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Magnetic Reconnection at a Three-dimensional Solar Null Point

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Abstract: Using a specific solar null point reconnection case studied by Masson et al [1] we have started investigating the dependence of the reconnection rate on boundary driving speed, numerical resolution, type of resistivity (constant or numerical), and assumed stratification (constant density or solar-like). Our resistive MHD simulations start out from a potential magnetic field containing a null-point, obtained from a SOHO magnetogram extrapolation approximately 8 hours before a C-class flare was observed. The magnetic field is stressed with a boundary motion pattern similar to the horizontal motions observed by SOHO during the period preceding the flare. The general behavior is nearly independent of driving speed and numerical resolution, and is also very similar in stratified and non-stratified models, provided only that the boundary motions are slow enough. Here, we quote results from the reconnection rate study of a selected and representative simulation case.

Introduction

We have performed large-scale resistive MHD simulations starting from a potential extrapolation magnetic field, based on observations of Active Region AR10191, by the Solar & Heliospheric Observatory (SOHO), about 8 hours prior to a C-class flare on Nov.16, 2002. The full Solar disk showed relatively modest activity, with AR10191 being the dominant magnetic feature during this event (fig.1). We extracted the region (fig.1 inset), making corrections for foreshortening and warping of the image; but the true field topology is likely far from potential, thus very difficult to reconstruct. We chose to implement two model classes; constant density, and stratified solar-like density. Photospheric driving of the MHD fluid was realized through mimicking of the foot point motion estimated from the SOHO data, and consistent with the driving pattern used in the work of Masson *et al.*[1].

We outline the method of analyzing the reconnection process for one case selected from a larger array of simulations spanning an extended parameter set in driving velocity, density profiles, resistivity and numerical resolution. Complete details of all simulations and results can be found in Baumann *et al.*[2].

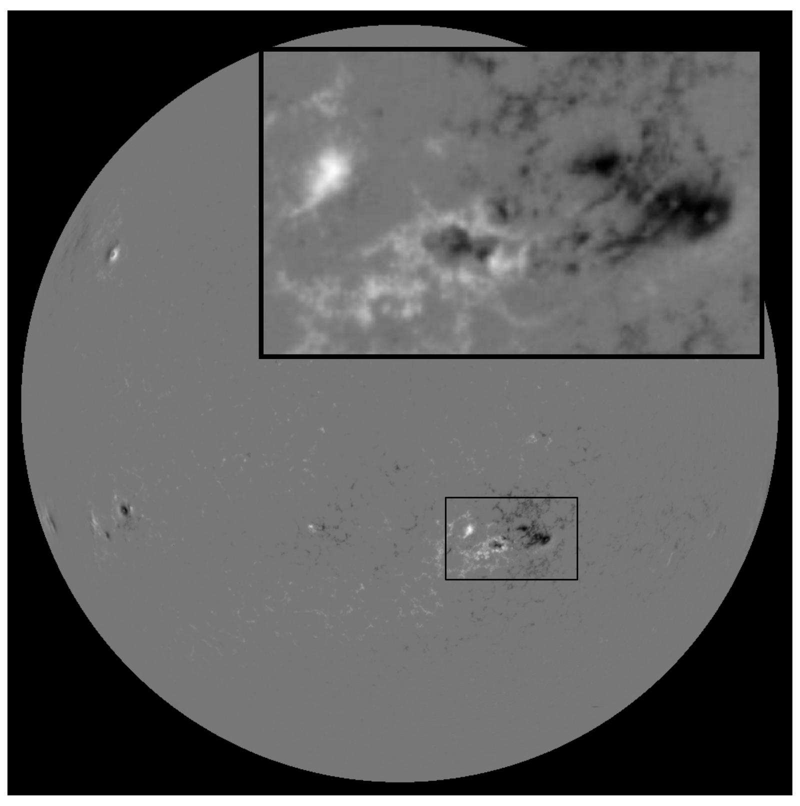


Figure 1: Full disc SOHO magnetogram 8 hours before the C-class flare of 16.November 2002, 06:27. Inset: enlargement of Active Region 10191.

Further we discuss challenges and tractability of producing realistic flare initial conditions *ab initio* with semi-empirical input of data from SOHO observations, and combining MHD models with PIC models of the plasmas in ARs..

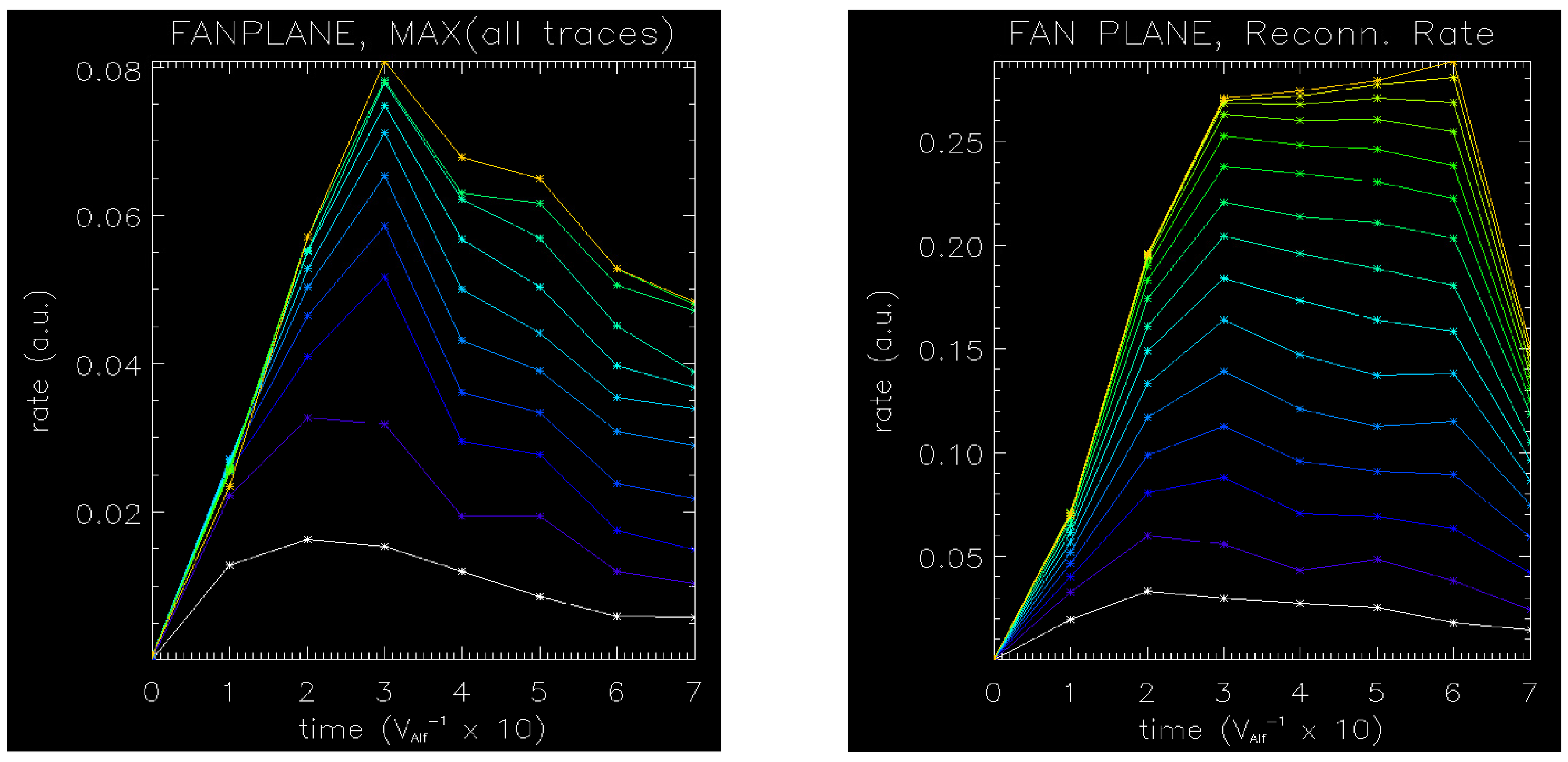
Reconnection Analysis, Method

A procedure for finding the magnetic null point and estimating reconnection rates and the extent of the reconnection region is described in detail in [4,6]. The null points position is improved to a sub-grid level using Newtow-Raphson iteration based on a trilinear interpolation of the B vector.

We then linearize the magnetic field around the null point, to first order, by Taylor expansion, based on the Jacobian

$$\boldsymbol{B}(\boldsymbol{r}) \sim \boldsymbol{B_0} + \overline{\overline{\boldsymbol{M}}} \cdot (\boldsymbol{r} - \boldsymbol{r_0})$$

giving us the planar approximation of the field in the fan plane. From this we form three eigenvectors, two in the fan plane (direction along strongest resp. weakest field), and one along the spine (fig.2 magnification inset).



FANPLANE, MAX(all traces)

FAN PLANE, Reconn. Rate

Figure 5: (left) maxima of the field aligned electric field, i.e. the field aligned dissipation. Every curve corresponds to a shell around the null of constant distance. The path integral is seen to converge for shell number 7 (see t=1) when taking the maxima only and reconnection saturates approximately t=3. (right) The difference, i.e. max(path integral)+abs(min(path integral)) gives the total reconnection rate along the path through the magnetic null point.

We then place hundreds of points around the null, in the fanplane, and trace the parallel electric field along magnetic field lines in the fan plane and on the spine.

By integrating the parallel electric field along each field line, and finding the maximum and minimum value for all integration trace routes as a function of distance from the null along the field line, a proxy for the magnetic reconnection rate is found. In effect we calculate

$$max\left|\int_l \boldsymbol{E}_{||}\partial l\right|$$

where $\mathbf{E}_{||}$ is given by $\mathbf{E}\cdot\mathbf{B}$, for a set of shells (here 15) at increasing distance from the null, and then form the difference

$$\Re \sim \max_{shell}\left[\int \boldsymbol{E}_{par}\right] + \left|\min_{shell}\left[\int \boldsymbol{E}_{par}\right]\right|$$

to finally estimate the reconnection rate as a function of distance from the null point.

In figure 3 the results of all individual traces are plotted for three stages in the evolution (initially, intermediate and late times) -- for run 3S (stratified density profile)[2]. The field aligned dissipation evolves from fluctuations close to zero reconnection (left) to strong dissipation and reconnection due to the driving (middle, and right).

Figure 5 shows the maxima (left) and estimated reconnection rate (right), as a function of time (abscissa axis), for all traces at 15 constant distance surfaces (ordinate axis) away from the null, thus representing the reconnection rate.

Method Validity

The reconnection analysis that we use has a number of shortfalls for cases where the field is highly non-linear:

1.Taylor expansion to 1st order, and the resulting Jacobian matrix used when placing the initial trace points will fail when the fan plane is strongly 'warped', i.e. higher order terms in the expansion is required for accurate determination.

2.The 'photospheric' driving quickly produces strong current sheets (fig.4) that are subject to various instabilities – a tearing mode, observed in some runs, give multiple null points in the current sheet formed between the inner and outer spines (fig.2, magnified inset). This leads to complex topologies involving separators, challenging accurate field line traces for any given instance of evolution.

3.The non-linearity of the magnetic field makes it difficult to trace magnetic field lines that follow the weak eigen vector direction, failing to represent the region in which the diffusion region has its largest extent according to [5]. This may lead to a underestimation of the peak values of the integrated parallel electric field.

Even with these shortcomings, the analysis has proven effective, at least in the first approximation, in estimating the size of the reconnecting region of the MHD simulations.

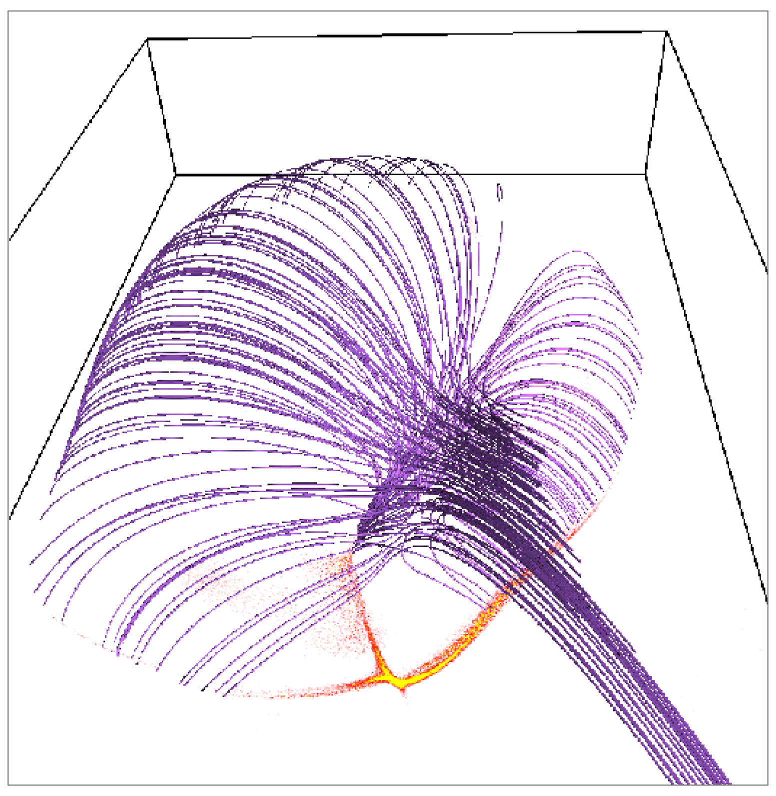


Figure 4.: Impact area of non-thermal electrons from run 5L in [3]. Shown is the electron energy (from orange increasing to yellow) added up at the lower boundary over a period of 5 sec. Additionally magnetic field lines (purple) passing close to the null are plotted.

3. The lack of a localised parallel E-field is the reson why the reconnection rate does not converge with distance for the shown study case. This indicates a large smooth distribution of parallel electric fields, as it is seen to be the case in the middel panel of fig.3. This is in contrast to the findings of the PIC simulations based on the evolved MHD snapshot [3], where strong currents quickly develop very localized down the inner spine and part of the fan plane. This is seen in fig.4 which shows the impact of accelerated particles in the photospheric plane, nicely showing the intersection of the fan plane and inner spine. We speculate that the discrepancy is likely in part due to the reconnection analysis failing to capture the critical directions well, as mentioned before; the method should be improved fpr these complex field structures. Rather, the transition from MHD regime to the PIC regime is well formed and continuous -- model-wise [3].

4. We do not observe a strong transient in reconnection rates; the stressing of the potential field evolves rather quietly, with little build-up of free energy in the system [2,3]. A likely explanation is that subsequent flux emergence was the actual reason for the AR10191 to eventually go unstable.

In conclusion; using snapshots from MHD simulations (such as the presented case) as initial conditions for PIC simulations may well turn out to be the only viable means of producing detailed plasma physical realisations of flaring Coronal volumes, however, only after a sufficiently complex and stressed environment has been primed by large scale MHD simulations. A thorough more precise reconnection analysis is warranted before choosing regions for kinetic treatment. Presently, we do this in a simple two step approach where we first run the MHD simulation [2], and subsequently choose an interesting time from which the PIC experiment is initiated in 'MHD mode' [3].

In light of the semi-empirical MHD simulations reported here and in [2], we believe that going to fully synthetic models including long-term driving and the inclusion of flux emergence will be necessary for success in building flaring ARs simulations and launching of CMEs.

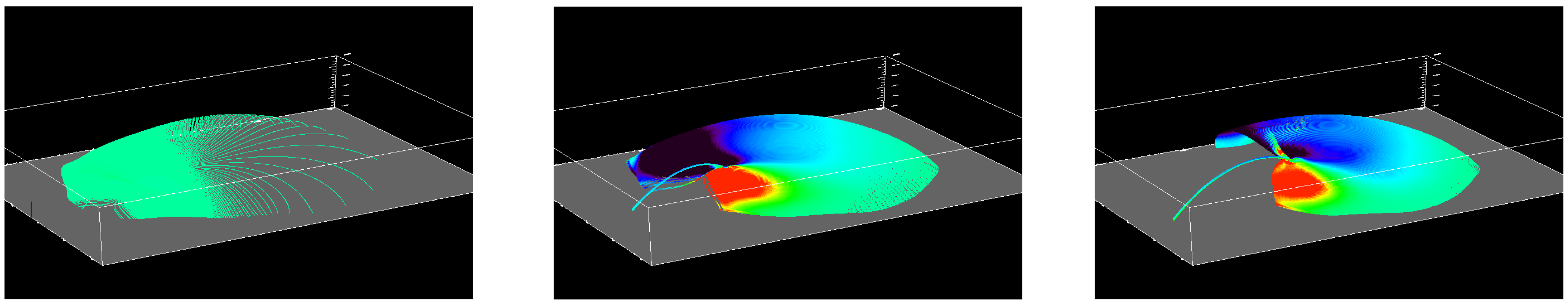


Figure 3: field line traces of the parallel electric field, along paths with starting points at the magnetic null point, run 3 of [2], for three snapshots during the evolution, t=1, 30 and 60 in units of 1/V_Alfvén, corresponding to approximately driving displacement times of 0, 1 and 2 of run 3S in reference [2]. Color scale compares directly across the panels. Green is zero—level. Not easily seen in middle panel is a few traces with relatively high values of field aligned dissipation, they fall just below the spine axis in a separate bundle and could indicate a strong reconnection evetnt taking place below the spine. Also, right panel (late time) shows the beginning of a strong reconnection 'jet' moving left on the fan plane (close to spine, far side of fan plane.

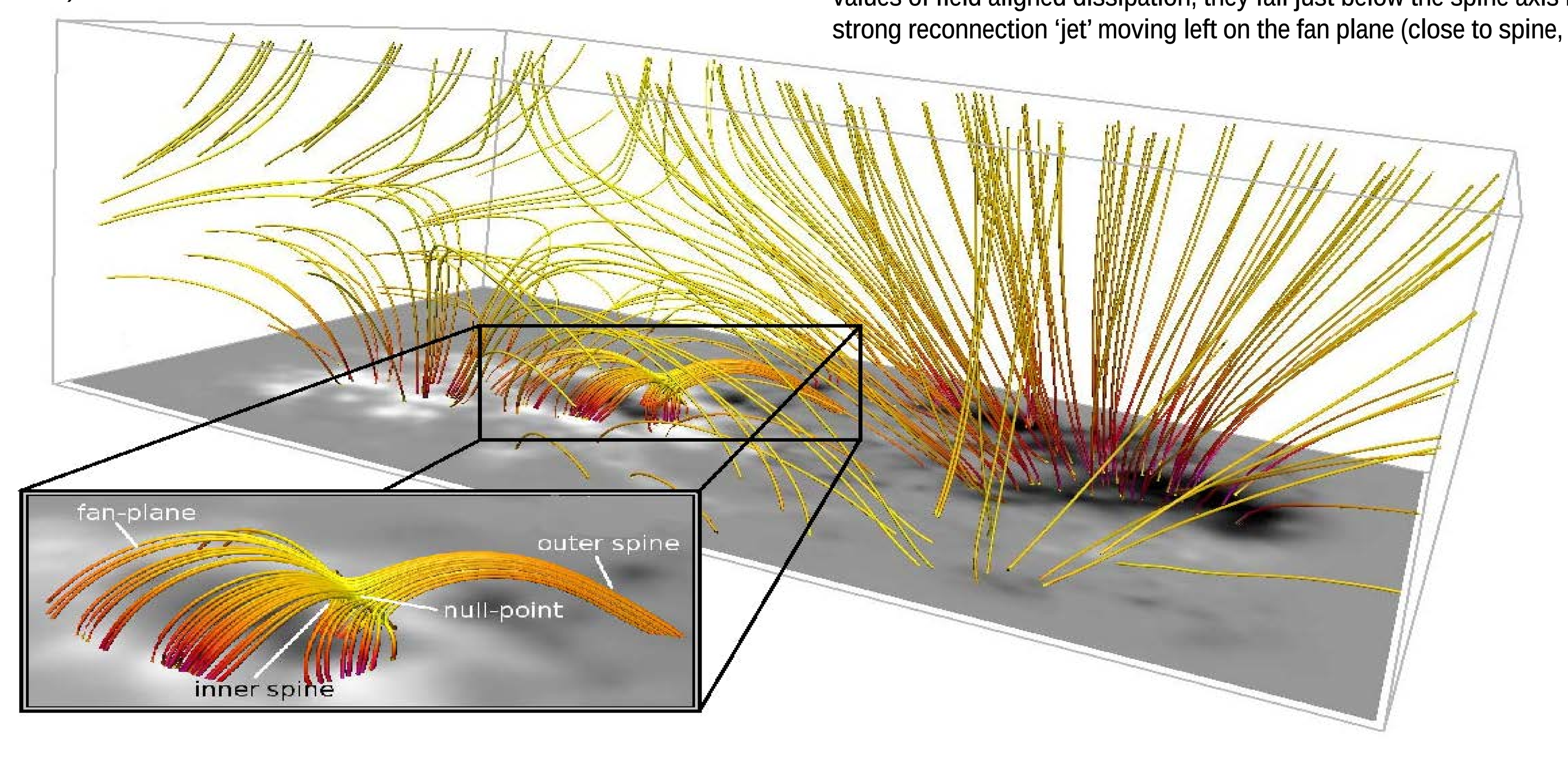


Figure 2: Extrapolated potential magnetic field structure on top of the generating magnetic stencil from Active Region 10191, obtained from the SOHO Magnetic Doppler Imager archives. Color designates magnetic field strength (magnitude). Details on simulation setup given in Baumann *et al. [2]. (image aspect slightly distorted)*

We currently effort refining the analysis to better include asymmetric null topologies.

This first estimate can be used for limiting our detailed particle-in-cell simulation starting from the MHD snapshot where the MHD field goes critical (high current densities, fast evolution). A first-of-its-kind detailed kinetic simulation of the active region based on initial conditions from the MHD runs described here is presented in the paper by Baumann *et al.*[3].

Discussion

1. The results from Bauman et al 2011 [2] shows that most of the work imposed by the boundary motion goes into changing the potential energy of the associated magnetic field. Therefore only little free magnetic energy is avaialble for generating a flare situation, and no explosive reconnection event is found in the experiment.

2. Seen in the light of this, then the reconnection rates never become very high, and a strong localisation of a large value of the parallel electric field around the 3D null is never required.

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