Global MHD simulations of ejections of magnetic flux ropes

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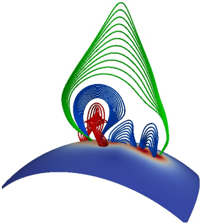
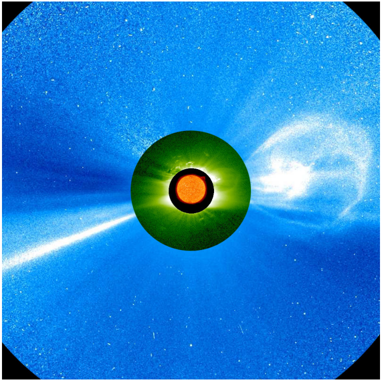
Copenhagen, SolarCast-1
November 11th 2015

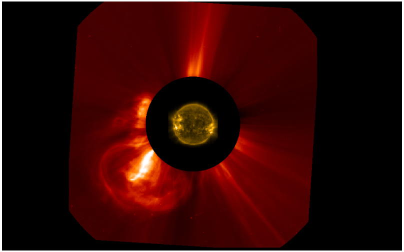


Coronal Mass Ejection

- Coronal plasma and magnetic field
- Speed: $\sim 450\ km/s$
- Speed range: 100 to 3000 km/s
- Space Weather impact
- Three components structure

Coronal Mass Ejection





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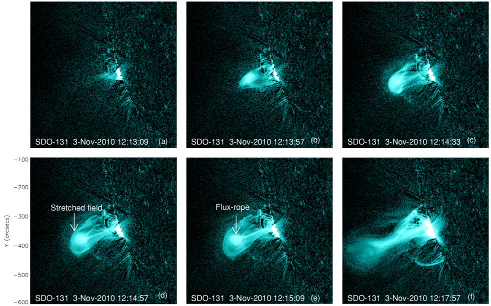
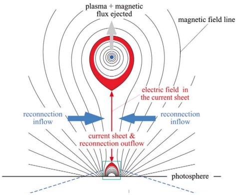
Ejection of Flux Rope

The ejection of a flux rope is believed to be the progenitor of CMEs.
It is also a component of the flare standard model.

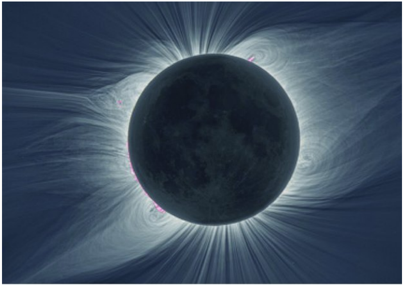




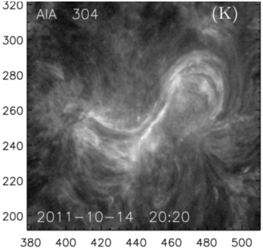
Cheng et al., 2011

Flux Ropes in the solar corona

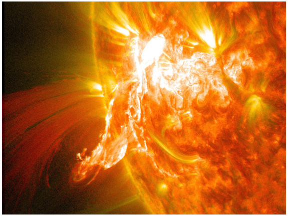
Habbal et al, 2010



Romano et al., 2014

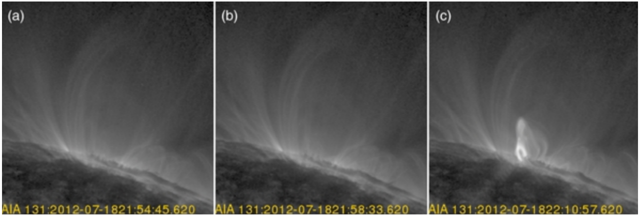


(NASA SDO)



Life of flux Rope: formation

Patsourakos et al., 2013

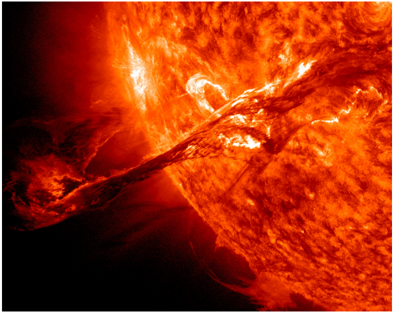


- Formation of flux rope: accumulation of free magnetic energy

Flux rope formation

- Slow formation: days or weeks
- Quasi-static evolution. ($t >> \tau_{Alf}$)
- Magnetic evolution: $\beta << 1$ everywhere

Life of flux Rope: ejection



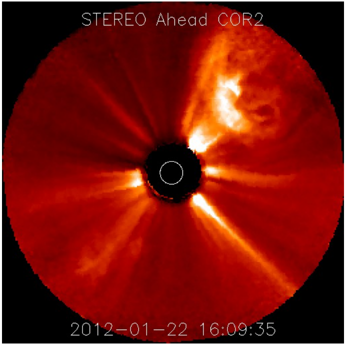
- Flux rope ejection: release of energy

Flux rope ejection

- Fast ejection: flux rope travels out of the corona in $\sim$ 2 hours
- Highly dynamic evolution. ($t \sim \tau_{Alf}$)
- Full MHD: plasma is locally compressed. ($\beta \geq 1$)

Boundary conditions of Space Weather

- At $\sim 4\ R_{\odot}$ CME are blown in the solar wind
- Magnetized plasmoid
- the Solar Wind can deflect the ICME
- The CME plasmoid can rotate
- The "Bz" component of the magnetic field (perpendicular to ecliptic) is crucial for the impact of the ICME on the Earth-magneosphere



Space Weather forecast: arrival time and properties of CMEs

For Space Weather forecast, we need:

- efficiency on computation
- accuracy on the injection of the CME in the solar wind

Model the life span of Flux Rope

Global Non-Linear Force Free Field (GNLFFF) evolution model

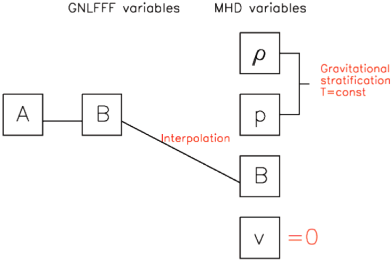
Flux rope formation

- Decribes a magnetically dominated evolution
- Models the evolution of corona for weeks
- Computationally efficient: magnetofrictional technique

MHD Simulation with the MPI-AMRVAC code

Flux rope ejection

- Accounts for plasma and magnetic field
- Models multi-β domain



Formation of a flux rope

Global Non-Linear Force-Free Field Model

Mackay & van Ballegooijen, 2006.

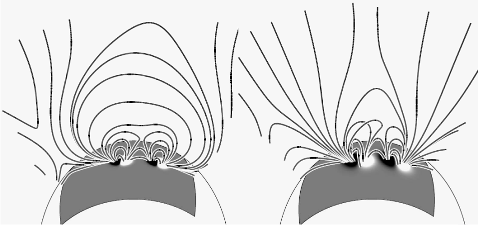
$$\vec{j} = \nabla \times \vec{B} \quad (1)$$

$$\vec{B} = \nabla \times \vec{A} \quad (2)$$

$$\frac{\partial \vec{A}}{\partial t} = \vec{v} \times \vec{B} - \eta_c \vec{j} \quad (3)$$

$$\vec{v} = \frac{1}{\nu} \frac{\vec{j} \times \vec{B}}{B^2} + v_0 e^{-(2.5R_\odot - r)/r_w} \hat{r} \quad (4)$$

$$\eta_c = \eta_0 \left(1 + c \frac{|\vec{j}|}{B} \right) \quad (5)$$



Ejection of the flux rope: 3D MHD Simulation

MPI-AMRVAC: KU Leuven

MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0, \tag{6}$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) + \nabla p - \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B})}{4\pi} = +\rho \vec{g}, \tag{7}$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0, \tag{8}$$

$$\frac{\partial e}{\partial t} + \vec{\nabla} \cdot [(e + p)\vec{v}] = \rho \vec{g} \cdot \vec{v} - \mathbf{n^2} \chi(\mathbf{T}) - \nabla \cdot \tilde{\mathbf{F_c}}, \tag{9}$$

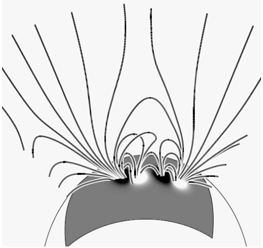
$$\nabla \cdot \vec{B} = 0 \tag{10}$$

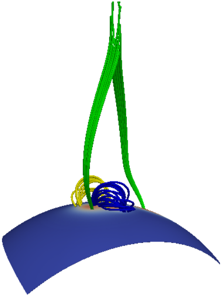
$$\frac{p}{\gamma - 1} = e - \frac{1}{2} \rho \vec{v}^2 - \frac{\vec{B}^2}{8\pi}, \tag{11}$$

$$\vec{g} = -\frac{GM_\odot}{r^2} \hat{r}, \tag{12}$$

Eruptive magnetic configuration: Pagano et al., 2013

- it is possible to couple the GNLFFF model with the MHD AMRVAC code
- we follow the life span of a flux rope from formation to ejection
- the stress accumulated during the formation justifies a flux rope ejection



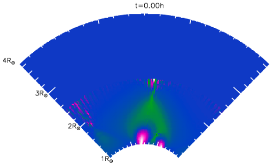


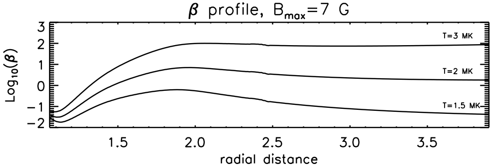
Initial Condition

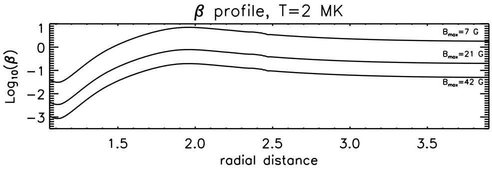
$$\rho = \rho_0 \frac{B^2}{B_0^2} + \rho_{background}$$
$$p = cost$$

Step 2: exploration of parameters space

	B_{max}=7 G	B_{max}=21 G	B_{max}=42 G
T=3.0 MK	X	69 km/s	335 km/s
T=2.0 MK	X	303 km/s	718 km/s
T=1.5 MK	104 km/s	498 km/s	838 km/s







- A set of MHD simulation shows under which conditions the coronal atmosphere favours the ejection
- Ideal MHD + Gravity

3D Non-ideal MHD Simulation: density and temperature distribution

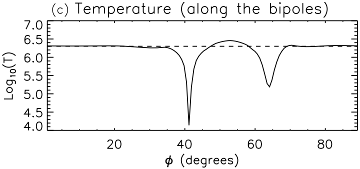
$$T(\vec{B}) = F(B_\theta/|B|, T_{min}, T_{out})(1 - G(|B|)) + T_{out}G(|B|)$$

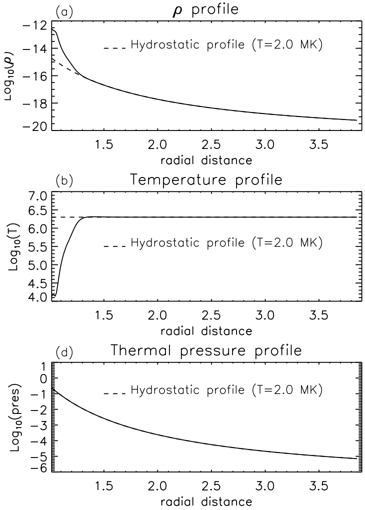
$$G(|B|) = e^{-\frac{|B|^2}{2B_*}}$$

$p =$ gravitational stratification

$$\rho = \frac{p}{T(\vec{B})}\frac{\mu m_p}{k_b}$$

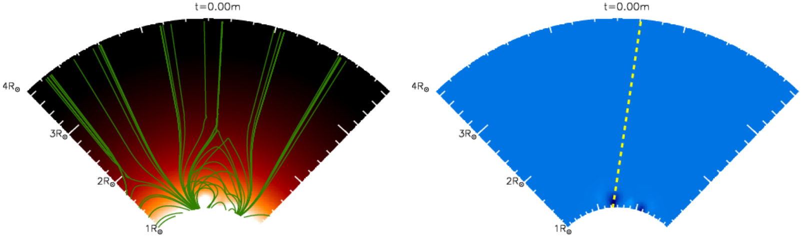
- $B_\theta/|B|$ shapes the temperature profile
- The flux rope is along θ direction
- T_{out} sets the outer corona temperature





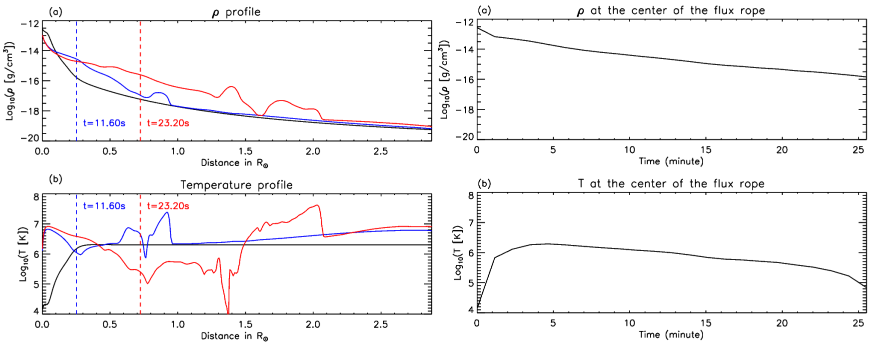
MHD evolution

2D plane through the centre of the bipoles



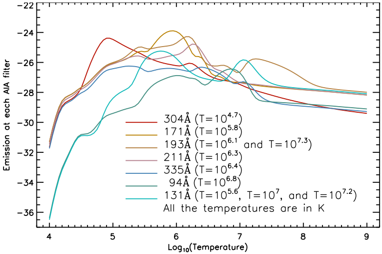
- Flux rope ejection: dense and cold plasma expelled
- Ejection reaches 4 $R_\odot$: it turns into a CME
- The flux rope is ejected towards the null-point.

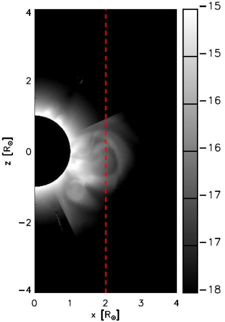
MHD evolution



- A front at constant density if formed
- The flux rope always presents a density excess and a temperature dip
- The density of the flux rope decreases by about 4 order of magnitudes
- The temperature of the flux rope initially increases to 1 MK and then it cools down to 10^5 K

AIA emission synthesis

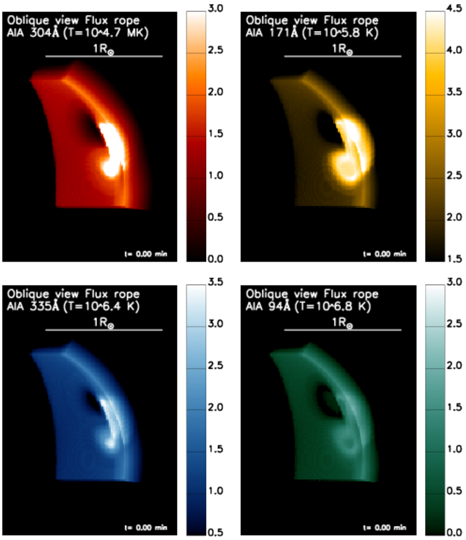




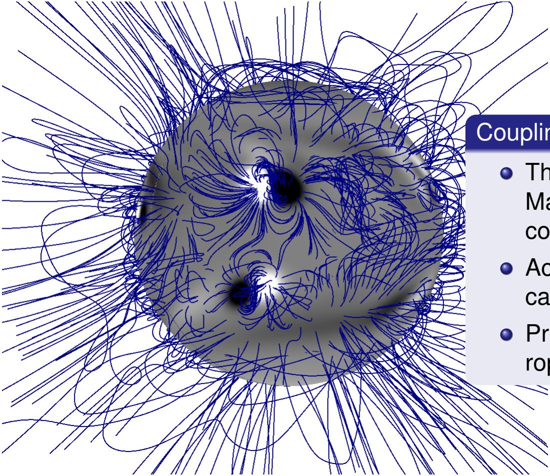
- $EM_{ch.}(n, T) = n^2\zeta(T)_{ch.}$
- $\zeta(T)_{ch.}$ is given from the AIA SSW tool
- Compute $EM_{ch.}(n, T)$ from each plasma element and integrate along the line of sight.
- Flux rope at 24° from plane of sky

Step 3: Non-ideal MHD and forward modelling

- Synthesised images match AIA observed flux rope ejections
- Flux rope ejection visible in 304$\AA$ and 171$\AA$
- Heating highlighted in 335$\AA$ and 94$\AA$



Towards a Space Weather application



Coupling MHD simulation with Global code

- The Global code uses a series of Magnetograms as boundary conditions
- Accounts for flux emergence and flux cancellation at the solar surface
- Predicts the formation of most flux ropes

Non-Potential Model for the Coronal Magnetic Field

- Long Term simulations (months ~ years).
  - Build up free magnetic energy

- Two coupled components:

Photosphere: Data Driven Flux Transport Model
- accurately reproduces B_r obs. on Sun.
- includes flux emergence (+/- ve helicity).

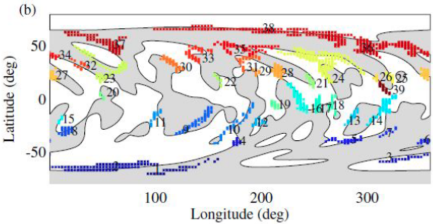
Corona : Magnetofrictional Relaxation
- quasi-static evolution
- non-linear force-free states, $\mathbf{j} \times \mathbf{B} = \mathbf{0}$
- transport of helicity across the Sun
- development of sheared fields along PIL
(van Ballegooijen and Martens 1989)

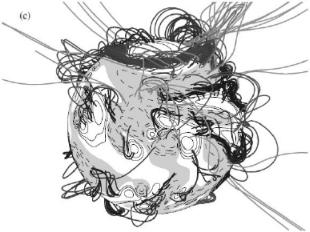
- Development and Application:
  van Ballegooijen et al 2000;
  Mackay and van Ballegooijen 2006a,b;
  Yeates et al. 2007, 2008a,b, 2009a,b.

6 months: May-Aug 1999

Formation of Flux Ropes

- Evolution for 3.5 solar rotations (96 days).

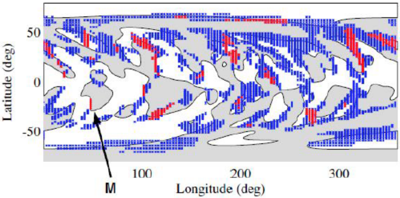


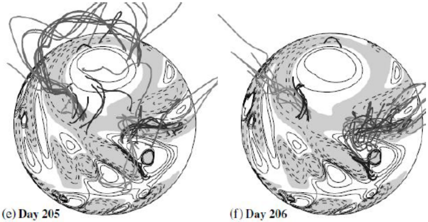


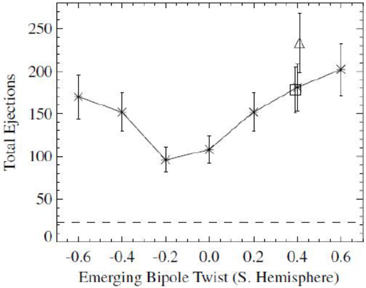
- Number of flux ropes : 28-48.
- Sustained by new flux emergence.
- Number has little dependence on helicity of emerging bipoles.
- Size, formation rate depends on emerging helicity.

Ejection of Flux Ropes

- Ejections: 96-108 days







A0 - 0.67 ejections/day.

A6 - 1.28 ejections/day.

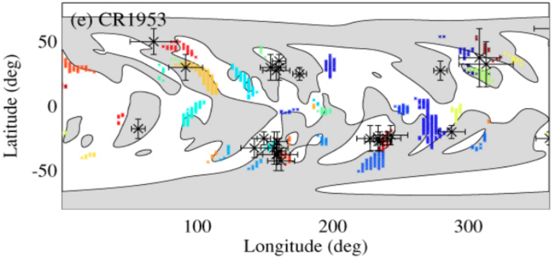
CDAW – 2.25 good events/day

50% observed CME rate.

Comparison with Observations !

- Yeates et al. 2010: comparison of flux rope ejections and CME source locations from EIT EUV events.

4.5 months : 330 CMEs (Lasco), only 98 identified in EIT 195 Å events.



Comparison problematic.

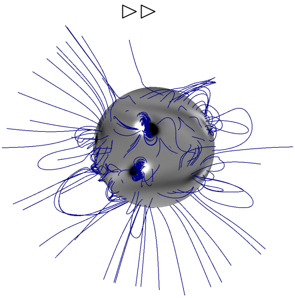
Outcome : +ve correlation 0.49

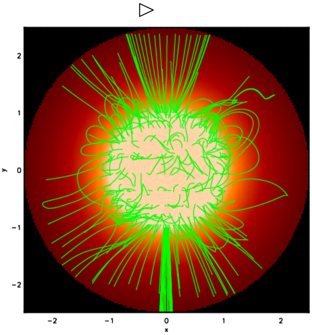
- Two classes of CMEs:

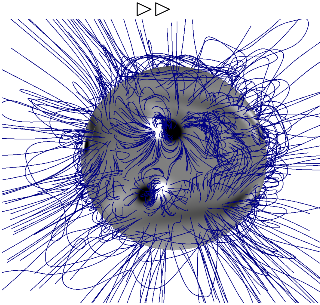
  ½ - gradual flux rope formation (outside AR, single events).

  ½ - recurrent CMEs in AR (short timescale).

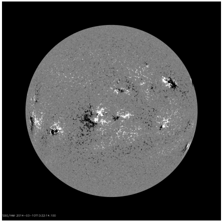
- Multiple CME mechanisms operate on different time/spatial scales.



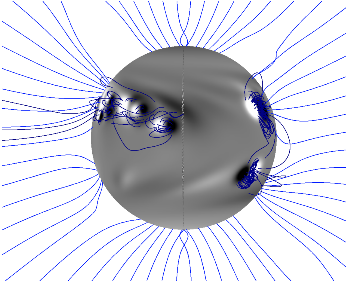




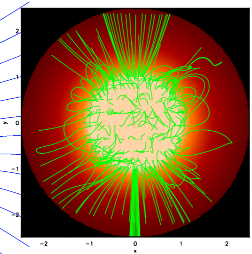
- Continuous simulation of the global corona during formation and ejection of flux ropes.
- Couple the two models either ways.
- Computational efficiency of the GNLFFF model
- Accuracy and generality of MPI-AMRVAC MHD simulations



$\frac{t}{t_{CPU}} \sim 15$



$\frac{t}{t_{CPU}} \sim 0.0005$



From magnetograms to GNLFFF

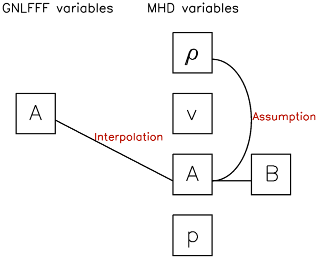
From GNLFFF to MHD

Feasible approach for Space Weather Forecast.

GNLFFF $\sim 30K$ more efficient than MHD

A vec formulation

- MHD is solved in terms of $\vec{A}$
- $\nabla \cdot \vec{B} = 0$
- Communication with theoretical models better defined in terms of $\vec{A}$



$\vec{A}$ MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0,$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) + \nabla p - \frac{(\vec{\nabla} \times \vec{\nabla} \times \vec{A}) \times (\nabla \times \vec{A})}{4\pi} = +\rho \vec{g},$$

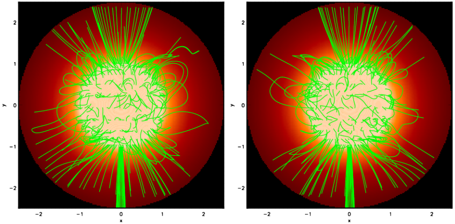
$$\frac{\partial \vec{A}}{\partial t} = \vec{v} \times (\vec{\nabla} \times \vec{A}),$$

$$\frac{\partial e}{\partial t} + \vec{\nabla} \cdot [(e + p)\vec{v}] = \rho \vec{g} \cdot \vec{v} - n^2 \chi(T) - \nabla \cdot \vec{F_c},$$

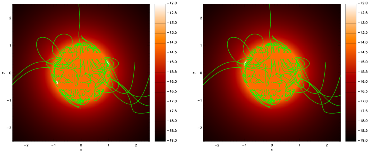
$$\frac{p}{\gamma - 1} = e - \frac{1}{2}\rho \vec{v}^2 - \frac{(\vec{\nabla} \times \vec{A})^2}{8\pi},$$

$$\vec{g} = -\frac{GM_\odot}{r^2}\hat{r},$$

MHD Global Simulation



- 256 x 256 x 512 points
- r=1 $-$ 2.5 $R_\odot$
- B splitting
- B_0 spherical harmonics



$\vec{B}$ MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0,$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) + \nabla p - \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B})}{4\pi} = +\rho \vec{g},$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0,$$

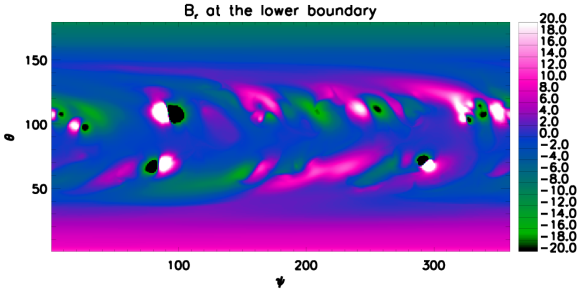
$$\frac{\partial e}{\partial t} + \vec{\nabla} \cdot [(e+p)\vec{v}] = \rho \vec{g} \cdot \vec{v},$$

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

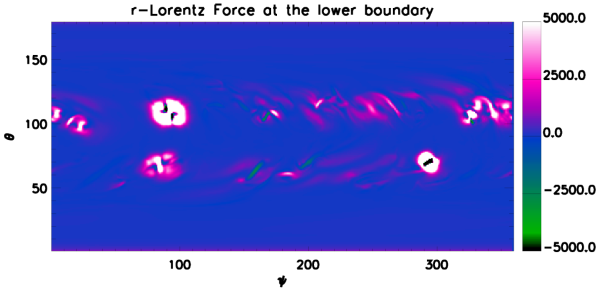
$$\frac{p}{\gamma - 1} = e - \frac{1}{2}\rho \vec{v}^2 - \frac{\vec{B}^2}{8\pi},$$

$$\vec{g} = -\frac{GM_\odot}{r^2}\hat{r},$$

Initial Condition



Different flux rope structures are on the solar disk



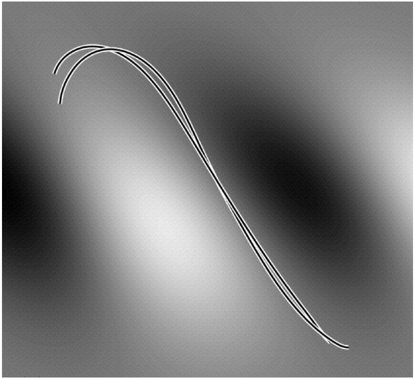
The Lorentz force excess underneath leads to upward motions

$$\epsilon_x = \frac{\left|\vec{B}\times\nabla\vec{B}_x\right|^2}{\left|\nabla\vec{B}_x\right|^2}\ \epsilon_y = \frac{\left|\vec{B}\times\nabla\vec{B}_y\right|^2}{\left|\nabla\vec{B}_y\right|^2}\ \epsilon_z = \frac{\left|\vec{B}\times\nabla\vec{B}_z\right|^2}{\left|\nabla\vec{B}_z\right|^2}$$

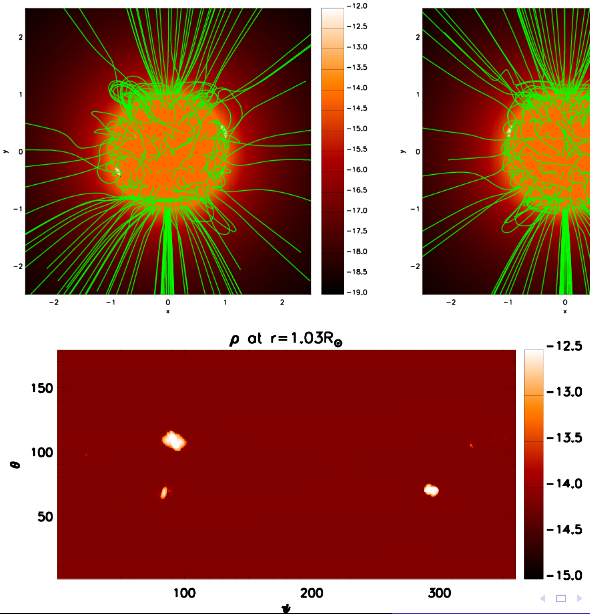
$$\epsilon = \sqrt{\epsilon_x^2 + \epsilon_y^2 + \epsilon_z^2} \tag{13}$$

$$T = \left(tan^{-1}\left(\frac{\epsilon - B^\star}{\Delta B}\right)/\pi + \frac{1}{2}\right)(T_{flx} - T_0) + T_0$$

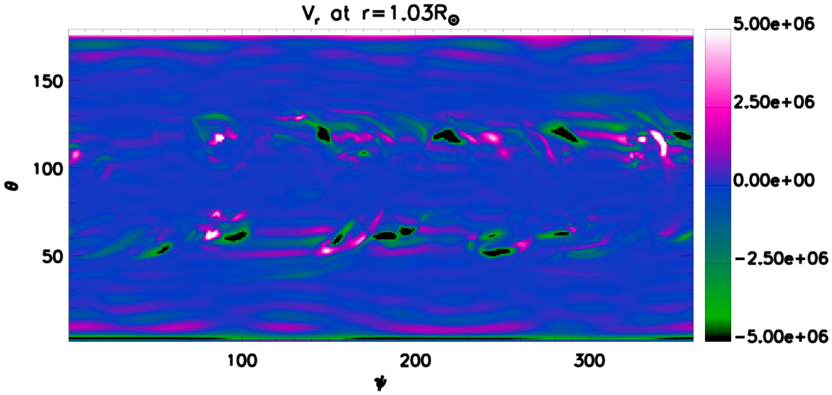
$$\rho = \frac{\mu m_p p}{k_b T}$$



Initial Condition

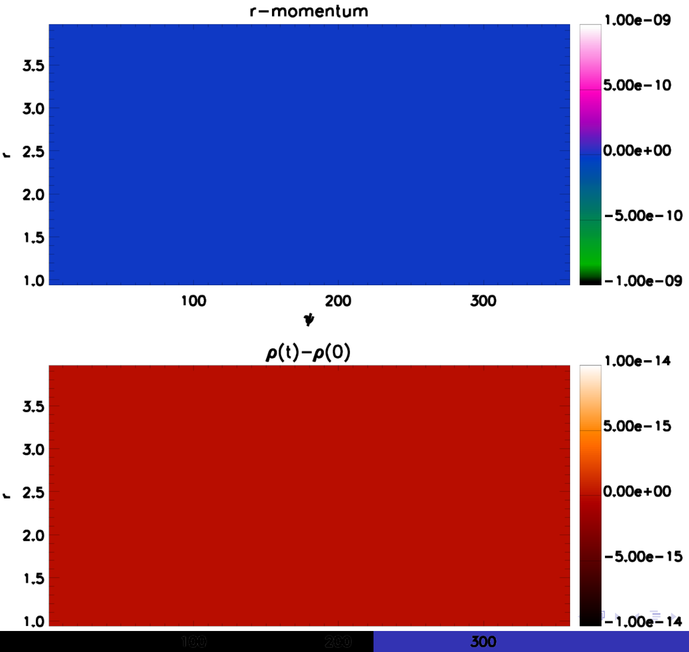


Evolution

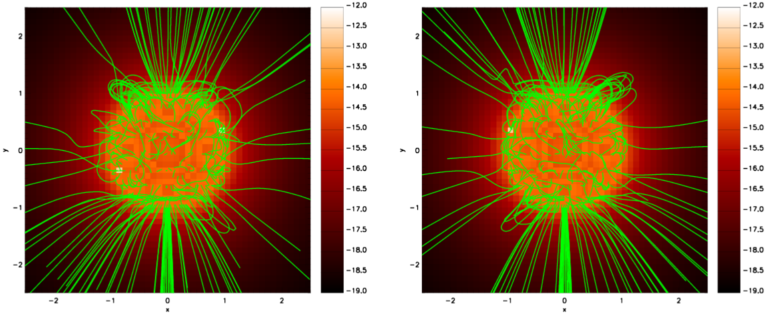


V_r at $r=1.03R_\odot$
150
100
50
θ
100
200
300
φ
5.00e+06
2.50e+06
0.00e+00
−2.50e+06
−5.00e+06

Evolution


r−momentum
3.5
3.0
2.5
2.0
1.5
1.0
100
200
300
1.00e−09
5.00e−10
0.00e+00
−5.00e−10
−1.00e−09
ρ(t)−ρ(0)
3.5
3.0
2.5
2.0
1.5
1.0
100
200
300
1.00e−14
5.00e−15
0.00e+00
−5.00e−15
−1.00e−14

Evolution


y
x
2
1
0
−1
−2
−12.0
−12.5
−13.0
−13.5
−14.0
−14.5
−15.0
−15.5
−16.0
−16.5
−17.0
−17.5
−18.0
−18.5
−19.0

Conclusions

- MHD simulation of flux rope ejections
  - The coupling of GNLFFF and MPI-AMRVAC is a reliable technique to model the life span of a single flux rope
  - This model is able to reproduce the main features of a flux rope ejection (time scale, shape)
  - We idenfied a parameter space where the ejections are favoured
  - Using also Non-Ideal term in the MHD simulation we can reproduce AIA/SDO observations of flux rope ejections
- MHD simulation of flux rope ejection in the global corona
  - The mutual coupling of GNLFFF and MPI-AMRVAC will lead to a feasible way to provide Space Weather models with accurate and realistic boundary conditions.

Get operative

- Automatization of flux emergence
- Recognition of ejection criteria for flux rope
- Automatization of coupling Global Model to AMRVAC
- Couple back AMRVAC to the Global Model

Future work

- Outlook
  - Gobal simulations of the solar corona
  - Study on the ionization state of the plasma during flux rope ejections
  - Simulation of specific events (02-08-2011)