MHD modeling of the inner heliosphere and its transients

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Ruhr-Universität Bochum, Germany

Cosmic Rays and the Heliospheric Plasma Environment
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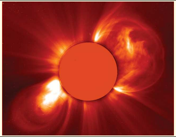
Talk outline:

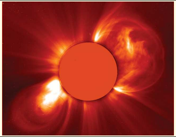


Coronal mass ejection (CME):
large blob of solar plasma ($m \approx 10^{13}$ kg, $v_0 \approx 20 \ldots 3000$ km/s) ejected spacewards

Why care about CMEs?

1. Major manifestation of solar activity
2. CMEs relate to many other fields of solar physics
   - flares $\leftrightarrow$ CMEs
   - particle acceleration at shocks
   - global flux removal, ...
3. Commercial application: "space weather"
   - safety concerns for astronautics,
   - satellite communication failures, etc.

$\Rightarrow$ urgent need to predict outbreak and IP evolution!



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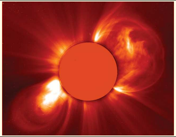

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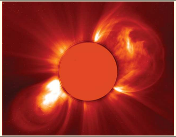

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What makes CME modeling a demanding task?

1. The CME phenomenon spans vast temporal and spatial scales. ⇒ Need to specialize on selected aspects/phases.
2. Initial (pre-eruptive) conditions are poorly known (just surface magnetograms, coronagraph images, in-situ obs.)
3. CMEs exhibit diverse structure, esp. when interacting. $\sim$10(!) morphological classes [Howard et al. 1985].
4. CME propagation is inherently 3D.

Focus of MHD-based CME models can be on

- initiation/eruption [not this talk]
- propagation (expansion, trajectory, acceleration/travel time)
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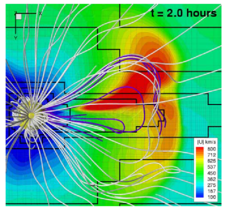

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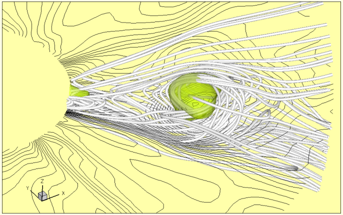

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Major (technical) challenge: High resolution requirements due to

1. need to track features $\ll R_\odot$ across $> 214\ R_\odot = 1$ AU
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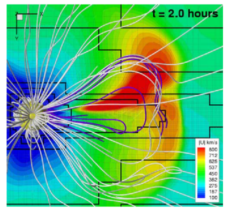

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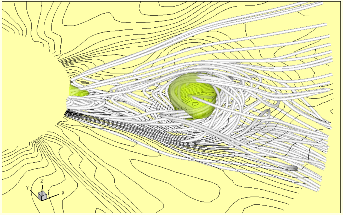

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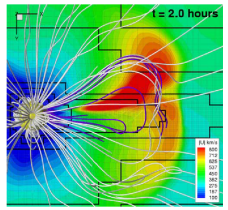

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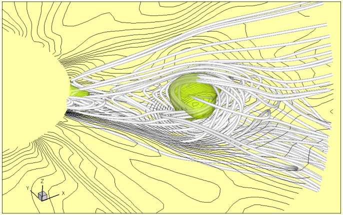

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- expansion near ecliptic
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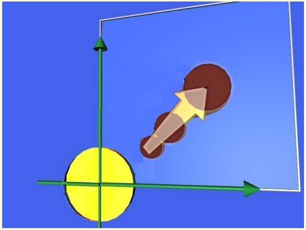

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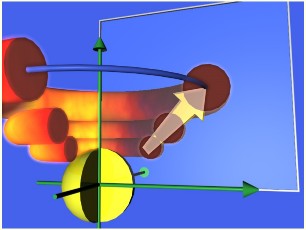

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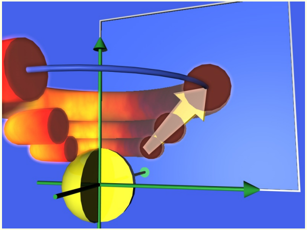

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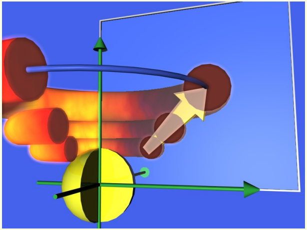

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- specially tailored grids, esp. spherical with radially varying $\Delta r = \Delta r(r)$
- mesh refinement techniques [BATS-R-US, AMRVAC, ...]
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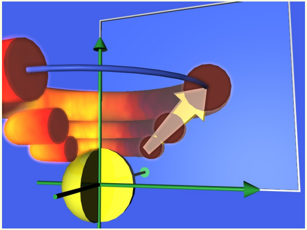

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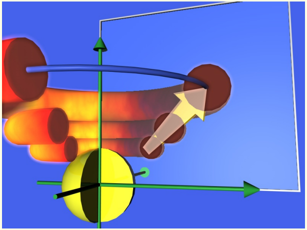

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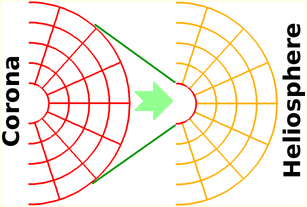

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1. Geometry (2-D / 2.5-D / 3-D)
2. Method of initiation (of 2nd order for large r) (shearing footpoints / flux emergence / density-driven)
3. Goal: "principal" study (idealized setting, few parameters) vs. realistic forecast (as much physics as possible)
4. Realization of boundary conditions at $r = R_\odot$ (analytic or observationally derived, e.g. from magnetograms) and the background solar wind
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Further categories (cont'd): Heating functions

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- isothermal $\gamma = 1$ or adiabatic $\gamma = \gamma_0 \leq 5/3$ ($p \sim \rho^\gamma$)
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  - Ad-hoc heating [e.g. Hartle & Barnes 1970, Manchester et al. 2004]
    e.g. $Q(\mathbf{r}) = q(\mathbf{r})\,[T_0 - T]$ $\Rightarrow T \to T_0$ "target temp."
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  - $S = \mathbf{u}_1 \cdot \nabla \left(p_1 \rho_1^{-5/3} \right)$ with $(\cdot)_1$ from $\gamma = 1.05$ run
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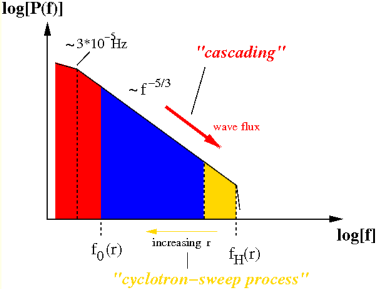
SW heating by Alfvén waves

Concept:
Waves are excited near $R_\odot$, travel along $\mathbf{B}$, get shifted up in f, and dissipate at f_h.
Variables: either scalar fields $\varepsilon_\pm$ or full spectrum $P(f, \mathbf{r}, t)$.



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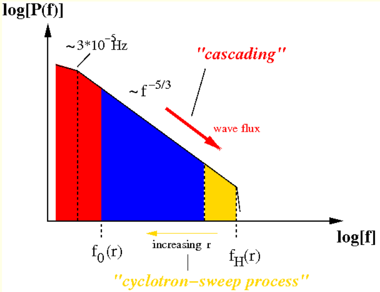

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- wave pressure $p_{\mathrm{w}}(\mathbf{r}) = (1/2) \int_{f_0}^{f_{\mathrm{h}}(\mathbf{r})} P(f, \mathbf{r})\, \mathrm{d}f \;\hat{=} (\varepsilon_+ + \varepsilon_-)/2$
- heating term $Q_{\mathrm{w}} = F(f_{\mathrm{h}}, \mathbf{r}) - P(f_{\mathrm{h}}(\mathbf{r}), \mathbf{r})\, [\mathbf{u} \pm \mathbf{v}_{\mathrm{A}}] \cdot \nabla f_{\mathrm{h}}(\mathbf{r})$

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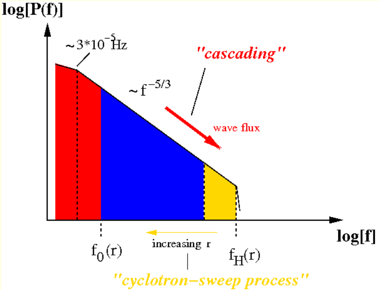
→ see Bidzina's talk (next)



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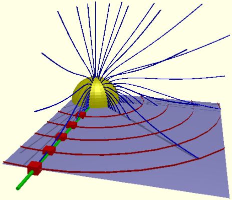
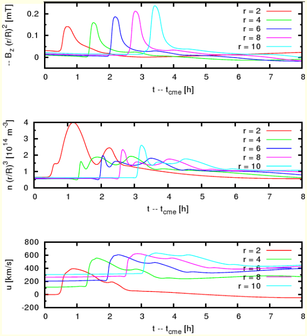
Some findings from principal models

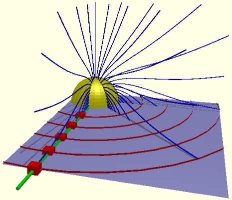
1. Some indication of approximately self-similar evolution [e.g. Kleimann et al. '09]
2. CME development strongly depends on
   - background SW (higher speeds in fast, dilute winds) [Jacobs et al. 2005] and
   - the initial polarity w.r.t. $\mathbf{B}_{sw}$, influencing the CME's speed, shape, and deflection.

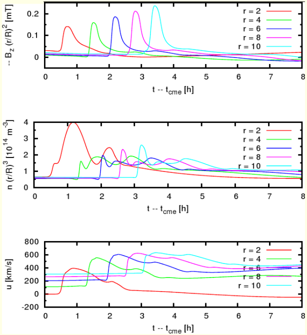


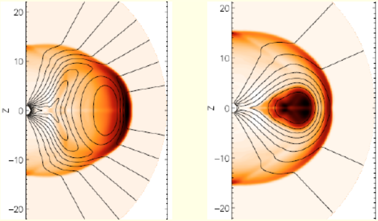


Some findings from principal models

1. Some indication of approximately self-similar evolution [e.g. Kleimann et al. '09]
2. CME development strongly depends on
   - background SW (higher speeds in fast, dilute winds) [Jacobs et al. 2005] and
   - the initial polarity w.r.t. $\mathbf{B}_{\mathrm{sw}}$, influencing the CME's speed, shape, and deflection.



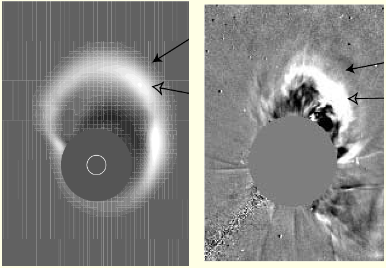




[Chane et al. 2006]

Comparison to (satellite) observations

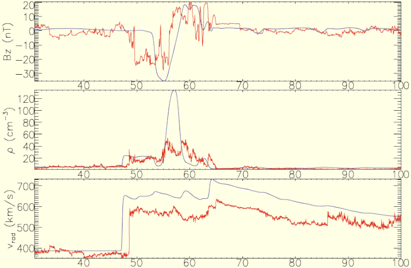
Coronagraph (LASCO)



SWMF (3D, MDI init)

Lugaz et al. [2007]

in situ (ACE @ L_1)

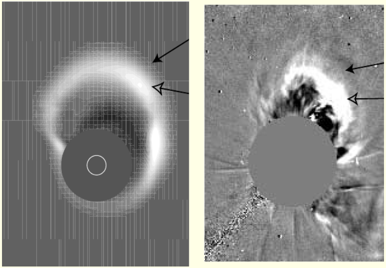


VAC (2.5D, analyt. init)

Chané et al. [2008]

Comparison to (satellite) observations

Coronagraph (LASCO)



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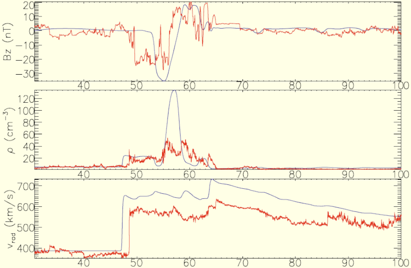

VAC (2.5D, analyt. init)

Chané et al. [2008]

<u>NB:</u> Models are quite sensitive to chosen parameters [e.g. Schrijver et al. 2008], but published results often consider only limited parameter ranges.

Conclusions

- CMEs are a very diverse class of heliospheric transients.
- 3D MHD simulations are indispensable to model a CME's life cycle, with the long-term goal of reliable forecasts.
- Modeling results/predictions crucially depend on initial parameters and physical effects included.
- Models benefit from high-quality S/C data input to
  1. constrain IC/BCs and
  2. allow for a posteriori verification of results.
- Simple models can be useful, provided their limitations are taken into account. $\rightarrow$ Importance of comparative studies!