MODELING THE STEADY SOLAR WIND WITH AN OBSERVATIONALLY DRIVEN FLUXON CORONAL MAGNETIC FIELD

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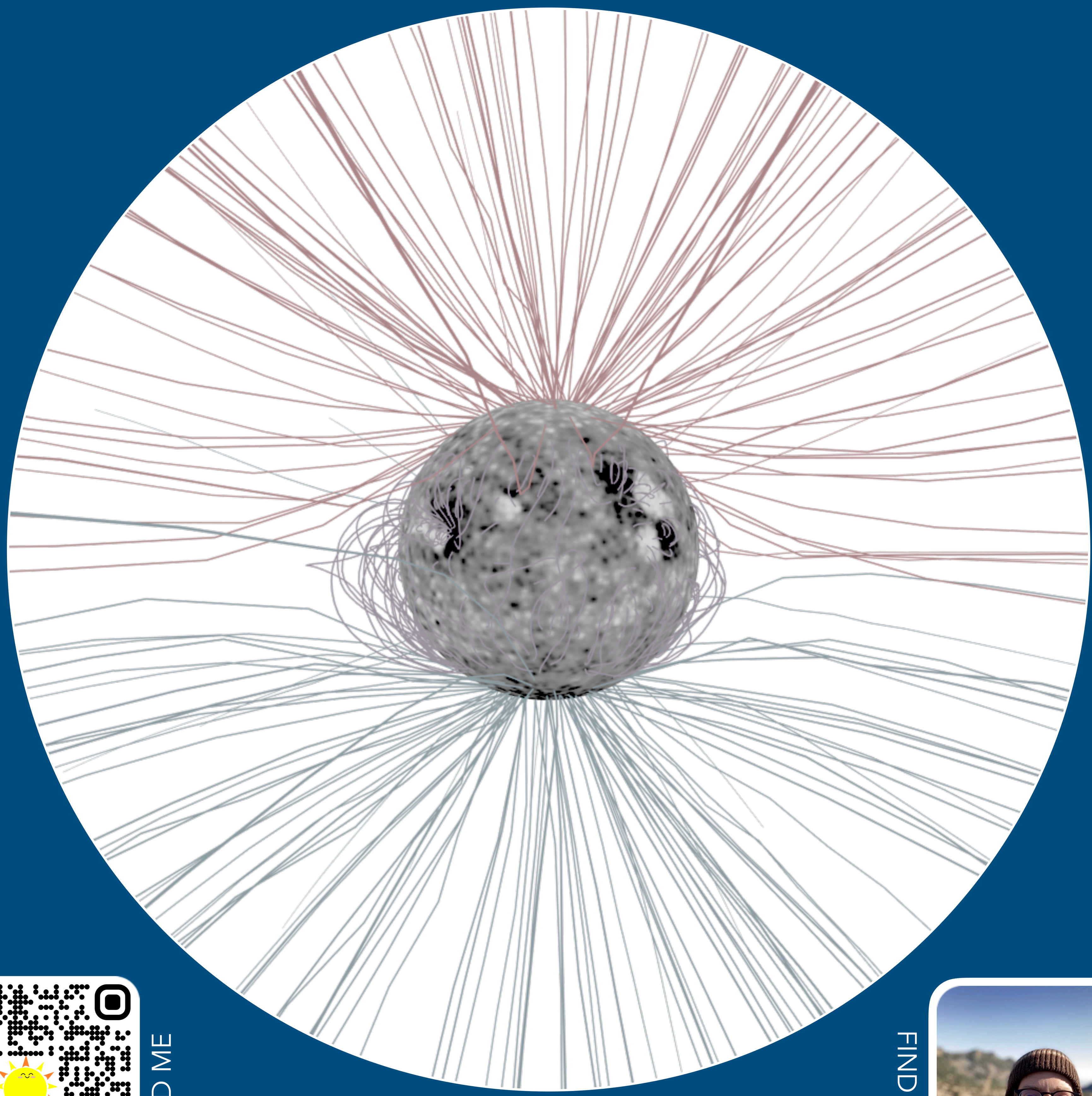
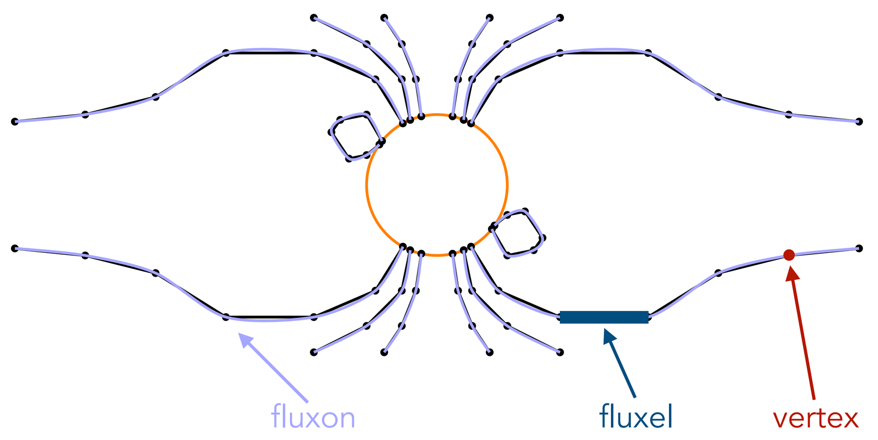
The Field Line Universal relaXer (FLUX) code models the solar corona as a collection of discrete analogue magnetic domains, via a quasi-Lagrangian grid of discrete field lines - fluxons. Topologically open fluxons are used to compute a set of modified isothermal Parker solar wind solutions and interpolated onto a grid. The FLUX model provides a flexible and efficient framework for modeling of the coronal magnetic field and the steady solar wind.



WHAT ARE FLUXONS?

Fluxons are discrete representations of solar magnetic field lines, each carrying a quanta of magnetic flux. Modeled fluxons allow for exact conservation of topology, avoiding reconnection unless manually or procedurally triggered.

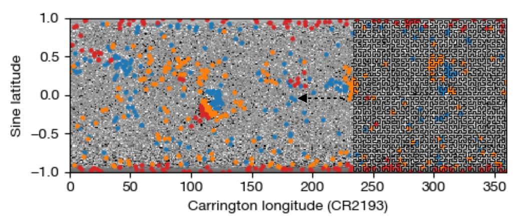
A given model of fluxons then relaxes to a series of force-free equilibria in time. Scaling with the complexity of the 2D boundary condition, the model is exceedingly computationally efficient.



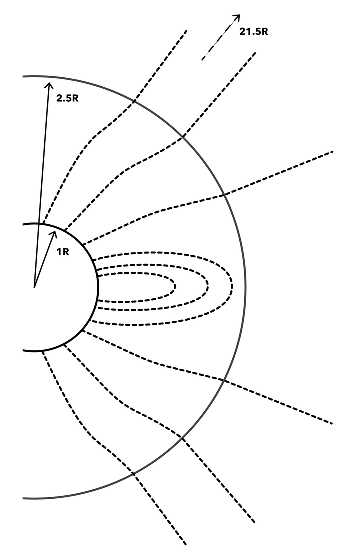
MOTIVATION

- Determine if reconnection-free models improve solar wind modeling, in comparison with existing tools
- Isolating the effect of geometric expansion in open fieldlines to determine the role in solar wind speed and density
- Development of real-time capable solar wind predictive model
- Assimilation of coronal and in-situ data in a full 3D background coronal model
- Advantage of background coronal modeling that preserves connectivity and tracks the history of a bundle of magnetic flux

MAGNETOGRAM ASSIMILATION



A space-filling Hilbert curve is used to walk through synoptic magnetograms to map magnetic flux onto a fluxon (dithering).

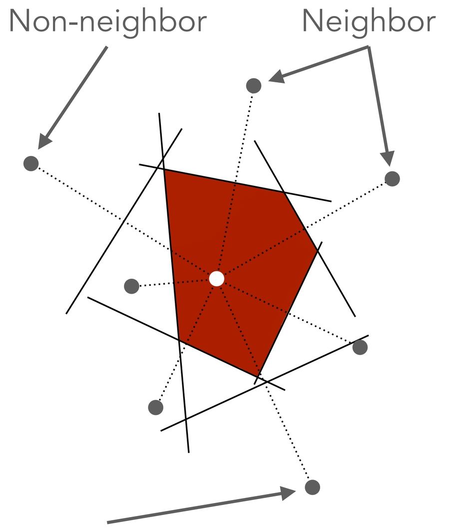


These initial boundary points are traced using a PFSS extrapolation to set the initial open (red) / closed (blue, orange) topology, initializing the fluxon model configuration for further relaxation to a force-free state out to 21.5 solar radii.

VORONOI CELL GENERATION

A two-dimensional hull cross-section is constructed perpendicular to each fluxel, and extruded to endpoints. Neighbor fluxels are projected into the plane, and a compact hull shape is generated from perpendicular bisectors.

The magnetic flux within each fluxon is partitioned into segments of uniform magnetic field as a fraction of angular extent. This generates current sheets between anti-parallel fluxons, and vice-versa prevents them.



FORCE DISCRETIZATION

For a flux tube with constant magnetic field strength, the Lorentz force can be field-normalized and broken into curvature and magnetic pressure components as,

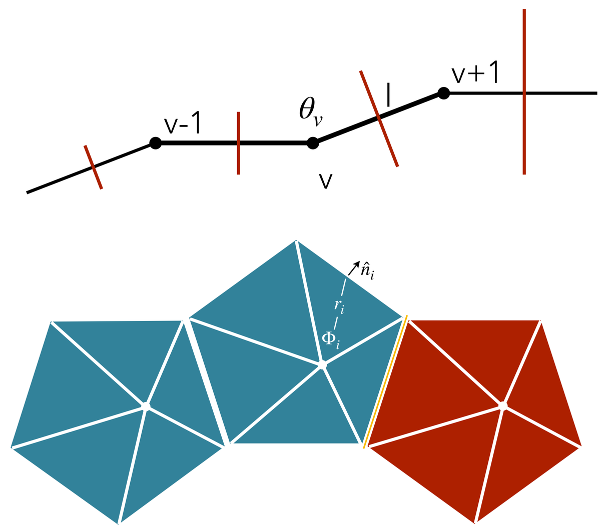
$$\frac{8\pi}{AB^2}\frac{d\mathbf{F}}{ds} = \underbrace{(\hat{B}\cdot\nabla)\hat{B}}_{(\mathscr{F}_{cn})} - \underbrace{\frac{\nabla B}{B}}_{(\mathscr{F}_{pn})}$$

Curvature force

$$F_{cn,v} = \frac{1}{2}\int_{v-1}^{v+1}\mathscr{F}_{cn}\,ds = \frac{l}{2}\frac{2\Delta\theta_v}{l} = \Delta\theta_v$$

Pressure force

$$F_{pn} = \int_{v}^{v+1}\mathscr{F}_{pn}\,ds = l\frac{\langle\nabla_\perp B\rangle}{\langle B\rangle} = l\sum_i(\hat{n}_i\phi_i)/(\pi r_i)$$



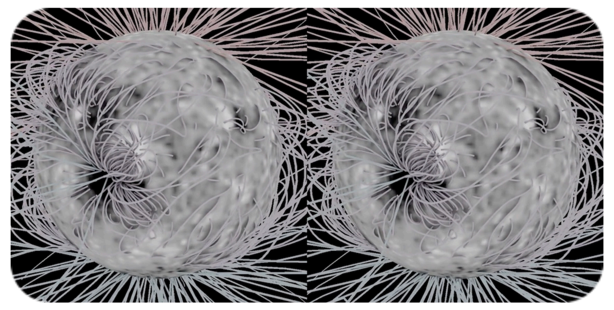
READ ME

FIND ME

RELAXATION

Relaxation steps towards force-free equilibrium:

$$\underbrace{\Delta\mathbf{x_i} = \partial\tau}_{\text{Eulerian quasi step coefficient}}\underbrace{\left(\frac{|\sum\mathbf{F_j}|}{\sum|\mathbf{F_j}|}\right)^2}_{\text{Stiffness coefficient}}\underbrace{\mathbf{r_{min,i}}}_{\text{Distance to nearest neighbor}}\underbrace{\sum\mathbf{F_j}}_{\text{Series of forces applied to each vertex}}$$



Stereoscopic animation of a relaxed data-driven fluxon simulation

Vertex points are shifted towards equilibrium, with modifications to prevent oscillations around equilibrium. This process is stopped with a stability threshold.

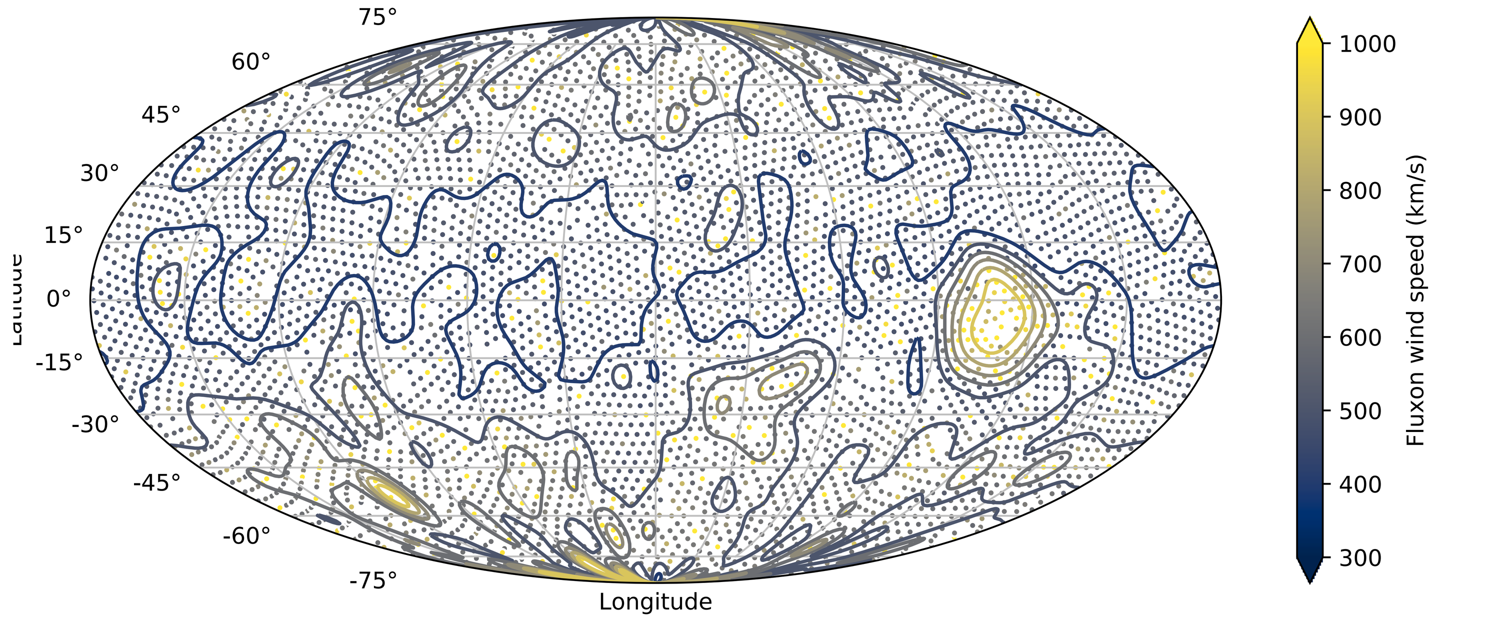
SOLAR WIND PROFILES

Modified 1D isothermal Parker solar wind solution along each open fluxon:

$$\frac{dv}{dr} = \frac{v}{r}\,\frac{rg - 2c_s^2\left[1 + \frac{r}{2f_r}\left(\frac{df_r}{dr}\right)\right]}{c_s^2 - v^2} \qquad f(r) = \underbrace{\frac{A(r)}{A_0}}_{\text{Derived from fluxel hull geometry}}\left(\frac{r_0^2}{r^2}\right) \qquad c_s = \sqrt{\frac{2kT}{\mu m_p}}$$

A shooting method and binary search tree are utilized to solve for a transonic solar wind solution. The resulting open fluxon wind solutions are then mapped and interpolated onto a spherical surface at 21.5 solar radii.

SOLAR WIND MAPPING



Fluxon intersections with a sphere set at 21.5 solar radii are mapped with circles above, indicating individual fluxon wind speeds. These values are then interpolated onto the full spherical surface, mapped with contours above.

DISCUSSION

Our model allows for the isolation of geometric expansion in open magnetic fieldlines to explore the role of geometry in setting solar wind speed and density, distinct from other effects such as intermittent reconnection.

The work described here for the Fluxon Rapid Assimilative Nowcaster (FRAN) provides a flexible and efficient framework for a real-time capable solar wind predictive model.

CONCLUSIONS

- Here we describe the creation of a framework for modeling of the solar wind, using data-driven boundary conditions as input, with the goal of providing a real-time capable solar wind modeling tool.
- The FLUX model provides an MHD simulation framework that is computationally efficient and scales seamlessly from targeted regions to full corona.
- Refinements to solar wind calculations result in physical transonic solutions and boundary mapping out to 21.5 solar radii.
- The creation of three-dimensional visualization frameworks enable streamlined data exploration.