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Synthetic Radio Maps of CMEs in the Lower Corona

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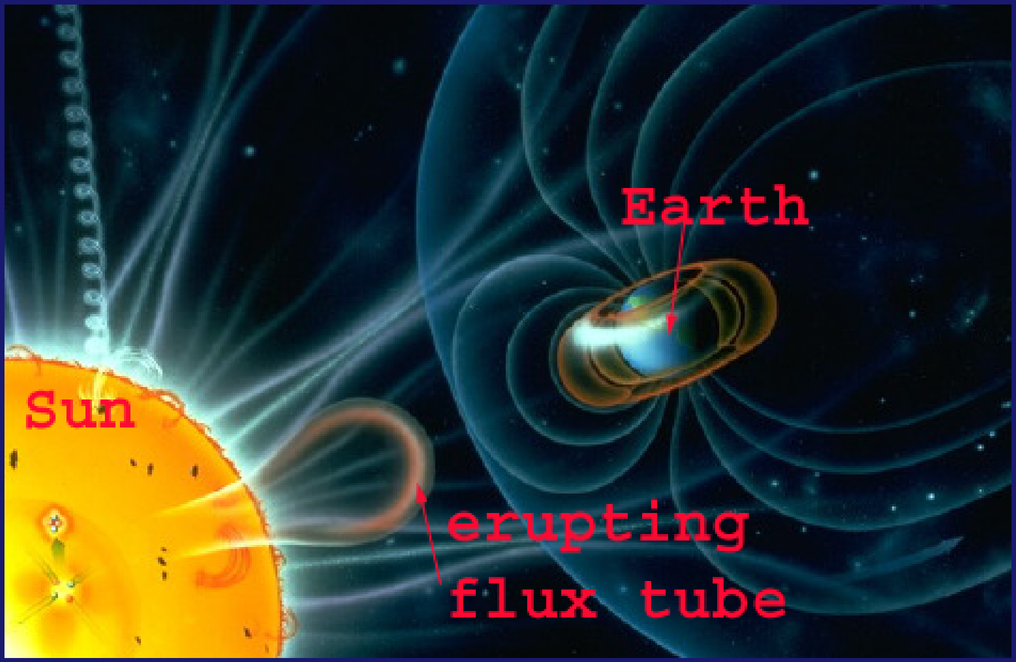
Composition

- ▷ CME observations in the inner heliosphere
- ▷ The radiation model
- ▷ The MHD-Model (2 1/2 D)
- ▷ Synthetic radio maps (with movie)
- ▷ The MHD-Model (3 D)
- ▷ Movies of 3 D simulation results
- ▷ Conclusions

The Solar-Terrestrial System



Transient phenomena in the solar corona interact with the magnetosphere of the Earth

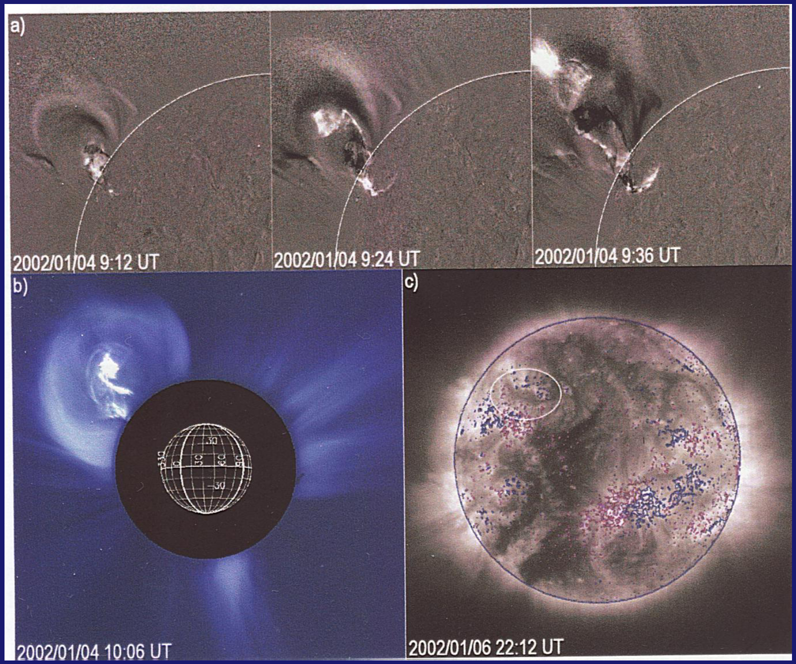
Features:

→ There is dense solar material within the flux tube

→ The flux tube is driven out in the diverging magnetic field of the Sun

⇒ "Coronal Mass Ejection" = CME

CME Observations



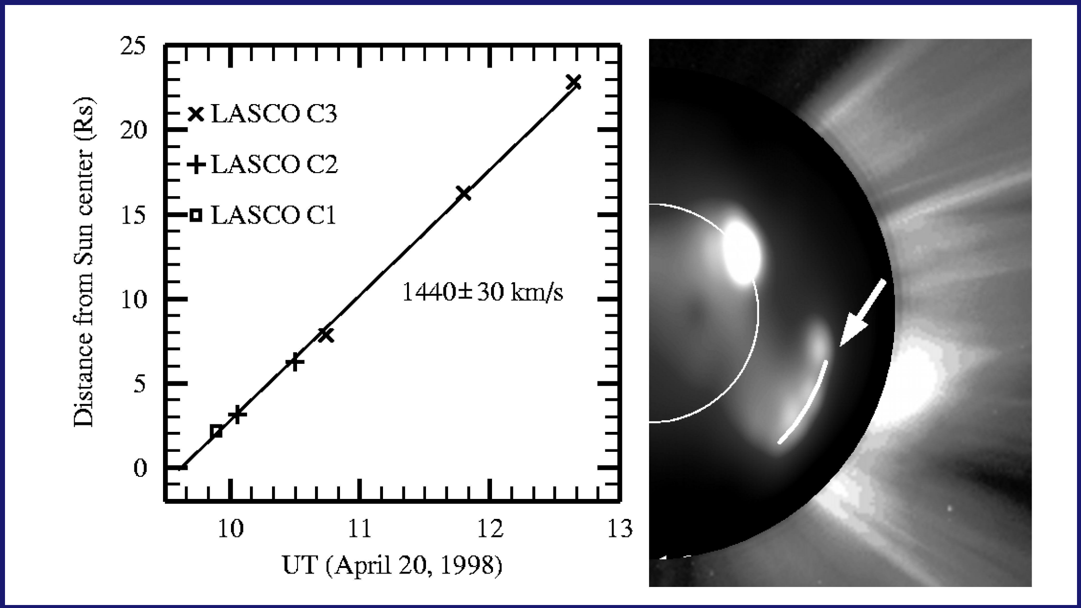
CME as seen in EIT (a), LASCO C2-coronagraph (b) and MDI magnetogram (c) images [Cremades and Bothmer, 2004]

→ A magnetic field arcade system that encircles hot material erupts from the limb of the Sun (a)

→ The system develops self-similarly until it is seen in white light at larger heliocentric distances (b)

→ The magnetogram reveals the orientation of the flux tube as being parallel to the line of sight of the observer (c)

Radio-map observations of CMEs



Nançay radio telescope observation [Maia et al., 2000]

frequency: 164 MHz

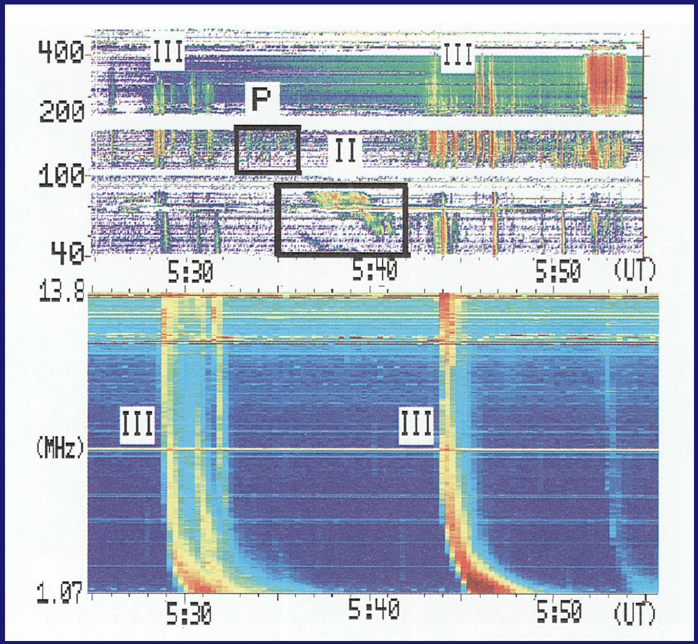
Features:

→ solid line (arrow): CME shock front, extrapolated from LASCO observations

→ around solid line: radio emissivity enhancement (type II)

→ enhancement appears around 1.7 $R_\odot$ and dims when CME moves out

Radio type II bursts



Type II / III radio-bursts are attributed to traveling shock waves of CMEs / flares that accompany CMEs [Aurass et al., 2002]

→ frequency-drift to lower frequencies in time

→ Drift is due to decrease of plasma frequency with decreasing density in the solar corona

⇒ Radiation is caused by conversion of first or second harmonic Langmuir-waves at ion-acoustic waves as scattering centers

Further observational facts

▷ Four further CME events with shock-identification like in Maia et al., [2000] have been investigated [Vourlidas et al., 1999]

▷ The association between interplanetary type II bursts and CME-driven shocks is firmly established [Cane, Sheeley & Howard, 1987]

▷ Reiner & Kaiser, [1999] demonstrated unambiguously that interplanetary type II radio emission is generated upstream of the CME-driven shock

▷ Observed metric type II radio-bursts above about 100 MHz are assumed to be due to second harmonic plasma radiation [Gopalswamy et al., 2005]

▷ Other radio emissions like first order plasma radiation [Gopalswamy et al., 2005] or gyrocyclotron type IV emission in magnetic loops of the CME [Bastian et al., 2001] have been identified in CME events

▷ Here, we restrict ourselves on the modelling of the second harmonic plasma emission component of the radiation

The radiation model (I)

Second harmonic plasma emissivity:

$$j_{sh}(2\omega_p) = 5.83 \times 10^{-12} \left(\frac{T_e}{T_{e0}}\right)^{3/2} \frac{|E|^4}{\sqrt{n_0}}, \text{ watts m}^{-3}\text{sr}^{-1} \quad (1)$$

[Papadopoulos et al., 1974]

$\omega_p = \left(\frac{n_0 e^2}{\epsilon_0 m_e}\right)^{1/2}$: plasma-frequency

T_e: electron temperature

$T_{e0} = 1.2 \times 10^5$ kelvin

$|E|$: electric field of Langmuir turbulence at saturation level

n_0: electron number density

The radiation model (II)

$$|E| = \left(\frac{n_b}{n_0}\right)^{1/6} \frac{1}{e}\sqrt{\frac{2m_e}{\epsilon_0 n_b}} J \text{ [Manheimer, 1974]} \qquad (2)$$

n_b: electron beam density
J: current density
$n_b \approx 10^{-9} n_0$ from ISEE-3 s/c measurements

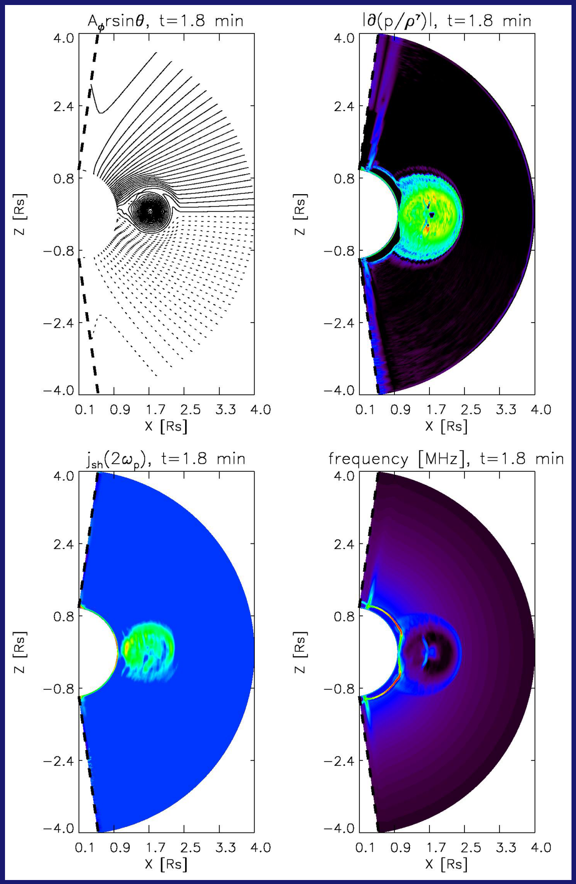
$$J = -\frac{1}{\mu_0}\left\{\frac{1}{r\sin\theta}\frac{\partial^2}{\partial r^2}(A_\phi r\sin\theta) + \frac{1}{r^3\sin^3\theta}\left[\sin^2\theta\frac{\partial^2}{\partial\theta^2}(A_\phi r\sin\theta) - \sin\theta\cos\theta\frac{\partial}{\partial\theta}(A_\phi r\sin\theta) + A_\phi r\sin\theta\right] - \frac{1}{c^2}\frac{1}{r\sin\theta}\frac{d^2(A_\phi r\sin\theta)}{dt^2}\right\} \qquad (3)$$

A_ϕ: vector-potential

The MHD-model (2 1/2 D)

- ▷ solution of MHD equation in r- and θ-coordinates, ϕ-coordinate is assumed to be constant
- ▷ simulation box between 1 and 4 $R_\odot$
- ▷ Parker solar wind with 300 km/s, flux-rope initially at 1.35 $R_\odot$, 0.35 $R_\odot$ radius
- ▷ B-field 525 gauss at solar surface and within CME, internal pressure 3 $\times$ external pressure

Synthetic radio maps (I)

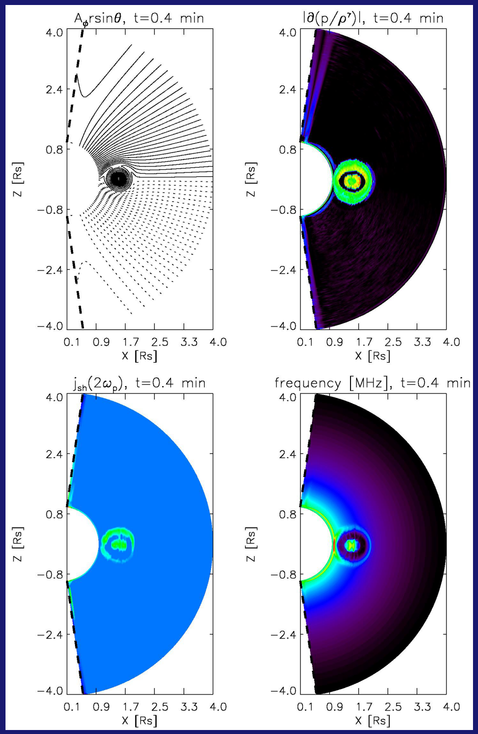


→ On display: field lines (a), entropy-jump (b), second harmonic plasma emissivity (c) and frequency-distribution (d)

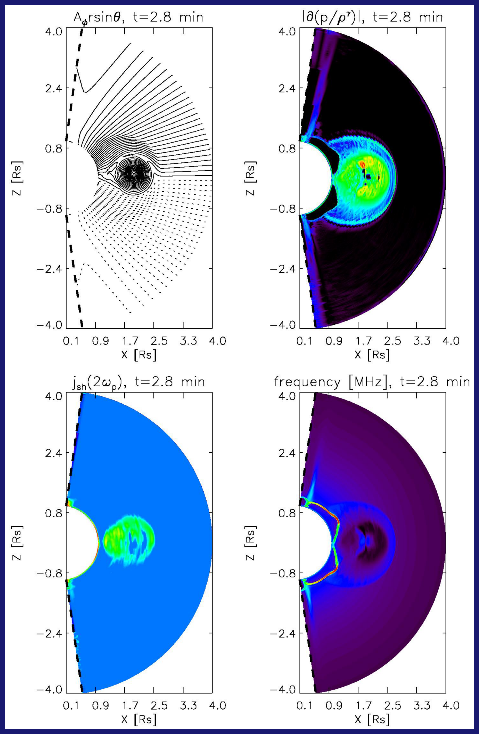
→ Reconnection at northern edge of CME ⇒ enhanced emissivity in northern hemisphere of CME

→ Density pile up behind shock front ⇒ Ring area of enhanced plasma frequency behind shock front (blue)

Synthetic radio maps (II)



Previous state at 0.4 min

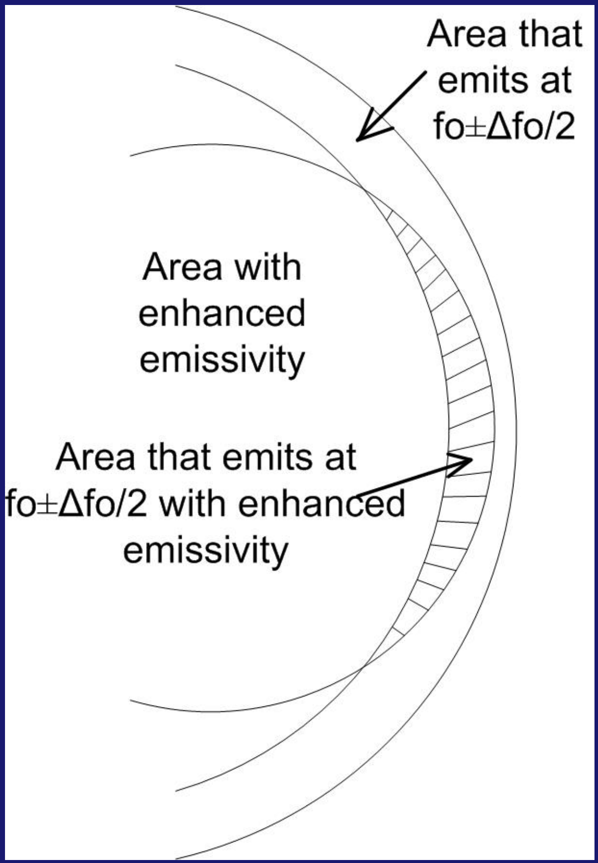


Past state at 2.8 min

Left: The shock develops; Right: The shock front broadens

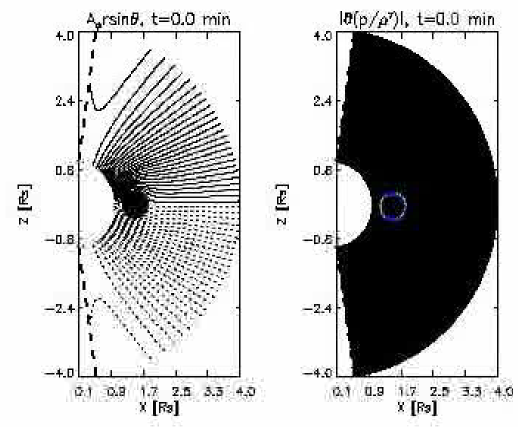
In both cases: Overlap of area with enhanced plasma frequency (blue in (d)) with area with enhanced plasma emissivity (green in (c)) is less pronounced

Synthetic radio maps (III)



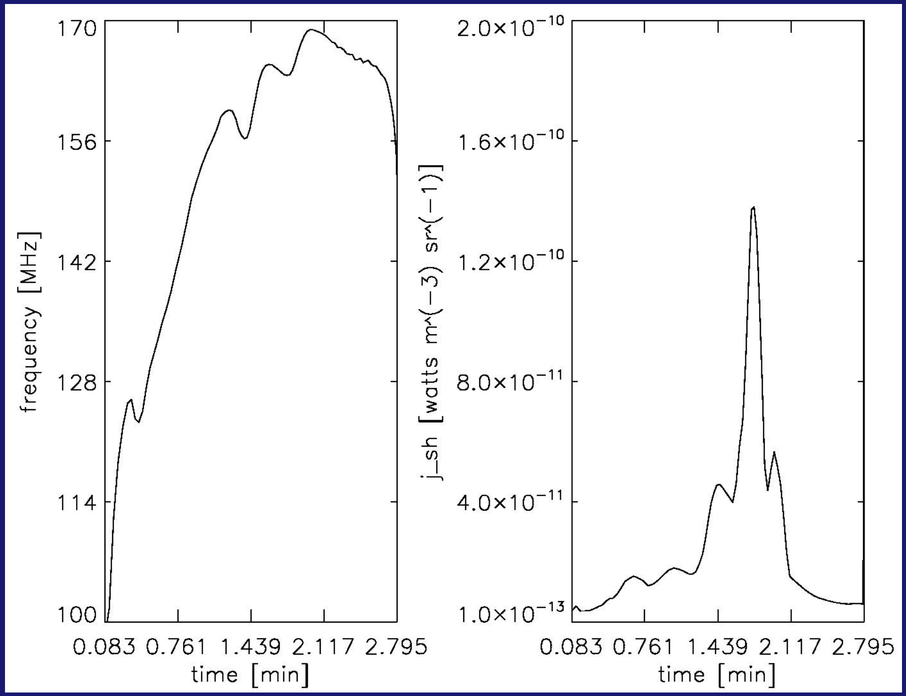
→ The overlap of the ring area with plasma frequency $f_0 \pm \Delta f_0/2$ with the circular area with enhanced plasma emissivity is the region of the radio source that can be detected with a telescope that receives at a frequency f_0 (164 MHz) with a band width of Δf_0

Synthetic radio maps (IV) - The movie



- ▷ The reconnection intensifies at the northern edge
- ▷ The shock encircles the CME like the hat of a mushroom
- ▷ The central area of the CME starts glooming; but it dims when the CME moves outward
- ▷ The ring of enhanced plasma frequency follows the shock and broadens

Synthetic radio maps (V)



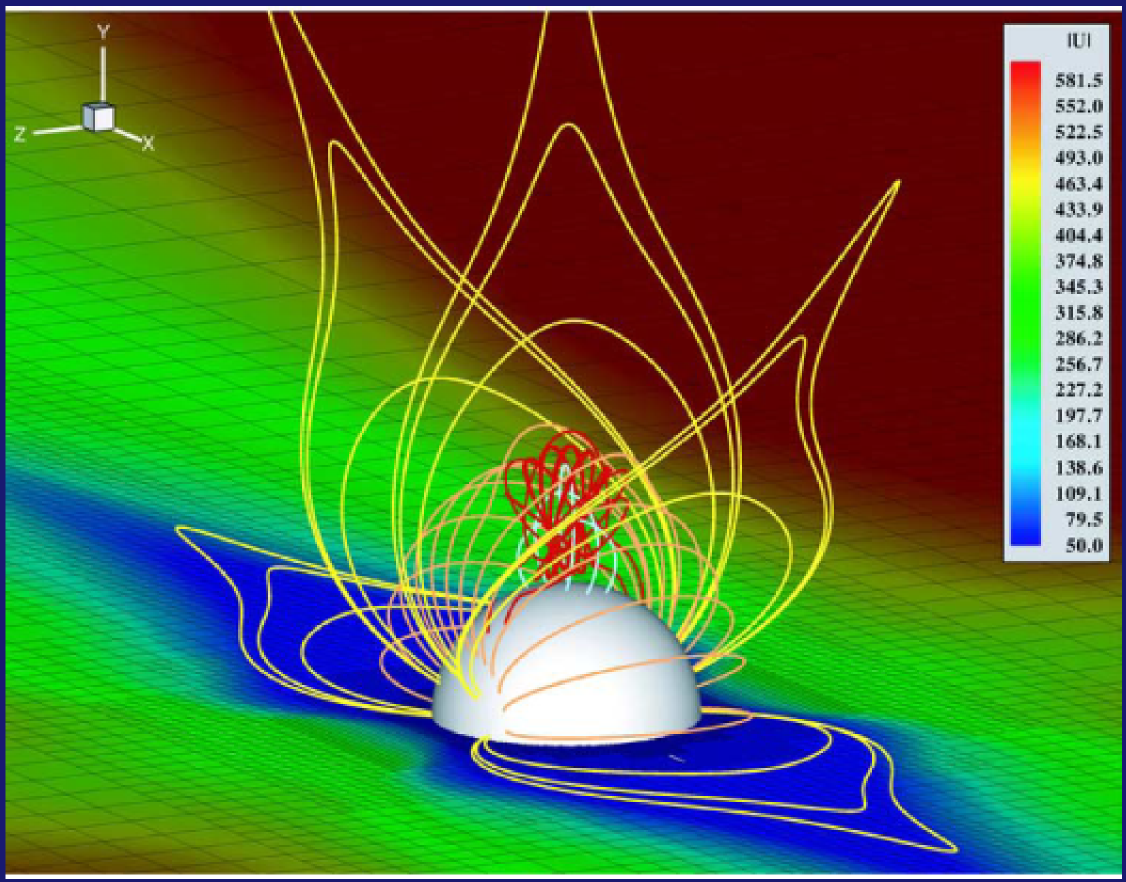
Development of the frequency and emissivity in the shock front

- ▷ The emission frequency increases due to the steepening of the shock and reaches ≈ 164 MHz after a while
- ▷ In the long run, the emission frequency decreases again due to the spherical expansion
- ▷ This creates an increasing and then decreasing radio emissivity signal
- ▷ It is what we see in the observations ⇒ Explanation of the observations

The MHD-model (3 D) (I)

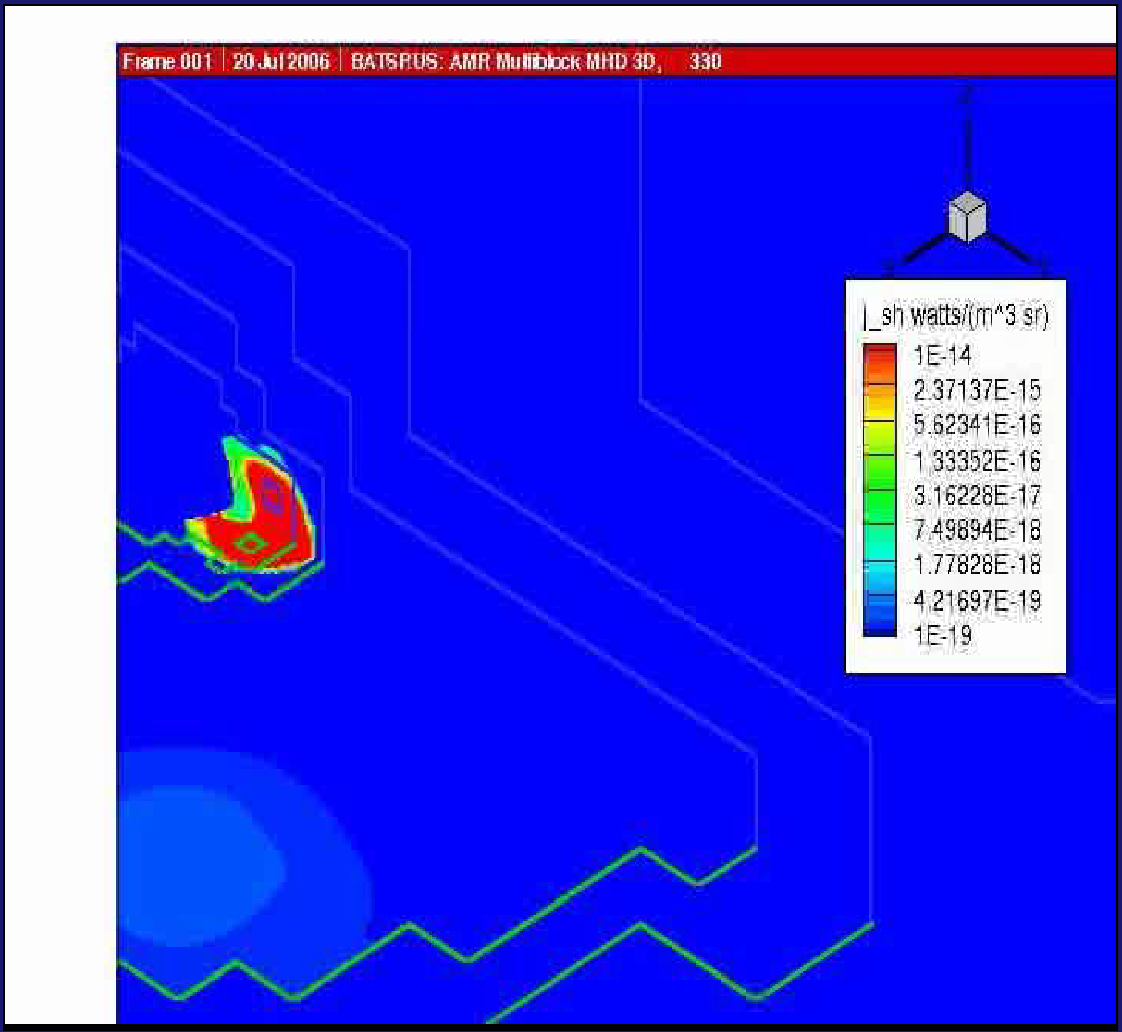
- Cartesian simulation box with size 32 $R_\odot$ and $\approx$ 3,000,000 cells
- The MHD-equations are solved with the help of a Riemann-solver on this grid
- Adaptive mesh refinement at places with large gradients of the fields
- The code runs on a parallel computer with six or more parallel processors
- The CME is introduced as a twisted flux-tube
- The magnetic field of the Sun consists of an arcade system over the solar equator and open field lines above the poles of the Sun

The MHD-model (3 D) (II)



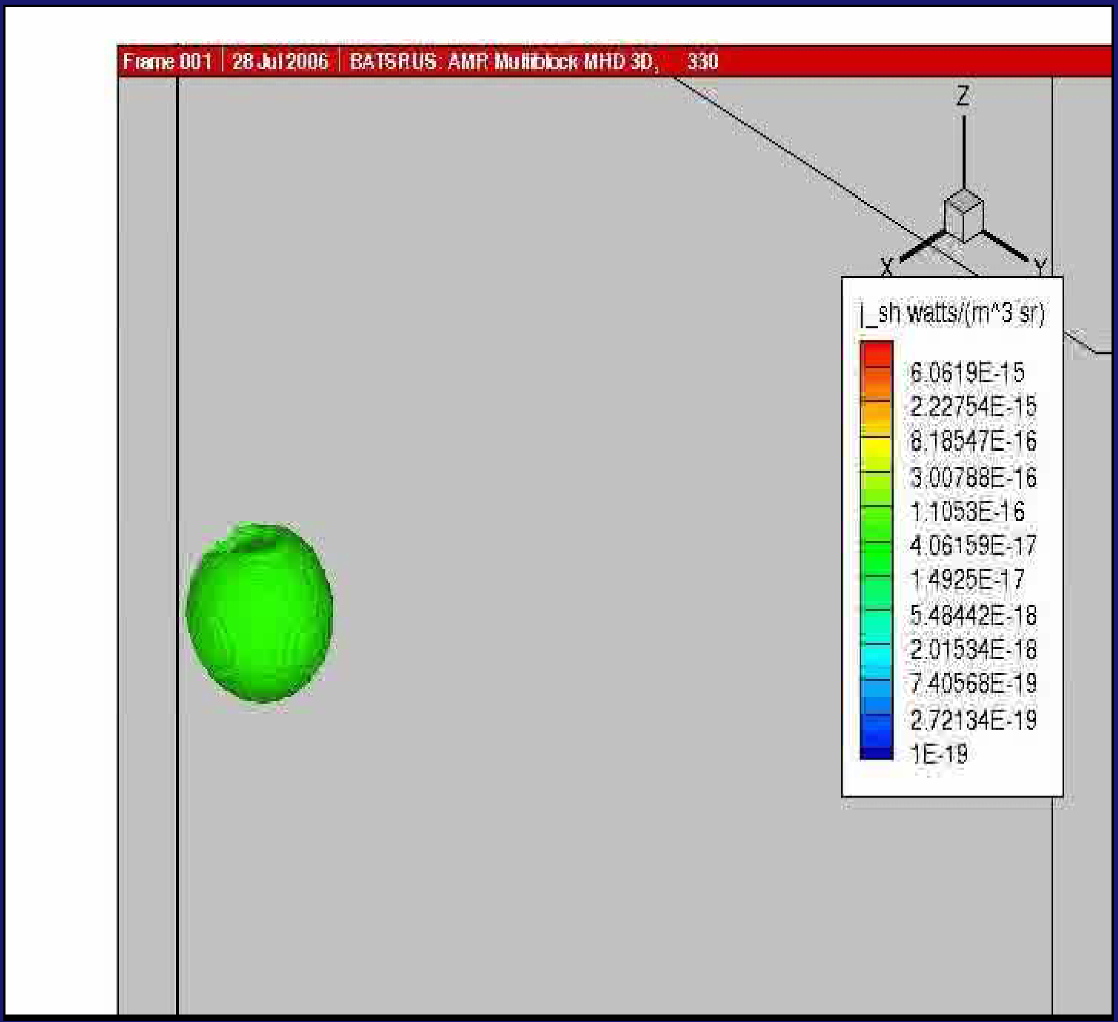
→ The initial magnetic field configuration of the code

Movie (I): Plasma emissivity in 3 D



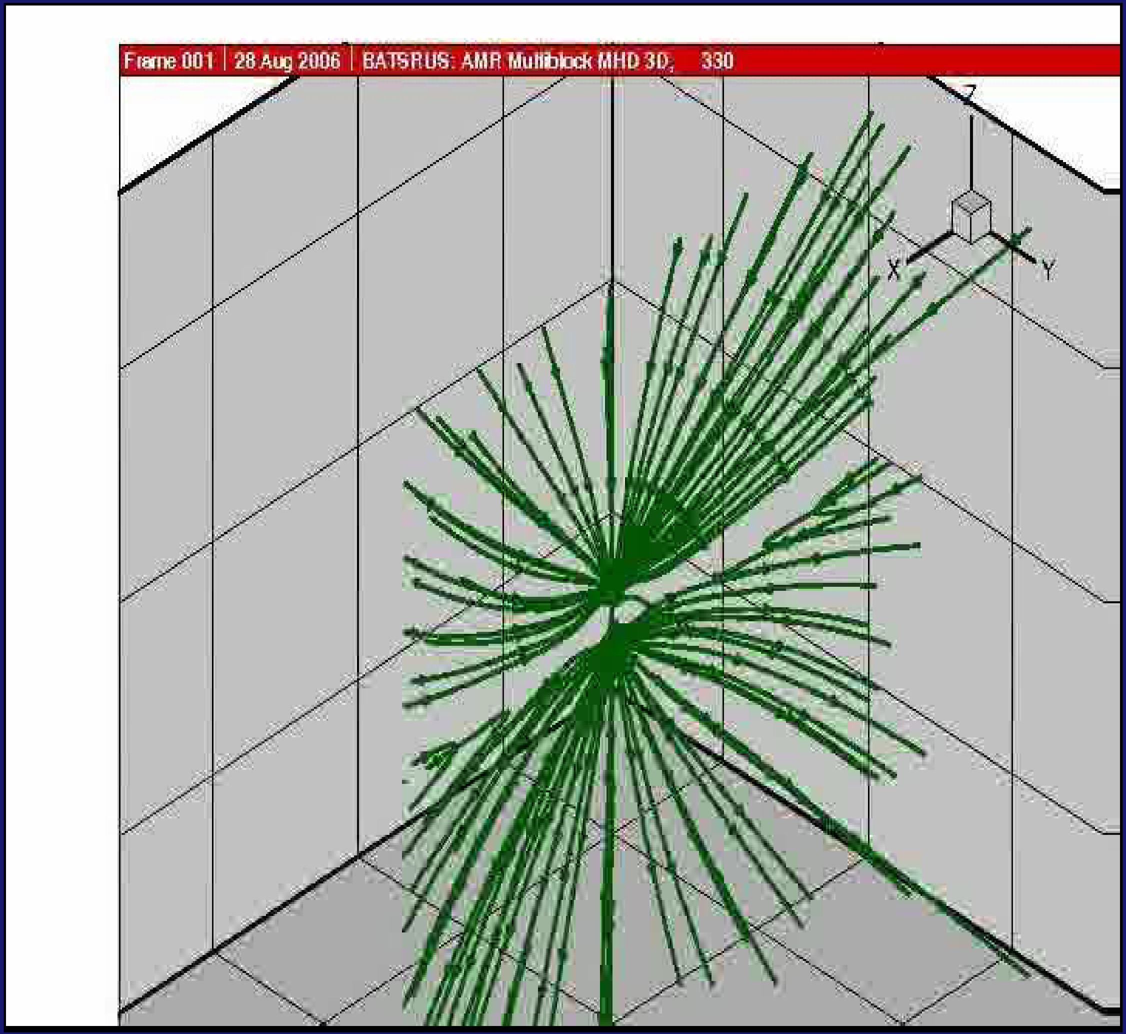
- ▷ Contour plots of the second harmonic plasma emissivity in the x-y- and in the y-z-plane
- ▷ An atomic mushroom like structure that expands moves out
- ▷ Enhancements of emissivity in the shock that runs in front of the CME and in the reconnection region with jets and glooming dissolved magnetic field lines at the rear of the CME

Movie (II): 3 D Tracing of the CME shock fronts



- ▷ Iso-surface of the emissivity within the shock front of the CME that moves out
- ▷ ⇒ Tracing of the CME shock waves that move particles (SEP-events)

Movie (III): The “melon seed corn” effect



- ▷ The CME as a magnetic bubble emerges from the surrounding radial solar magnetic field
- ▷ ⇒ Reconstruction of the magnetic fields that accelerate CMEs

Conclusions

- ▷ The center part of the CME is a region of enhanced plasma emissivity
- ▷ Magnetic reconnection at the northern edge and compression at the front edge enhances the emissivity
- ▷ Within the shock region there is an enhanced emission frequency $\Rightarrow$ Shocks of CMEs are sources of high frequency plasma emission
- ▷ We obtain good agreement with the Nançay radio-telescope measurements
- ▷ In 3 D we get tomographic radio emission images of the CME-eruptions
- ▷ The emission can be used to trace 3 D shock structures that accelerate particles
- ▷ The 3 D simulation gives reconstructions of the magnetic fields that accelerate CMEs