Comparing coronal models for the PSP-P1 passage

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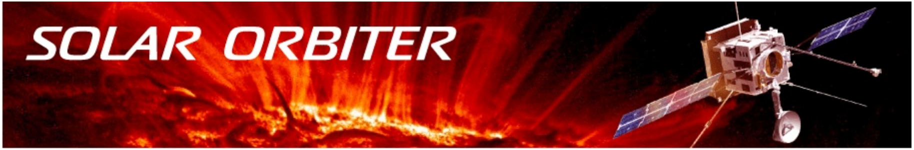


STFC project ST/S006559/1 Solar Orbiter Community Project - Linking Remote and In Situ Observations Through Numerical Modelling Tools of the Solar Corona and Heliosphere

The connectivity problem

The connectivity information is required for

- Satellite operations
- Science data exploration

The deceptively simple goal of Find the field line connecting SO to the photosphere is actually equivalent to Simulate a self-consistent, time-dependent, data-driven 3D model of the coronal magnetic field from the photosphere up to the satellite position

Connectivity models have different approach, depending on goal (operation vs science)

- Nowcast vs forecast mode
  - input from synoptic to actualized magnetograms
  - forecast based on forward evolution of nowcast full-Sun magnetograms
- Split of corona in rigidly rotating corona (<2.5 Rs) plus solar wind model (*e.g.*, Parker spiral)
- Low-corona (self-consistent solar wind) plus heliospheric model

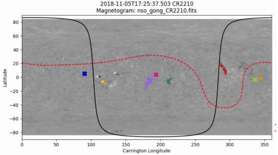
- Questions: Is there a best model/strategy for operation? And for science? Can we estimate connectivity errors?
- Goal: develop a set of analysis tools for comparison and validation of models

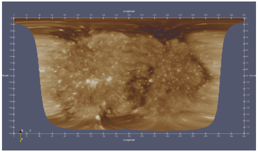
The Parker Solar Probe 1st Perihelion

SO on-the-road test: use PSP in combination with modeling to point Hinode

	31-oct	01-nov	02-nov	03-nov	04-nov	05-nov	06-nov	07-nov
NSO Predictions (PFSS assuming nearly-radial field out to PSP)								
Carr. Lon	336,71	330,2	326,76	325,74	327,55	332,206	337,938	343,041
Lat	-67,32	-67,22	-67,47	-67,5	-67,347	-67,447	-67,578	-67.4520
CCMC Predictions (WSA-NLIL) -- This will be updated regularly								
Carr. Lon	349,6	343,5	335,9	116,9	116	117,2	120,1	156,8
Lat. from North	23,2	22,7	22,6	100,4	100,4	101,5	117,5	109,4
PSI Predictions (MAS)								
Carr. Lon	319,23	322,31	325,53	326,55	326,74	326,07	324,33	320,61
Lat.	4,61	3,08	2,34	1,94	1,64	1,57	1,88	2,53
Connect_Tool (IRAP, MADAWG) -- This will be updated regularly (3-day lead time)								
Carr. Lon 00:00 slow sw						337.25	340.54	346.65
Lat 00:00 slow sw						-50.90	-50.48	-46.89
Carr. Lon 00:00 fast sw						323.35	323.34	339.28
Lat 00:00 fast sw						-51.01	-50.38	-49.67
Carr. Lon 12:00 slow sw						336.64	344.19	348.30
Lat 12:00 slow sw						-51.01	-49.68	-48.51
Carr. Lon 12:00 fast sw						330.59	334.26	342.92
Lat 12:00 fast sw						-51.19	-51.89	-49.99

Estimated connectivities for PSP-P1





Connectivities (top) and EUV re-projected map from combined STEREO and AIA (bottom)

- Relatively homogeneous in longitude
- Huge dispersion in latitude
- “Erratic” jumps of the connectivity in time
- Match with observations

Why are models’ predictions so different, even for a quiet time?

$\Longrightarrow$ Analysis of the models is needed

PSP-P1 coronal models

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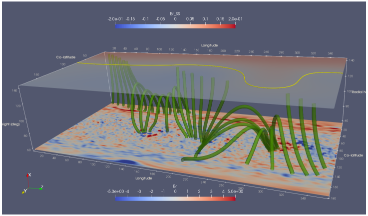
Overview

2 current-free models (IRAP, WSA) and 2 with currents (DUMFRIC, PSI-MAS)

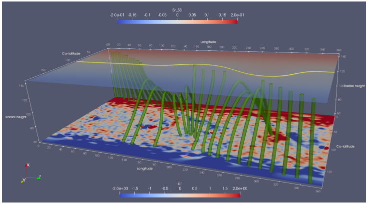
IRAP

- Nowcast and forecast
- PFSS (plus Parker spiral to satellite)
- Coronal model up to 2.5Rs
- Data from NSO, WSO, ADAPT
- Potential field



WSA-ENLIL

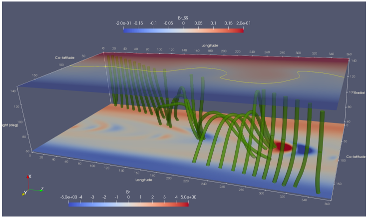
- Nowcast and forecast
- Up to 2.5Rs plus MHD to 1AU
- GONG (SOLIS) synoptic
- Forecast with ADAPT flux transport update
- Potential field



Overview-continued

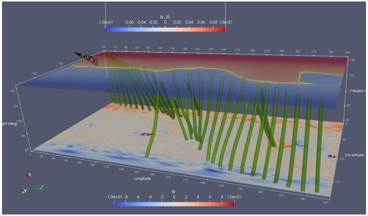
DUMFRIC

- Nowcast and forecast
- Magnetofrictional relaxation with SW drag
- Coronal model up to 2.5Rs (plus Parker spiral to satellite)
- Mgm evolution by flux transport model plus hand-inserted ARs
- Nonlinear field



PSI-MAS

- Nowcast
- Up to 30Rs plus heliospheric simulation
- HMI synoptic map
- MHD time-dependent with heating model
- Nonlinear field



- Models in spherical geometry, here flattened to Cartesian for visualization
- Different discretizations but same analysis routines
- Different volumes, but analysis restricted to $2.5R_s$

Magnetograms

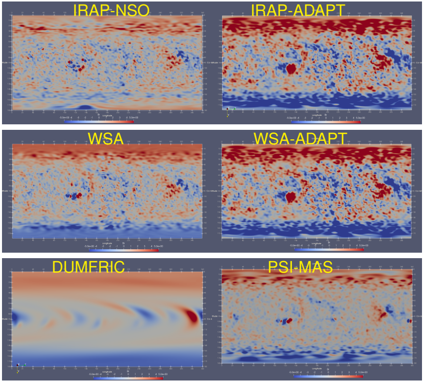
Different sources

- NSO/GONG
- WSO
- HMI

Different strategies

- ADAPT
- Evolution plus modeling
- Field recalibration

Quite different boundary conditions



Vertical field at the bottom of the coronal models

Dimensional values of $\vec{B}$, E_B, Φ_{tot} strongly depend on input mgm
$\Longrightarrow$ inter-calibration?

Comparison of models

Magnetic energy

The free energy is a measure of the non-potentiality of the model

Model	E [a.u.]	E/E_{p}
IRAP-NSO	3.0	1.31
IRAP-ADAPT	15.6	1.15
WSA	3.8	1.10
WSA-ADAPT	12.4	1.04
DUMFRIC	4.4	1.15
PSI-MAS	2.4	0.99

Magnetic energy E and the energy to potential energy E/E_{p}

- E reflects different normalization **and** input mgm
- Very different levels of "non-potentiality" (0-30%)
- Only PSI-MAS and DUMFRIC have currents
- PSI-MAS close to potential

For an input field $\vec{B}$ and corresponding potential field $\vec{B}_{\mathrm{p}} = \vec{\nabla}\phi$ with same $\vec{B}\cdot\hat{n}$ on $\partial\mathcal{V}$, define

$$E_{\mathrm{J}} = \frac{1}{2}\int_{\mathcal{V}} \left(\vec{B} - \vec{B}_{\mathrm{p}}\right)^2 \mathrm{d}\mathcal{V} \quad \text{or} \quad \tilde{E}_{\mathrm{J}} = \frac{1}{2}\int_{\mathcal{V}} \vec{B}^2\,\mathrm{d}\mathcal{V} - \frac{1}{2}\int_{\mathcal{V}} \vec{B}_{\mathrm{p}}^2\,\mathrm{d}\mathcal{V}$$

as the energy of the current-carrying part of the field.

Thomson theorem : $E = E_{\mathrm{p}} + E_{\mathrm{J}}$ the potential field is the minimal energy state, unless the field is not solenoidal, then

$$E_{\mathrm{div}} = E_{\mathrm{J}} - \tilde{E}_{\mathrm{J}} = \frac{1}{2}\int_{\mathcal{V}} \phi\left(\vec{\nabla}\cdot\vec{B}\right)\mathrm{d}\mathcal{V}$$

For PSI-MAS is $E_{\mathrm{div}}/E = 2\%$ and $E_{\mathrm{J}}/E = 2\%$, *i.e.*, $E_{\mathrm{div}} \simeq E_{\mathrm{J}} \Longrightarrow$ requires more accurate evaluation (*e.g.*, Valori *et al.*, 2013) especially because **it might be due to our interpolation, not to the simulation**

Potential field computed using PFSSPY by A. Yeates

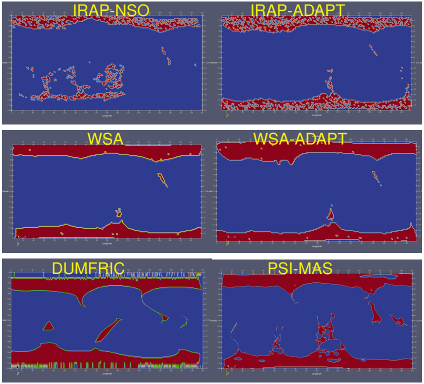
Open flux

Model	Φ_{tot} [a.u.]	Φ_{open}/Φ_{tot}
IRAP-NSO	15.4	0.09
IRAP-ADAPT	29.5	0.16
WSA	17.5	0.18
WSA-ADAPT	30.2	0.20
DUMFRIC	11.6	0.40
PSI-MAS	12.1	0.29

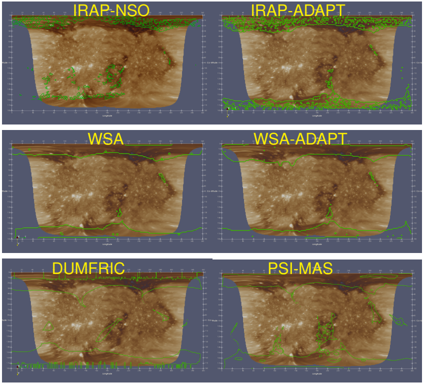
Total unsigned flux Φ_{tot}, fraction of open to total flux Φ_{open}/Φ_{tot} (Paraview tracer)

- Significant differences in Φ_{open}/Φ_{tot} (10-40%)
- All capture some of the CH, none is perfect
- PSI-MAS (and DUMFRIC?) seems to catch CH extension best
- To be included in the MADAWG online tool

Open flux maps



STEREO-AIA193 and open-flux contour



Open flux and fl tracers

The comparison of open flux maps and CH is one of the few observational test available

Φ_{open}/Φ_{tot}	Full	N-pole	S-pole
IRAP-NSO	0.10	0.02	0.02
IRAP-ADAPT	0.26	0.09	0.11
WSA	0.23	0.09	0.10
WSA-ADAPT	0.25	0.08	0.12
DUMFRIC	0.52	0.14	0.16
PSI-MAS	0.34	0.10	0.13

Fraction of open to total flux Φ_{open}/Φ_{tot} for the sull sun, and above/below $\pm 65^\circ$ (SSW tracer)

Polar (bipolar) flux affects the global shape of the field

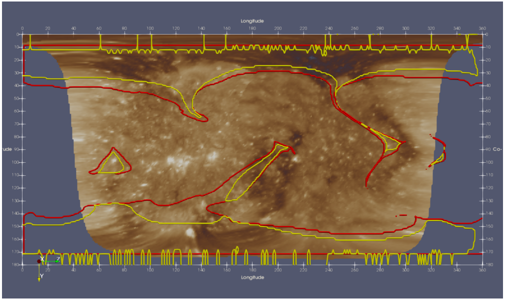
- Significant differences on polar fluxes too
- Small imbalance
- Dependence on fl tracer can be as big as 20%

... not the same values as in the previous slide ...

Using different streamline tracers (from Paraview or SSW)

- Qualitatively similar but
- Different open flux boundaries
- Affect flux estimations

of the same coronal model!



DUMFRIC: Open flux for SSW (red) and Paraview (yellow) tracers

Tuning of tools is required before using them for validation

Open flux and PFSS

The PFSS is the workhorse especially of near-realtime models

Open field map and Φ_{open}/Φ_{tot} depend on where the top boundary is placed (see *e.g.*, Linker Apj 2017)

Right: Open flux maps for the same mgm but top boundary at (a) $2.5R_S$ (b) $2.0R_S$ (c) $1.4R_S$ and (d) $1.3R_S$

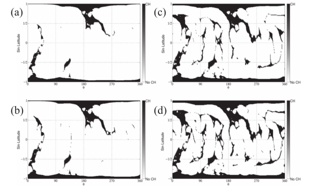
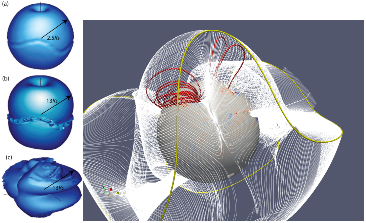


Figure 2. Open field regions (black) for four PFSS models using the NSO VSM CR2098 map for the boundary condition. (a) $R_{SS} = 2.5R_S$, (b) $R_{SS} = 2.0R_S$, (c) $R_{SS} = 1.4R_S$, and (d) $R_{SS} = 1.3R_S$.



Shape of SS for PFSS and MHD simulations (Riley ApJ 2006) and PFSS null line at SS

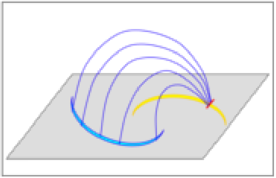
- PFSS-like BC assume spherical source surface (SS) at the same height (2.5 R_s), *at all times of the solar cycle*
- At the SS, the PIL of Br is a null line $\Longrightarrow$ strong topological constraint

Choose the height of the SS that best match EUV-CH open-flux maps

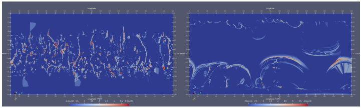
Quasi-Separatrix Layers

Quasi-Separatrix Layers: volumes of high values of the connectivity gradients, represented by high values of the squashing factor *Q* (see *e.g.*, Demoulin 2006)

Q can be used to synthetically characterize the field topology

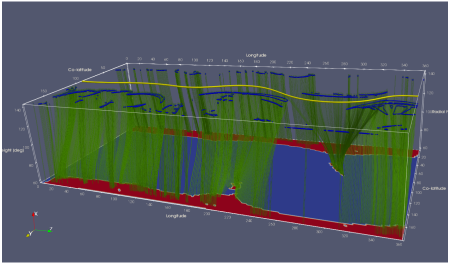


Q can be very complex at the photosphere (small scales) easier at the top



WSA: Q at the photosphere and source surface

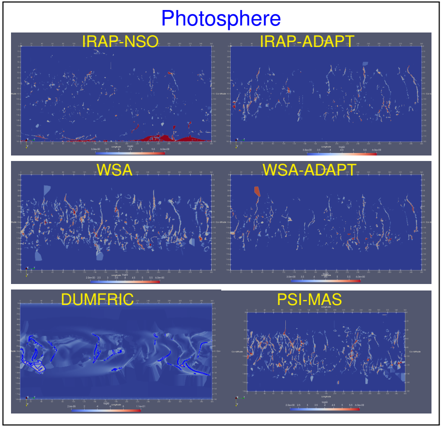
Right: Connection between open flux and Q at source surface

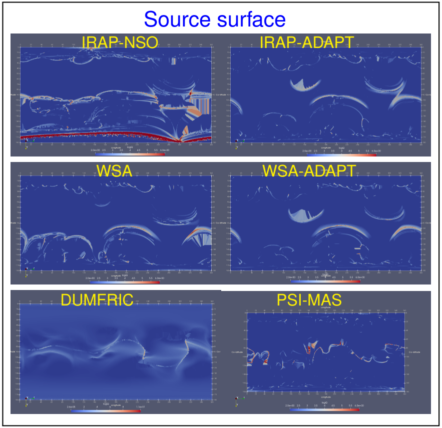


Useful to, *e.g.*, address the model's sensitive regions at source surface

Q maps are computed using QSLsquasher by S.Tassev

QSL maps





- Very different topology, except for IRAP-ADAPT and WSA-ADAPT at SS (similar mgm)
- PSP field line crossing a SS high-Q layer $\Longrightarrow$ jump in the connectivity at the photosphere
- Still too much structure in Q $\Longrightarrow$ deeper computation and better saturation
- To be included in the MADAWG online tool

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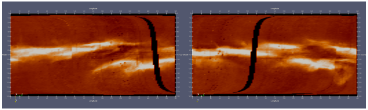
White light



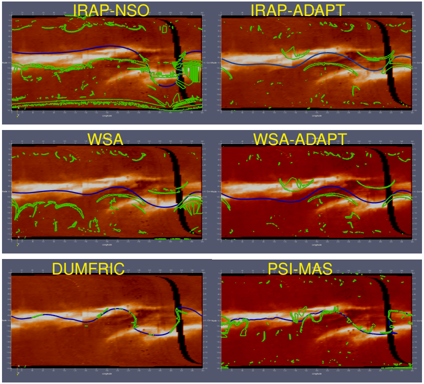
East- and West-limb white light stacks

White-light synoptic maps from LASCO-C2 stack of East- or West-limb slices at 3Rs
Prepared by A. Kouloumvakos (IRAP)

- All models' PIL roughly align with WL
- But none reproduces the fine structure
- *Some* occasional resemblance with QSLs
- Synoptic (WL) vs 'instantaneous" (PIL,QSLs) and height mismatch

- To be included in the MADAWG online tool

Some models are non-potential ⟹ compare with currents

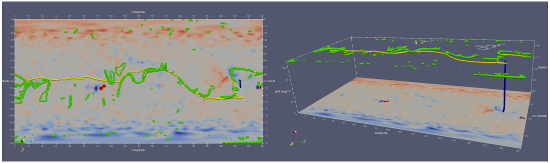


Outlook

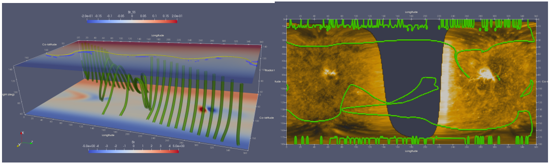
- CH vs open-flux optimization
- Inter-calibration of magnetograms

Polarity from PSP data

- Compare with QSL
- Compare with *in-situ*
- Polarity on PSP trajectory across PIL at SS



PSP field line in the PSI-MAS model, and log $Q = 3$ isolines



The DUMFRIC model for the PSP-P2, and open flux isolines

PSP-P2 4th April 2019

- More complex corona
- More models available
- Same level of prediction dispersion

Suggestions for additional metrics are welcome!

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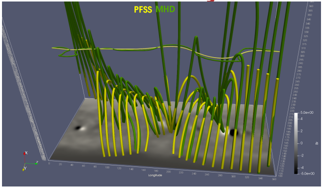
Summary

A set of tools is being developed for

- Quantitative comparison of coronal models
  - Fluxes and energy
  - Field lines and topology
  - Coronal holes, QSLs
  - Comparison with EUV and WL
- Test of diagnostics for inclusion in the MADAWG online-tool



PSI-MAS and PFSS comparison

We have learnt few **preliminary** information about the models for PSP-P1

- Large differences in open flux
- PSI-MAS and DUMFRIC seems to match CH shape best
- PSFF may require additional tuning to improve CH matching
- Quite different topology
- Q maps at SS identify regions of connectivity jumps
- Input mgm may lead to similar SS topology nonetheless
- WL maps are not very discriminant

To identify which combination of BC and model works best requires extensive application of analysis