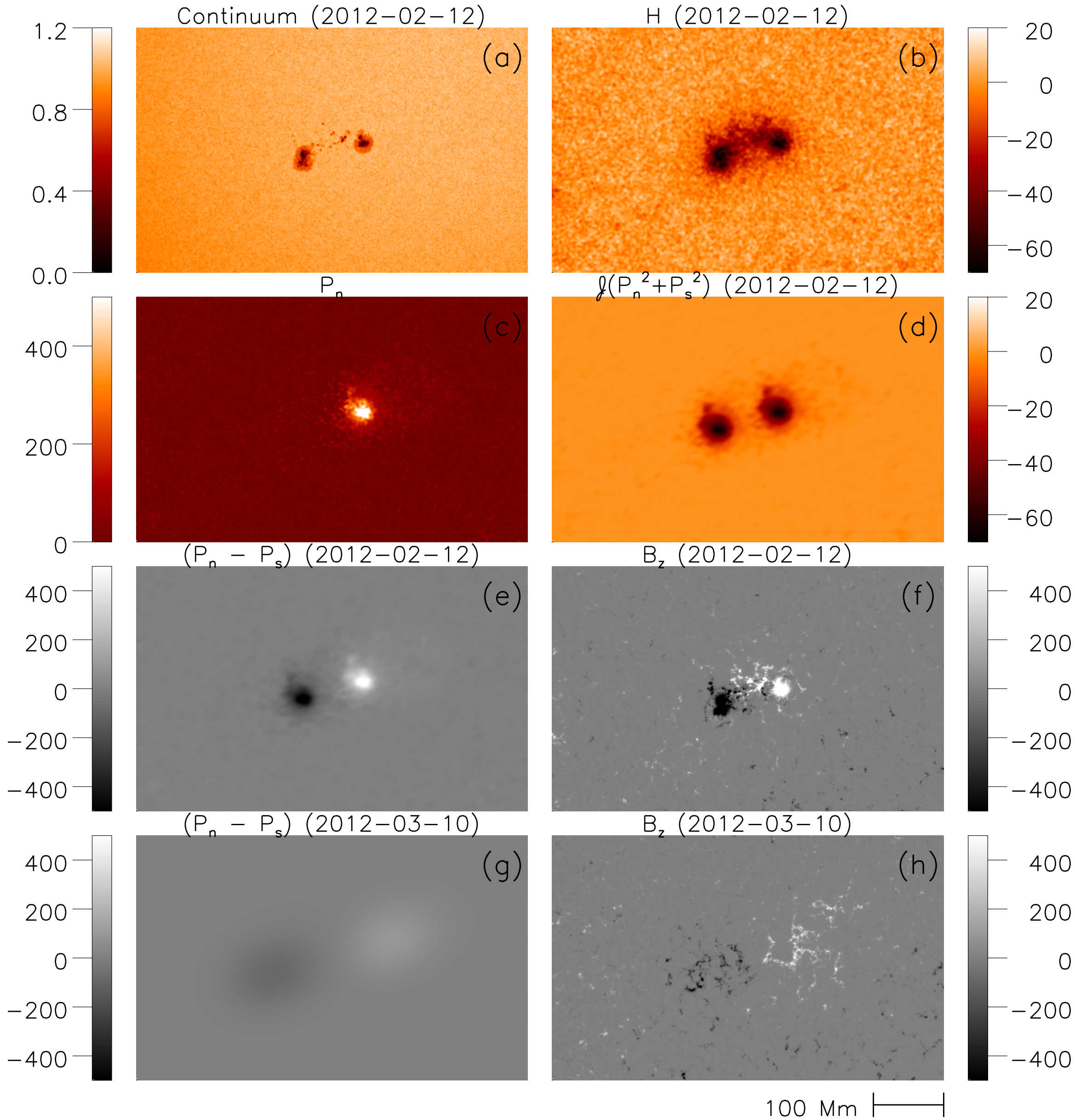
- Once a fully emerged contingent of bipolar magnetic flux has become apparent on the Sun's surface it tends broadly to evolve , drifting apart in opposing directions
- Use Hale polarity law
- Apply warping advection by differential solar rotation and meridional flow, also subject to generally anisotropic diffusion (Wang, Nash & Sheeley 1989).
- Applying the evolution operators: we model the subsequent evolution of the dipolar magnetic flux distributior

$$\frac{\partial}{\partial t} P_g(\boldsymbol{\rho},\ t) = \mathcal{E}_g(\theta) P_g(\boldsymbol{\rho},\ t),\ g \in \{\text{“}n\text{”}, \text{“}s\text{”}\},$$

$$U_g(\tau) = e^{\mathcal{E}_g \tau},$$

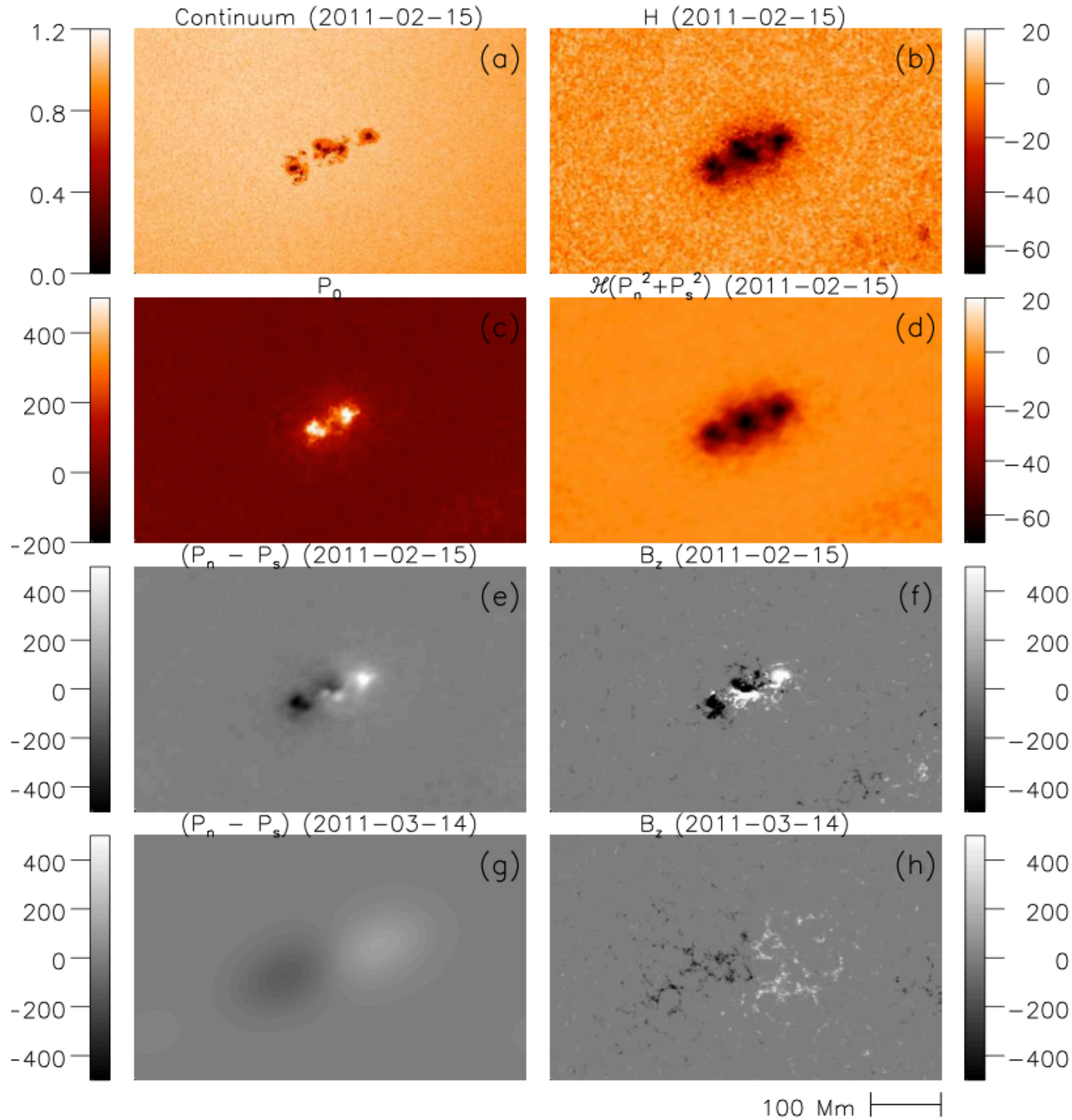
$$P_g(\boldsymbol{\rho},\ t_2) = U_g(t_2 - t_1) P_g(\boldsymbol{\rho},\ t_1),\ g \in \{\text{“}n\text{”}, \text{“}s\text{”}\}.$$

Simple Configuration



The magnetic extrapolation illustrated in Figure 6 for the simple bipole configuration of NOAA AR11416 is applied here to more magnetically complex NOAA AR11158 (2011-02- 13)

Complex Configuration

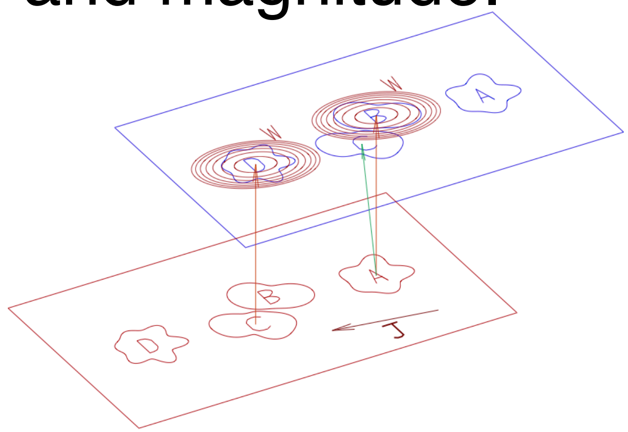


The magnetic is applied here to more magnetically complex NOAA AR11158 (2011-02- 13)

Donea, Lindsey (2018)

Future Work

- Machine Learning for Recognition-Detection, Classification, Parametrization ofComplex magnetic configurations:
- Where greater complexity gets interesting is when the different bipoles have different separations, **J**, both in direction and magnitude.



- Methods are being developed and tested to employ the Hale Polarity Law to estimate the magnetic polarity distribution of far hemisphere active regions identified by seismic observations.