Fieldline Connectivity to the Sun
Ensemble Forecasting

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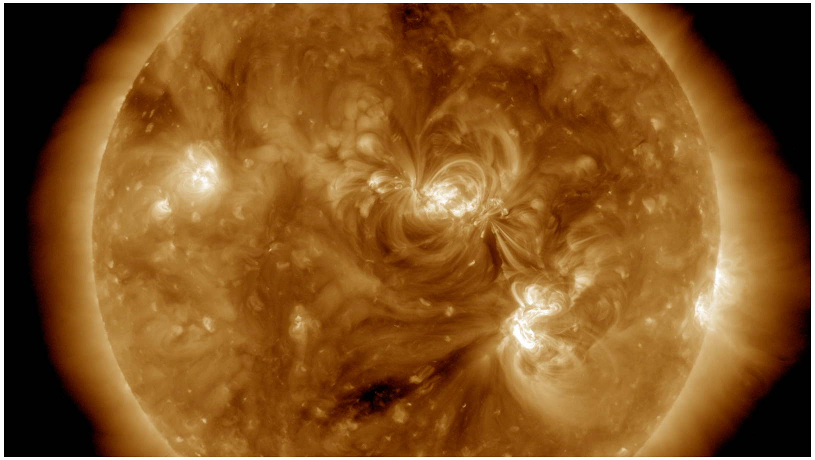
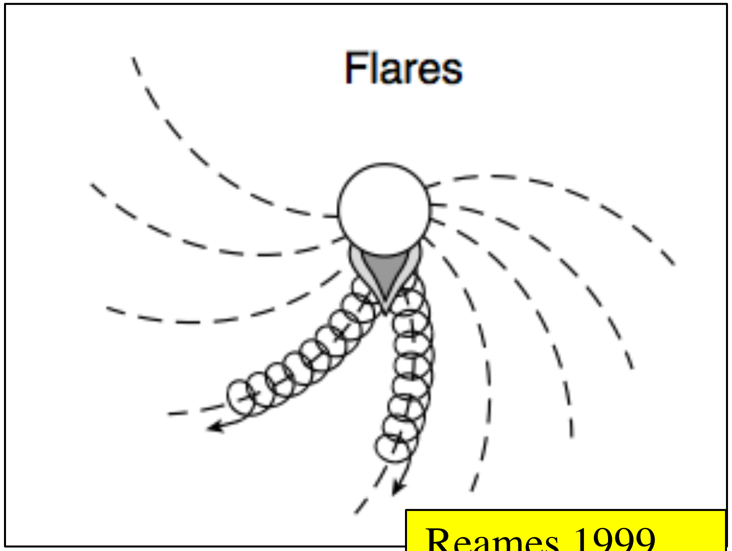
11th NASA Space Exploration and Space Weather Workshop - October 17th

Motivation

- Anticipating Prompt SEPs from Flares
- Energetic particles spiral along fieldlines
- Flares can temporarily open field lines or SEPs may leak to nearby open fieldlines
- Are we connected to near the flare site by an open fieldline?





Reames 1999

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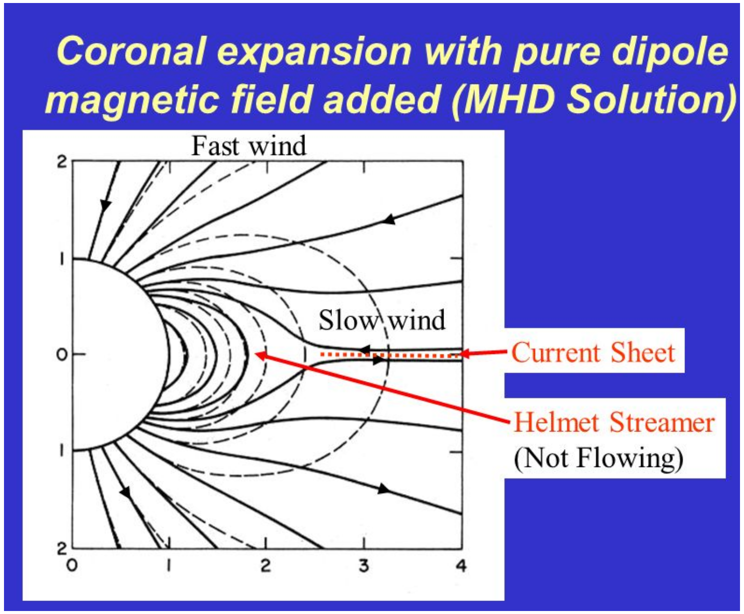
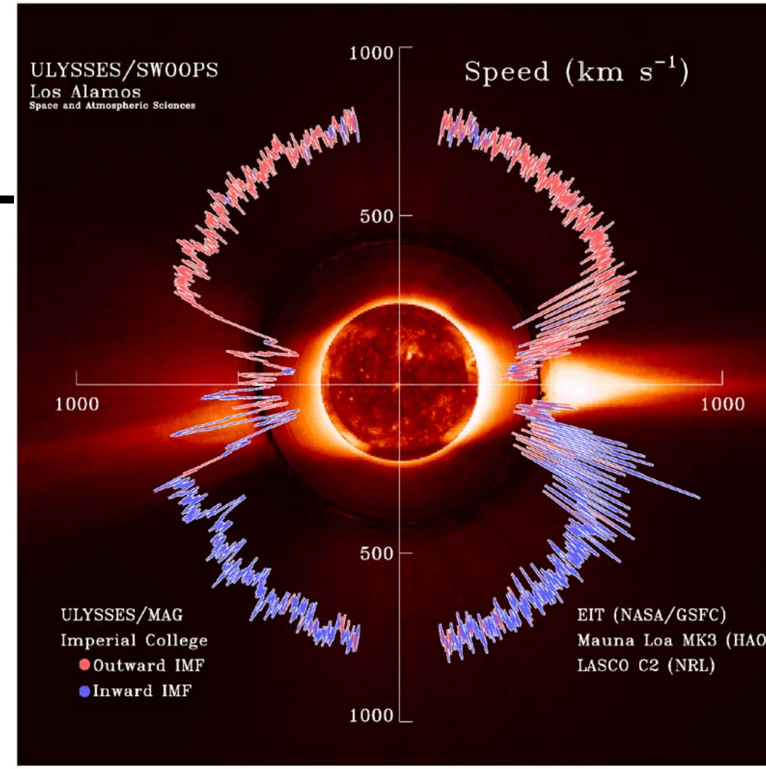
Typical System State





- Coronal field open at high latitudes
- Coronal field closed around low latitude sunspot groups
- Heliospheric Current sheet
- Parker Spiral
- Slow wind / Fast wind

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Models of Fieldlines in Ambient Solar Wind

- Simplest – Archimedean Spiral
  - Based on latest wind at L1 and solar rotation rate

- Slightly more sophisticated – PFSS Coronal model + Spiral
  - Combines a potential field model below $2.5R_\odot$ with Archimedean spiral

- Additional Complexity – Wang-Sheeley-Arge (WSA)
  - PFSS + SCS ($2.5 – 5R_\odot$) + kinematic wind approx. ($5R_\odot$ – 1AU).

- More Complex – WSA + ENLIL 3D MHD
  - WSA (PFSS+SCS(to 0.1AU)) + ENLIL 3D MHD (0.1AU – 2AU)

- Input Sources
  - Single Frame Synoptic photospheric magnetograms (GONG, NSO, SDO, etc)
  - Time evolving models of the surface flux – eg ADAPT

Archimedean Spiral
(Ignore all the messy details!)

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Assumptions

- Solar wind flows radially.
- Field is frozen in the plasma.
- Field is dragged open everywhere.
- Sun rotates every ~25 days.
- Solar rotation gives fieldlines a spiral shape
  - Tighter spirals for slower wind

Fieldline Footpoint Location Calculation

Transit time of solar wind from Sun to Earth

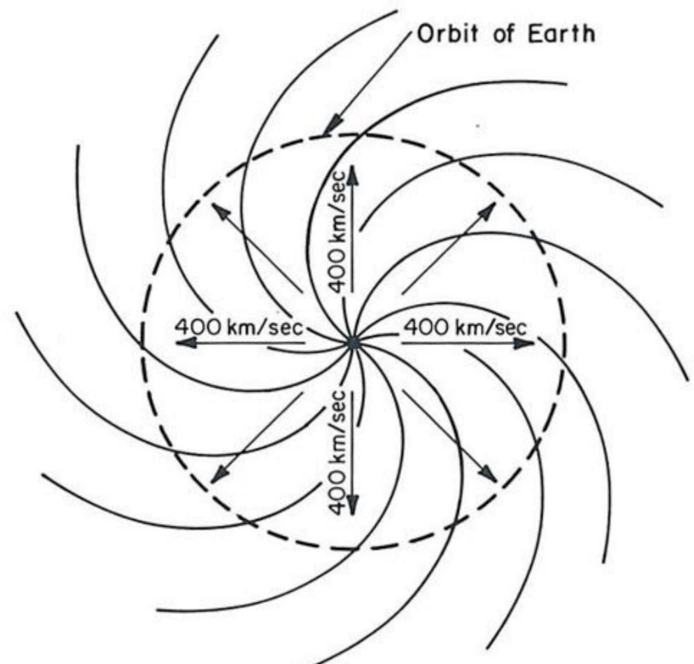
$$\delta t = 215\, Ro/v_r$$

Longitudinal offset from sub-Earth Longitude

$$\delta\phi = +\Omega \sin\theta \;\; \delta t$$

Latitudinal offset from sub-Earth Latitude

$$\delta\theta = 0$$



Parker (1963)

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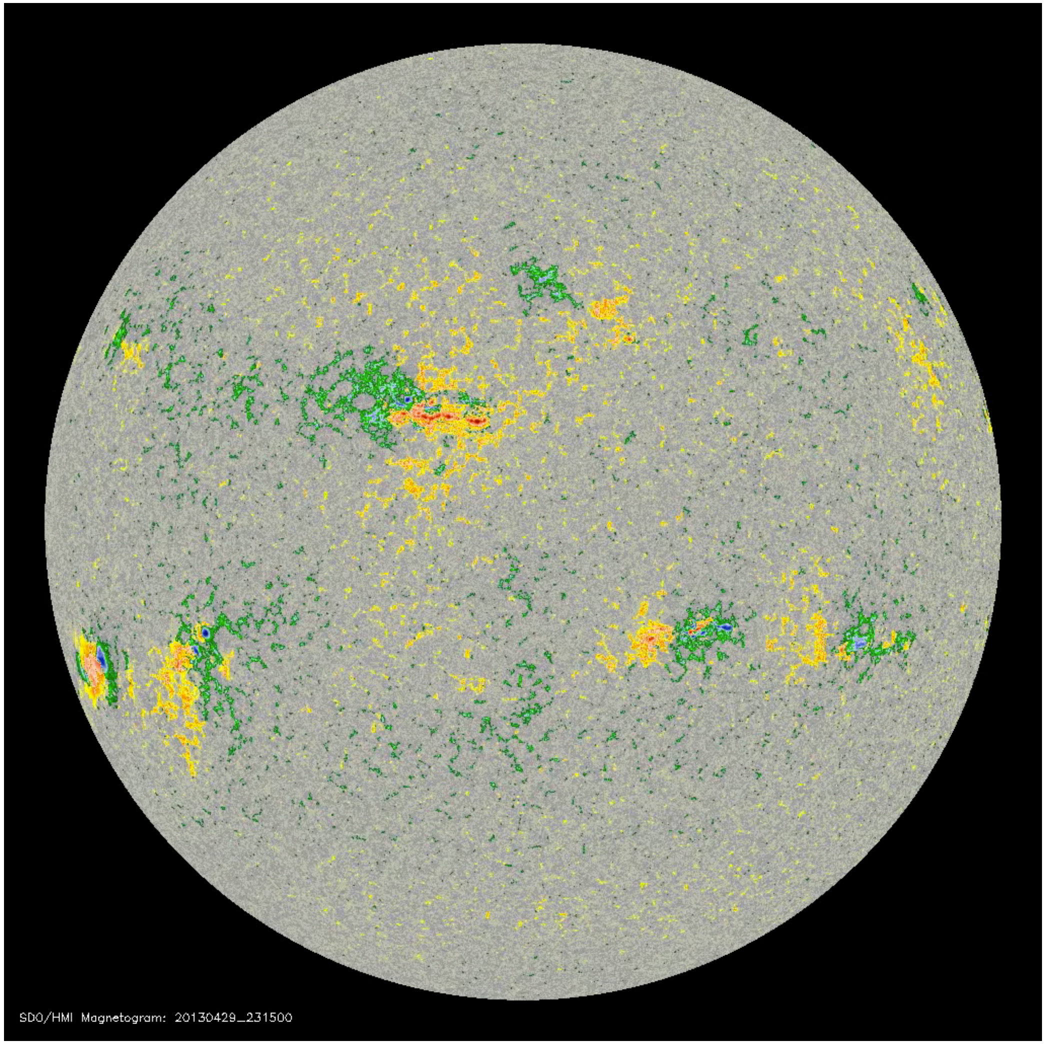
Coronal Magnetic Field is Messy!



SDO/HMI
4/29/13 – 5/1/13

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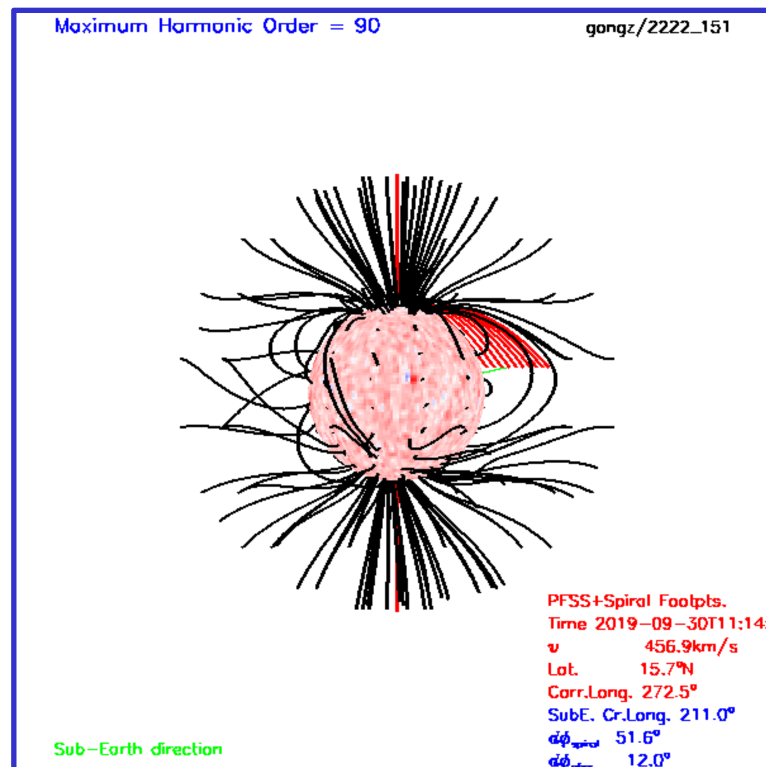
Potential Field Source Surface (PFSS) + Spiral Model

- Field must match the surface flux distribution from the input photospheric synoptic magnetogram
- Assumes no currents exist between $r = R_\odot$ and the source surface at $r = 2.5\ R_\odot$.
- Assumes field is radial at the source surface
- Solution of Laplace's equation
  - Analytic
  - spherical harmonic expansion
- Heliospheric field determined from simple Parker (Archimedean spiral) based on time varying wind speed measured at 1AU.
- Obvious weakness – the real solar field is not globally radial beyond $2.5R_\odot$!
  - Has a current sheet!

$$\boldsymbol{J} = \nabla \times \boldsymbol{B} = 0$$

$$\Rightarrow \quad \boldsymbol{B} = \nabla\phi$$

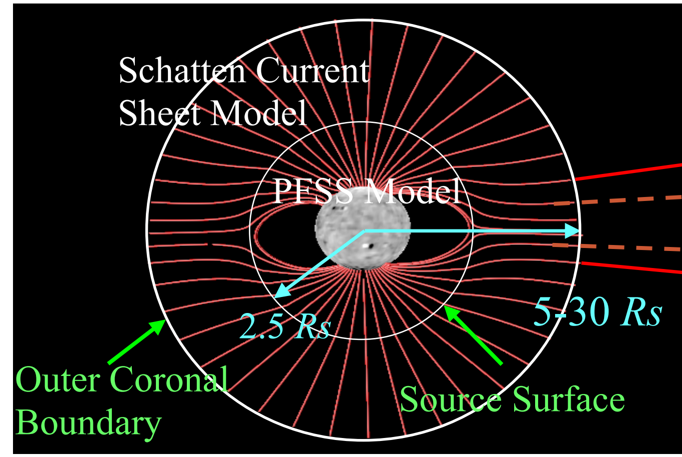
$$\Rightarrow \quad \nabla \cdot \boldsymbol{B} = \boxed{\nabla^2\phi = 0}$$

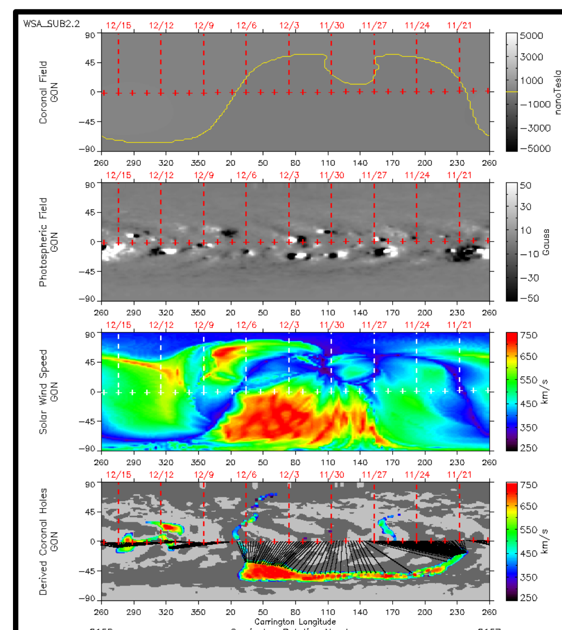


WSA

1. Adds a Current Sheet component to the PFSS model to represent the heliospheric current sheet.

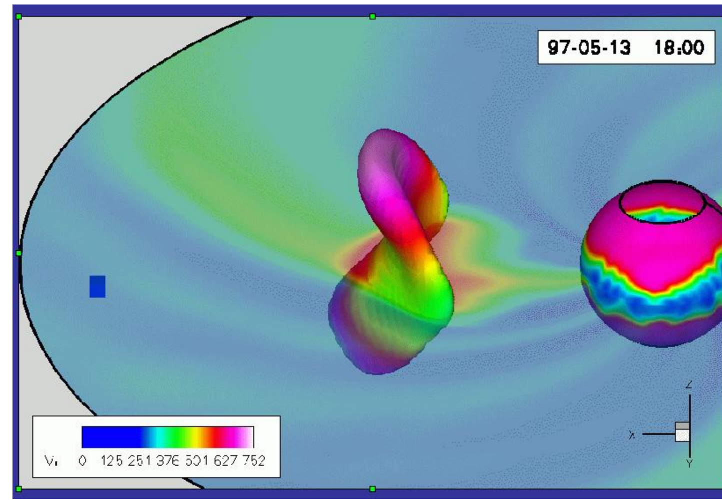
2. Propagates the solar wind using an empirical formula for the wind speed at the outer boundary of the SCS component.
   - Wind speed is a function of the rate of expansion of the flux tube and the proximity of the fieldline footpoint to the nearest coronal hole boundary

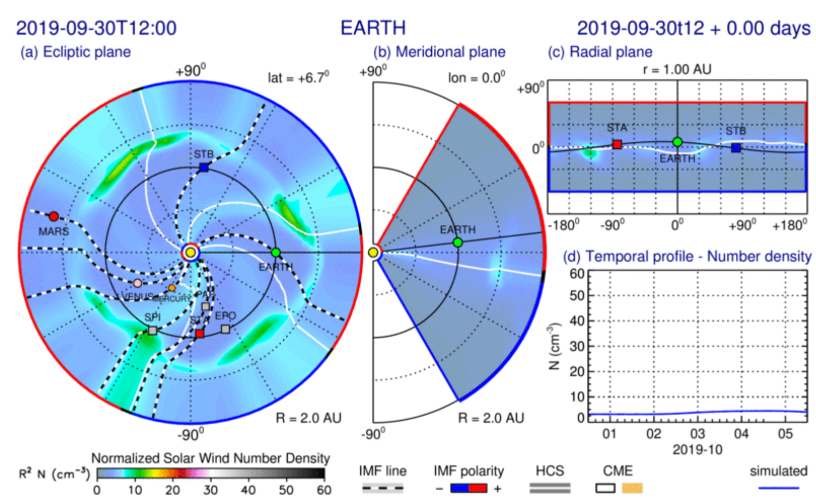




WSA/ENLIL (Odstrcil)

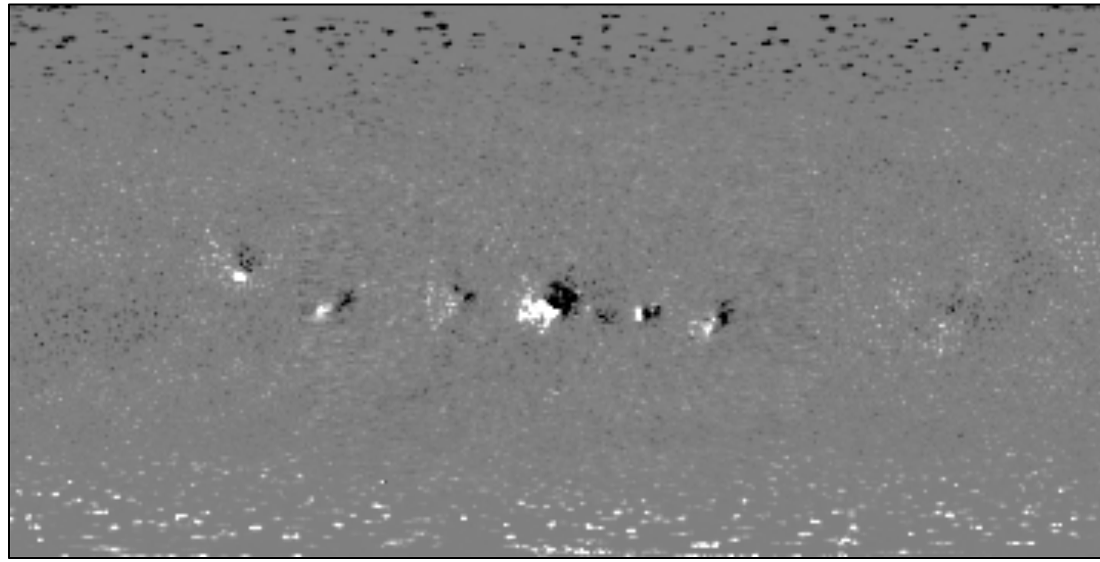
- Time dependent Heliospheric 3D MHD
- Rotating inner boundary at $21.5R_\odot$
- Based on WSA field and wind speed, *but*
  - Azimuthal field component added
  - Azimuthal offset added to allow for wind propagation time from 1 to $21.5R_\odot$
  - $v \rightarrow (v - 50)$ km.s^{-1}, with floor of 250 km.s^{-1} and ceiling of 650 km.s^{-1}
  - $n\,v^2 = 300 \times 650^2$ (constant KE)
  - $n\,T = 300 \times 0.8$ (constant pressure)
- Outer boundary at 2AU
- Can run ambient or cone model cases





Surface Flux Evolution - ADAPT

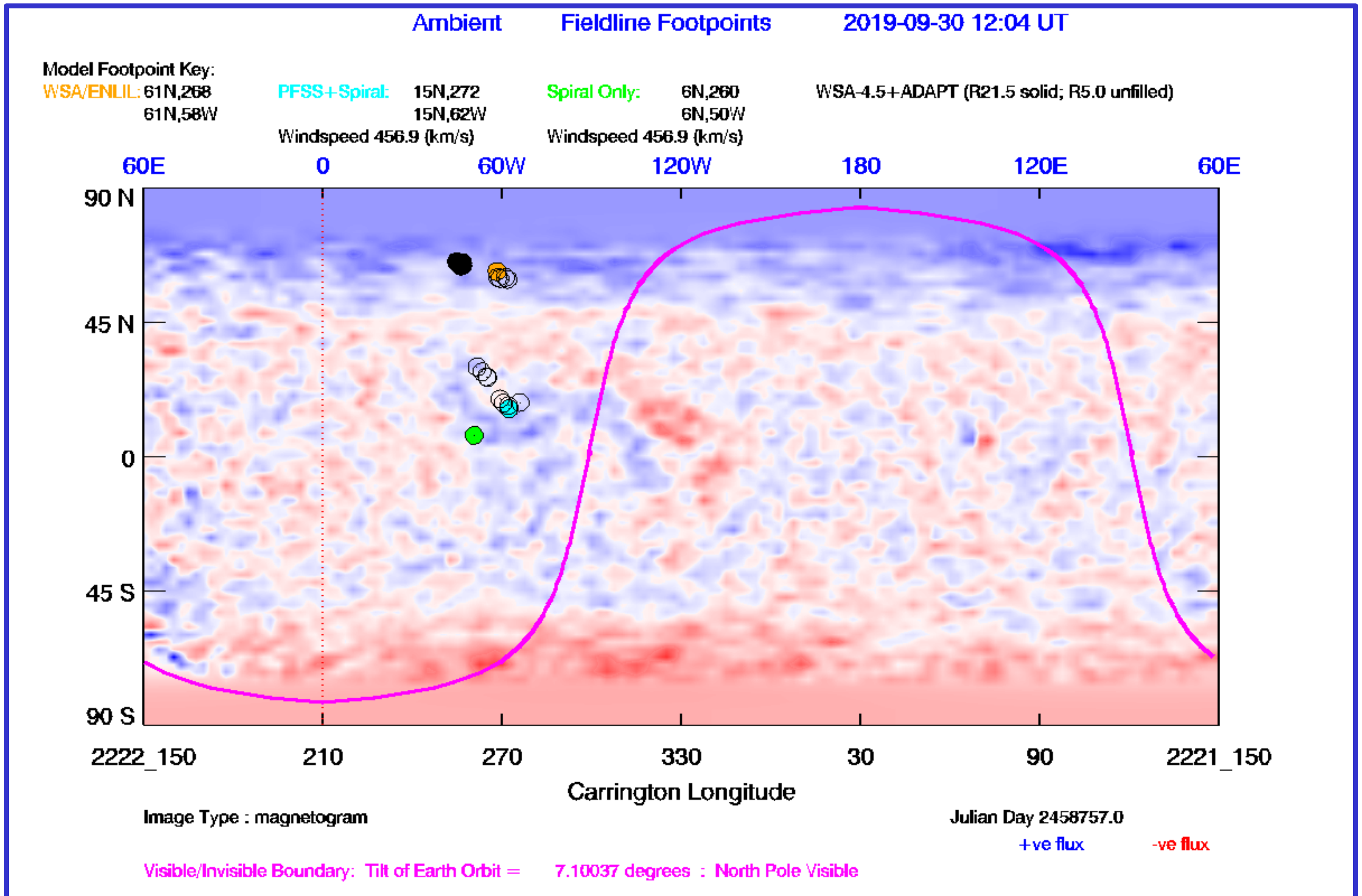
- Models need global surface field
- Far side is not observed
- Field does evolve when on far side



- Surface flux evolution models model this with known flows and statistically based realizations of emergence/submergence
- eg ADAPT – Henney et al
- Others, SURF, DeRosa?
- ADAPT (Air Force Data Assimilative Photospheric Flux Transport) – 12 time series (‘realizations’)

ISWA Cygnets – Earth Only

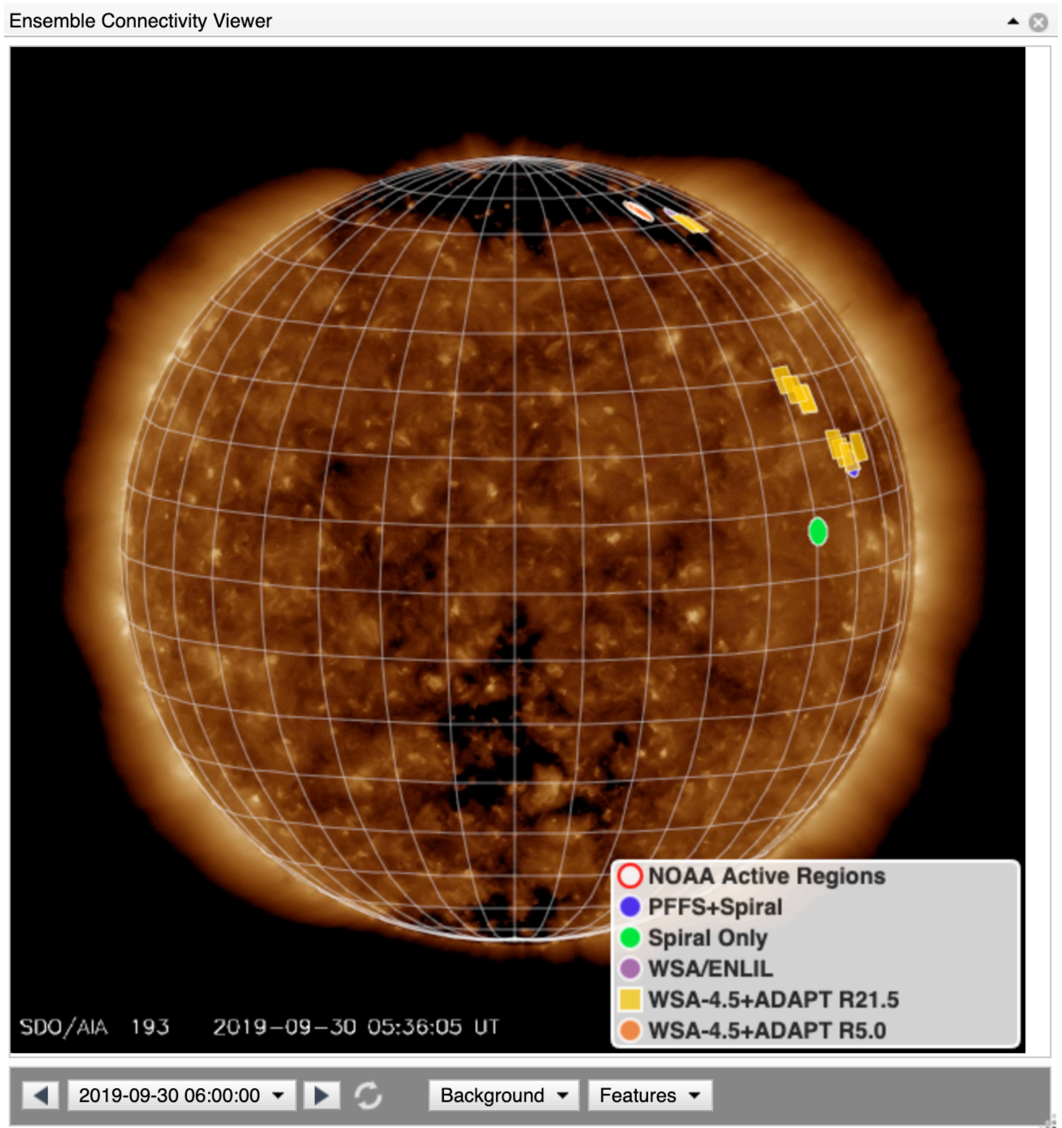
- All forecasts of footpoint connectivity to Earth from different models



5 day forecast

Background is surface magnetic flux

ISWA Cygnets – Earth Only



'SolarScape' View

Background is SDO/AIA 193Å

Can add locations of active regions and proximity alerts

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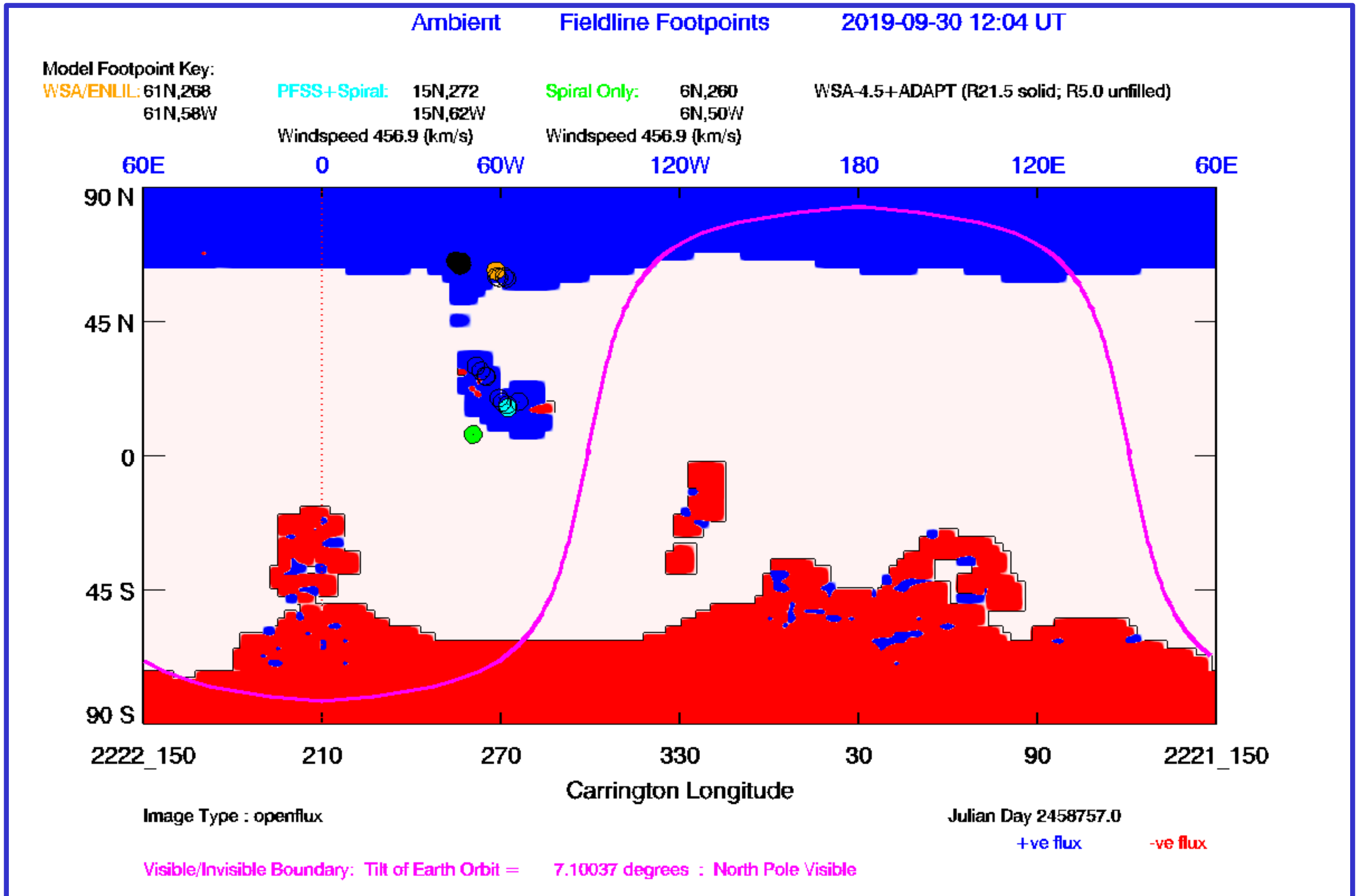
ISWA Cygnets – Earth Only

- All forecasts of footpoint connectivity to Earth from different models

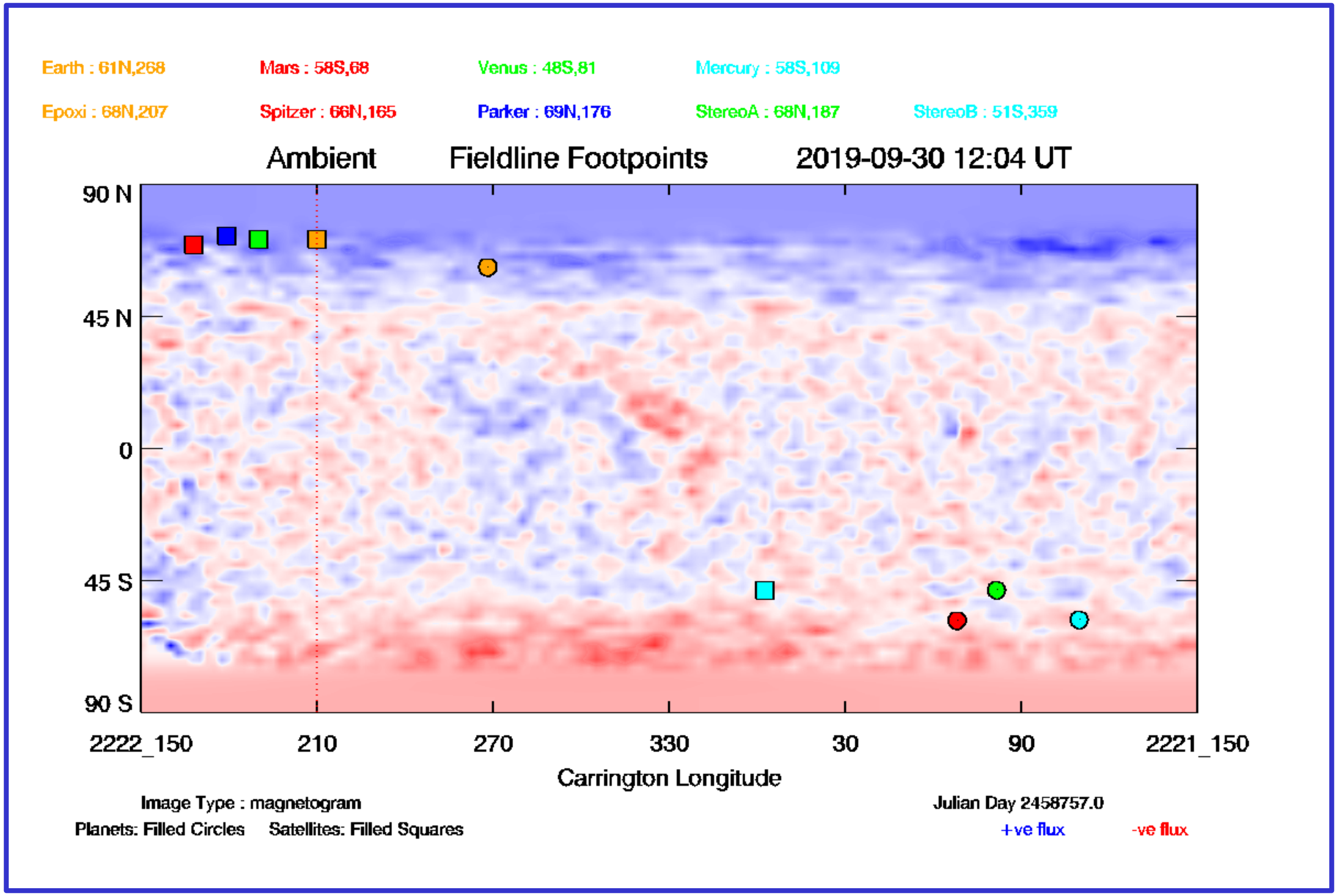


5 day forecast

Background is pattern of open and closed flux

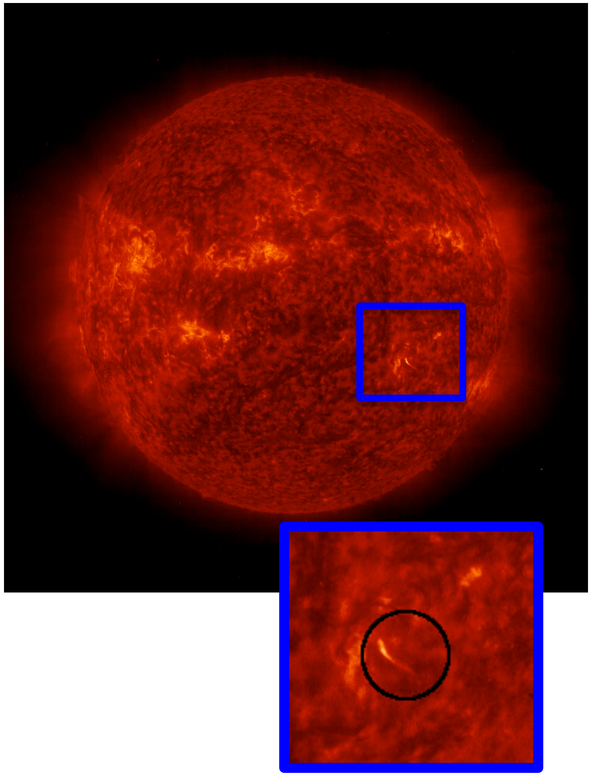
ISWA Cygnet
Inner Planets and Flight Missions

- WSA-ENLIL forecasts of footpoint connectivity to different inner heliosphere objects



Validation

How do we know what the right answer is?



<u>Method</u>

- Develop a list of impulsive SEP bursts recorded near Earth
- Establish the source events on the solar surface (Soft X-ray, EUV, Hα, type III)
- Focus on small events because these are less likely to have wide propagation cones
  - These small events are not themselves a space weather threat
- Model fieldline connectivity at the time of the SEP burst
- Compare model's Earth connected fieldline footpoint with the 'observed' source location

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Model 'Accuracy'

SEP Event Number	Longitude Offset ASM	Longitude Offset PFSS +Spiral	Longitude Offset WSA	Longitude Offset WSA/ ENLIL	Latitude Offset ASM	Latitude Offset PFSS +Spiral	Latitude Offset WSA	Latitude Offset WSA/ ENLIL
1	2E	20E	1E/10E	20E	30N	38N	93N/91N	29N
3	44W	56W	56W/57W	56W	22N	6N	6N	8N
4	10E	13W	7W	5W	11N	32N	38N	46N
5	12E	9E	22W/19W	8E	11N	8S	6S	1S
6	29E	37E	13W/14W	2W	24S	52S	56S	58S
8	30W	32W	35W	47W	26S	11S	11S	12N
9	15E	12E	9E	7E	8N	17N	29N	42N
11	10E	2W	34W/32W	20W	10N	2S	0S	0S
13	6E	1W	5E/34E	34E	23S	3S	1N/7S	16N
14	10E	0	9W/13W	5W	10S	8S	8S	16N
15	95W	88W	93W/78W	88W	10N	25N	27N/40N	27N
15*	46W	39W	44W/29W	39W	16N	31N	33N/46N	33N
16	24W	26W	32W/31W	26W	15S	24S	26S/25S	23S
18	28E	13E	38W	20W	16N	1S	13S	41S
19	10E	50E	68E/66E	56E	26S	30S	29S	22S
20	27W	3E	16E	16E	16S	27S	24S	24S
Average	23	25	27/32	24	17	19	27/24	25
Average Excl. 3,15,19	17	14	18/22	18	17	19	29/25	26

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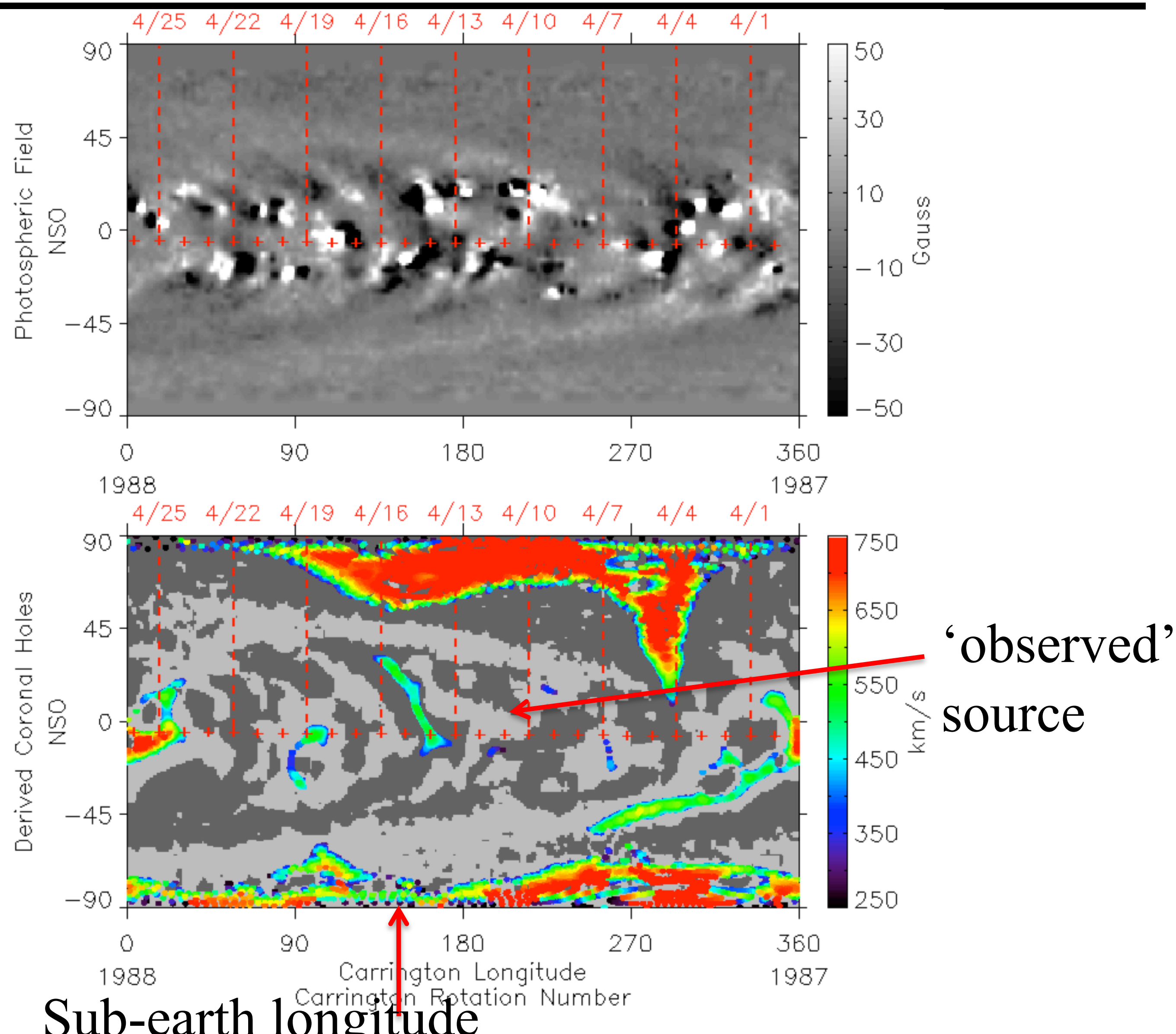
Absence of Low Latitude Flux (event #19)



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Support Slides

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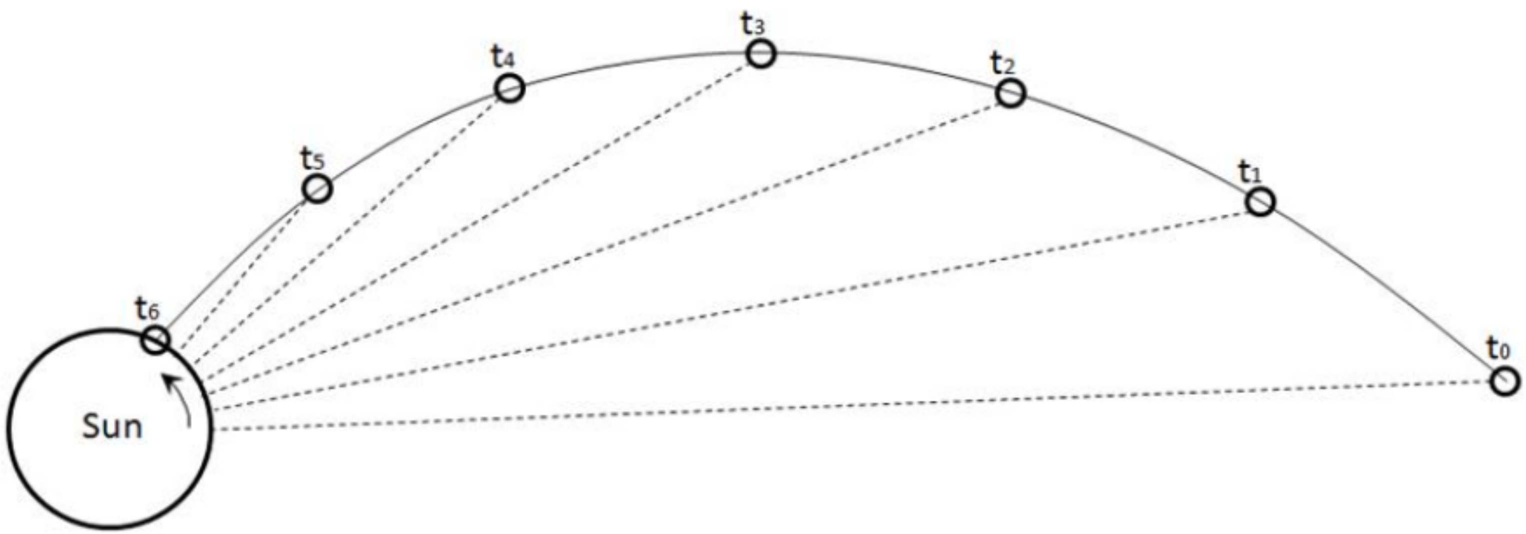
Corona

$(1 - 2.5r_o)$

Eclipse
2016
Indonesia

Total Solar Eclipse 2016

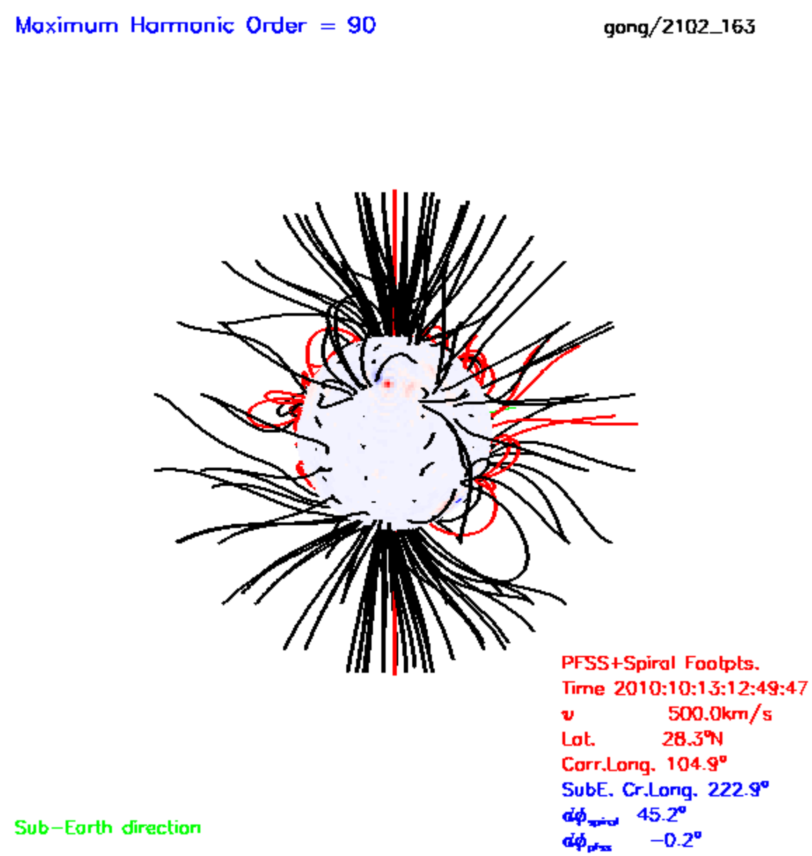
Archimedean Spiral



- Wind drags field in radial direction at local wind speed
- Solar rotation gives fieldlines a spiral shape
  - Tighter spirals for slower wind
- Model can provide footpoint longitude nowcasts
- Footpoint latitude is always given by the angle of the ecliptic plane

Potential Field Source Surface (PFSS)

- Altschuler and Newkirk(1969), Schatten (1971)
- Assumes simplest model of coronal field
  - Current-free between 1r_o and 2.5r_o
- Radial field imposed at 2.5r_o
- Photospheric magnetic field determined from LOS synoptic magnetogram
- Heliospheric field determined from simple Parker (Archimedean spiral) based on time varying wind speed measured at 1AU.



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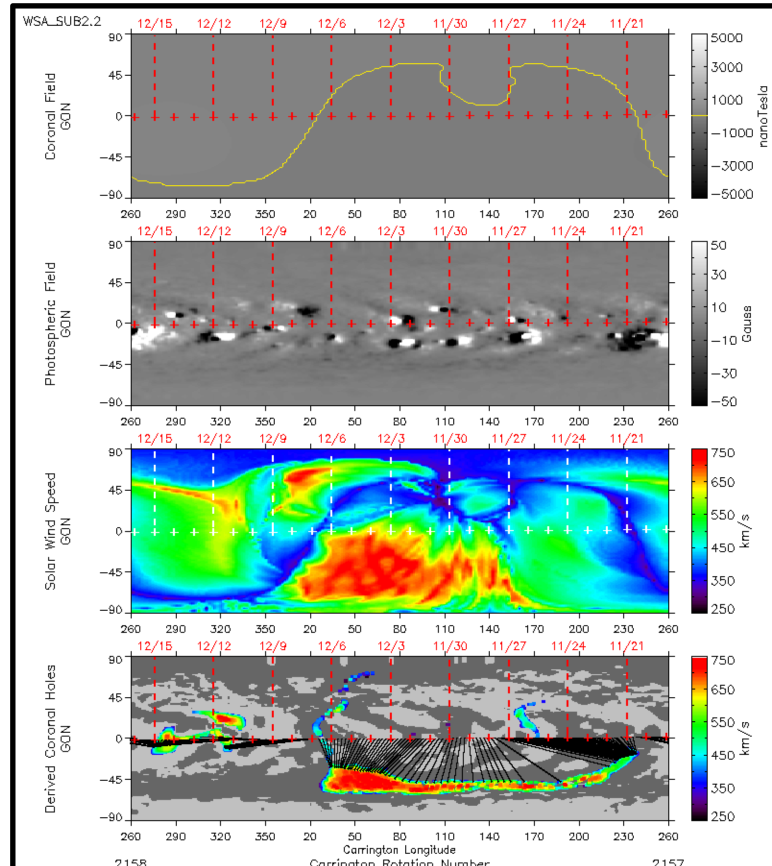
Wang-Sheeley-Arge (WSA) Model

- PFSS from surface to $2.5R_o$
- Pseudo-potential solution from $2.5R_o$ to $21.5R_o$
  - Solves separate potential problems for regions of +ve and –ve radial flux
  - Introduces a current sheet at boundary plane
- At $21.5R_o$ defines a local wind speed using an empirical formula based on
  - Rate of expansion of flux tubes
  - Proximity of fieldline footpoint to the nearest coronal hole boundary

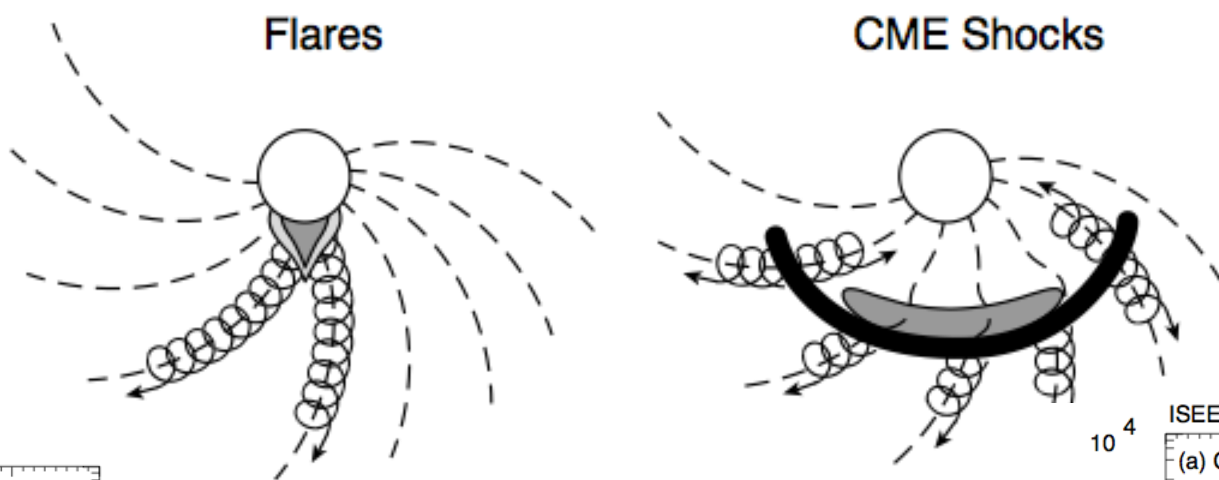


Sources of SEPs

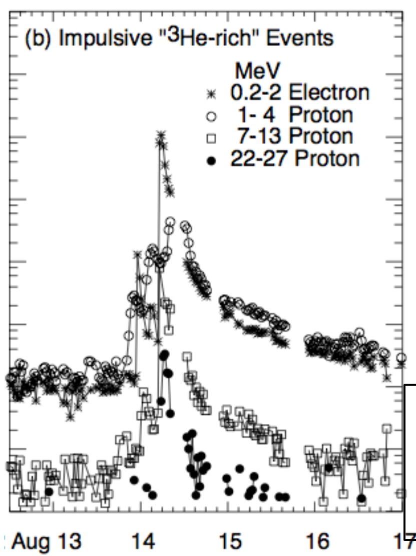
New Picture:

Reames 1999

Impulsive

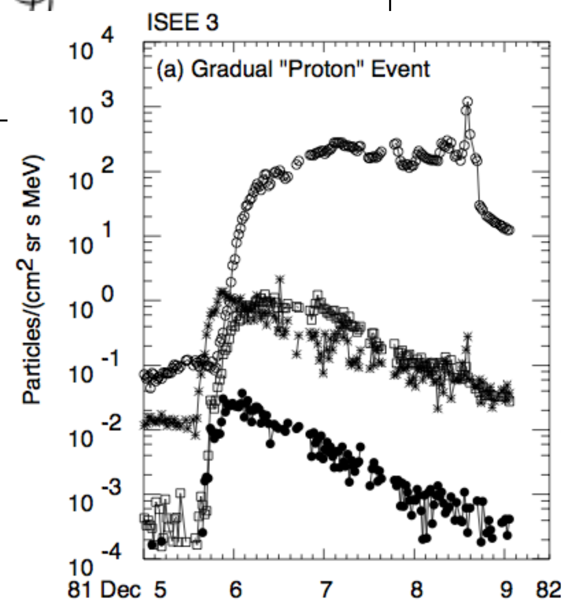


Gradual

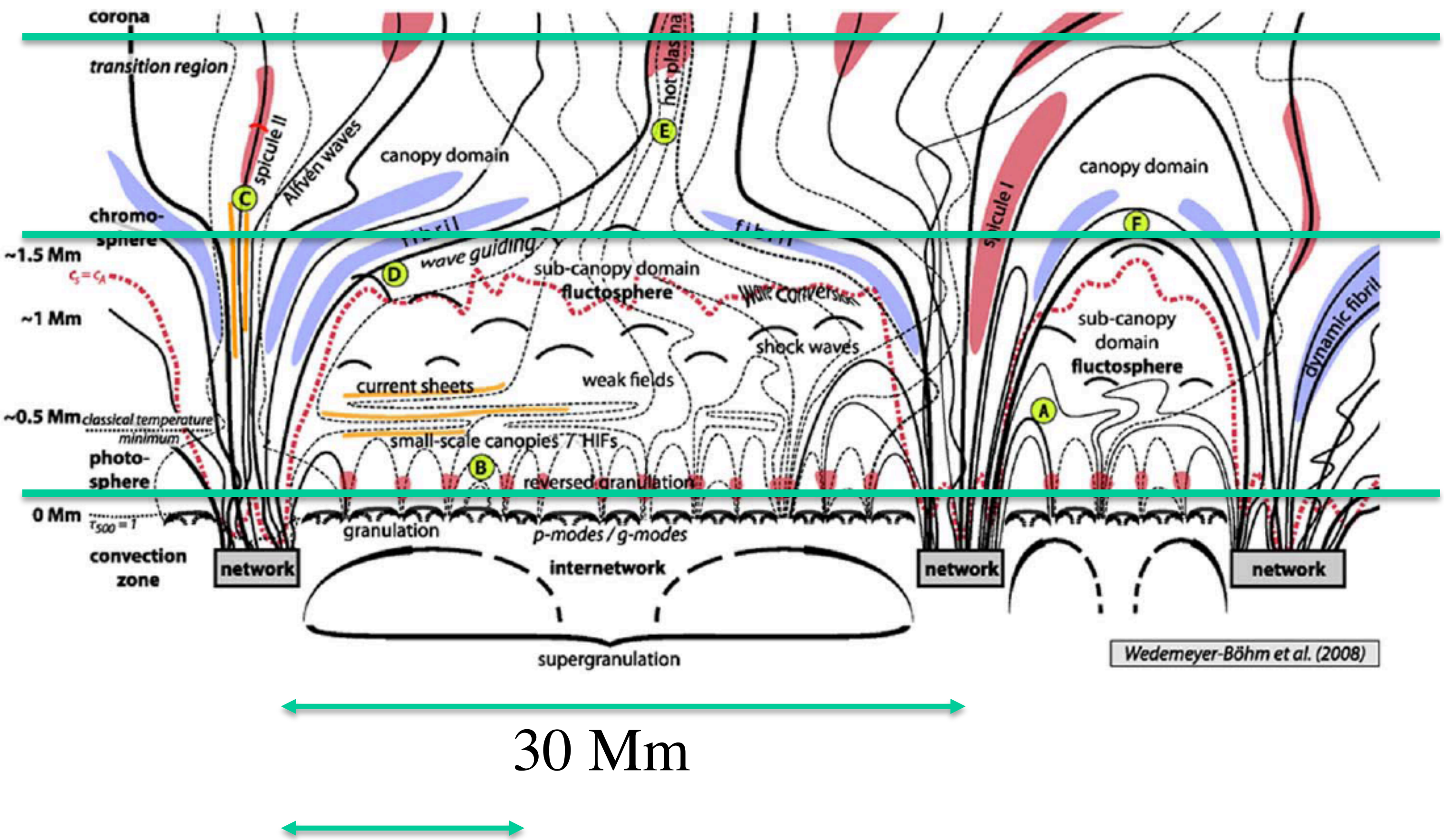


Mechanisms ?

- Resonant wave-particle interactions
- Direct acceleration in reconnection sites



Magnetogram Height and Model Inner Boundary



Coronal model base

Chromospheric magnetograms

Photospheric magnetograms

GONG Pixel size

Aspect ratio distorted – Height enhanced by factor of 10

Particles and Fluids

- Plasma at any point is a collection of charged particles with a distribution of velocities.
- All charged particles spiral along field lines
- The majority of the particles are slow enough that they ‘collide’ frequently with each other, travelling short distances between collisions, exchanging momentum and so sharing an average local flow speed.
  - These are treated as a fluid
  - The fluid flow is driven by gradients in pressure, gravity and Lorentz forces
  - The fluid wants to move out radially and will do so unless constrained by the magnetic field
  - If the fluid carries enough oomph it can force the field to adjust to accommodate its movement
  - In a low resistivity plasma the fluid and field are locked together – the so called ‘frozen-in’ theorem.
- Particles in the high energy tail of the velocity distribution have much longer (proportional to v^4) mean free paths and so essentially move independently
  - There are too few of these to carry a sufficiently large current that could modify the field.
  - Therefore these simply spiral along the fieldlines

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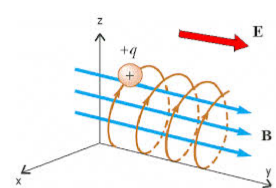

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Basic Picture of Solar Wind and IMF

- Magnetic Field at surface – active regions, plage, quiet sun, coronal holes
- All charged particles spiral along field lines
- Charged particles in the plasma have a distribution of velocities
- Low velocity particles have a short mean free path – they frequently exchange momentum with each other and so on larger scales their motion is the average 'flow' speed of the collide with each other over short distances – their flow speed is determined by the collective 'group' properties of the low velocity particles
- The bulk of the plasma obeys a Frozen in condition
  - Pressure gradients mean wind wants to flow radially
  - Competition between field and flow
  - Ratio of ram pressure to magnetic pressure determines which dictates
  - Field wins near active regions in low corona – dictates plasma movement
  - Flow wins in weak field regions and at distance from the sun – flows drag field
    - Solar Wind opens weak field
- Energetic particles have very low collision frequencies
  - Behave independently of the bulk flow
  - Spiral along fieldlines
  - Objects connected along fieldlines to openflux near boundary with flaring ARs may experience prompt SEP events.

Some Basic Concepts 1

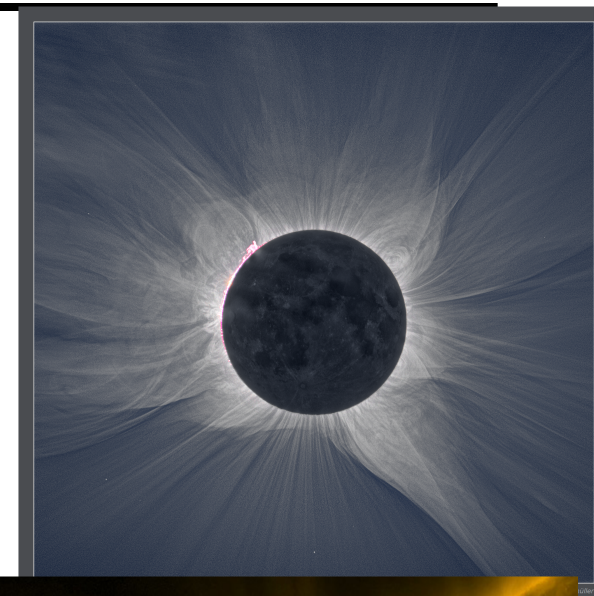
- Where electrical resistivity is low, ionized plasma and magnetic field are locked together – the ‘frozen-in condition’
- In MHD the Lorentz force decomposes into ‘magnetic tension’ + ‘gradient of magnetic pressure’

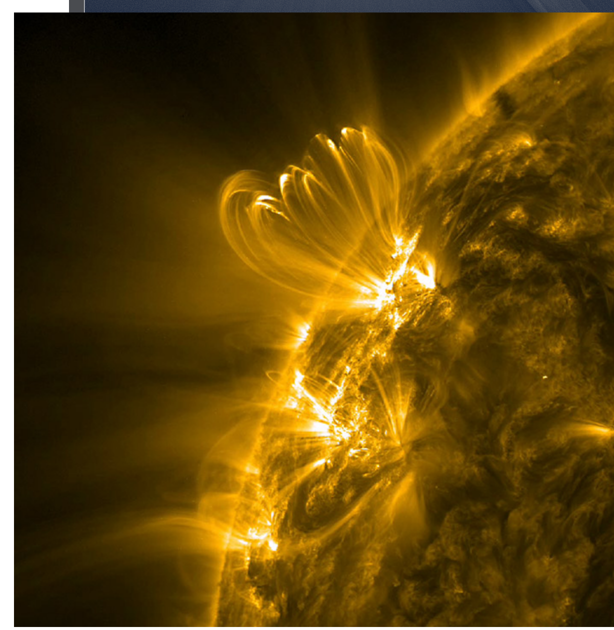
$$\boldsymbol{J} \times \boldsymbol{B} = -\ \boldsymbol{\nabla}\,(B^2/8\,\pi\,) + (\boldsymbol{B}\cdot\boldsymbol{\nabla})\boldsymbol{B}$$

Wants to expand Magnetized volume

Wants to unbend fieldlines

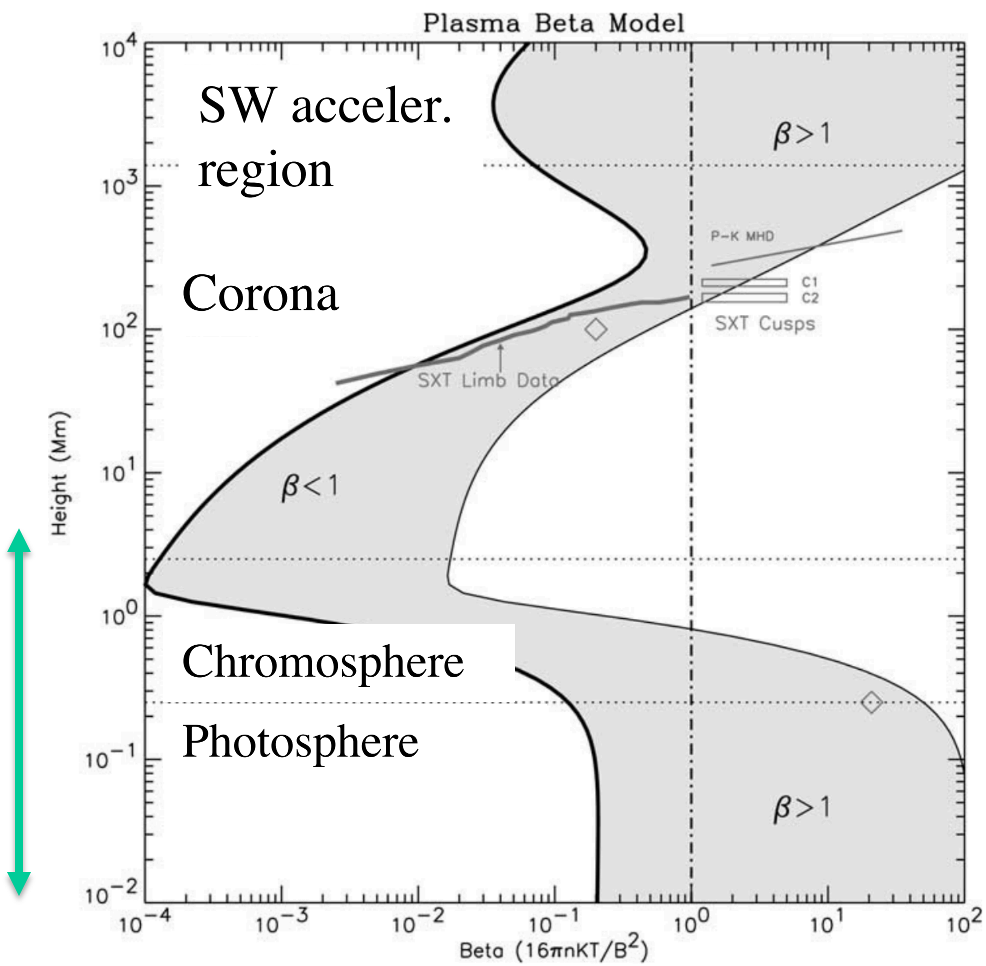
- Gas pressure ($p = 2nkT$) competes with magnetic pressure ($p_B = B^2/8\pi$)
  - Plasma $\beta = p/p_B$
- Where gas pressure dominates, the wind flow drags the fieldlines with it.
- Where magnetic pressure dominates, closed fieldlines trap the wind in loops close to the sun.





Some Basic Concepts 2

Plasma β above an active region



Flows drag field

Field controls plasma

Flows drag field

Assumptions behind Ideal MHD

- Quasi-neutrality
  - Plasma is locally neutral (on the macroscopic length scales we consider)
- Plasma motions are much slower than the speed of light
  - $v << c$
- Electron and ion velocity distributions are close to Maxwellian
- The electrical resistivity is so small that we assume it is zero

Equations of Ideal MHD

Conservation of mass

$$\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)\rho=\boldsymbol{0}$$

Conservation of momentum / force balance

$$\rho\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)\boldsymbol{v} = \boldsymbol{J}\times\boldsymbol{B}-\boldsymbol{\nabla}p+\rho\boldsymbol{g}$$

Magnetic force

Conservation of energy

$$\left(\frac{\partial}{\partial t}+\boldsymbol{v}\cdot\boldsymbol{\nabla}\right)\rho e = -\nabla\cdot(p\boldsymbol{v}) - \boldsymbol{\nabla}\cdot\boldsymbol{q}+H-R$$

Equation of state (how the gas can store energy internally)

$$e=\frac{3}{2}\,p = 2\rho k_b T/m_p$$

Induction equation

$$\frac{\partial}{\partial t}\boldsymbol{B}=\boldsymbol{\nabla}\times(\boldsymbol{v}\times\boldsymbol{B})$$

From Ohms law – currents appear where the field changes quickly

$$\boldsymbol{J}=\boldsymbol{\nabla}\times\boldsymbol{B}$$

Fieldlines must close !

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

WSA/ENLIL (Odstrcil) Ambient Solar Wind Modeling

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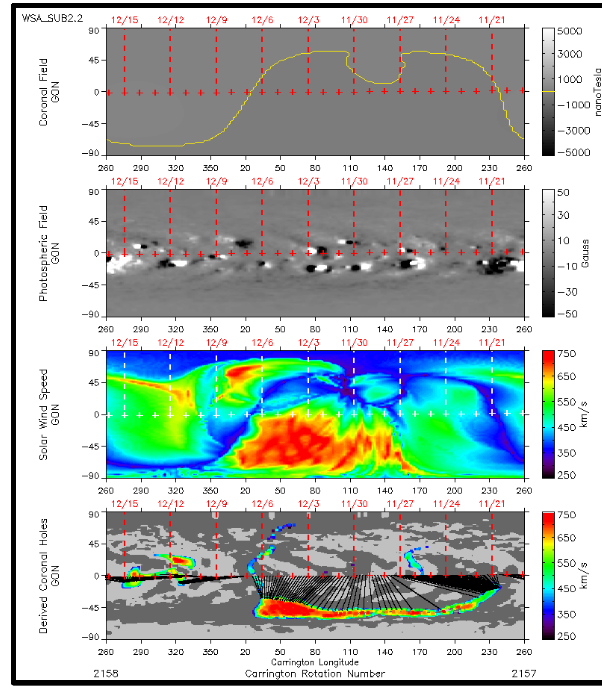
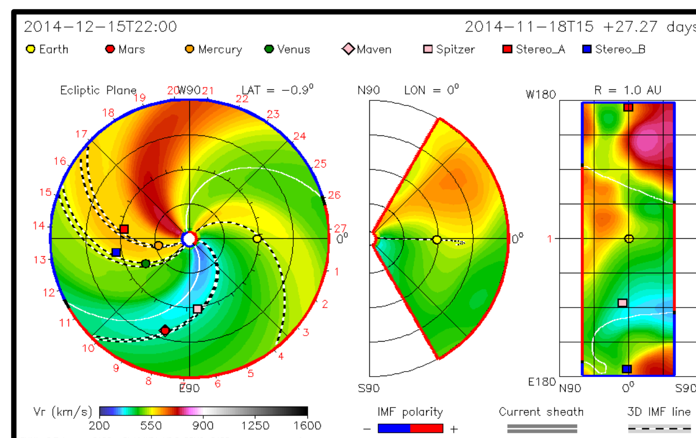
- WSA provides model of the coronal field inside 0.1AU and the solar wind flow speed on the sphere at 0.1AU ($21.5R_{\odot}$)
  - Input is low resolution time independent synoptic (diachronic) LOS photospheric magnetograms
- ENLIL uses MHD to model from 0.1AU outward
- ENLIL takes the WSA solution at 0.1AU, and adds,
  - Mass density – uniform mass flux at 0.1AU
  - Temperature – uniform pressure at 0.1AU
  - Longitudinal component of ***B***





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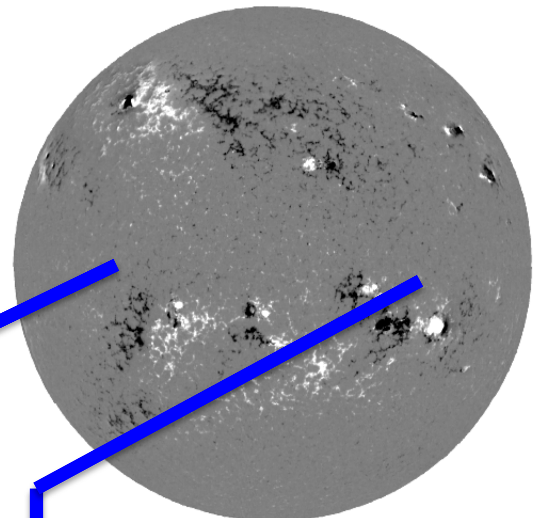
MHD Codes

- The most complete physical treatment that our models offer
- ENLIL, MAS(in CORHEL), AWSoM

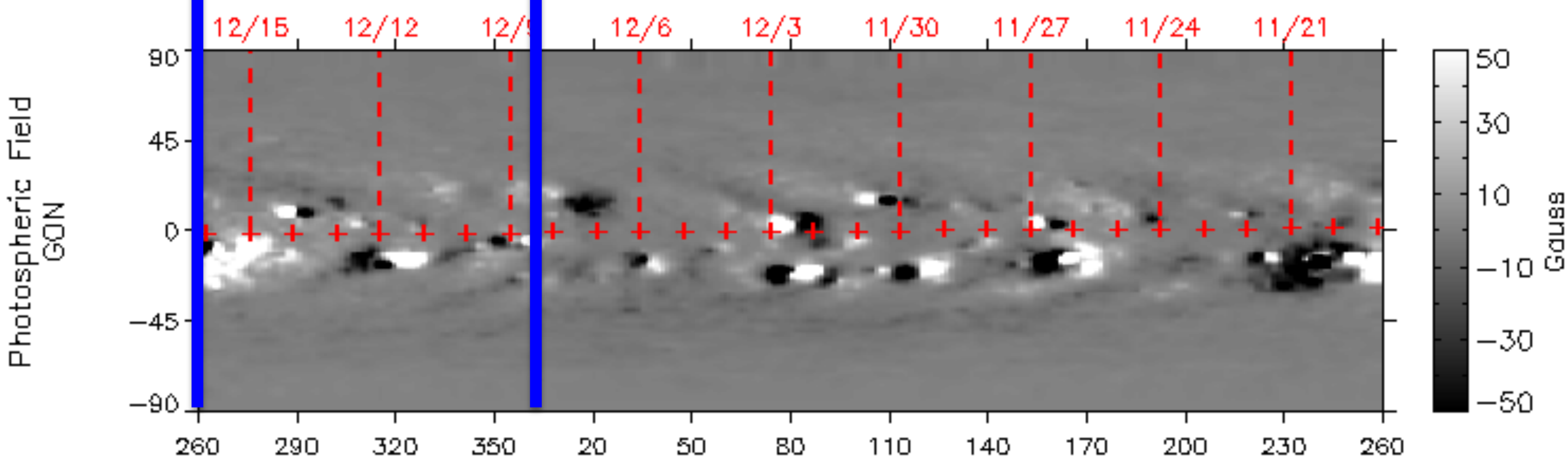
- MHD codes are <u>expensive</u> to run
- Algorithms are <u>complex</u> and therefore <u>fragile</u>
- Results must be reviewed carefully for physical sense

Synoptic Magnetograms

Full Disk
Photospheric
Magnetogram



- Daily synoptic maps hourly from GONG
- Full rotation ‘science quality’ maps posted within about 2 months



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Some Basic Concepts 3

- In MHD, parcels of plasma talk to each other through sound and alfven waves.
- Sound waves cannot propagate upstream in a supersonic flow.
- Beyond the sonic point (~ 5 - 10 Solar radii) and the super-alfvenic point (~10-20 Solar radii), information travels outward only.
  - Equilibrium MHD solutions in the corona must allow waves to slosh back and forth between the surface and the super-alfvenic point – Slower to complete!
  - Beyond the super-alfvenic point the solution is determined by information propagating outward only – Faster to complete!
- Solar wind codes set their inner boundary at 21.5 or 30 r_o which greatly simplifies their inner boundary condition

ENLIL (Odstrcil)
Ambient + Cone Model CME

- Adds a CME by inserting a blob of mass emerging through the inner boundary
- The cone model is based on the idea that close to the Sun CME propagates with constant angular and radial velocity, and so has the shape of a cone.
- No internal CME field