Preparing Photospheric Magnetic Field Measurements for Coronal/Heliospheric Models

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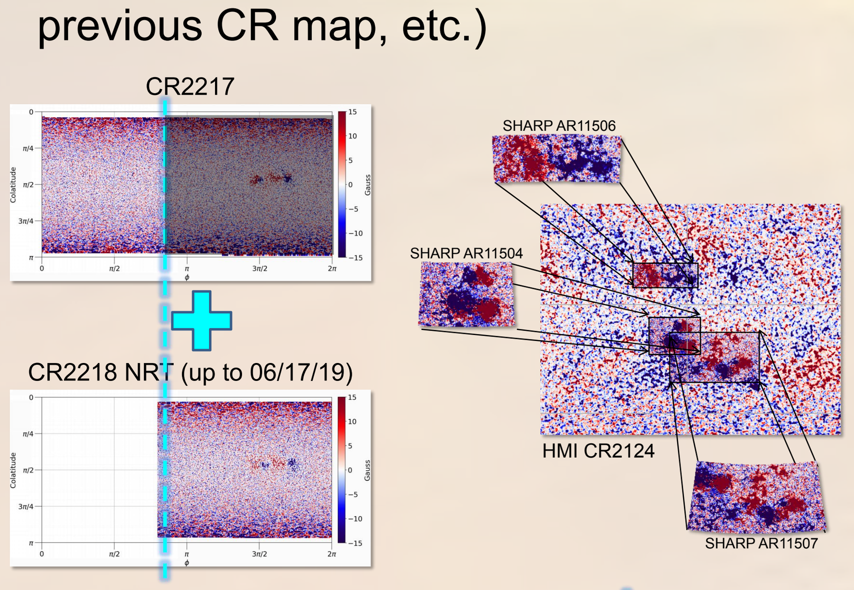
INTRODUCTION

Photospheric magnetic field observations are extremely important for models of the solar corona and heliosphere. They are used to specify magnetic boundary conditions, which largely determine the 3D structure of a model for a given time-period. However, due to limited surface coverage and systematic variations in data/model resolutions, such data must be processed before being used as input to models. Here we describe our pipeline (SPIFS) for transforming the available observational data into a form ready for use in our coronal and heliospheric models.
The result of each step applied to a real-world case (our 2019 total solar eclipse prediction) is shown.

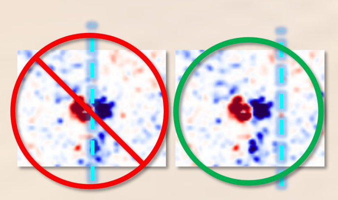
Selecting Data

- Several sources of observations, each with its own time-period, cadence, resolution, and calibration.

- Multitude of full-Sun data products including Carrington Rotation (CR) synoptic, "daily"/"hourly" patched CR, localized synchronic patches (e.g. SHARP), and synchronic flux evolution maps (e.g. ADAPT).
- Each data product has unique noise properties, data coverage, scaling factors, etc.
- It can be desirable to splice together custom maps from available data (e.g. inserting SHARP AR data into a full-Sun map, combining most recent CR data with previous CR map, etc.)

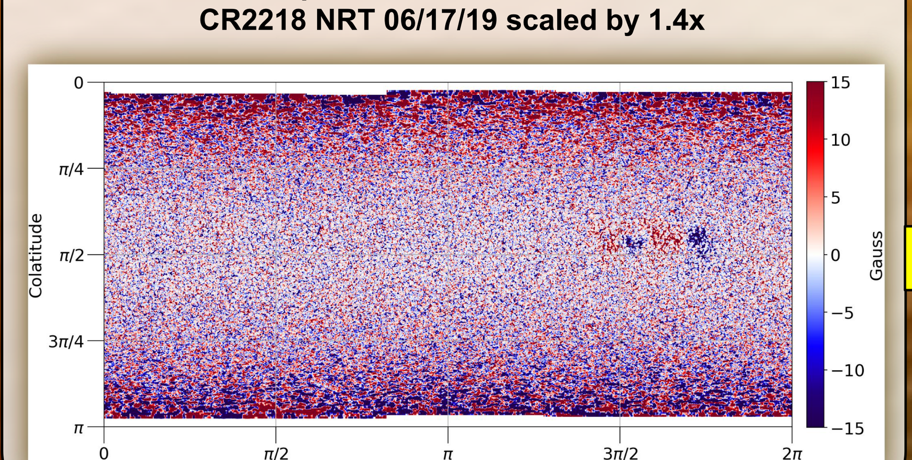


- When splicing, it is important not to cut through strong dipoles like ARs!



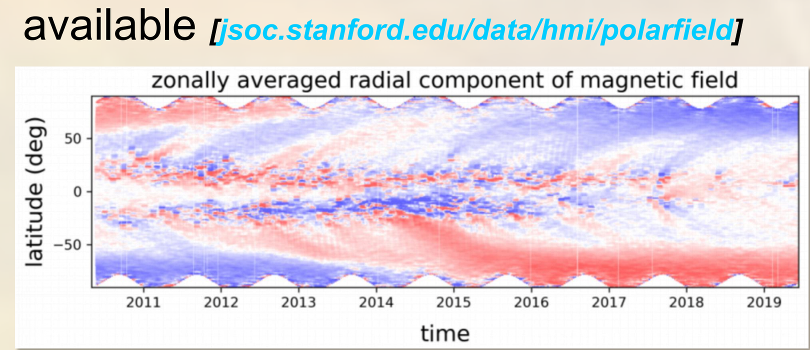
- To maintain consistency across instruments, maps can be scaled *[Liu et. al. (2012)]*

Composite of HMI CR2217 and CR2218 NRT 06/17/19 scaled by 1.4x

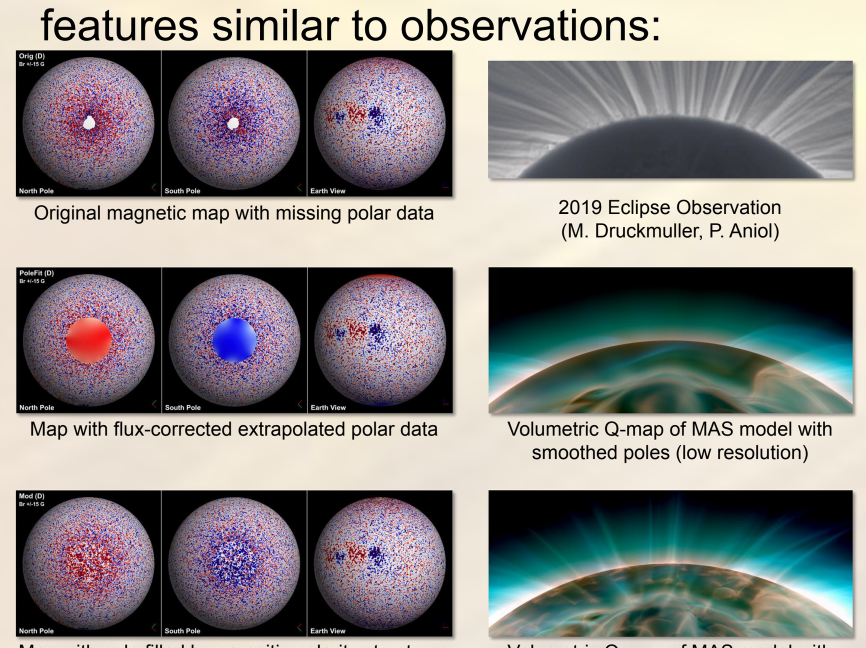


Pole fitting/filling

- Magnetic field data near/at the poles is either not available or not very reliable.
- Some data products include extrapolated/interpolated polar data.
- Can be advantageous to fill polar data manually.
- Two methods we employ:
  (1) Extrapolate from high-latitude data
  (2) Estimate average polar flux from nearest time that reliable data was available *[jsoc.stanford.edu/data/hmi/polarfield]*

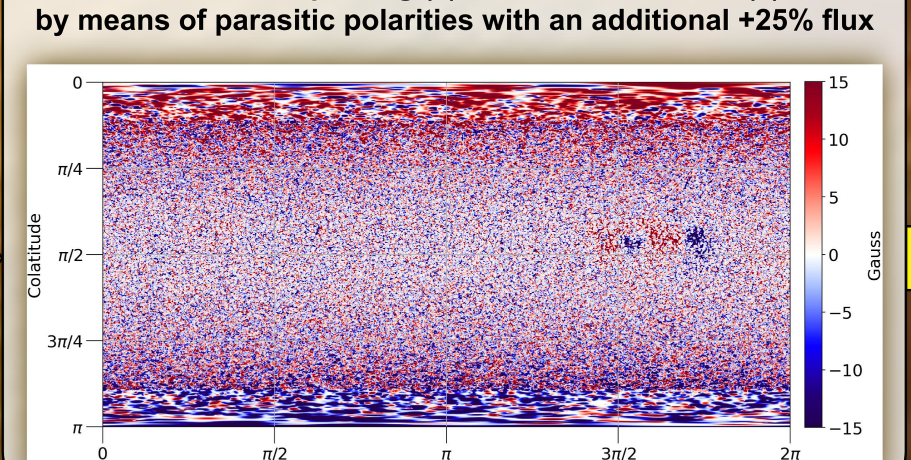


- Can fill polar data by inserting small randomized parasitic polarity Gaussian regions distributed to match the estimated/extrapolated flux. This causes coronal models to exhibit polar plume-like features similar to observations:



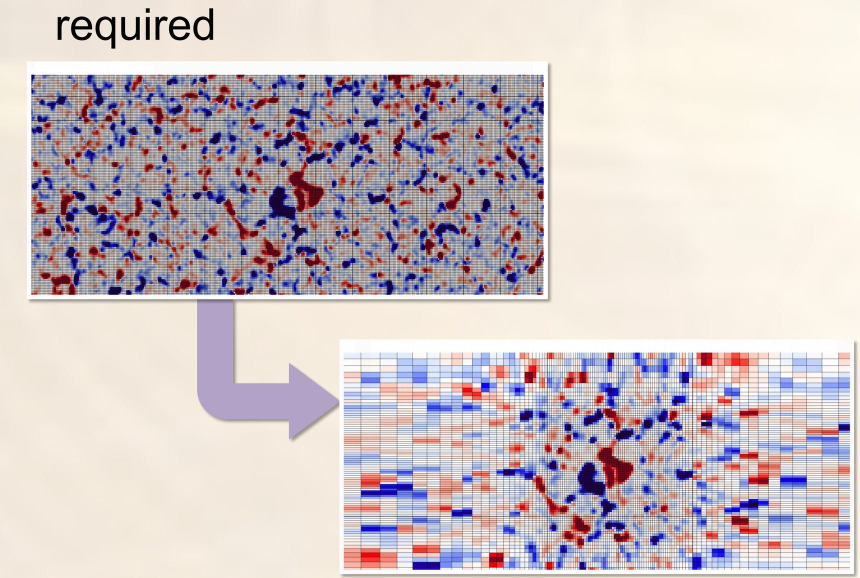
- Can add additional polar flux to better match observations *[Riley et. at. ApJ. 884 (2019)]*

Pole-filled map using (1), flux-corrected with (2), by means of parasitic polarities with an additional +25% flux

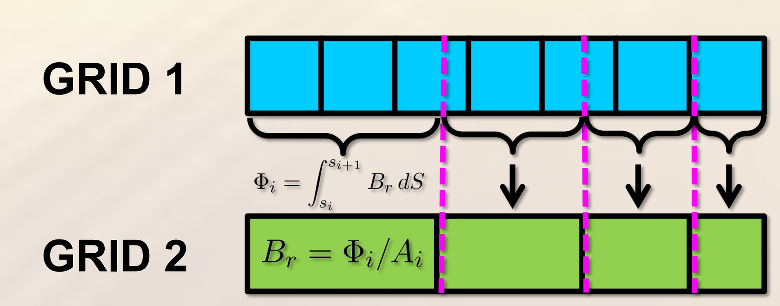


Interpolation

- Resolution of magnetic map different (typically larger) than a reasonable resolution of the model, so interpolation is required



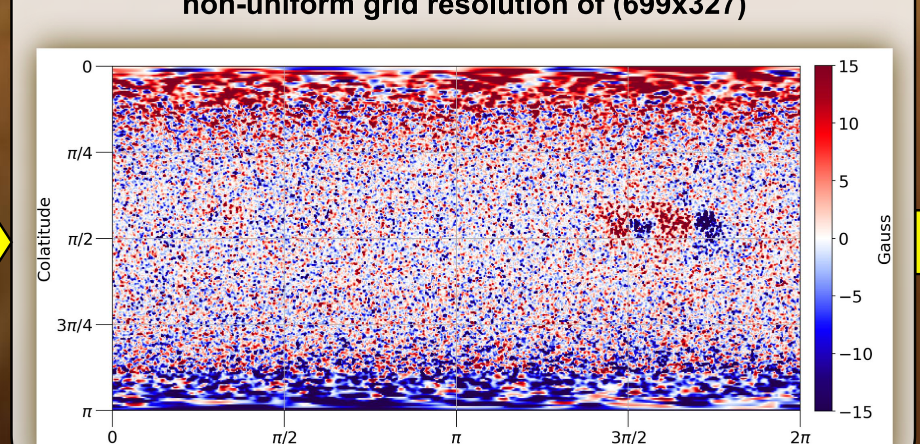
- Direct interpolation can introduce aliasing, discontinuities, and does not preserve net flux.
- Instead of interpolating Br values directly, we compute the net flux over the full and partial cells of the original grid that are within the region of the new grid cell. Then, the flux is converted into a Br value for the new cell:



$$\Phi_i = \int_{s_i}^{s_{i+1}} B_r\, dS \qquad B_r = \Phi_i / A_i$$

- This method maintains the net flux of the original map, and avoids aliasing and discontinuities.

(3600x1440) Map interpolated to the MAS coronal model non-uniform grid resolution of (699x327)



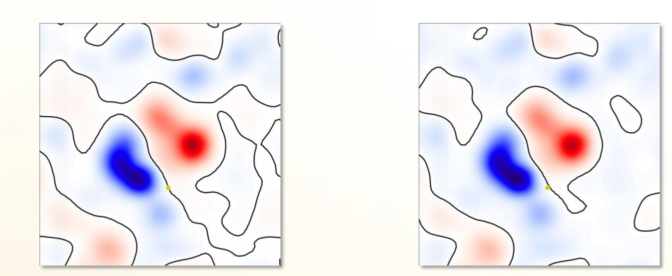
Flux-balancing

- Maps may not have a total zero net flux (unbalanced).
- Such flux imbalance is nonphysical and can cause a break-down in models (e.g. unsolvable potential field).
- Two chosen methods for flux balancing: (a) Additive (b) Multiplicative
- (a) Additive:

$$B_r^* = B_r - \frac{\Phi_+ + \Phi_-}{4\,\pi\, R_\odot^2}$$

$$\Phi_+ = \int_0^{4\pi} B_r\, d\Omega,\ \{\forall\, B_r > 0\} \qquad \Phi_- = \int_0^{4\pi} B_r\, d\Omega,\ \{\forall\, B_r \leq 0\}$$

Issues: May add a lot of flux to quiet regions and can move/manipulate neutral lines:



Br map showing surface neutral lines

Same map with added field strength at one pole, then flux balanced with (a)

- (b) Multiplicative:

$$B_r^* = \begin{cases} B_r / \sqrt{|\Phi_+/\Phi_-|} & \text{if } B_r > 0 \\ B_r\, \sqrt{|\Phi_+/\Phi_-|} & \text{if } B_r \leq 0 \end{cases}$$

Can use a mask to limit field modifications to desired areas (e.g. polar regions, back-side of Sun, ARs, etc.)

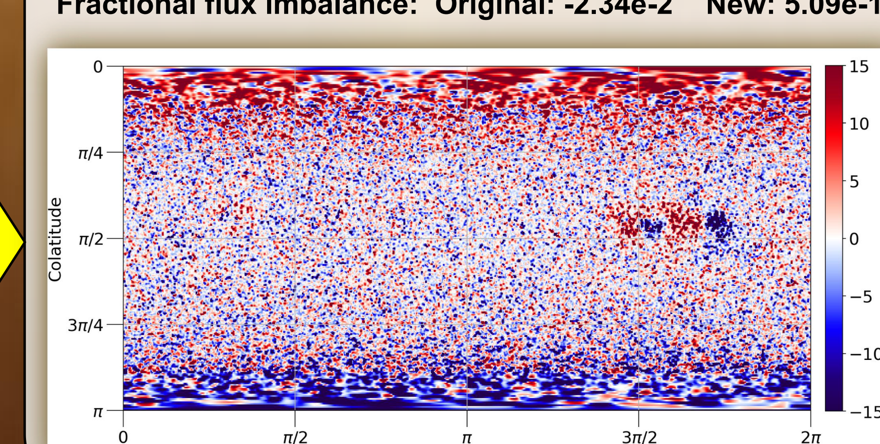
$$B_r^* = \begin{cases} M\, B_r + (1-M)\, B_r / x_m & \text{if } B_r > 0 \\ M\, B_r + (1-M)\, B_r\, x_m & \text{if } B_r \leq 0 \end{cases}$$

$$x_m = f + \sqrt{f^2 - \Phi_{o+}/\Phi_{o-}} \qquad M(\theta,\phi) \in [0,1]$$

$$f = -0.5\,(\Phi_{i+} + \Phi_{i-})/\Phi_{o-})$$

- In time evolution models, need to be careful of temporal discontinuities

Flux-balanced map using multiplicative flux balancing. Fractional flux imbalance: Original: -2.34e-2 New: 5.09e-14



Smoothing

- Even with flux integral interpolation, the map may contain small structures that the model cannot properly resolve.
- One solution is to smooth the map.
- Localized filters are easy to use and efficient, but can lead to artifacts/aliasing and may not be flux-preserving.
- Our solution is to apply a time-dependent surface diffusion equation with a non-uniform diffusivity:

$$\frac{\partial B_r}{\partial t} = \frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left[\nu(\theta,\phi)\,\sin\theta\,\frac{\partial B_r}{\partial\theta}\right] + \frac{1}{\sin^2\theta}\frac{\partial}{\partial\phi}\left[\nu(\theta,\phi)\,\frac{\partial B_r}{\partial\phi}\right]$$

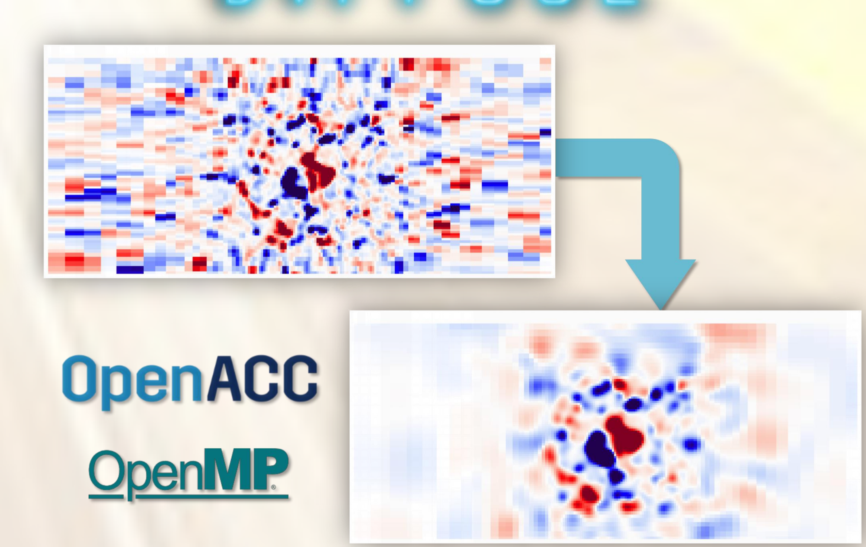
$$\nu(\theta,\phi) = \alpha_\nu\,(\nu_0 + \nu_f(\theta,\phi) + \alpha_{\nu_\Delta}\,\nu_\Delta(\theta,\phi))$$

where the diffusivity can be a constant (ν_0), a custom profile ($\nu_f(\theta,\phi)$), or grid-based:

$$\nu_\Delta(\theta,\phi) = \Delta\theta^2 + (\sin\theta\,\Delta\phi)^2$$

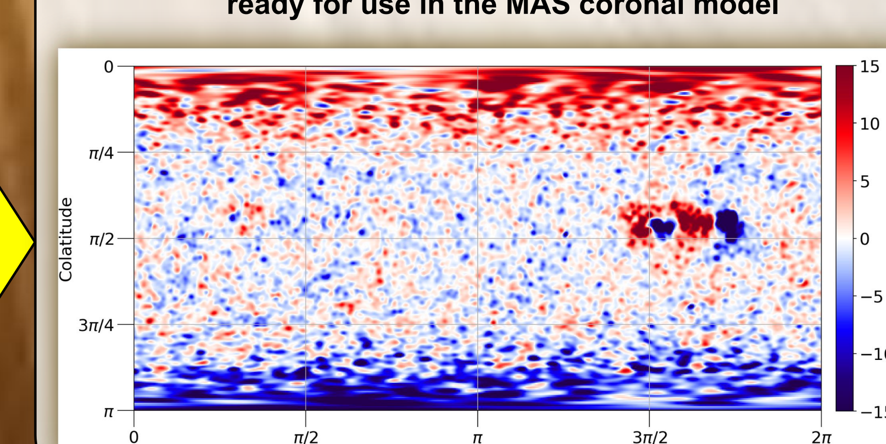
- The system is integrated for one unit of time using our tool:

DIFFUSE



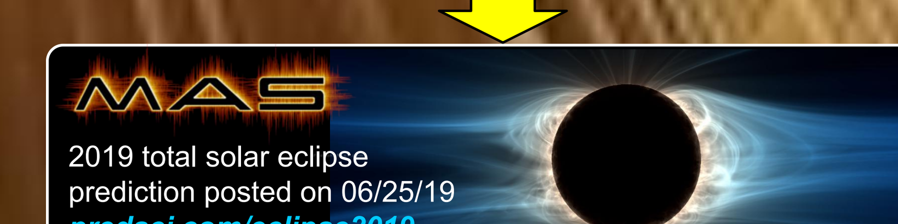
- DIFFUSE is a FORTRAN code that integrates the solution using RKL2 super time-stepping and is parallelized for a multicore CPU or NVIDIA GPU.

Final map, smoothed with a custom diffusivity profile, ready for use in the MAS coronal model



DISCUSSION

Photospheric magnetic field observations are critical for coronal and heliospheric models. The availability and quality of full-Sun data products are constantly improving, however even perfect data still requires important processing steps before being able to use in a model. These steps are not trivial and incorrect processing can have detrimental effects on a model's accuracy and stability. The SPIFS pipeline described here has worked well in real-world problems.



2019 total solar eclipse prediction posted on 06/25/19
predsci.com/eclipse2019