CME modeling at the CPA of KU Leuven

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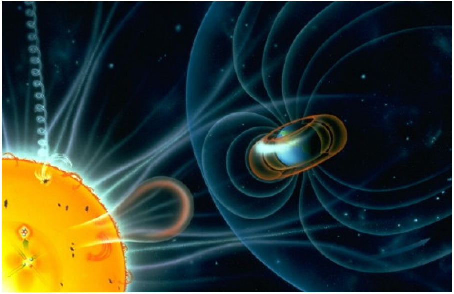
Motivation : space weather

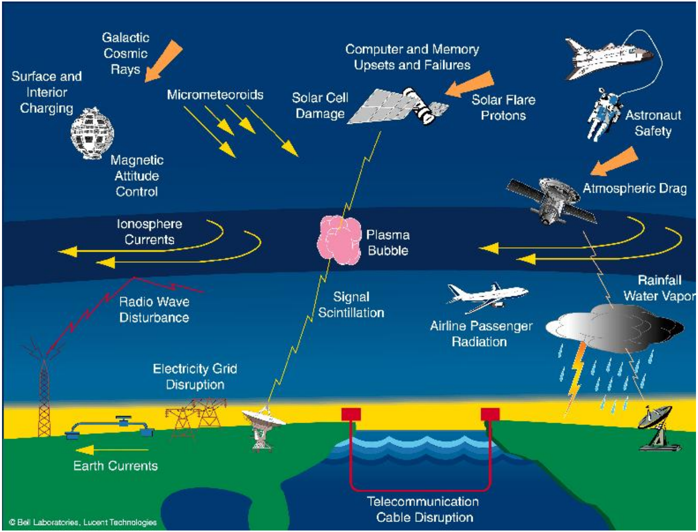
USA NSWP Strategic Plan:

"Space Weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and can endanger human life or health."



Space weather =
time-dependent disturbances of the Earth's magnetosphere driven by solar activity in a wide range of spatial and temporal scales

Space weather effects



Space weather : drivers

- drivers are of solar origin:, viz. transient phenomena superposed on the solar wind:
  - CMEs (most prominent)
  - eruptive flares
  - Solar Energetic Particle events
  - ...
- basic physical mechanisms not fully understood
- 2 out of 3 predictions are WRONG !

CMEs :

- typ. $400\,\mathrm{km/s}$, $10^{12} - 10^{13}$ kg!
- $E = 10^{24} - 10^{25}$ Joule
- known since 30 yrs only!
- they play a crucial role in SW!

Motivation

Construction of numerical models for the solar wind and CME initiation and evolution in order to improve prediction of space weather.

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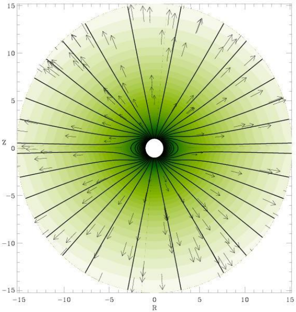
Comparative studies

Study the effect of the background solar wind and CME parameters on the initiation and evolution of IP CMEs and CME shocks.

- in an objective way, i.e. with the same numerical code, grid resolution (numerical dissipation), numerical technique, BCs & ICs, etc.
- in order to quantify the effect of the background wind and initiation parameters on the CME speed, the direction, density, magnetic field etc.

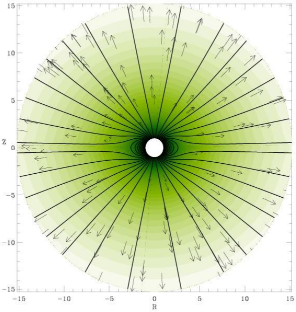
Solar wind models



Polytropic Wind

Color: density (log-scale), black lines: magnetic field lines, arrows: velocity

Solar wind models



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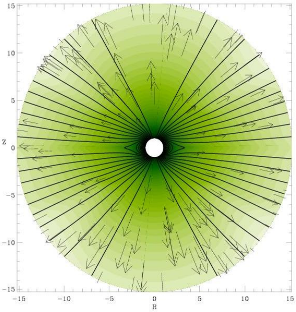
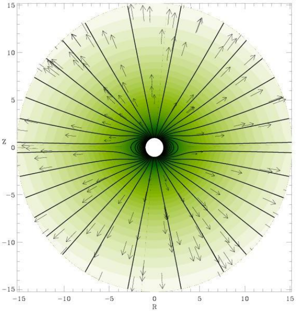


'Manchester' wind

Extra heating source term:

$$Q = \rho q_0 e^{-\frac{(r-r_0)^2}{\sigma^2}} \left(T_0 - \gamma \frac{p}{\rho}\right)$$

Solar wind models



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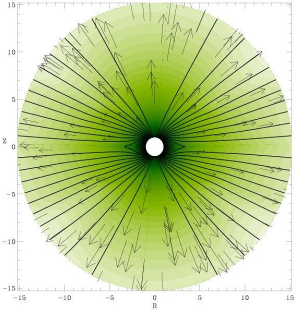

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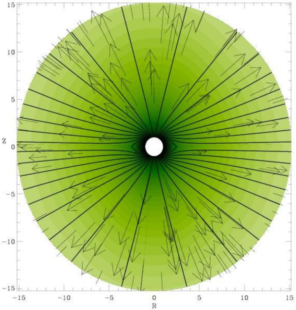


Polytropic Wind with Alfvén Waves

Has additional Alfvén wave pressure gradient.

Wind characteristics at $30R_\odot$

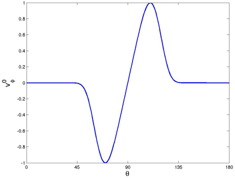
	Model 1	**Model 2**	**Model 3**
Density[m^{-3}]			
Pole	5.6×10^8	1.02×10^9	3.08×10^9
Equator	7.27×10^8	1.83×10^9	2.87×10^9
Ratio	0.77	0.56	1.07
Velocity[km/s]			
Pole	323	727	675
Equator	293	358	374
Ratio	**1.1**	**2.03**	**1.8**
Temperature[K]			
Pole	0.82×10^6	1.13×10^6	0.89×10^6
Equator	0.83×10^6	0.29×10^6	0.89×10^6
Ratio	0.99	3.87	1.0
Magnetic field[G]			
Pole	6.04×10^{-4}	3.7×10^{-4}	3.9×10^{-4}
Equator	6.1×10^{-5}	1.2×10^{-4}	2.0×10^{-4}
Ratio	9.89	3.06	1.95

CME initiation: Shearing

Add extra azimuthal velocity v_ϕ^0 at the solar surface to shear the footpoints of the magnetic field.

$$v_\phi^0 = v_0(t)\Theta e^{(1-\Theta^4)/4}$$

$$\text{with } \Theta = \frac{\theta - \pi/2}{\Delta\theta_m}$$



magnetic field lines

Background wind: Model 1, maximum shear velocity: 6 km/s.

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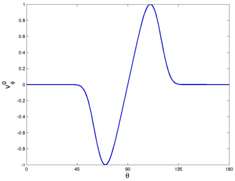
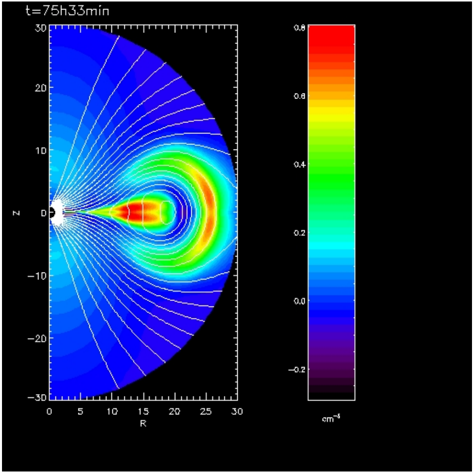


relative density $(\rho - \rho_{wind})/\rho_{wind}$

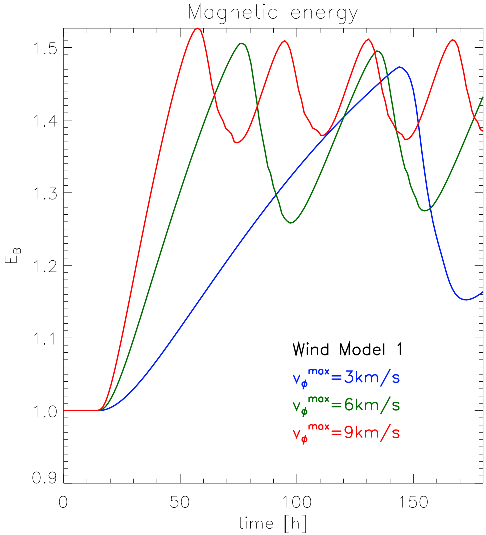


Background wind: Model 1, maximum shear velocity: 6 km/s.

CME initiation: Shearing - parameter studies

Shearing rate affects

- Δt to reach instability
- instability threshold in terms of energy
- amount of energy released
- velocity/acceleration of flux rope
- ...



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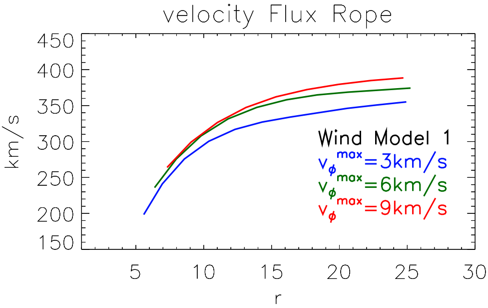

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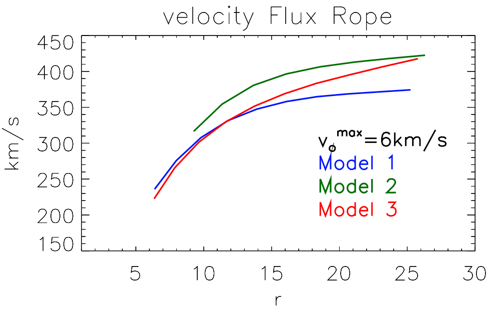
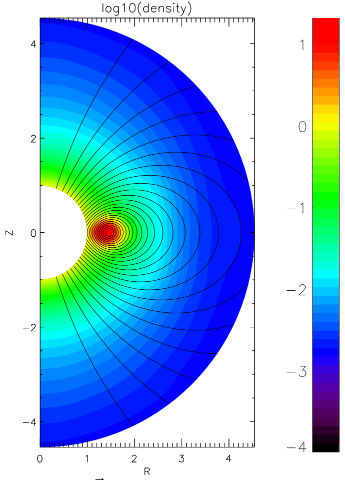


CME initiation: flux emergence / cancellation

Initial model

- cf. Chen & Shibata (2000)
- + **physics** : MHD (incl. gravity)
- + **geometry** : 2D (axisymmetric)
- + dipole field
  OR
  + **solar wind** ⇒

$$\vec{B}_0 = \vec{B}_{LC} + \vec{B}_{IC} + \vec{B}_{BG}$$



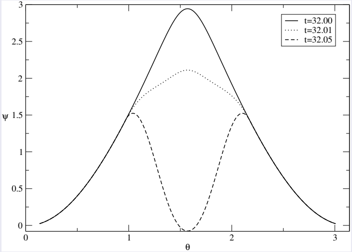
Initial ρ and $\vec{B}$ (relaxed until $t = 32$)

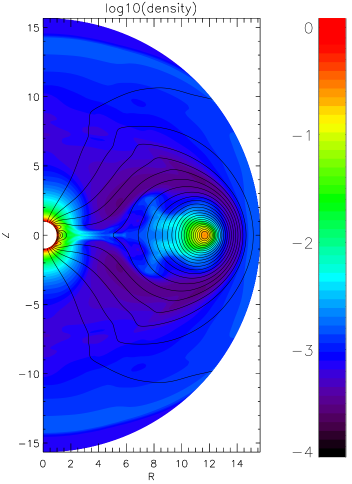
CME initiation: flux emergence / cancellation

Addition of flux

cf. Forbes & Priest ('84), Chen & Shibata ('00)

- at lower boundary ($r = 1R_\odot$)
- in region $\frac{\pi}{2} - 0.6 \leq \theta \leq \frac{\pi}{2} + 0.6$
- BC: $A_\varphi = A_\varphi(t_0) + c_e\, A_\varphi^+ \frac{t - t_0}{t_e - t_0}$

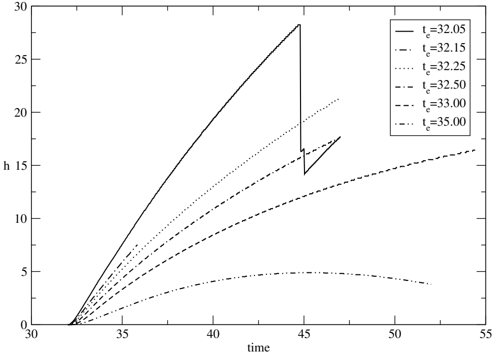




CME initiation: flux emergence / cancellation

Parameter study : t_e

- fixed amount of flux: $2\pi\, c_e\, \psi_0 \approx -6.6 \times 10^{20}$ Mx in Northern hemisphere
- vary *flux emergence rate*, i.e. $2\pi\, c_e\, \psi_0/\Delta t$ from -3×10^{18} to -5×10^{16} Mx/s



Height - time plot for difference flux emergence rates

CME initiation: flux emergence / cancellation

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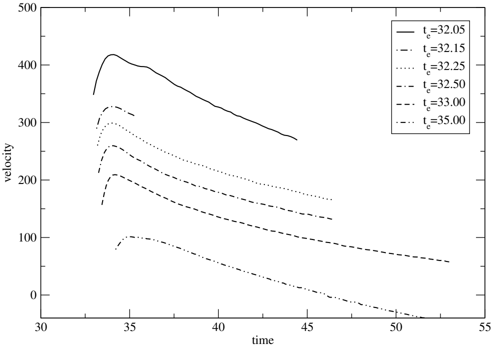
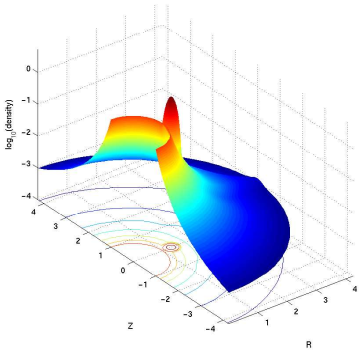


Velocity of the flux rope center vs. time

CME evolution: creating shocks

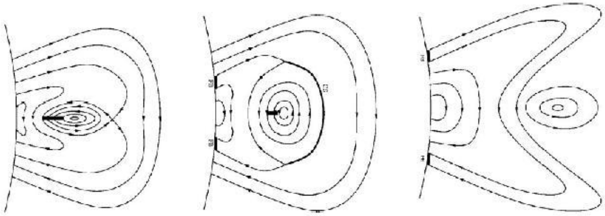
- Superpose a high-density & high-pressure plasma blob on the wind
- Initial perturbation of the density: $\rho_{CME} = 5N_0$
- Initial perturbation of the velocity: $1000\,\mathrm{km/s}$
- Plasma blob can contain a flux rope with same or opposite polarity of the background field



Initial perturbation of the density

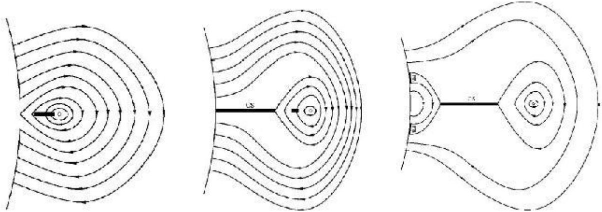
CME evolution: Low & Zhang (2002) confirmed!

'Normal' polarity flux rope



CME evolution: Low & Zhang (2002) confirmed!

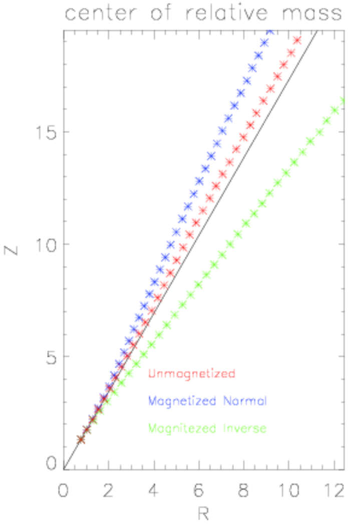
'Inverse' polarity flux rope



Magnetic polarity of the flux rope

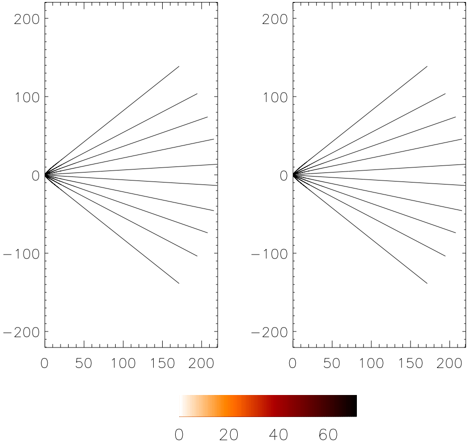
Effect on evolution path...

- magnetic polarity of flux rope influences evolution path CME!
- effect has been quantified for different background wind models
- here only shown for Wind model 3 and initial launch angle 60 degrees



CME evolution up to 1 AU

- self-similar evolution stops beyond 30 $R_\odot$
- difference normal/inverse polarity much smaller (e.g. density distr.)
- higher wind density at equator leads to serious deformation (compression) of the CMEs
- only difference :
  - about 6 hrs $\neq$ in arrival time
  - orientation of field

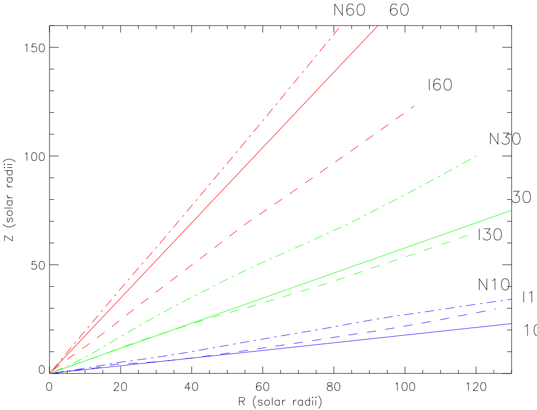


Relative density and magnetic field lines (INVERSE - NORMAL)

Evolution path (Centre of Mass)

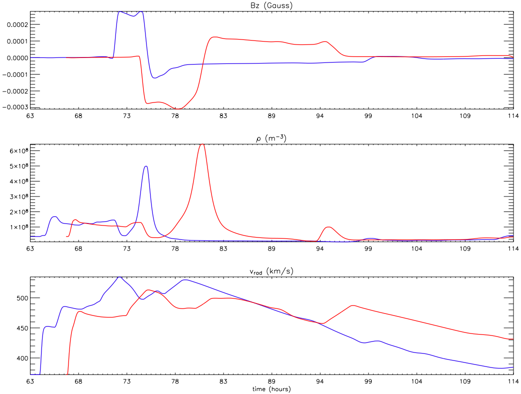
inverse CMEs still deviated towards equator but :

- difference smaller than at 30 $R_\odot$
- not true for $\theta_{\text{cme}} \leq 10°$ (due to high wind density at equator)



Simulated satellite data at 1 AU (Wind model 2)

- Normal (blue) and inverse (red) CME
- 3-part structure of CME
    1. leading shock
    2. dark cavity
    3. high density core in cavity
- leading shock front
- ...



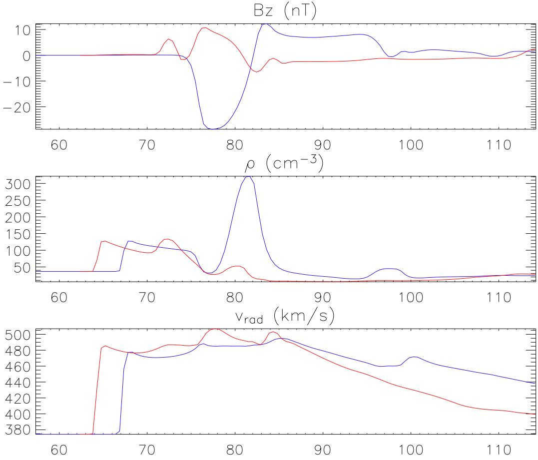
Simulated satellite data at 1 AU (Wind model 2)

effect of magnetic polarity flux rope :

for $\theta_{cme} = 10^\circ$:
magnetic cloud of

- normal CME misses
- inverse CME hits

the earth!



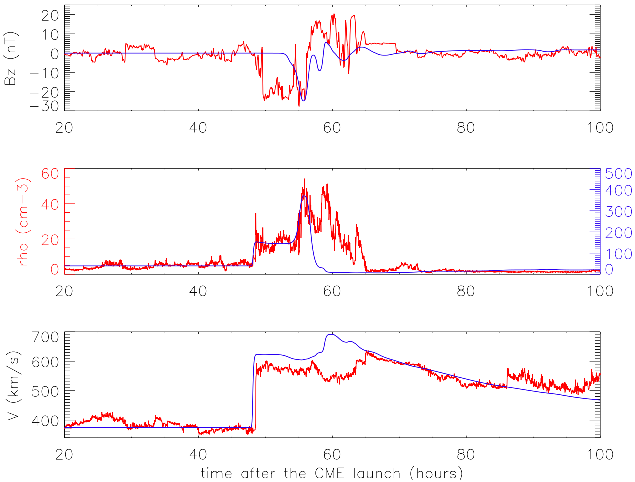
Inverse (blue) and normal (red) CME launched with $\theta_{cme} = 10^\circ$

Event study

- full halo CME observed by LASCO and EIT on April 4, 2000
- observed at 16:32 UT in C2 frame
- related flare observed by EIT at 15:24 UT
- C3 measurements : plane-of-the-sky speed is 984 km/s

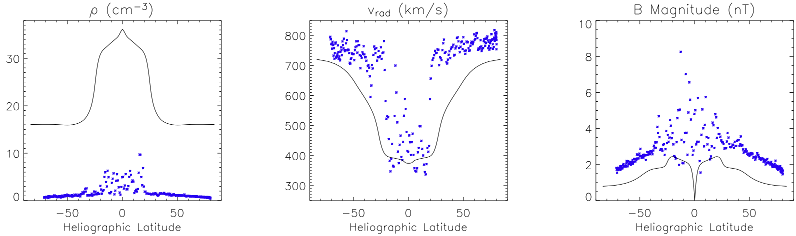
- try to match ACE data by
  - using wind model 2
  - playing with CME parameters (v_{cme}, θ_{cme}, B_{rope}, polarity)

Event study



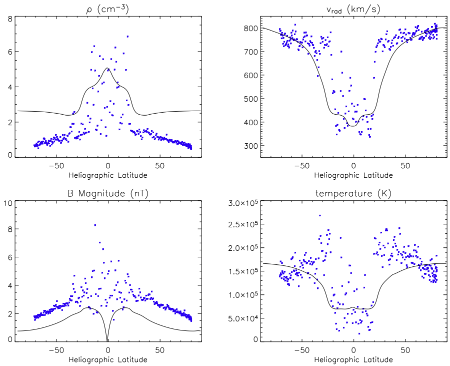
Best match : inverse CME with v_{cme} = 1700 km/s

However. . .



Comparison of Ulysses data (between 1/11/94 and 1/08/95, i.e. when spacecraft was evolving between 1.34 and 2.03 AU) and wind model 2 at 1 AU

New wind model



Comparison of Ulysses data (between 1/11/94 and 1/08/95, i.e. when spacecraft was evolving between 1.34 and 2.03 AU) and wind model 2 at 1 AU

Conclusions

The chosen **background wind model influences** :

- the initiation of the CME (threshold, energetics,. . .)
  - time of formation (threshold), energetics, speed, acceleration,. . .
- evolution of the CME
  - shape of leading shock front, shock speed, spread angle, mass distribution,. . .

Clearly, the initial parameters (shear velocity, polarity of fluxrope, v_{CME}, ρ_{CME}, θ_{CME},. . .) also influence the structure and evolution of the CME.