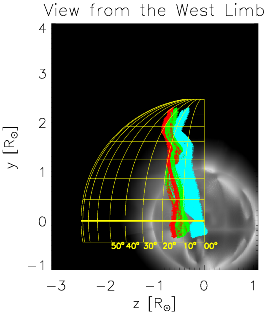
Future diagnostics of Coronal Mass Ejections with VL and UV coronagraphic data

P. Pagano[1], A. Bemporad[2], S.Giordano[2], D.Mackay[1]

[1]University of St Andrews, [2]INAF-Osservatorio Astrofisico di Torino

6th Metis Workshop
November, 22nd 2018



Coronal Mass Ejection with METIS

METIS observing CMEs

- Maps of Visible Light
- Maps of Polarised Light
- Maps of UV intensity

It is all together

White light/Polarised light

- mass
- Velocity
- trajectory
- structure
- shape

Lyman-α

- temperature

In this talk

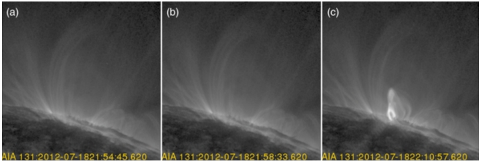
We focus on:

- Polarisation technique
- Temperature from Lyman-α
- Effects of non-equilibrium ionisation

We use MHD models to develop diagnostic techniques in realistic conditions

- Sand box to compare observed quantities with known distributions
- Test diagnostic technique in non-idealised conditions

Example: Life of flux Rope (formation)



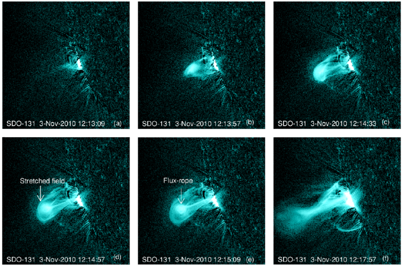
Patsourakos+2013

- 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

Example: Life of flux Rope (ejection)



Cheng+2011

- 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. ($\beta \geq 1$)

Strategy: Pagano et al.,2013. We couple two models.

NLFF field magnetofrictional model

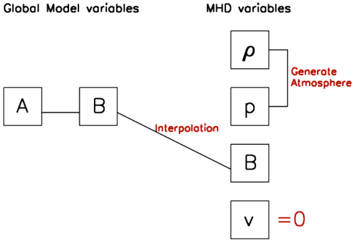
Flux rope formation/Magnetically driven evolution

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

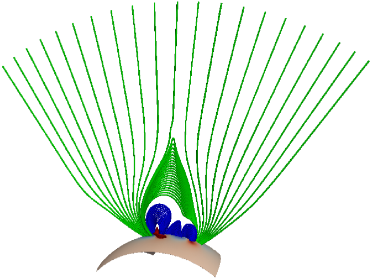
MHD Simulation - MPI-AMRVAC

Flux rope ejection/Dynamic events

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



3D Non-ideal MHD Simulation: magnetic configuration



Simulation

- $256 \times 128 \times 128$ points (r: $1 - 4R_\odot$)
- fixed grid in spherical geometry

$2.5 - 4\ R_\odot$

- $B_\phi = B_\theta = 0$
- $B_r(r) = B_r(2.5)\frac{2.5^2}{r^2}$

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

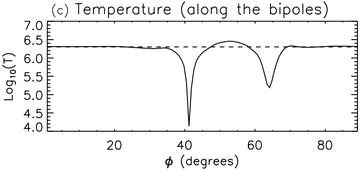
$$T(\vec{B}) = F(B_\theta/|B|, T_{min}, T_{out})(1 - G(|B|)) + T_{out}G(|B|)$$

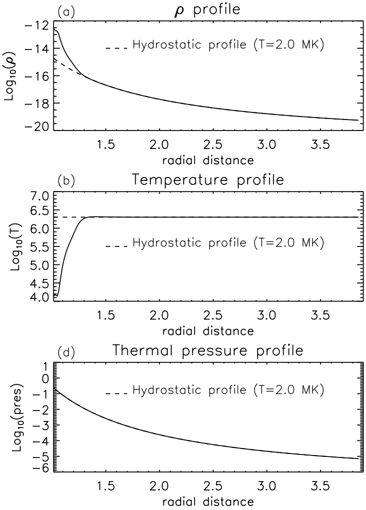
$$G(|B|) = e^{-\frac{|B|^2}{2B_*}}$$

$p =$ 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





Ejection of the flux rope: 3D MHD Simulation

MPI-AMRVAC: KU Leuven

MHD

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) + \nabla p - \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B})}{4\pi} = +\rho \vec{g} \tag{2}$$

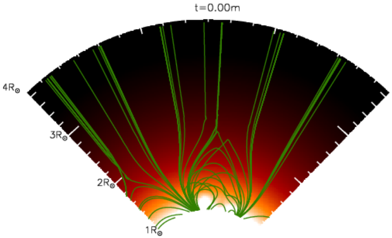
$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times (\vec{v} \times \vec{B}) = 0, \tag{3}$$

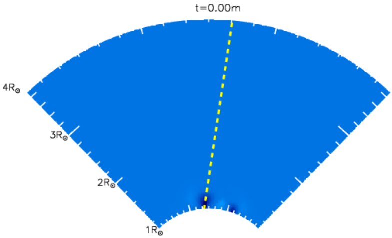
$$\frac{\partial e}{\partial t} + \vec{\nabla} \cdot [(e + p)\vec{v}] = \rho \vec{g} \cdot \vec{v} - n^2 \chi(T) - \nabla \cdot \vec{F_c} \tag{4}$$

$$\nabla \cdot \vec{B} = 0 \tag{5}$$

$$e = \frac{p}{\gamma - 1} + \frac{1}{2} \rho \vec{v}^2 + \frac{\vec{B}^2}{8\pi} \tag{6}$$

MHD evolution

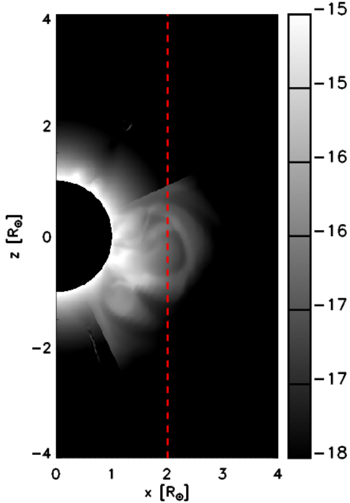


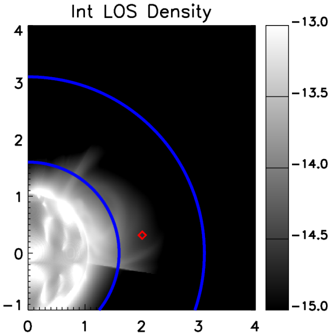


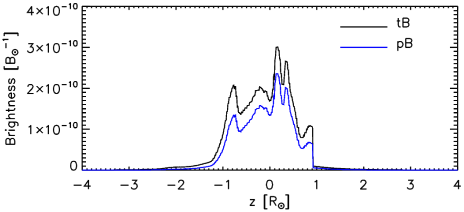
- The flux rope is ejected: dense and cold plasma is expelled
- The flux rope ejection turns into a CME
- The flux rope is ejected towards the null-point.

Polarization Ratio Technique: LOS reconstruction

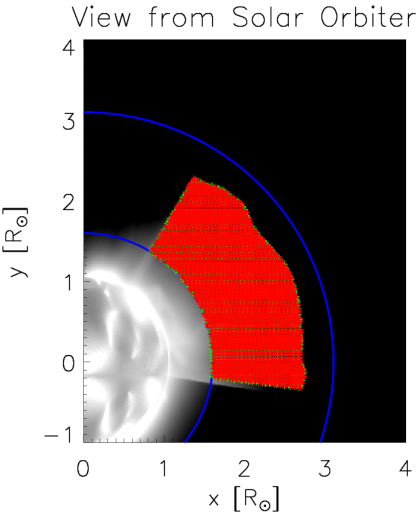
Synthesis of Total and Polarized Brightness from MHD simulation Minnaert, 1930







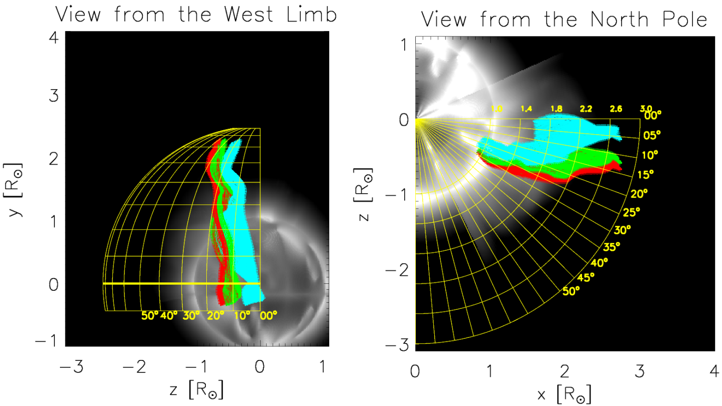
Polarization Ratio Technique: Reconstruction



Lines of sight

- We consider $\sim 200 \times 400$ lines of sight
- Red: cloud of points output from the polarization technique
- Green: cloud of folded centres of mass
- Subtraction of quite corona ($t = 0$)

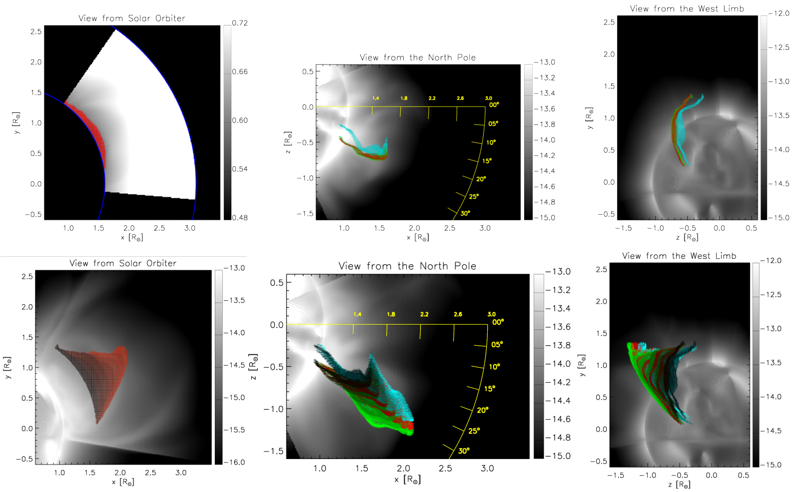
Polarization Ratio Technique: Reconstruction



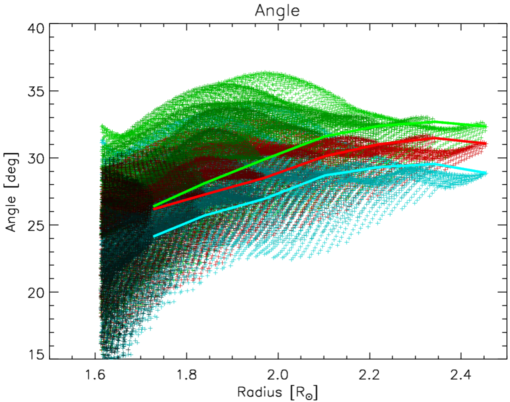
$$CM(x,y) = \frac{\int_{\infty}^{0} z[(\rho(z,x,y,t)-\rho(z,x,y,0))+(\rho(-z,x,y,t)-\rho(-z,x,y,0))]\,dz}{\int_{\infty}^{0} (\rho(z,x,y,t)-\rho(z,x,y,0))+(\rho(-z,x,y,t)-\rho(-z,x,y,0))\,dz}$$

- Polarization technique $\sim$ folded centre of mass. 2° red-green
- Significative offset from the centre of mass position. 10° red-blue

CME Evolution: Trajectory



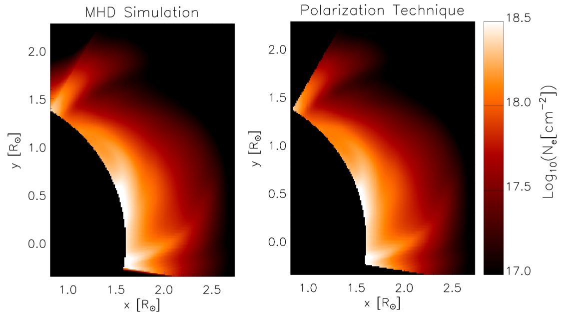
CME Evolution: Trajectory angle



- The tip of the cloud gives the CME trajectory
- The CME is deflected by about 5°
- The Folded Centre of Mass cloud is 2° farther from the POS than the Centre of Mass
- The Polarization Technique cloud is 3° farther from the POS than the Centre of Mass

The error associated to the CME trajectory is 3°

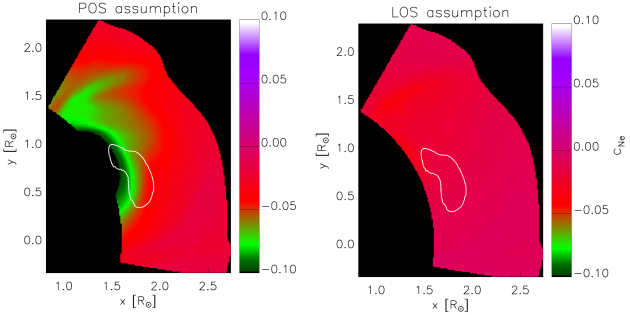
Polarization Ratio Technique: Column Density Reconstruction



- Column density maps are reproduced, including the internal structure
- Polarimetric reconstruction must assume all the plasma in one position

Polarization Ratio Technique: Column Density Reconstruction

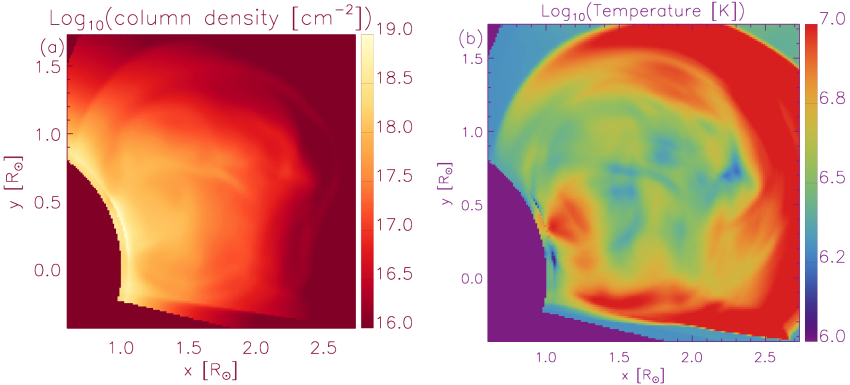
$$c_{N_e} = \frac{col(POL) - col(MHD)}{col(MHD)}$$



- LOS assumption reduces the error to less than 3%.

3D Non-ideal MHD Simulation: magnetic configuration

we want to use the combined information from VL,polarised light and UV to find CME temperatures. We apply this technique to a specific snapshot.



Lyman-α formation

$$I_{obs} = \int_{LOS} (j_r + j_c)\, dl$$

j_r radiative component

$$j_r = \frac{b\, B_{12}\, h\, \lambda_0}{4\pi}\, n_i \int_\Omega p(\phi)\, d\omega \int_0^{+\infty} I_{ex}(\lambda - \delta\lambda)\, \Phi(\lambda, \mathbf{n}')\, d\lambda\ ,$$

$$\delta\lambda = \frac{\lambda_0}{c}\, \mathbf{w} \cdot n'\ .$$

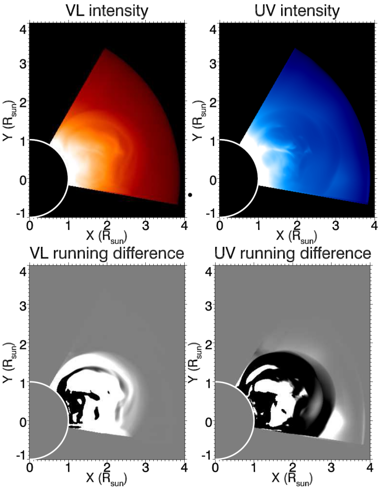
$$\sigma_\lambda(\mathbf{n}') = \frac{\lambda_0}{c} \sqrt{\frac{k_B\, T_{\mathbf{n}'}}{m_p}}\quad (cm),$$

j_c collisional component

$$j_c = \frac{b}{4\pi}\, n_e\, n_i\, q_{coll}$$

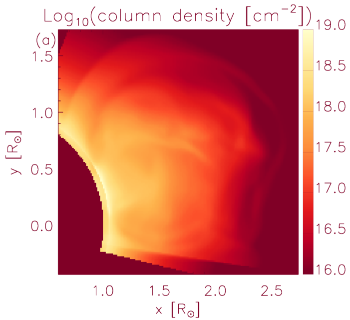
$$q_{coll} = 2.73 \times 10^{-15}\, T_e^{-\frac{1}{2}}\, (E_{12})^{-1}\, f_{12}\, \bar{g}\, \exp^{-\frac{E_{12}}{k_B T_e}}\quad (cm^3\ s^{-1}),$$

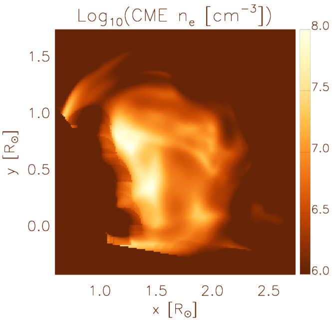
3D Non-ideal MHD Simulation: emission synthesis

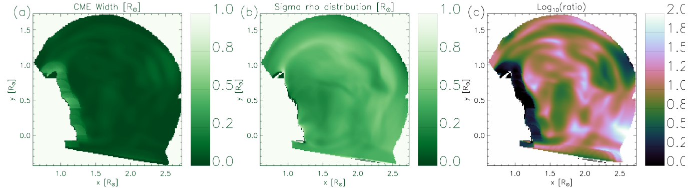


- VL and UV intensity show CME signatures
- VL generally presents more emission
- UV presents a more complex scenario

Measuring n_e

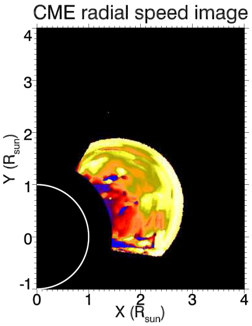




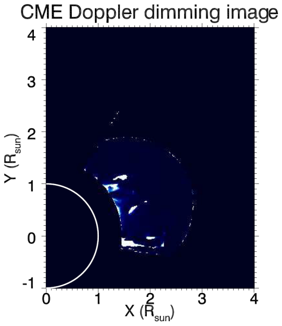


An estimation of the line of sight extension is required to derive n_e from the column density.

Measuring v_r



$0 - 1300\ km/s$



$0\% - 5\%\ km/s$

2D maps of radial velocity

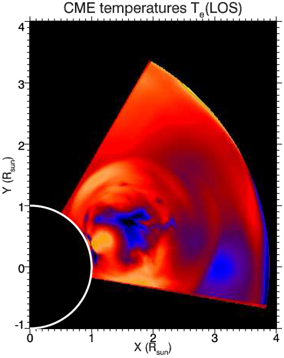
- Normalizing Radial Graded Filter (NRGF) (Morgan+,2006)
- cross-correlation between subsequent frames ($\sim 174s$)

Doopler dimming factor maps

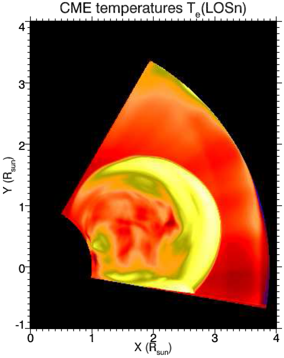
- Scale is 0%-5%
- CME front highly dimmed
- CME front is mostly visible as dimming structure in Lyman-α images

Measuring T, which T?

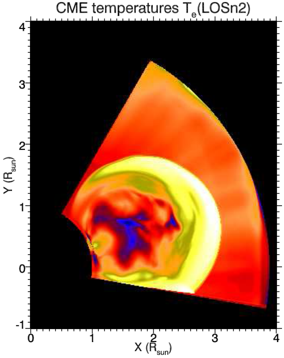
Is it the average T?



... or averaged on n_e?



... or averaged on n_e^2?



Study the ionization of the plasma during a flux rope ejection.

How the non-equilibrium ionisation effects change our diagnostics?

or

Is the plasma in ionisation equilibrium during CMEs?

Work in progress. Aims:

- Better insight on plasma state during flux rope ejection
- Improved capability to interpret UVCS observations
- ...and not only
- Improved capability to interpret METIS observations

Ionization of the plasma during a flux rope ejection.

Post-processing: [similar to Pagano+2008 on O VI and Si XII]

$$\frac{\partial n_{HI}}{\partial t} = -\vec{\nabla} \cdot (n_{HI}\vec{v}) + n_{HII}\left(\alpha_{II} n_{HII} - q_I n_{HI}\right)$$

$$\frac{\partial n_{HII}}{\partial t} = -\vec{\nabla} \cdot (n_{HII}\vec{v}) + n_{HII}\left(q_I n_{HI} - \alpha_{II} n_{HII}\right)$$

Ionization of the plasma during a flux rope ejection.

Advection: $-\vec{\nabla} \cdot (n_X \vec{v})$

- advection of HI and HII - explicit Godunov scheme
- Smoothened distribution of ρ, T, $\vec{v}$
- Flux limiter that slowly redistributes ions when too steep gradients

Ionization/Recombination: $n_X \left(q_{X-1} n_{X-1} - \alpha_X n_X \right)$

- ionization/recombination of HI and HII - implicit scheme
- $\Delta t = 0.1\ s$

Ionization of the plasma during a flux rope ejection.

Timescales

$$\frac{\partial n_{HI}}{\partial t} = -\vec{\nabla} \cdot (n_{HI}\vec{v}) + n_{HII}\left[\alpha_{II} n_{HII} - q_I n_{HI}\right]$$

$dt\left[-\vec{\nabla} \cdot (n_{HI}\vec{v})\right] \sim 2\ sec$

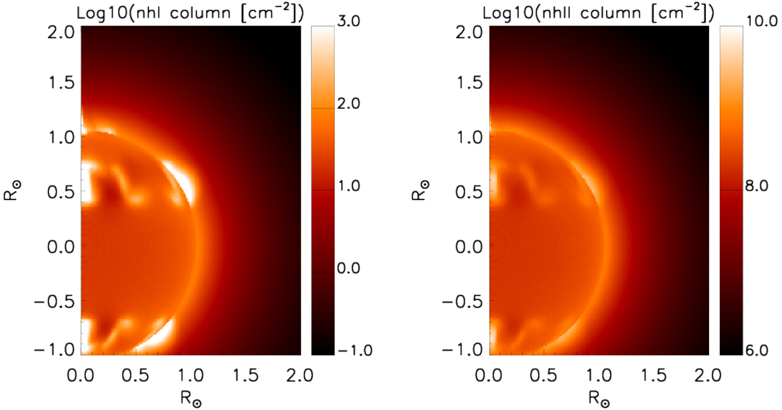
$dt\left[n_{HII}\left(\alpha_{II} n_{HII} - q_I n_{HI}\right)\right] \sim 10^{-7}\ sec$

Still quite slow computationally

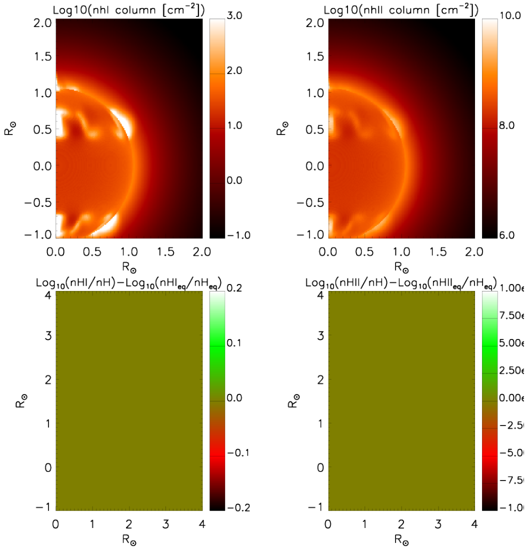
Ionization of the plasma during a flux rope ejection.

Ionization equilibrium at t=0

- $\vec{v} = 0$
- $[\alpha_{II} n_{HII} - q_I n_{HI}] = 0$
- $n_{HII} = \rho / m_p$



Ionization of the plasma during a flux rope ejection.



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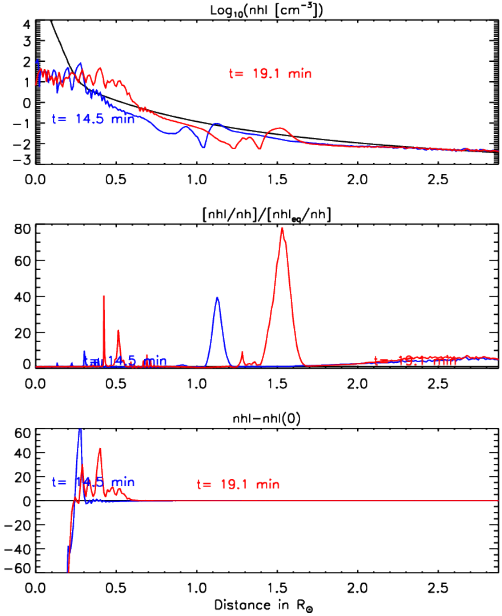
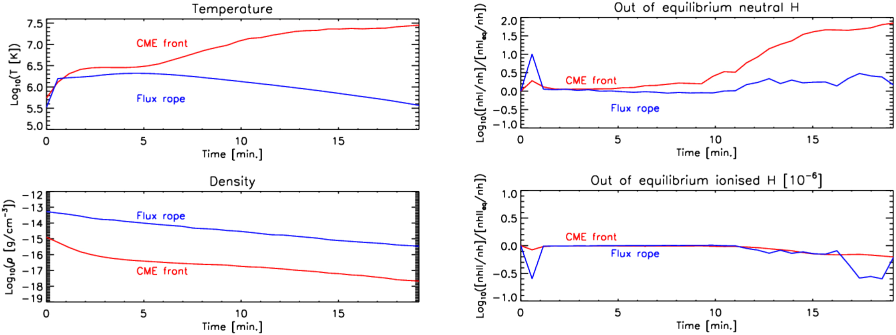


Ionization of the plasma during a flux rope ejection.



Conclusions

Using white light and polarised light we can

- Measure better the column density
- Find the position of the CME along the LOS
- Derive the 3D trajectory of the CME
- Estimate the LOS extension of the CME, i.e. its density

Adding Lyman-α

- Measuring a CME temperature
- Studying in details physics of CMEs: heating
- Studying in details physics of CMEs: reconnection

Special Session

Combining observations with models to derive CMEs properties: where we stand and what is next

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Registration opens

1st December 2018

Acknowledgments

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 647214).

European Research Council
Established by the European Commission