Understanding the Global Coronal Magnetic Fields using Data-constrained Magnetohydrodynamic Model

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Motivation

Our increased reliance on space based assets, different space exploration programs and navigation systems, demands monitoring the dynamics of solar coronal magnetic field as this modulates the space weather conditions (Schrijver et al. 2015). Modelling the solar coronal magnetic field accurately is challenging due to the difficulty in observing the coronal magnetic fields. Magnetohydrodynamic (MHD) models (Mikic et al. 1999; Usmanov et al. 2000; Reville et al. 2015; Hazra et al. 2021) have been used successfully to simulate the global Sun. The simulation results can be well constrained during a total solar eclipse during which we can observe the coronal magnetic field topology. In order to understand the evolution of the solar corona, we must study the coupled interaction of surface magnetic field, dynamical forces operating in the corona and the effect of solar wind. There are various methods to model the solar corona starting from PFSS to more realistic MHD models. Here we present some of our efforts to model the coronal magnetic field during the total solar eclipse which happened on 04 December 2021 across Antarctica.

Model Setup

For understanding the global coronal magnetic field dynamics, we have developed a module based on PLUTO architecture (Mignone et al., 2007) which solves the following set of time dependent equations on a spherical polar grid to reach a steady state. For faster computations we have chosen a coarser grid resolution with [64,64,64] points in [r,θ,φ] direction where the radial extent is until 30 $R_\odot$. The model equations are,

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \mathbf{v}) = 0$$
$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla\cdot(\rho \mathbf{v}\mathbf{v}) + \nabla P - \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B} = \rho \mathbf{g}$$
$$\frac{\partial E}{\partial t} + \nabla\cdot[(E+P)\mathbf{v} - \mathbf{B}(\mathbf{v}\cdot\mathbf{B}) + (\eta\cdot\mathbf{J})\times\mathbf{B}] = \rho\mathbf{v}\cdot\mathbf{g}$$
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla\cdot(u\mathbf{B} - \mathbf{B}u) = 0$$

where p is the total pressure (thermal and magnetic). The variables ρ, $\mathbf{v}$, $\mathbf{B}$, E denote the density, velocity, magnetic field and total energy density respectively. We use the ideal equation of state: $\rho\varepsilon = p_{th}/(\gamma-1)$ where $p_{th}$is the thermal pressure, ε is the internal energy per unit mass and γ is the polytropic index. Hence the total energy can be written as $E = \rho\varepsilon + \frac{(\rho u)^2}{2\rho} + \boldsymbol{B}^2/2$.

The length scale, unit density and unit velocity is chosen to be $R_\odot = 6.96\times10^{10} cm, \rho_\odot = 6.68\times10^{-16} gcm^{-3}$ and $u_\odot = 4.37\times10^{7} cms^{-1}$. The following initial condition is used in our simulation. The output of the SFT model (Bhowmik and Nandy 2018) at solar surface, a potential field extrapolation (Shatten et al 1969) on the B_r for the coronal magnetic field, and a spherically symmetric parker wind solution (Parker 1963) with $\gamma = 1.12$ (Totten et al.1995) to specify p, ρ, $\mathbf{v}$.

Results

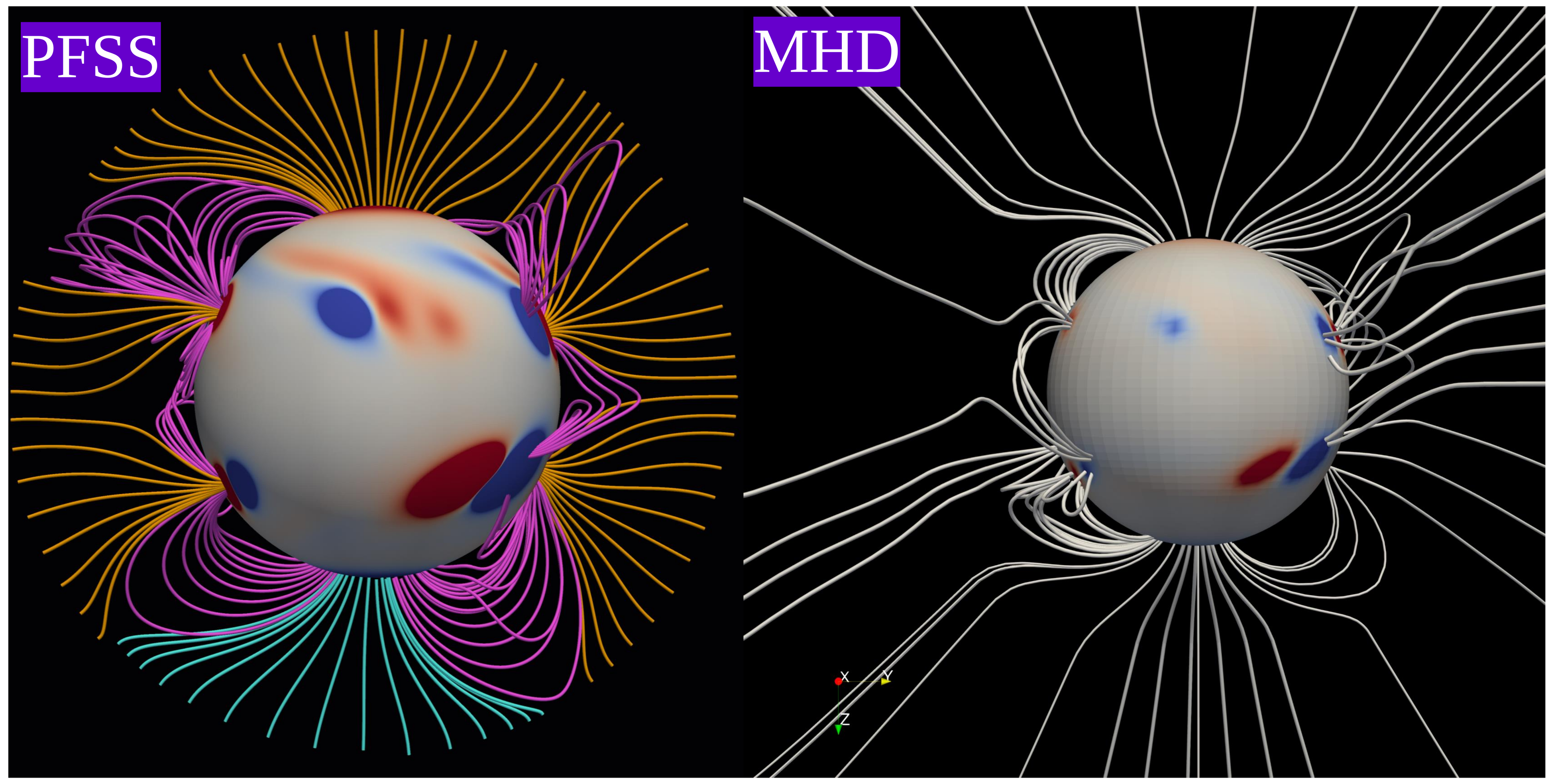


Figure 1. Potential field extrapolation and the MHD steady state

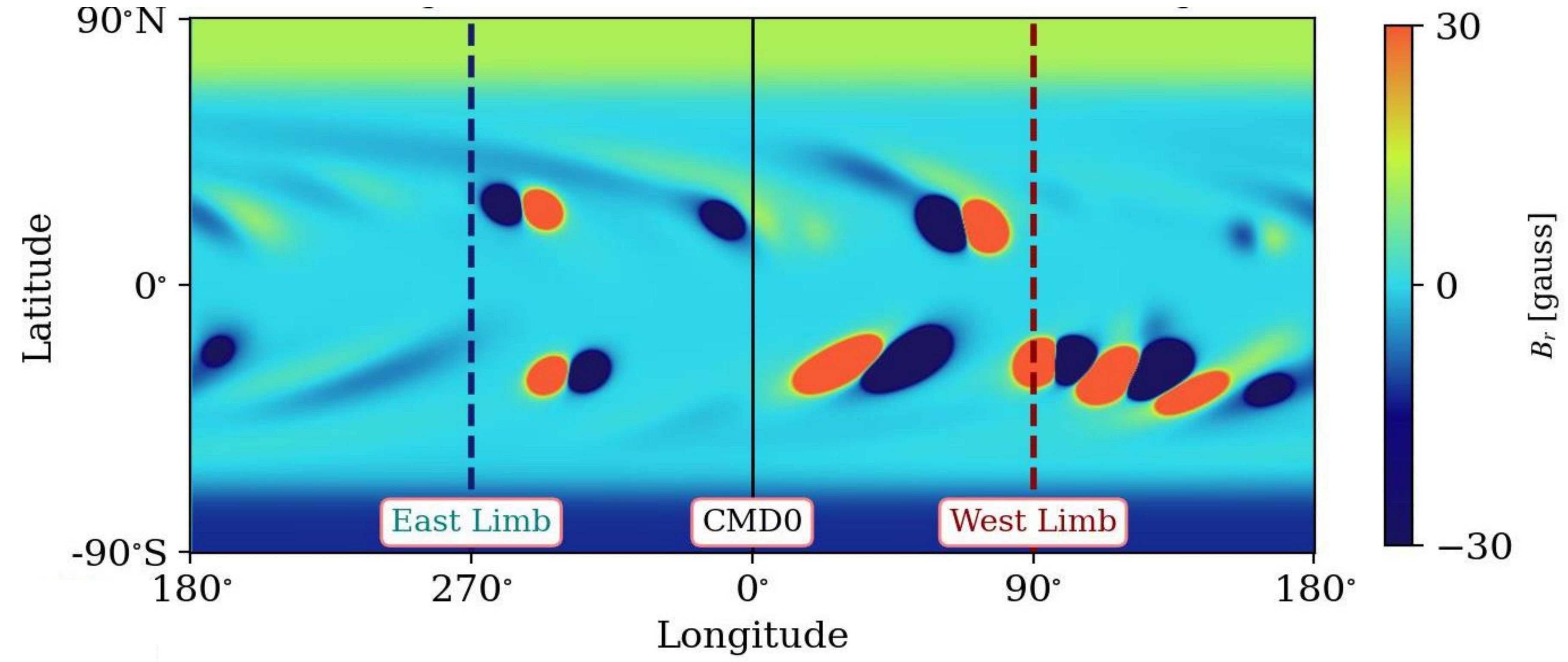
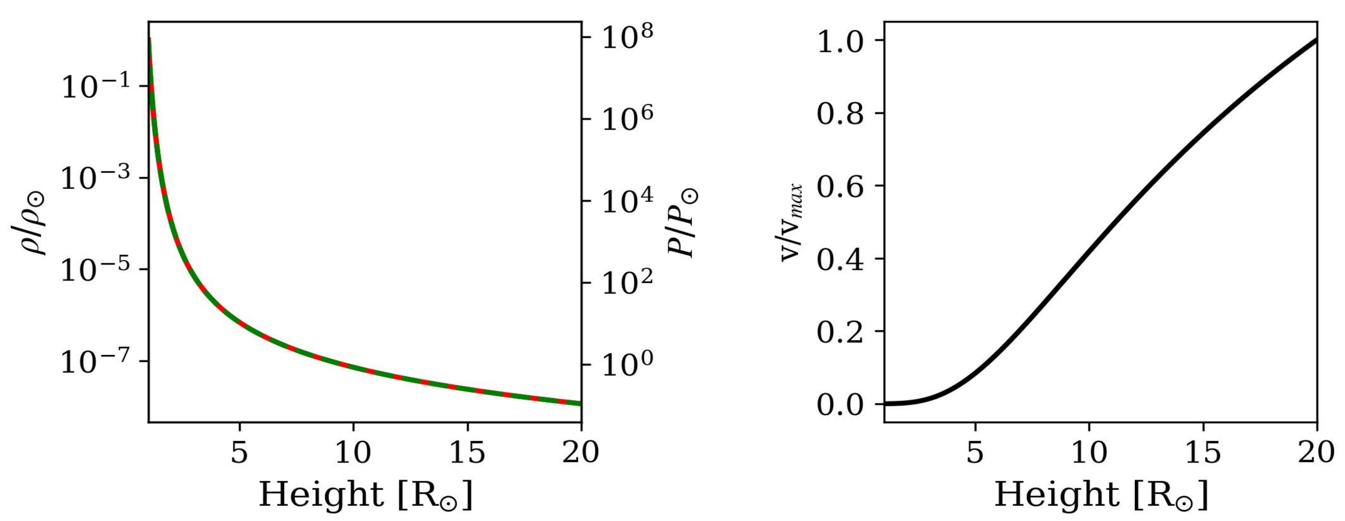


Figure 2. Surface magnetic field distribution generated using Surface Flux Transport model. The last solar active region input in this model was on 24 November 2021. The active region magnetic field strength is re-calibrated according to the HMI observed field strength.



Using the potential field as initial condition and the mentioned pressure, density and velocity profile a steady state is achieved with the MHD model.

Figure 3. Initial distribution of velocity, density and pressure.

Eclipse Observation

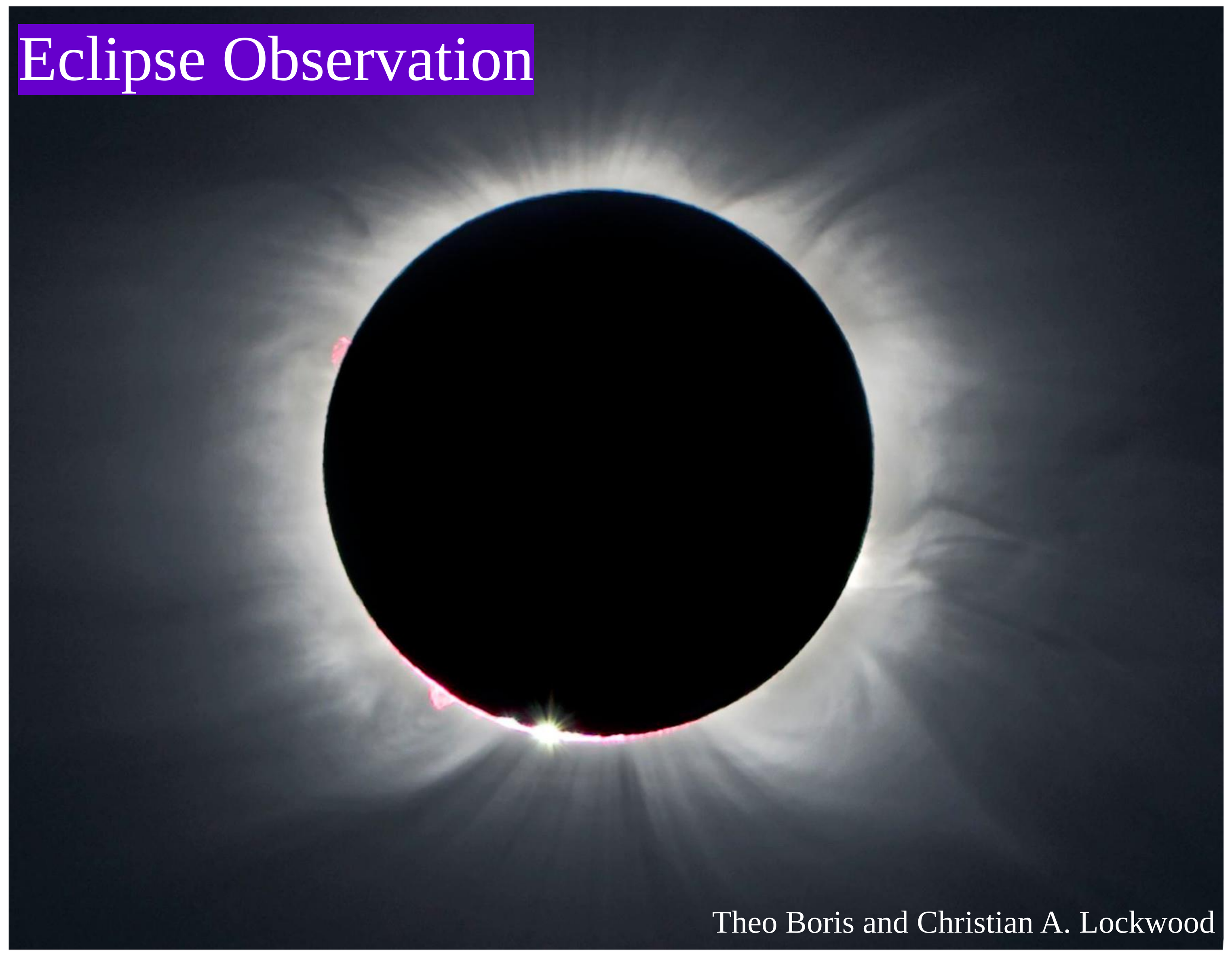


Figure 4. Coronal brightness during the total solar eclipse of 04 December 2021. This view is corrected to show solar north up.

Discussion

During a solar minimum period potential field extrapolations provide a good match to the observations of the coronal structure. In Nandy et al. (2018) it is shown for 2017 total solar eclipse. However, during solar maximum, flux emergence on the photosphere is frequent and this changes the overall coronal magnetic field topology. Non-potential extrapolations like NLFFF, Magnetofrictional model and Full MHD models are thought to be better suited for such phases. Using a coupled SFT and PFSS model we find a reasonably good match with the observations during solar activity minimum. In order to compare the results, we repeat this exercise during this high solar activity phase. In our MHD simulations we observe a reduction of tilt angle with respect to the equator in the streamer tips compared to the potential field extrapolation.

The output from the MHD model can be used as input to generate the polarization characteristics which will aid us in better comparison with the observations and constraining the model parameters. The thermodynamic quantities (p, ρ, T) and the specific heat ratio (γ) need to me modeled carefuly to achieve a low beta atmosphere. Such simulations can not only help us understand the coronal magnetic field evolution but also help support the interpretation of results of upcoming solar missions which have coronagraph e.g. ADITYA-L1, PUNCH and METIS. Also, when coupled with a solar wind model (Kumar et al. 2020), it will help us calculate the in-situ solar wind parameters.

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