OBSERVATIONS AND MODELING OF SHOCKS

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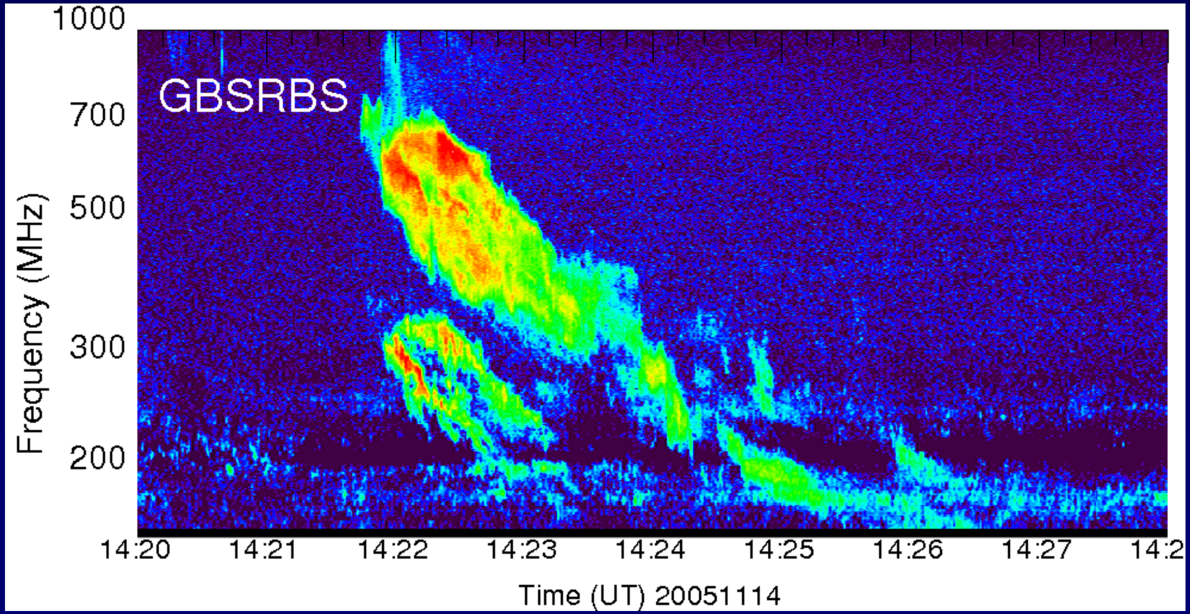
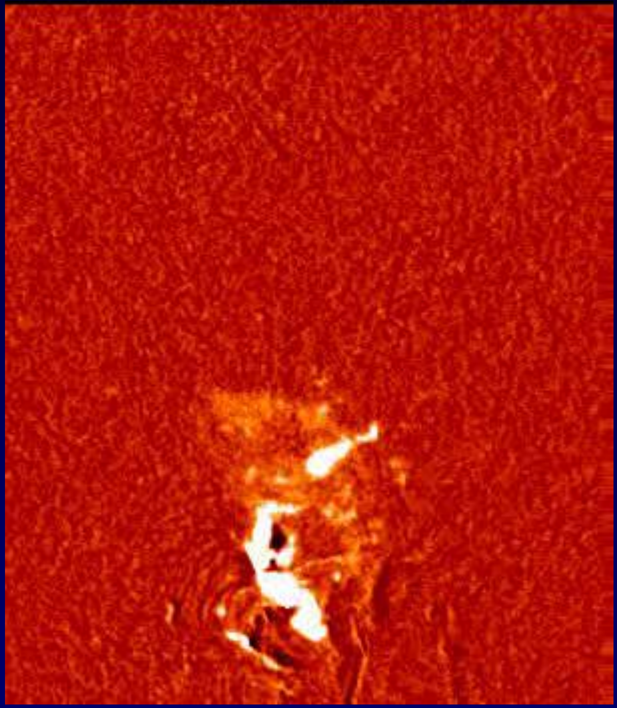
History

- Activation of distant filamens (Dodson,1949, ApJ, 110, 382)
- Type II radio bursts (Wild & McCready 1950 Aust.J.Phys. 3, 387)
- Moreton waves (Moreton & Ramsey 1960, PASP 72, 357)
- MHD (**Uchida,1960**, PASJ, 12, 376; ...;1974, Sol. Phys., 39, 431)
- EIT (Thompson, et al., 1998, GRL, 25, 2465)
- Numerical MHD
- SXR, HeI, coronagraphic...
- Since 2009/2010 > 200 papers

Observational signatures

- Type II radio bursts (Wild & McCready 1950 Aust.J.Phys. 3, 387)
- Moreton waves (Moreton & Ramsey 1960, PASP 72, 357)





KSO

Domain / Signature

in situ

IP
(radio, WL)

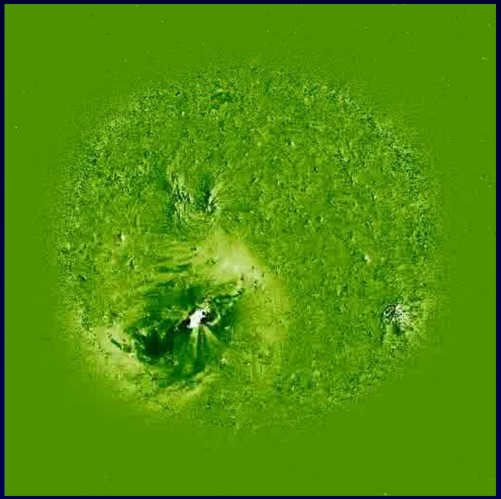
Corona
- radio type II
- WL fronts, streamers

Low Corona
(EUV)

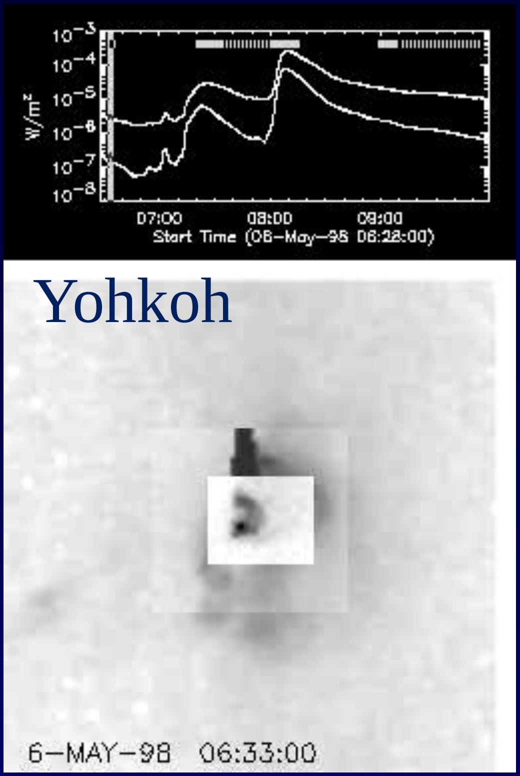
Upper Chromosphere & TR
(Hα, HeI, …)
Moreton, disturbed filaments, …

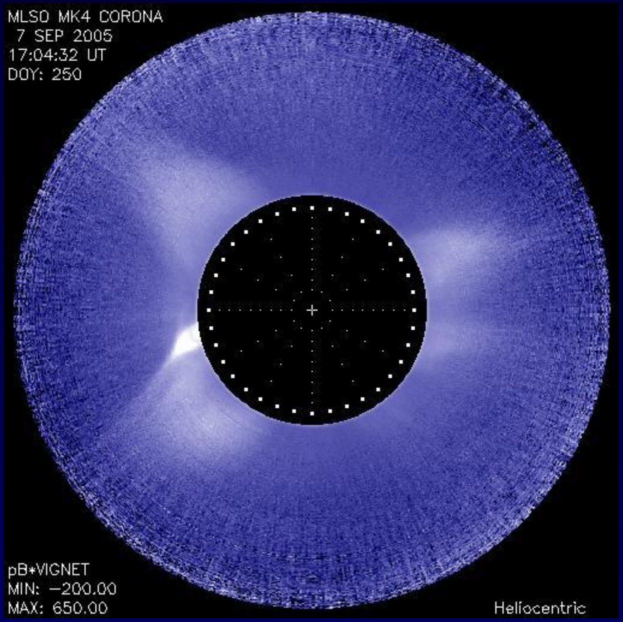
timing, kinematics, intensity, spectral, morphology, …

EUV, SXR, He, coronograph, radio,...

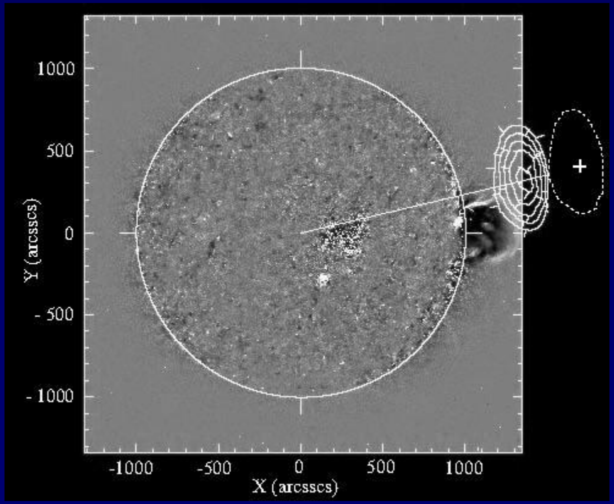


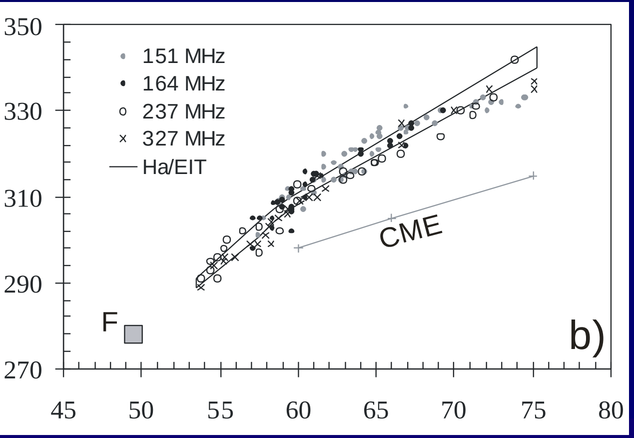
EIT/SoHO





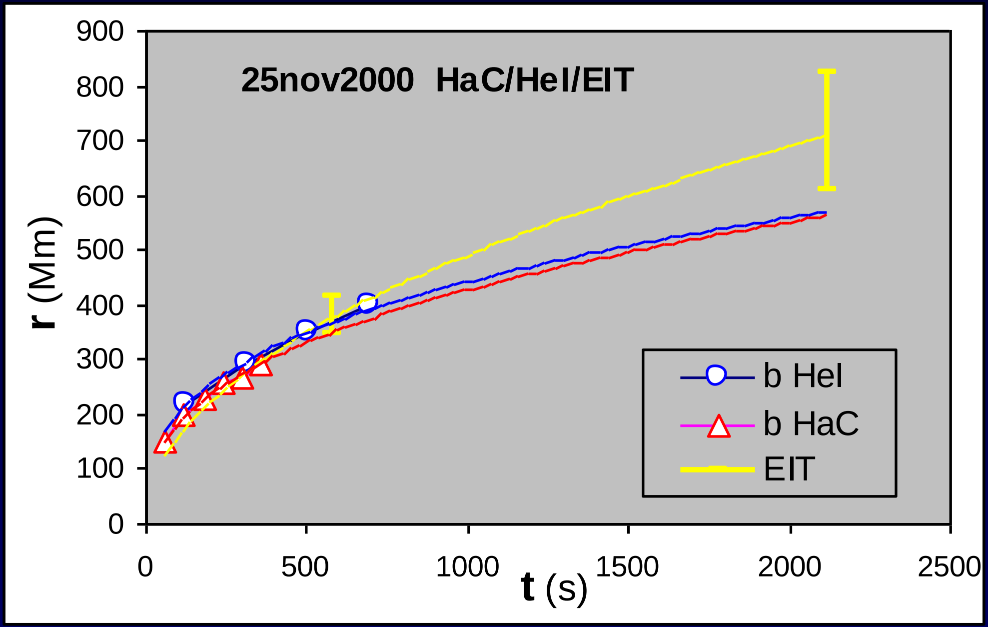
NRH

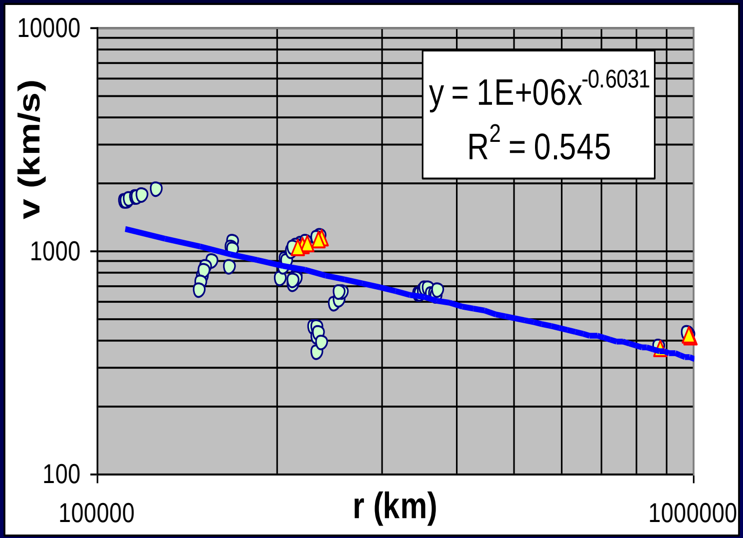


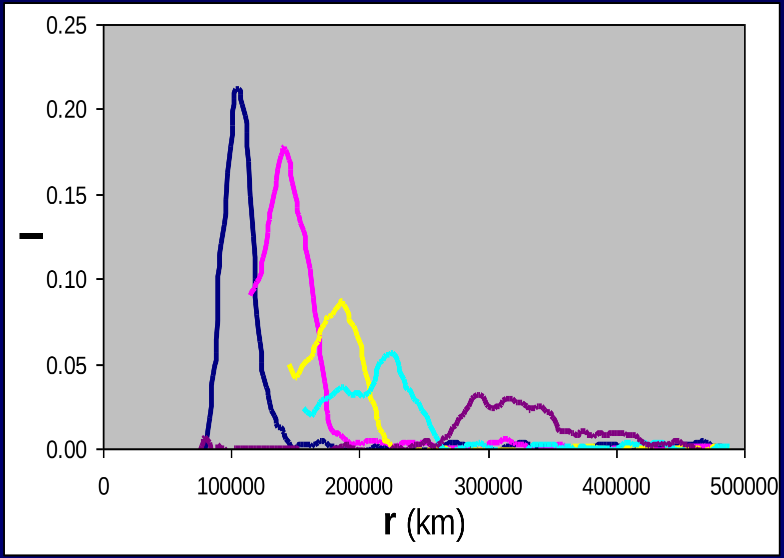


Kinematics

& evolution of perturbation







- Deceleration

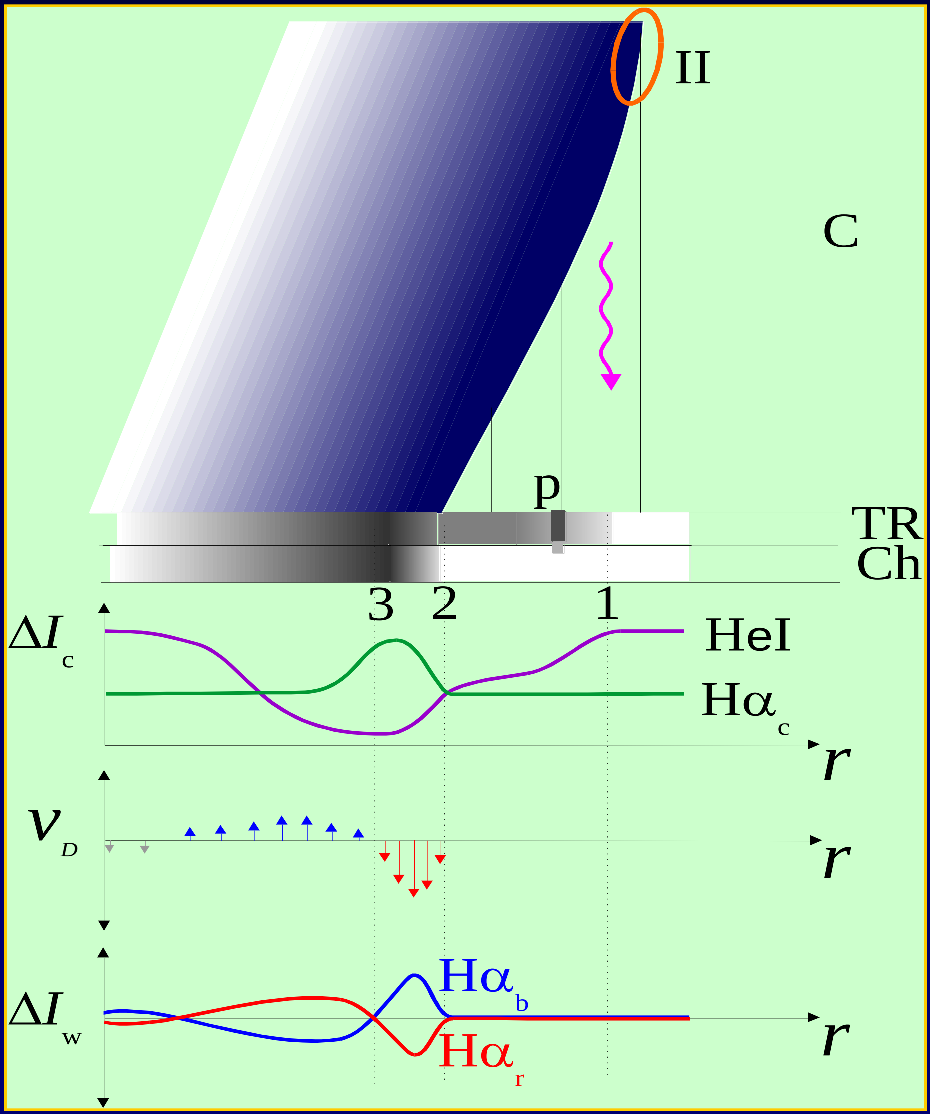
($v \approx 1000$ km/s $\rightarrow$ $v \approx 200\text{-}400$ km/s)

($v \propto r^{-1/2}$)

- Decreasing amplitude
- Broadening

Moreton/type II: fast-mode interpretation

(after Uchida: Sol. Phys. 1968, 4, 30 → 1974, 39, 431)



Moreton = initial, large amplitude phase

($M_{ms} \approx 2$ - 5)

HeI = "missing link"

EIT = distant, low amplitude phase

($M_{ms} \to 1$)

Type II burst = coronal signature

($M_{ms} \approx 1.1$ - 2)

Additional support for the fast-mode interpretation:

- Limb morphology/evolution
- Directivity = refraction into low-Alfven velocity
- Winking filaments
- Interaction with coronal holes (reflection)
- "Oscillatory relaxation" of the chromosphere
- Homologous events
- ....

Modeling

(formation mechanisms, evolution, particle acceleration, radiation processes, coronal diagnostics, intreplanetary propagation, geoeffectiveness…)

- ***Analytical approach (basic principles)***

  - (formation mechanisms and evolution)

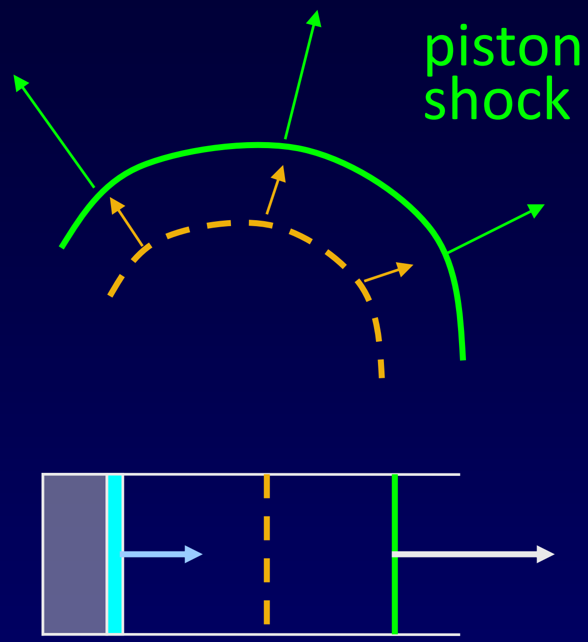
- ***Numerical (MHD) simulations***

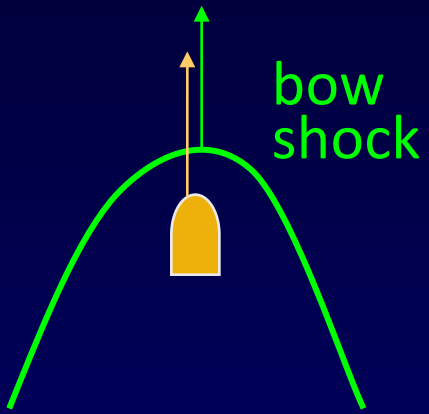
  - 1.5-D, 2-D and 2.5-D MHD in a simplified configurations (general characteristics and basic principles)
  - fully 3-D in realistic configurations (detailed analysis of well observed events; influence of ambient structures; coronal diagnostics)

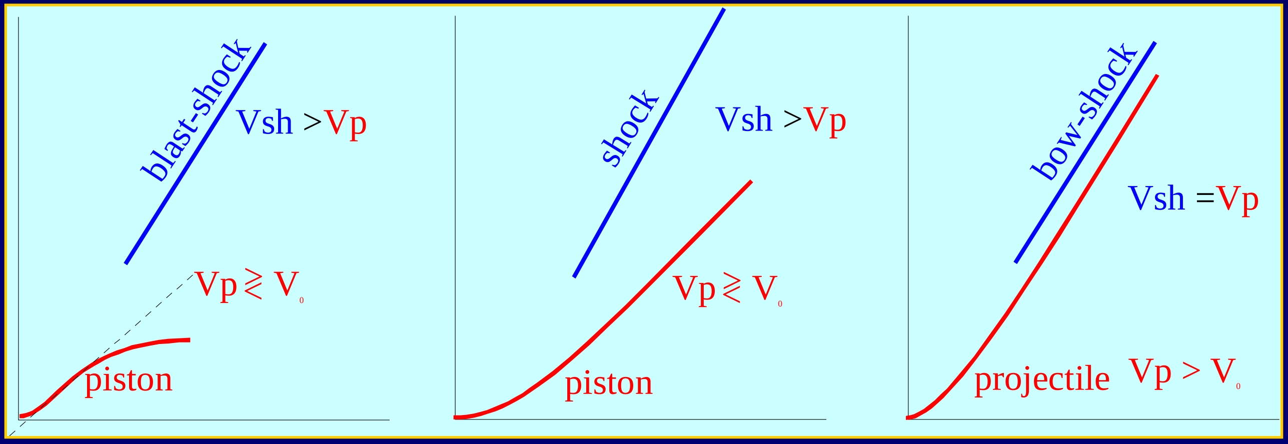
- ***Combined MHD/plasma-kinetic simulations***

  (particle acceleration; radiation processes)

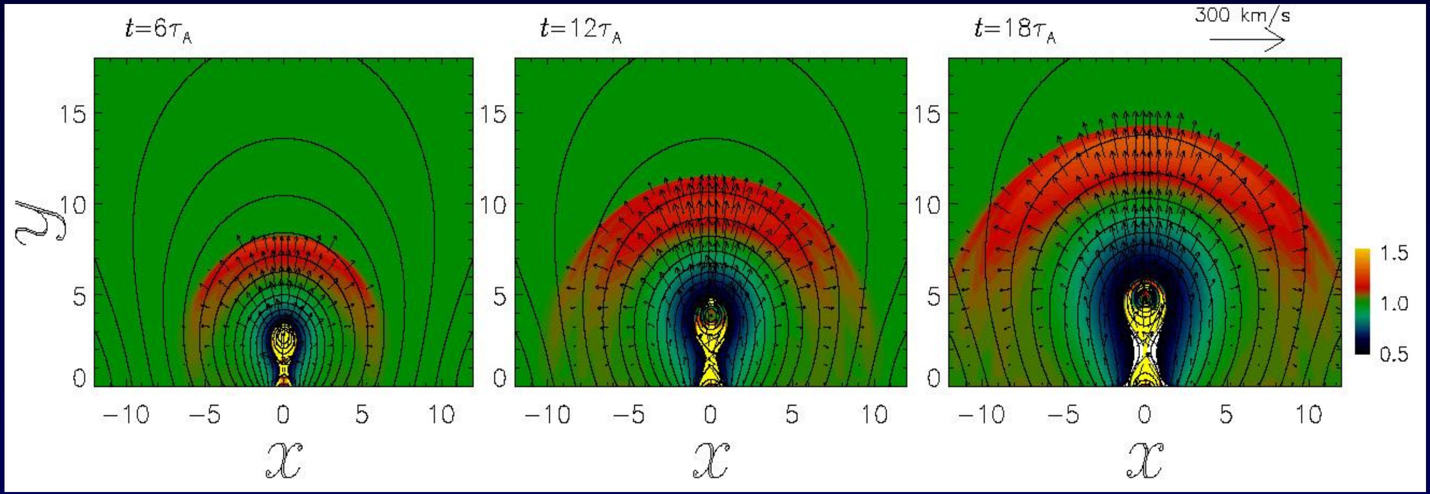
Formation mechanisms /terminology



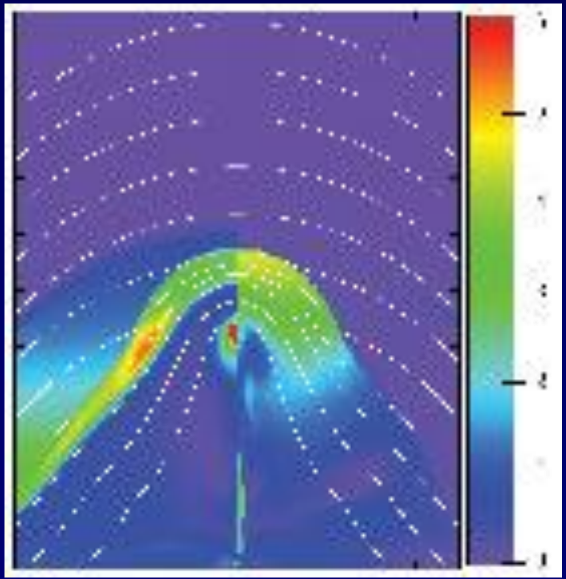




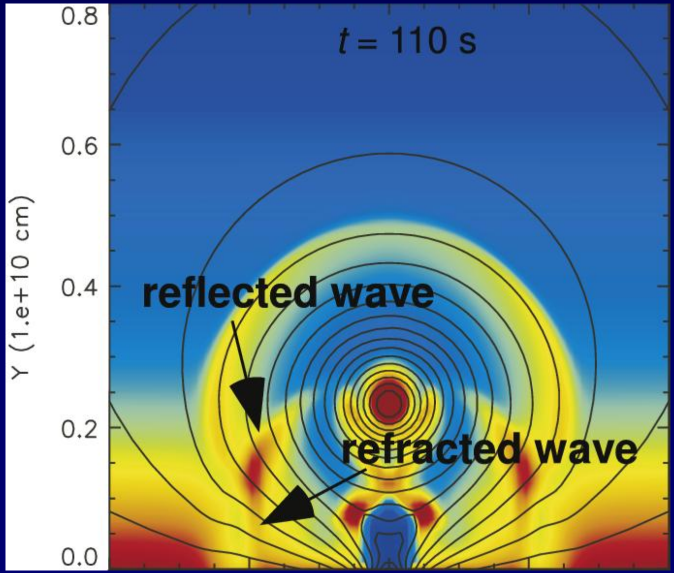
2.5-D MHD simulations: Bow shock



Chen et al. ApJ 2002 572, L99

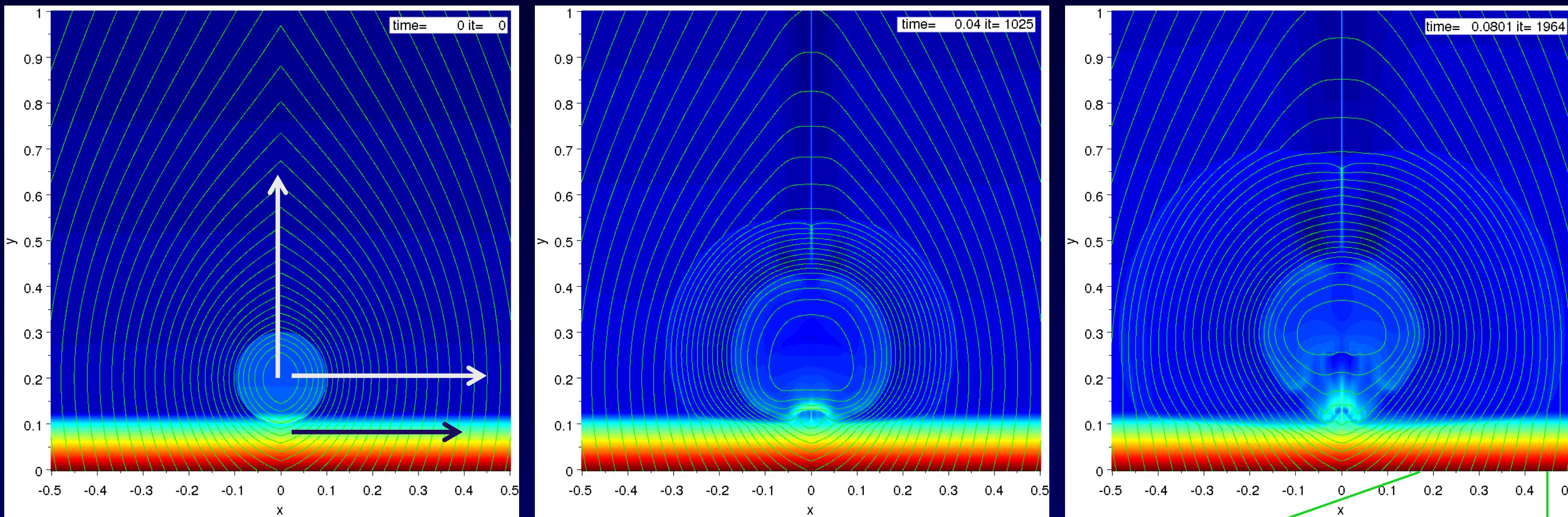


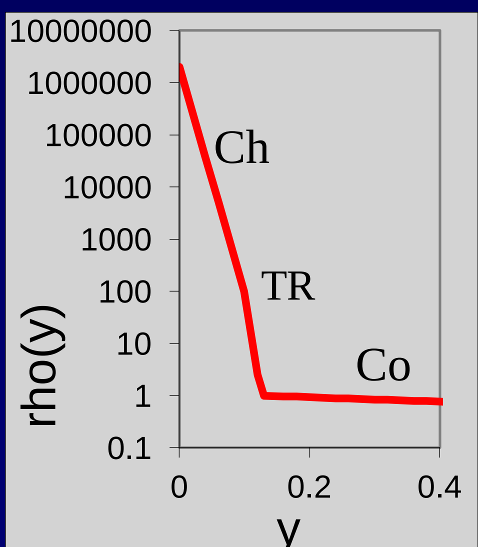
Pohjolainen et al. 2008 A&A 490,357

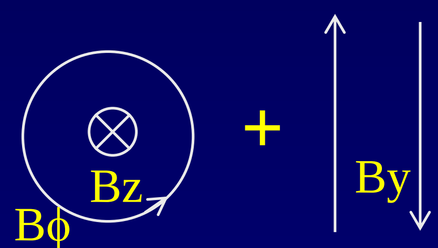


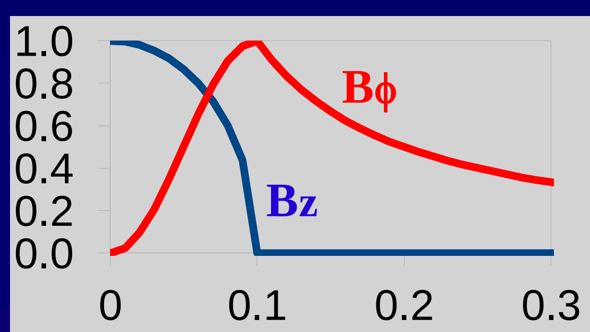
Wang et al. 2015 ApJ 805, 114

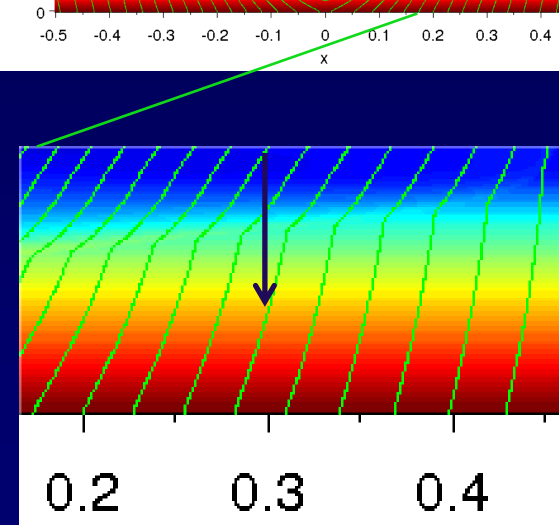
2.5-D MHD simulations: Piston shock







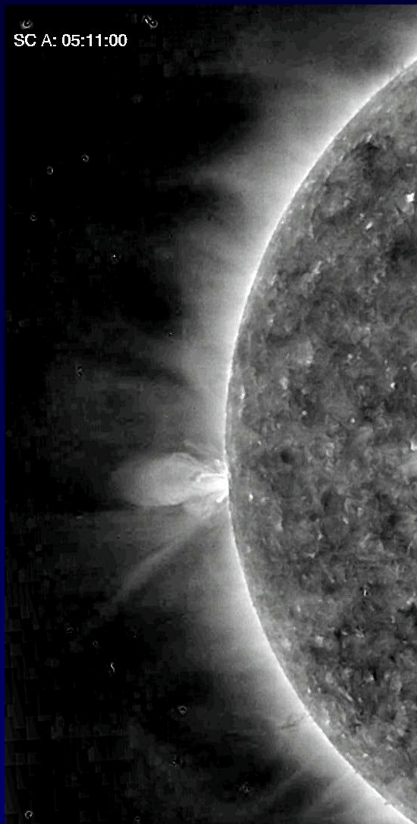




$\beta = 0$

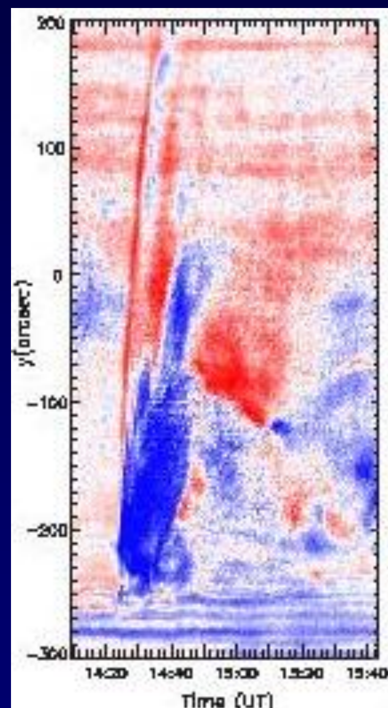
Vrsnak et al.
2015 SPh in press

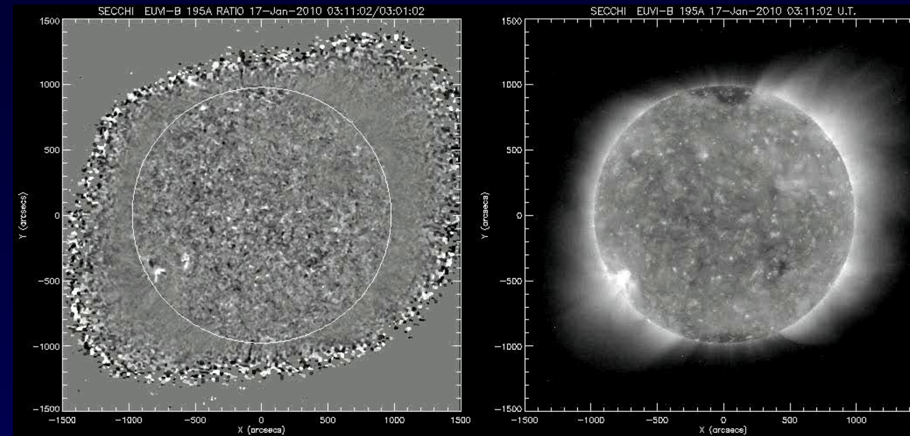
Observations / 2.5-D MHD simulation



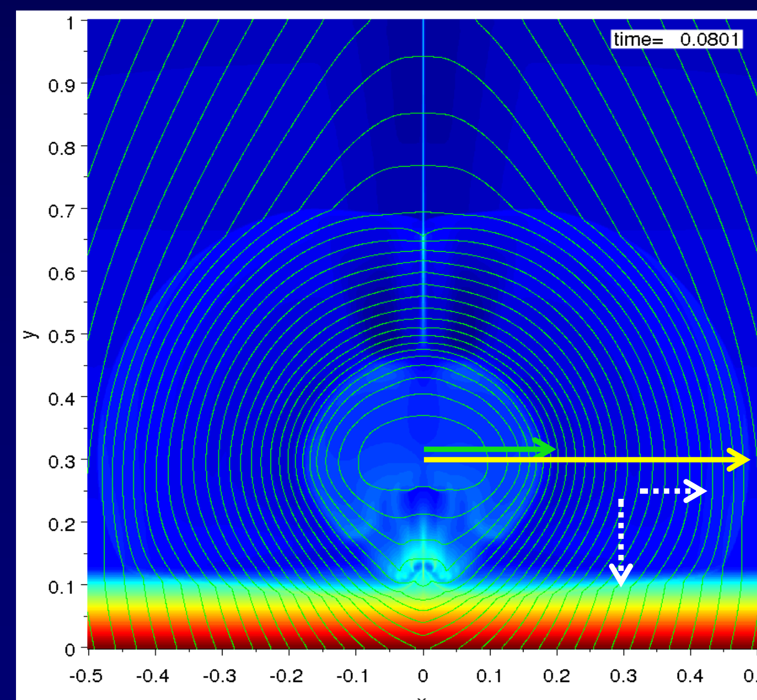
Patsourakos & Vourlidas
2009 ApJ 700, L182

Veronig et al.
2010 ApJ 743, L10
(EIS+AIA)



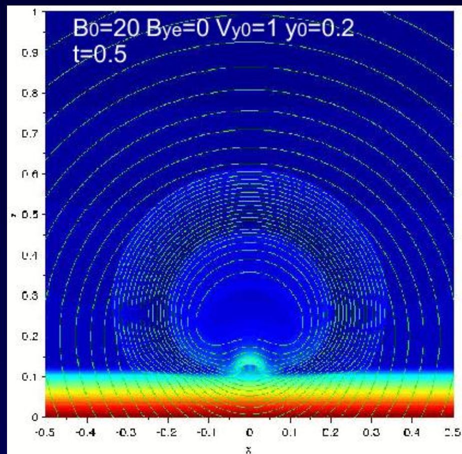


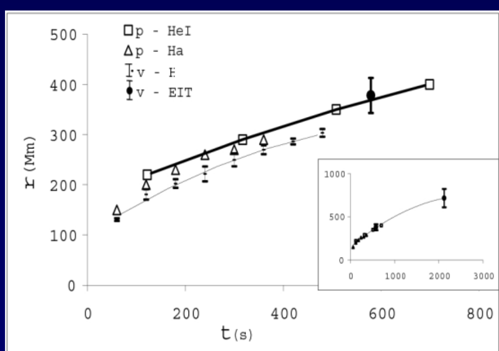
Veronig et al. 2010 ApJ 716, L57

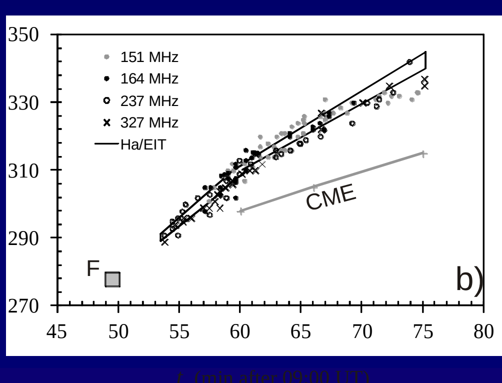


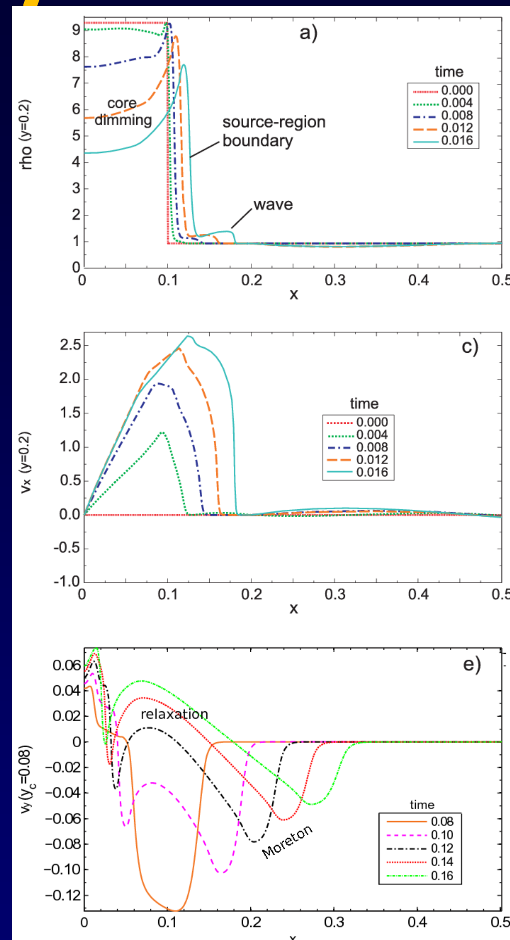
Vrsnak et al. 2015
SPh in press

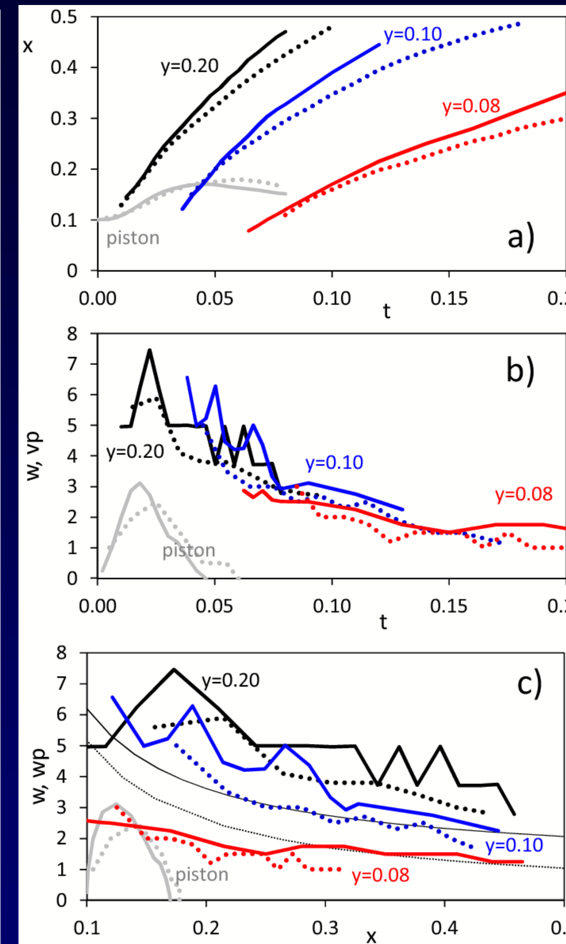
Observations / 2.5-D MHD simulation







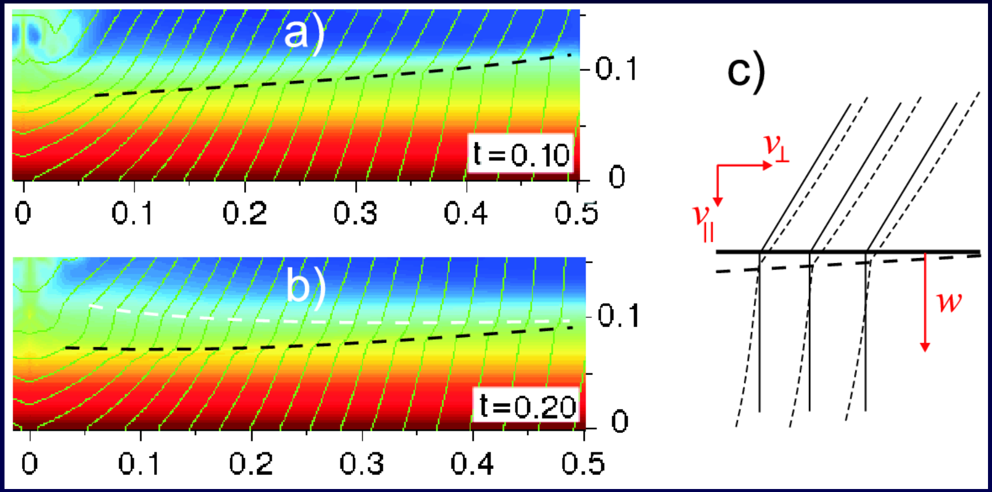




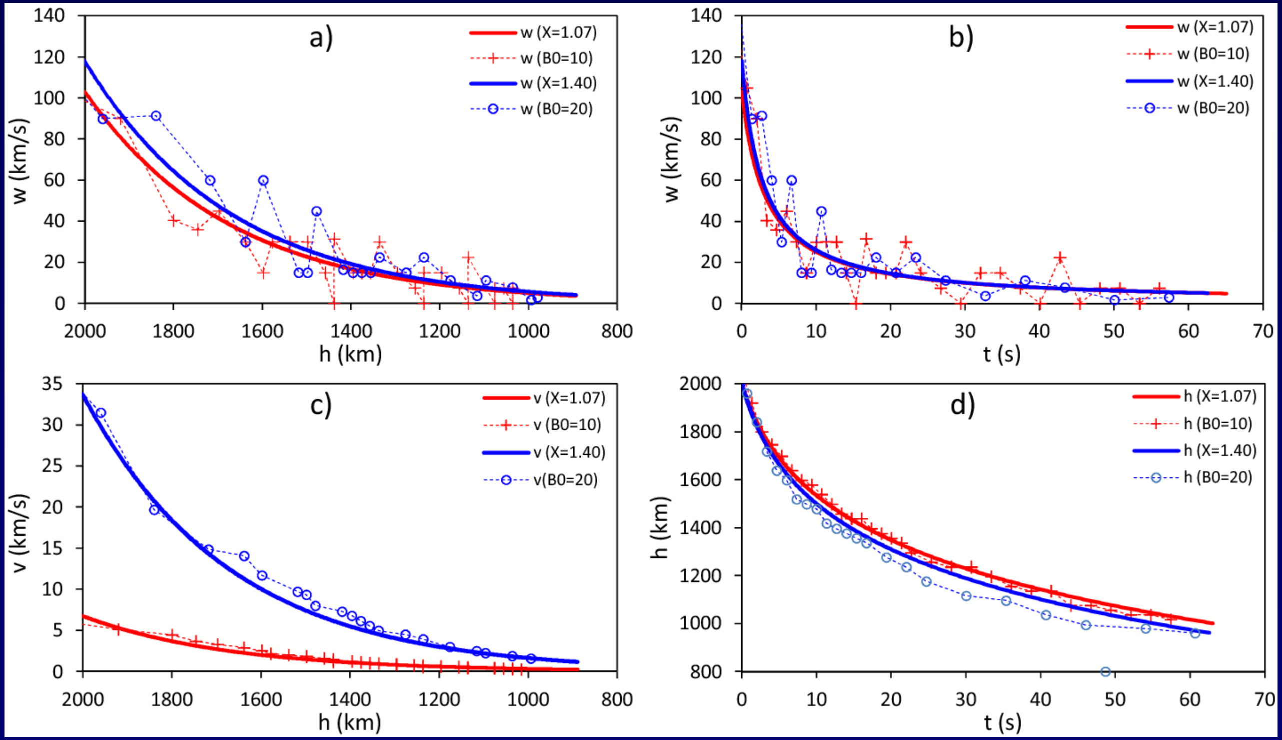
formation/driven phase → freely prop.:

- steepening + ampl. increase → shock
- deceleration; ampl. decrease
- corona/Moreton offset/delay

2.5-D MHD simulation: Moreton wave

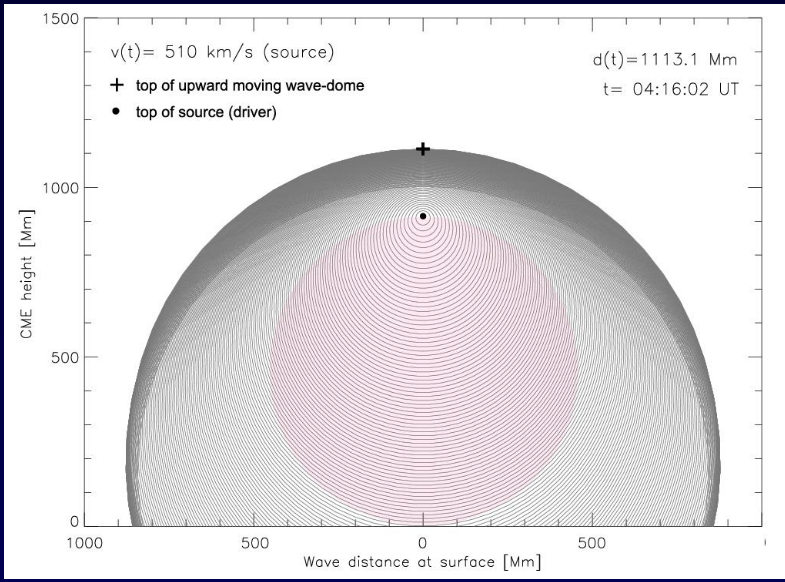


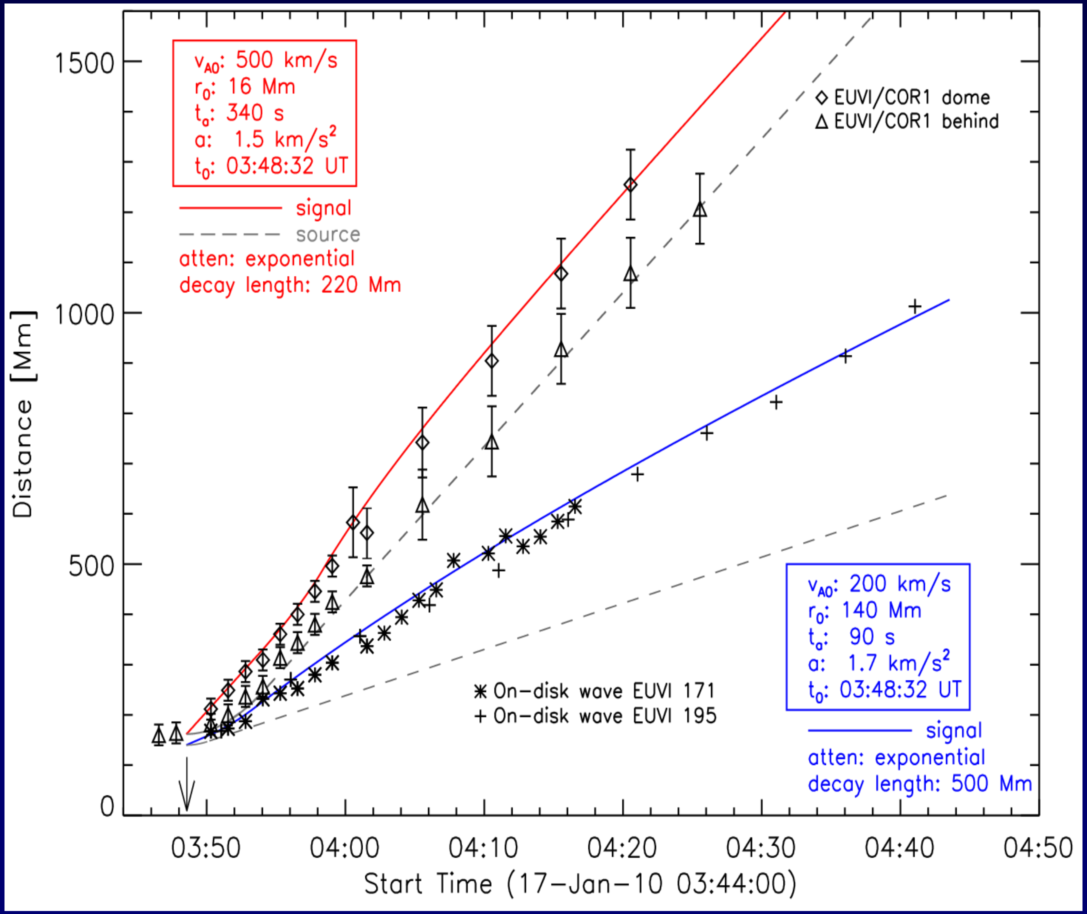
downward-propagating switch-on shock

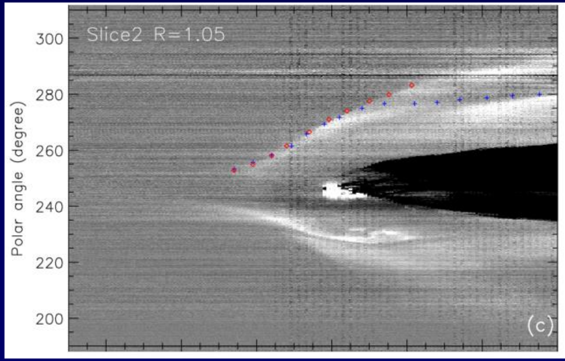


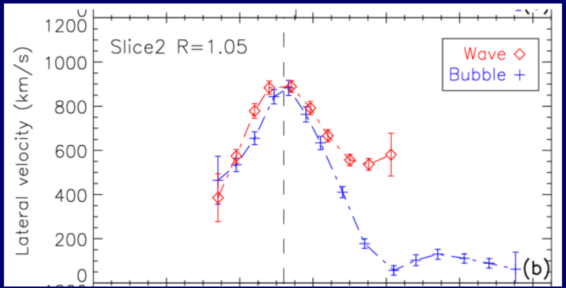
Bow/piston combination

Temmer et al. 2013 SPh 287, 441



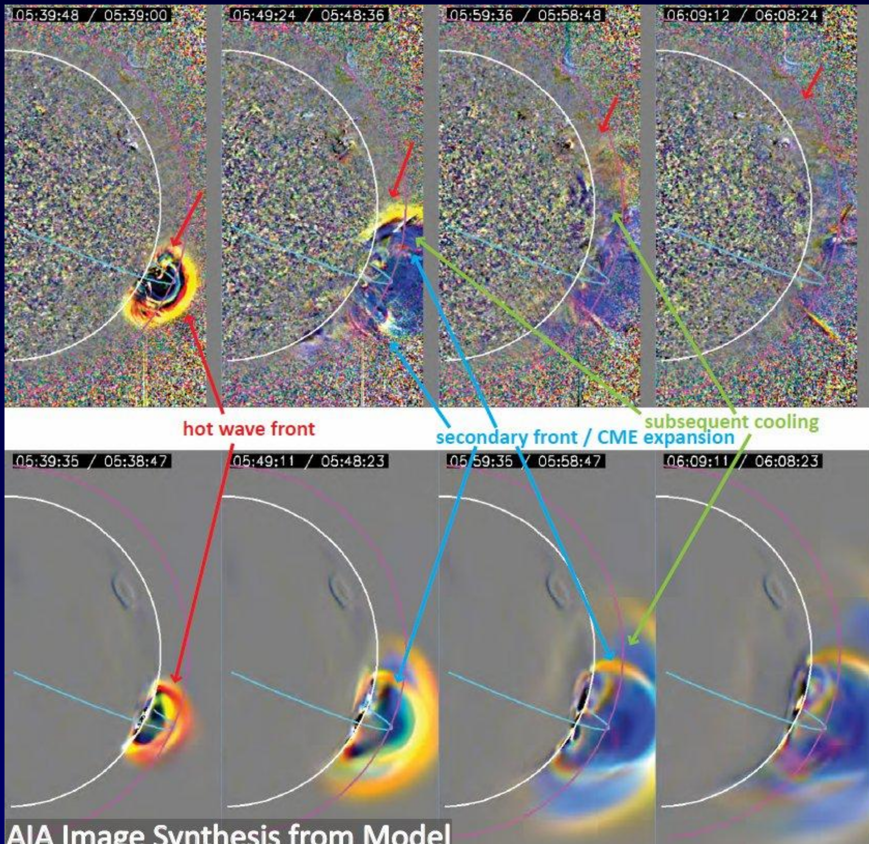


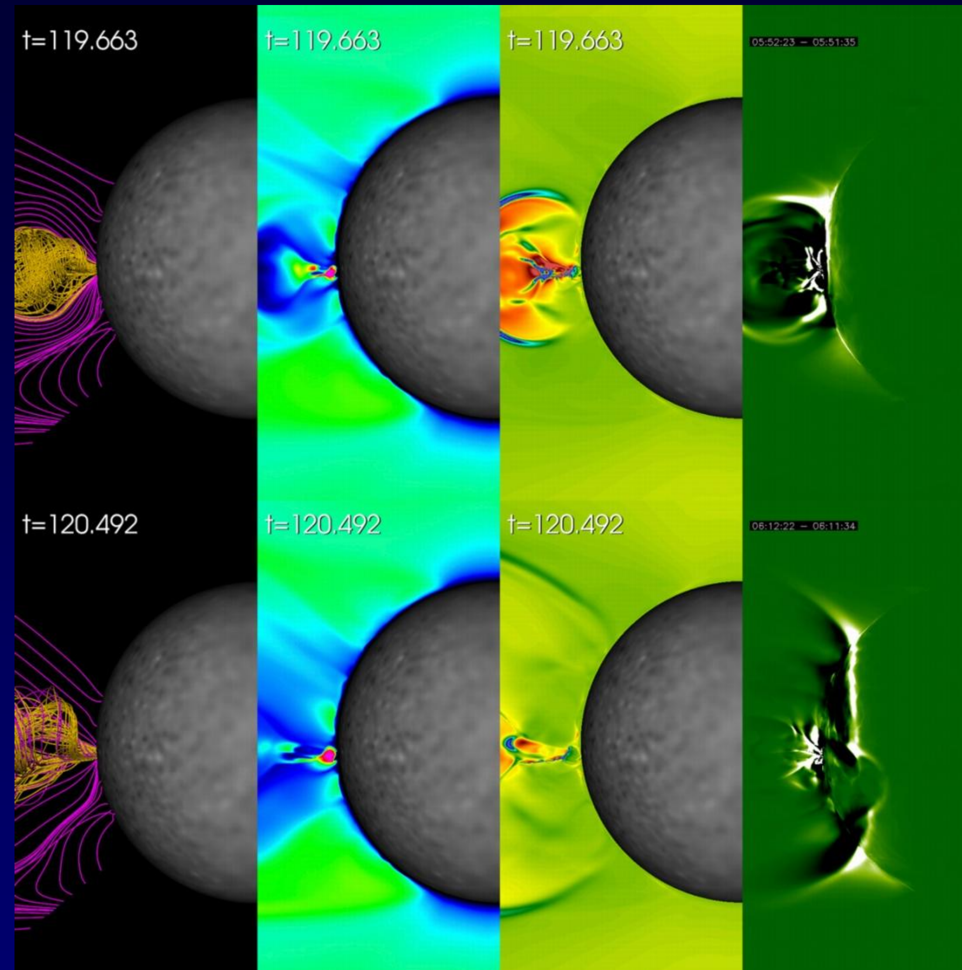


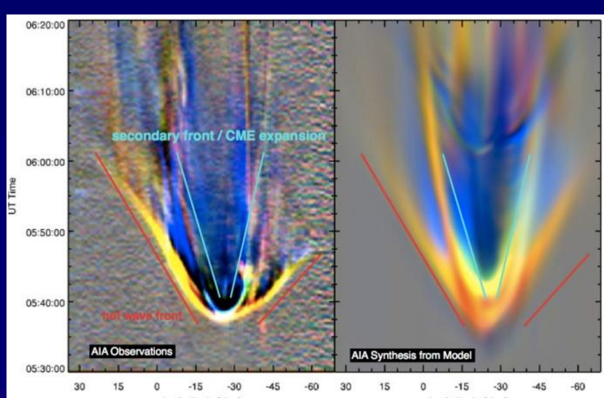


Cheng et al. 2012 ApJ 745, L5

Observations / 3-D MHD simulation

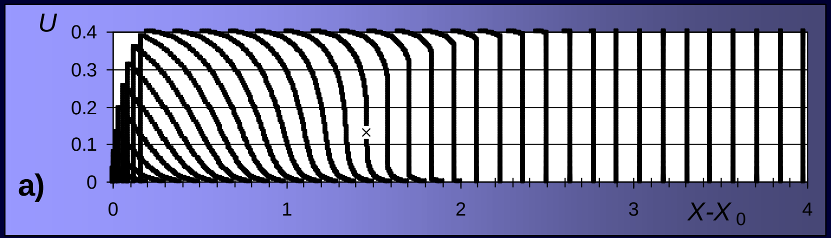




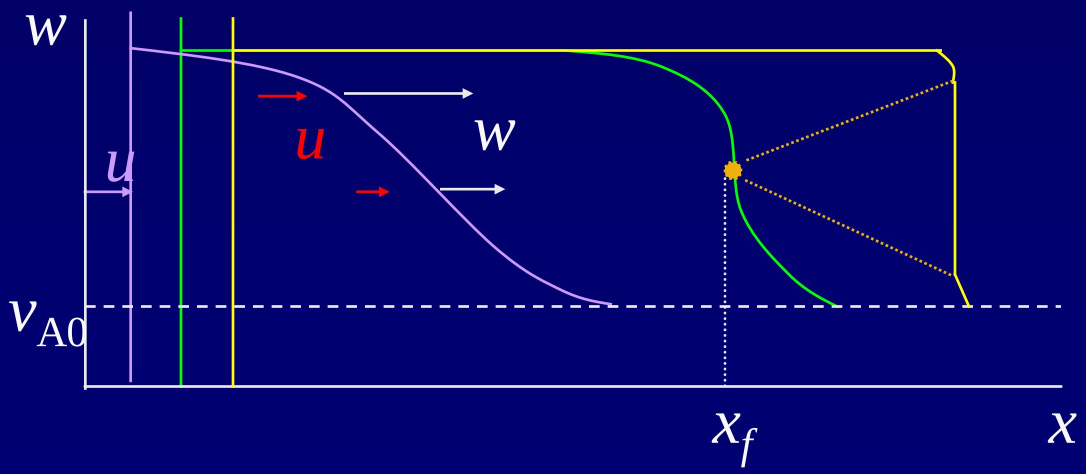


Downs et al. 2012
(Downs et al.: ISSI-Bern)

1D-Piston shock



- plasma motion perpendicular to the magnetic field (impulsive acceleration)
- large amplitude wavefront is created
- shock forms after certain time/distance due to the nonlinear evolution of the perturbation (signal velocity depends on the amplitude!)

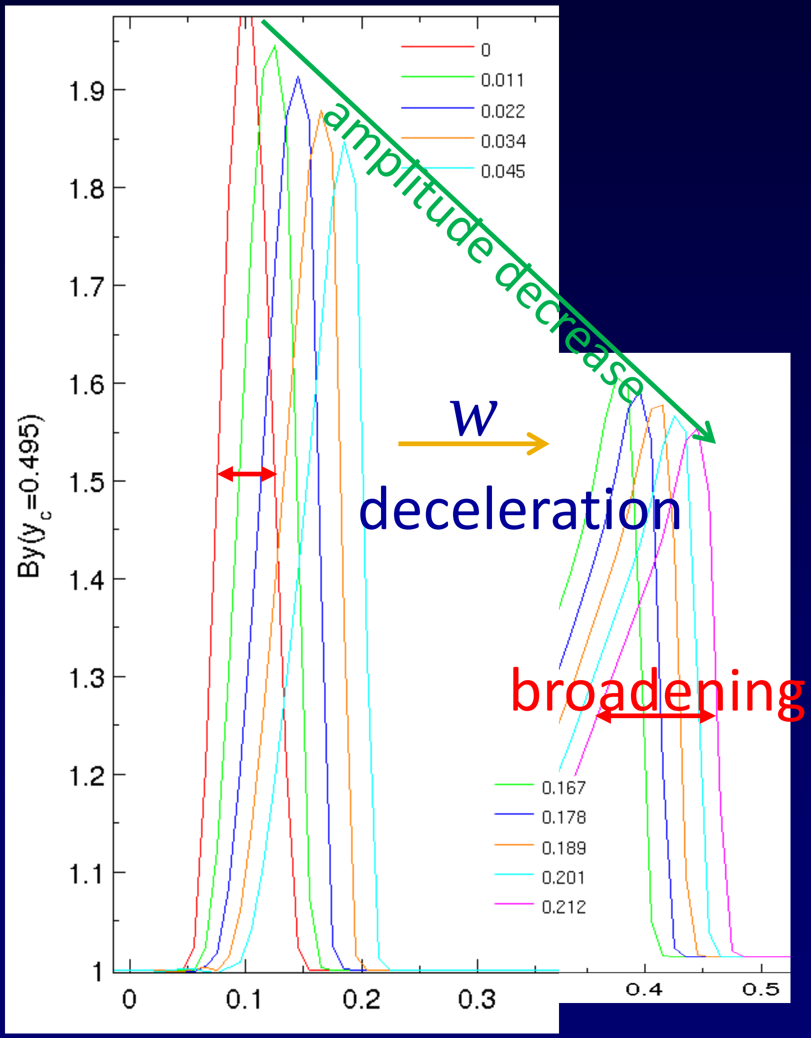


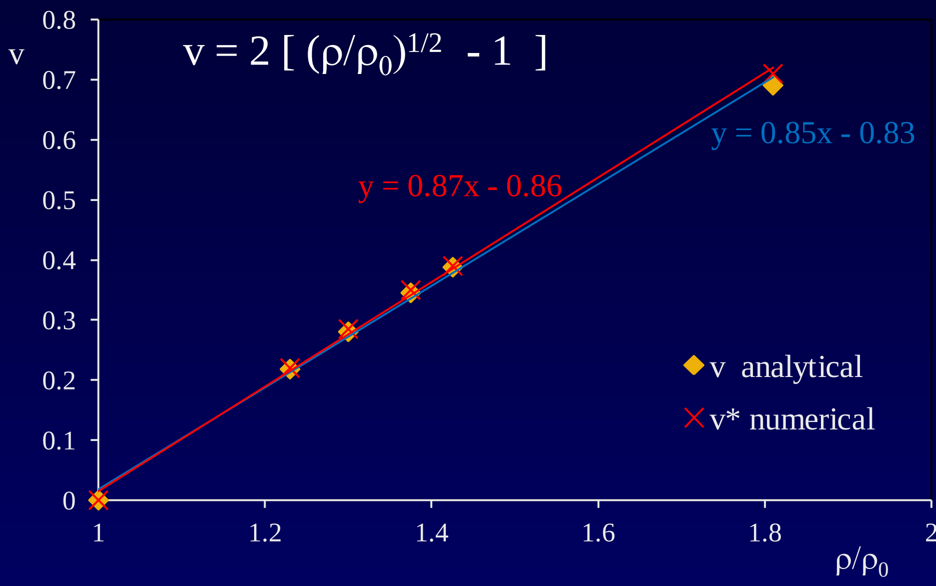
$$w(t) = w_0 + k\,u(t)$$

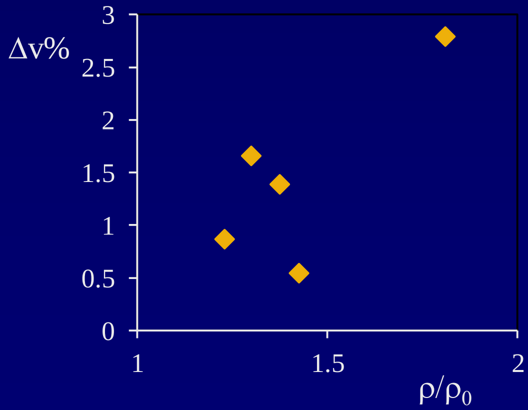
k=4/3, $w_0 = c_{s0}$ at $\beta >> 1$

k=3/2, $w_0 = v_{A0}$ at $\beta << 1$

Perpendicular 1-D Simple Wave

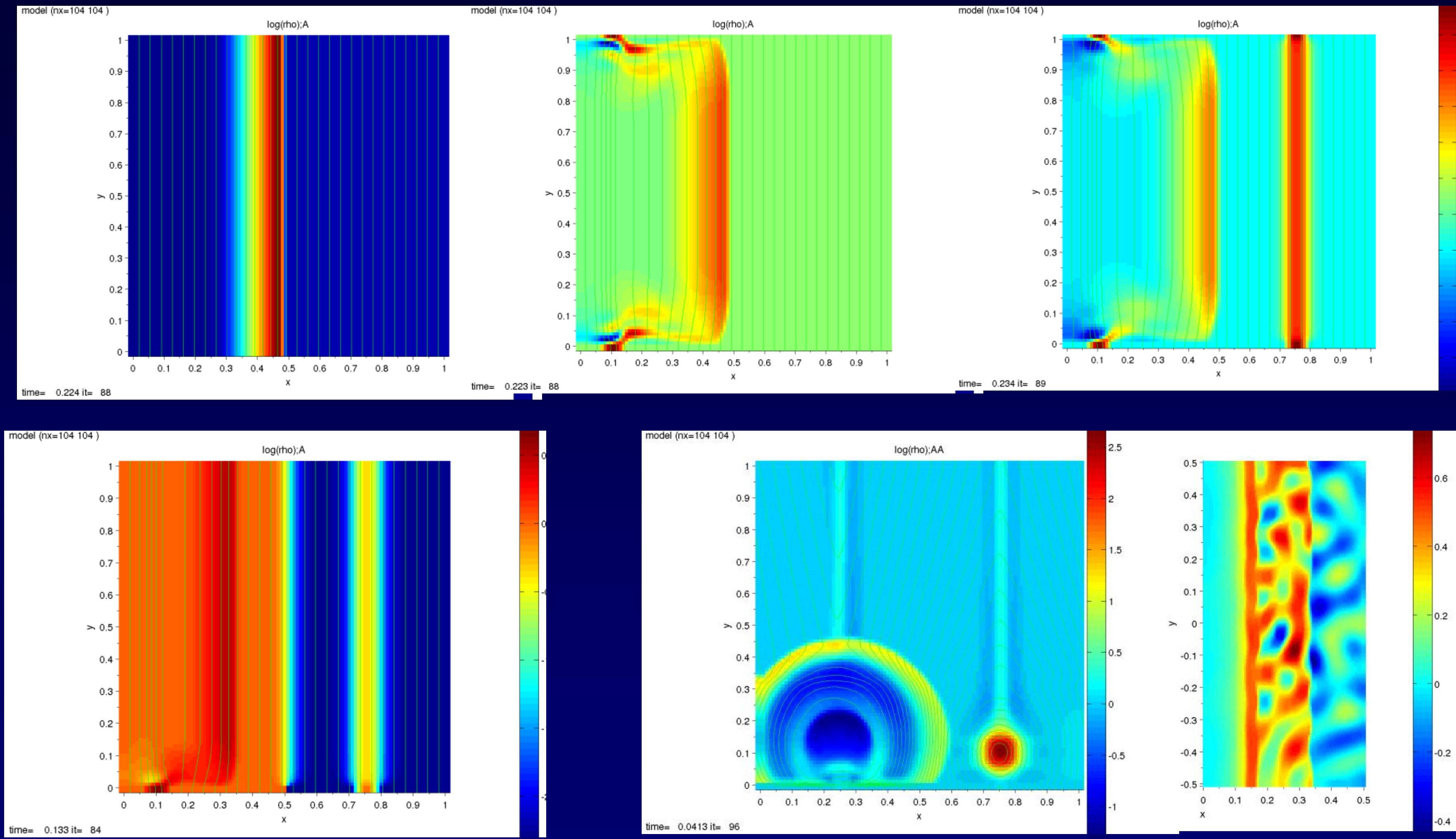






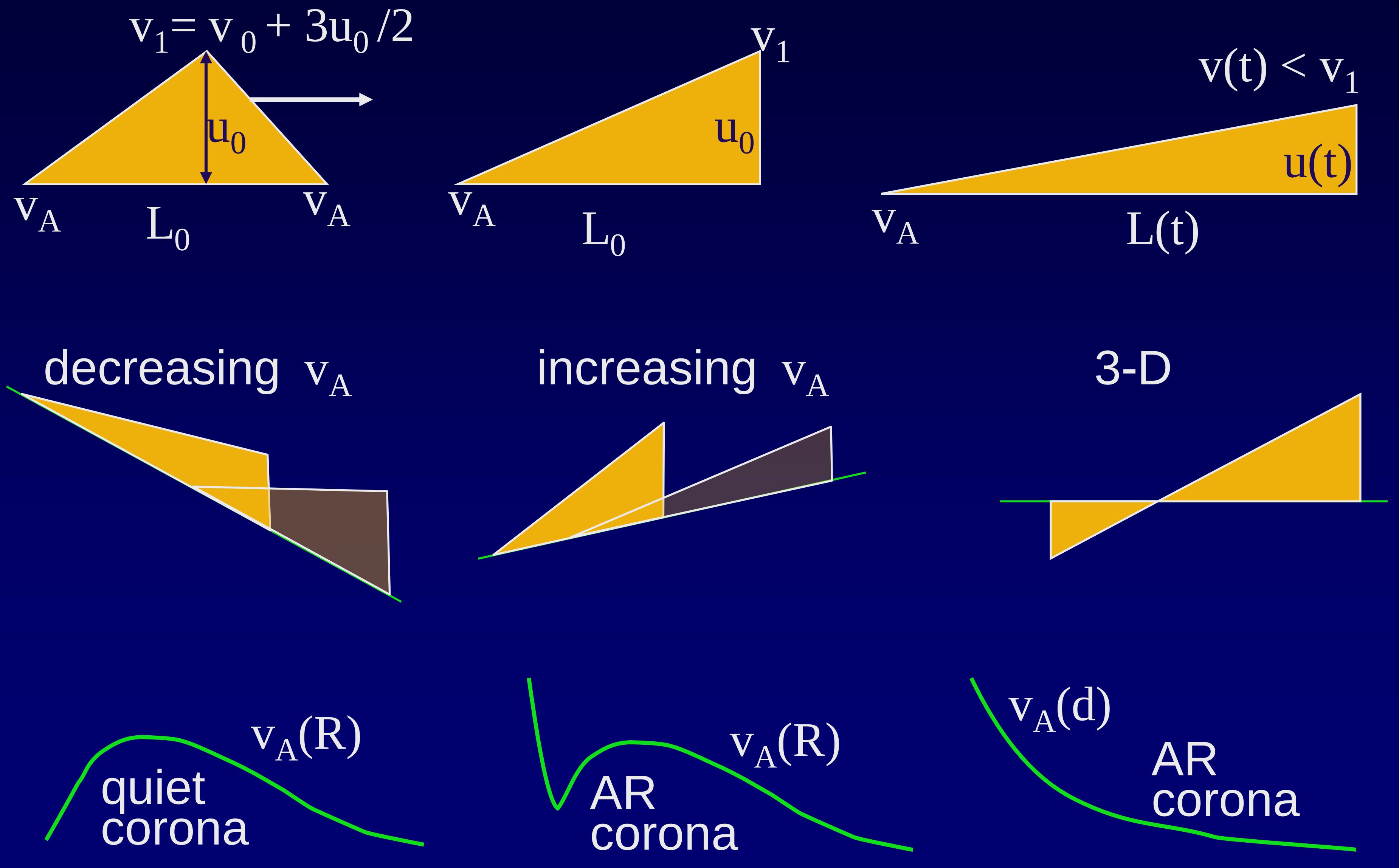
$\beta=0$: $w = v_{A0} + 3v/2$

Perp. 1-D freely-prop. simple wave



- different boundary conditions; $\beta = 0$
- different ambient conditions and obstacles (1D, 1.5D, 2D, 2.5D)

Simple wave - evolution



Conclusion

- upward (type II) = driven bow/piston shock
- lateral (EUV, He, Ha) = temporary piston ("CME overexpansion")
- the time/distance of the shock formation is determined by the source-region acceleration time-profile, and depends strongly on the spatial behavior of the Alfven speed
- to form a high-frequency type II burst and a Moreton wave (d_0~100 Mm; t_0~1 min), the source-region has to be compact, the expansion has to be very impulsive, and the Alfven speed has to decrease with distance rapidly
- Moreton wave appears only if shock is sufficiently strong; only upper chromosphere is affected

Thank you

for

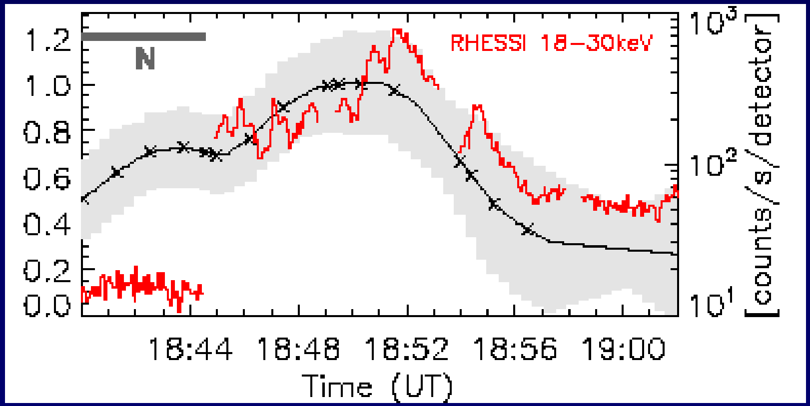
your attention

Timing: The driver is ...?

Flare, CME, or...?

Main problems:

- flare = low β, i.e., restricted expansion ?
- CME = not impulsive enough ?
- flare/CME synchronization

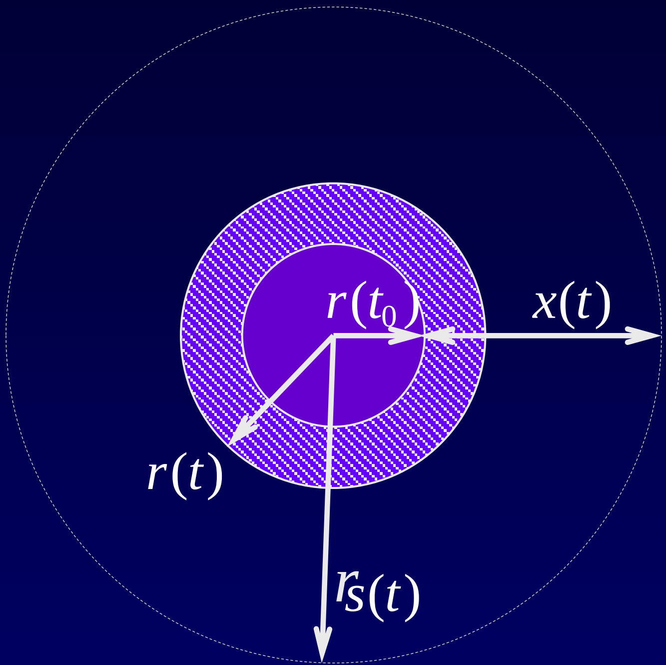


(Temmer et al. 2010 ApJ 712, 1410)

Possibilities:

- Bow shock (CME, small ejecta)
- 3-D piston (CME-flanks, flare)
- "alternatives"

"1D/3D" piston (analytical approach)



conservation of the energy flux:

$$g(u)\, r_s^{\alpha} = \text{const.}$$

($\alpha = 1$ → cylindrical; $\alpha = 2$ → spherical)

(e.g., for $\beta >> 1$: $g(u) = \rho\, u^2 w$

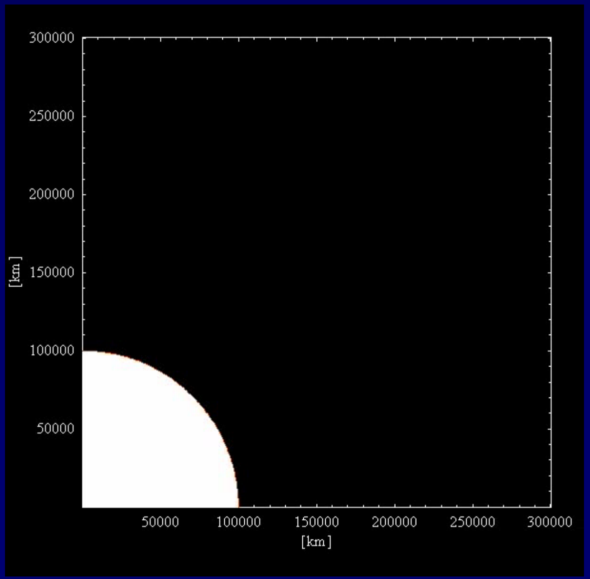
- For the cylindrical coordinate system:

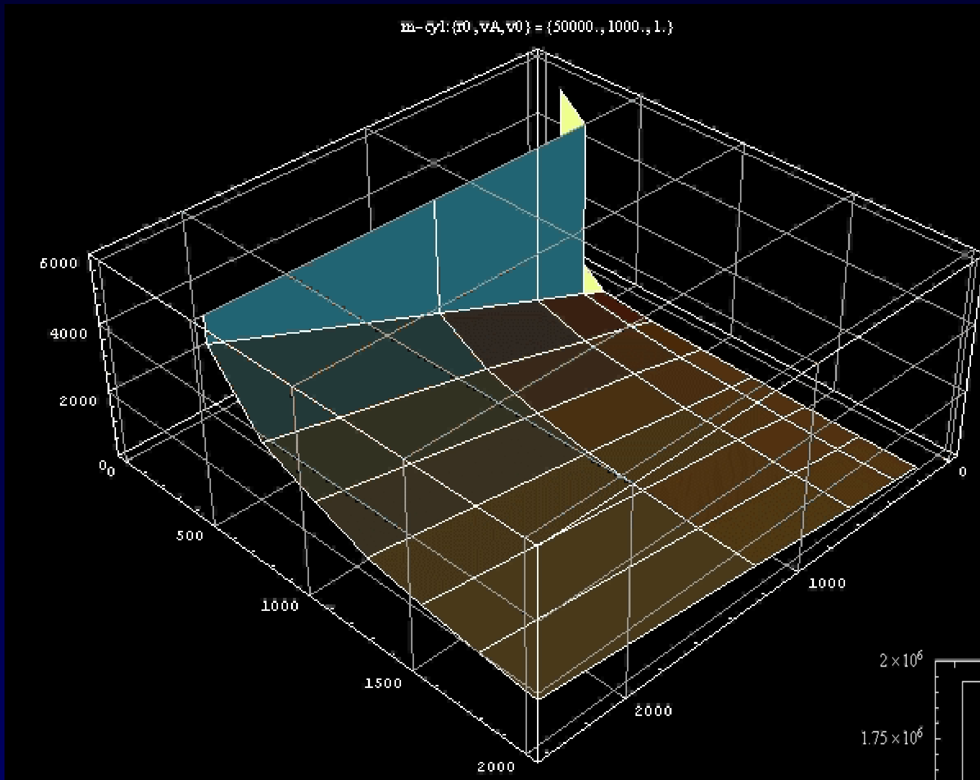
$$-r(t_0)\,g(u_0)\frac{1}{g^2(u)}\frac{\mathrm{d}g(u)}{\mathrm{d}t}\frac{\mathrm{d}u(t)}{\mathrm{d}t} = v_{A0} + ku$$

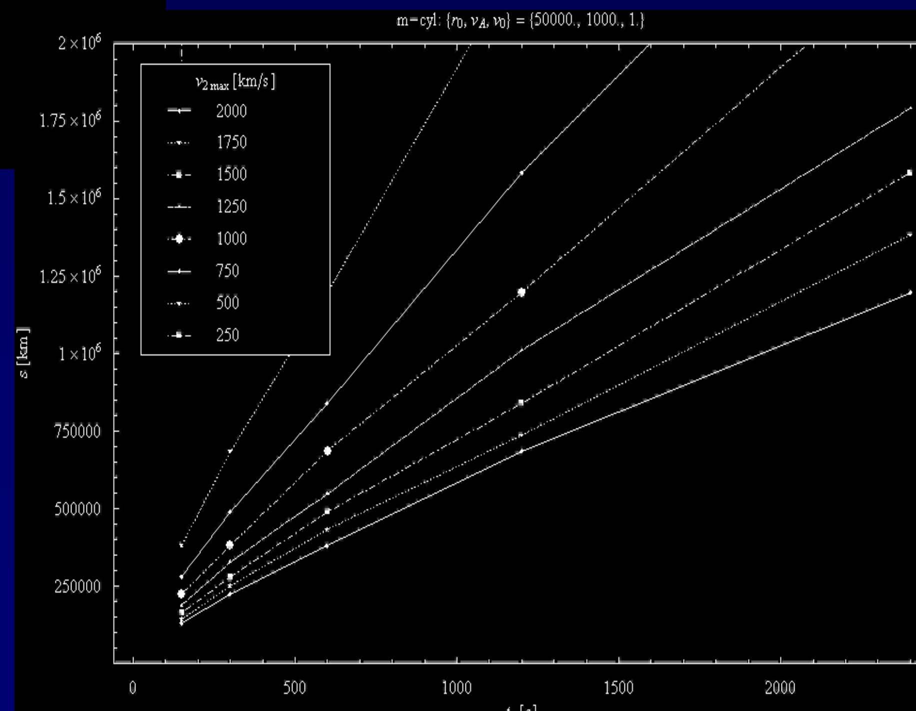
- For the spherical coordinate system:

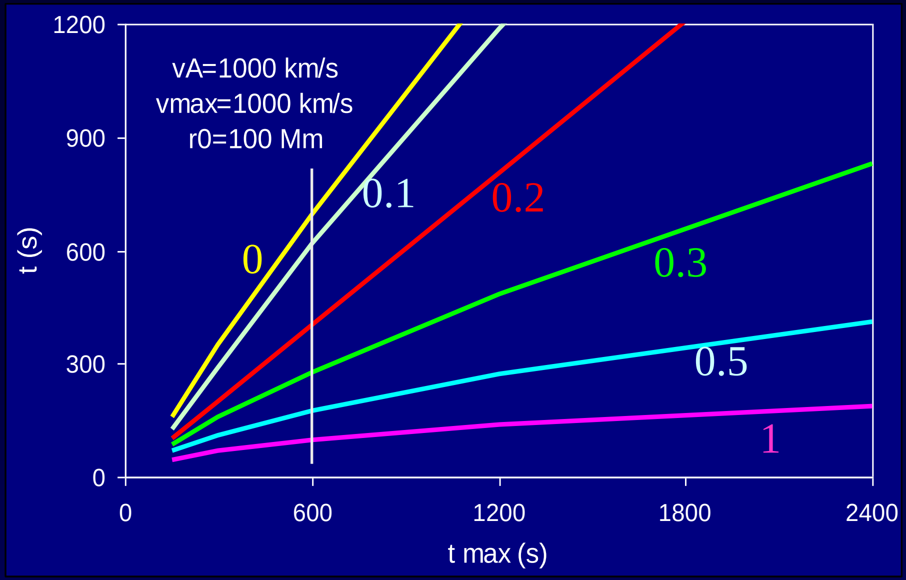
$$-\frac{1}{2}r(t_0)\sqrt{g(u_0)}\,[g(u)]^{-3/2}\frac{\mathrm{d}g(u)}{\mathrm{d}t}\frac{\mathrm{d}u(t)}{\mathrm{d}t} = v_{A0} + ku$$

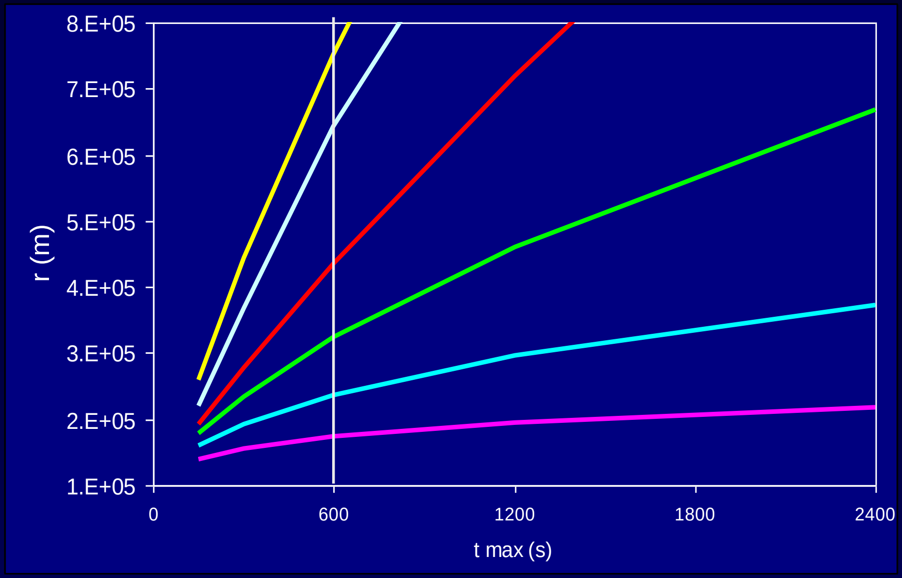
[the flow velocity boundary condition: $u_0 = u(t_0) = v_{CME}(t_0)$]



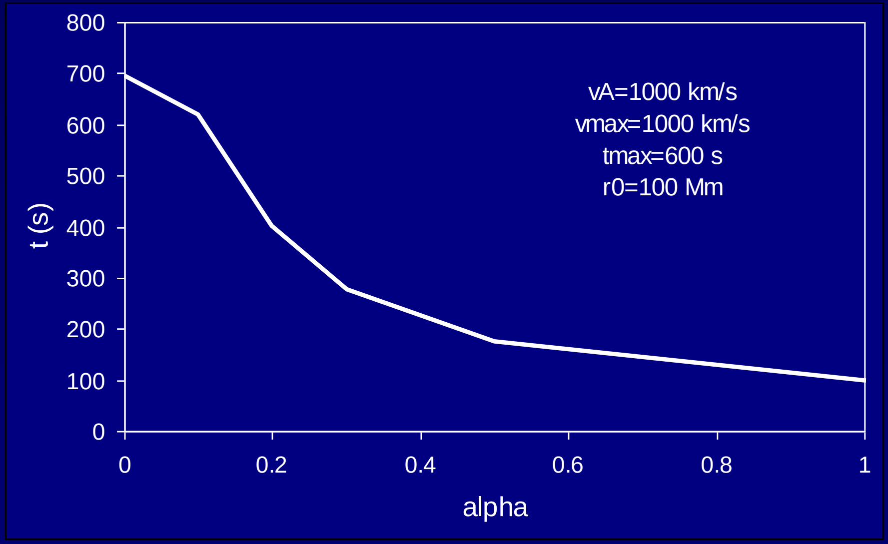

m-cyl: {r0, vA, v0} = {50000., 1000., 1.}
6000
4000
2000
0
0
500
1000
1500
2000
0
1000
2000

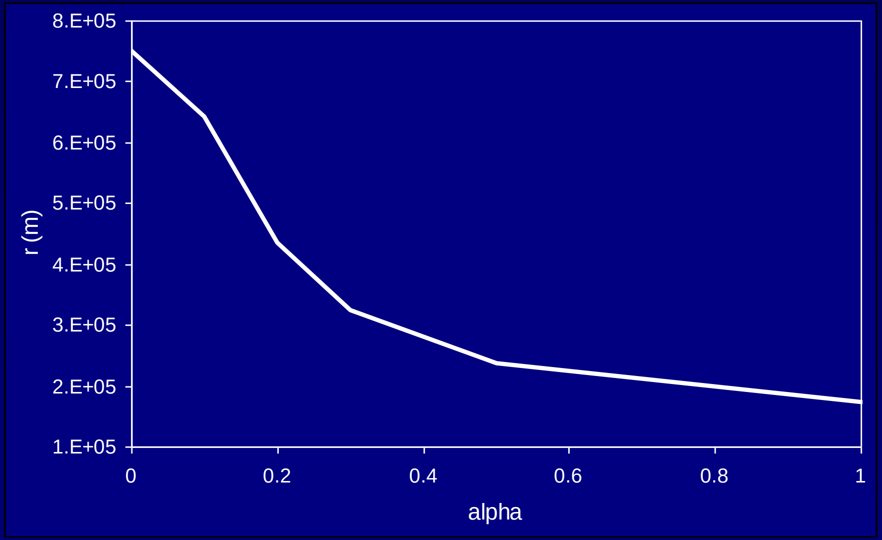

m-cyl: {r_0, v_A, v_0} = {50000., 1000., 1.}
$v_{2\,max}$ [km/s]
2000
1750
1500
1250
1000
750
500
250
2×10^6
1.75×10^6
1.5×10^6
1.25×10^6
1×10^6
750000
500000
250000
s [km]
0
500
1000
1500
2000
t_2 [s]

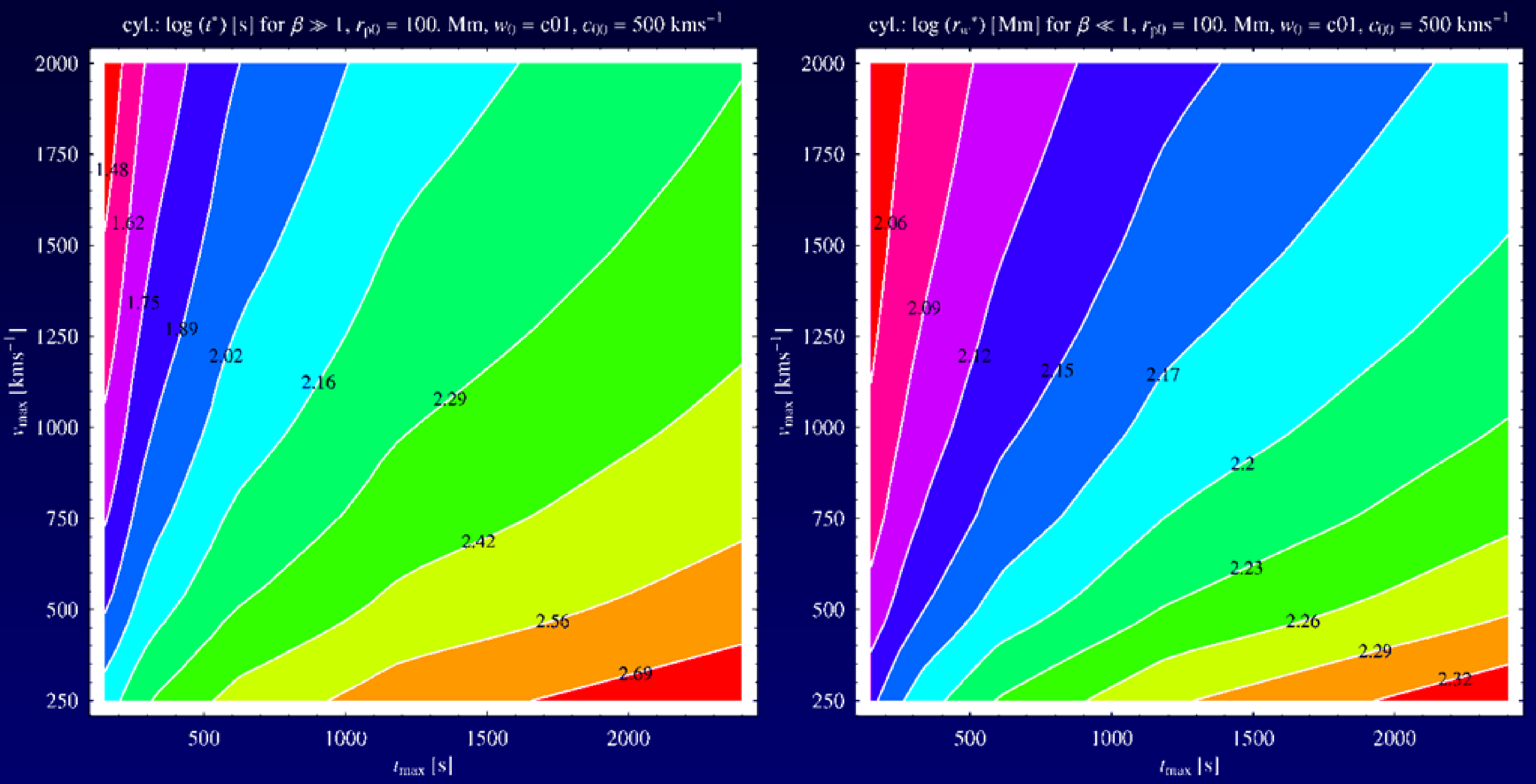




$$v_A = v_A(r_0)\,(r_0/r)^{\alpha}$$





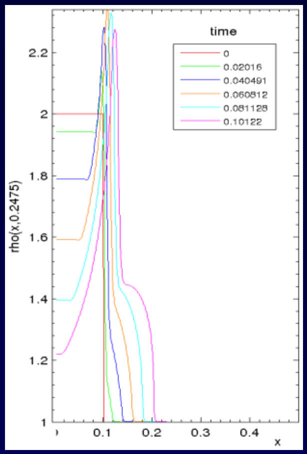


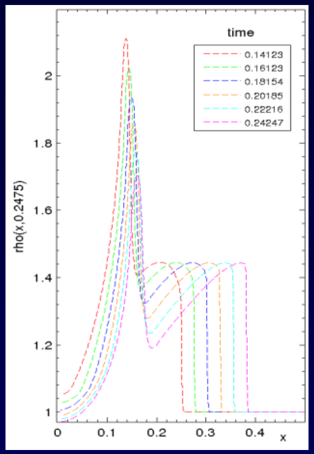
$v_A = 500(r_0/r)$ km/s

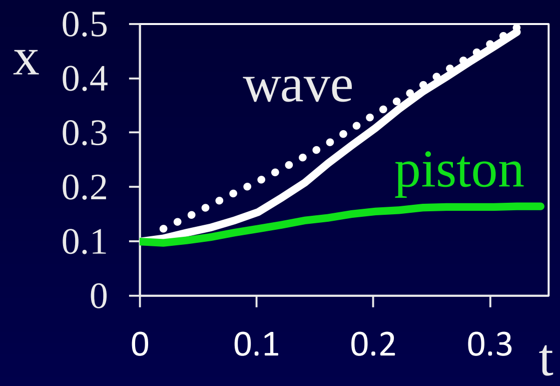
$[r_0 = 100$ Mm$]$

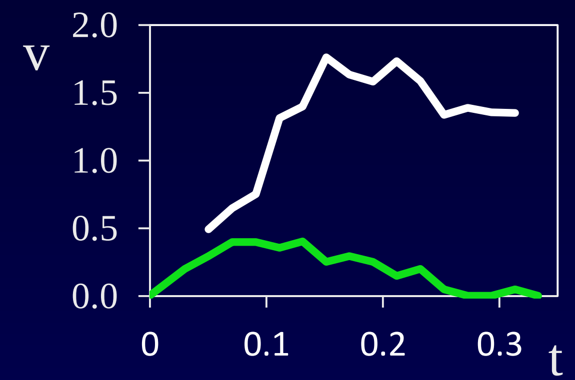
"1D/3D" piston (numerical approach)

1D - planar



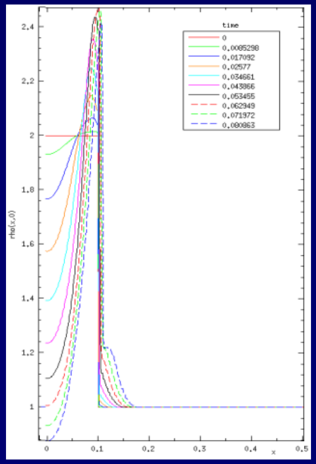


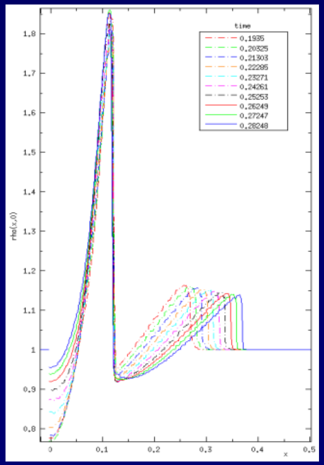


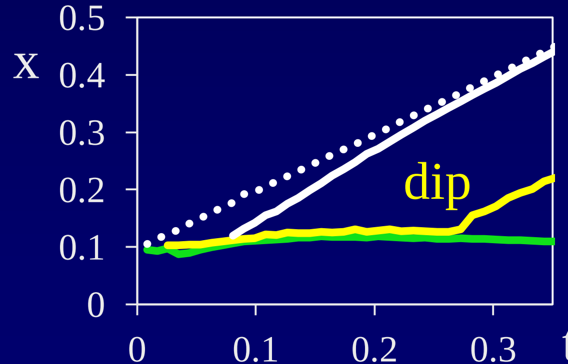


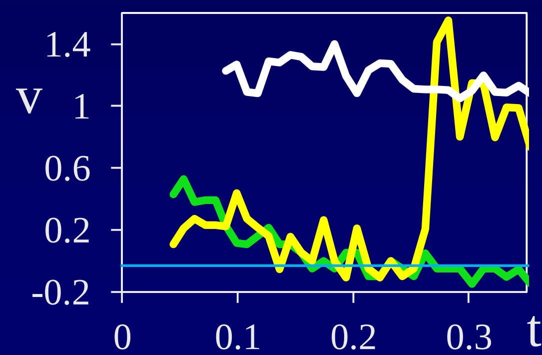
- amplitude growth + steepening → shock formation
- after t~0.15 ~const. amplitude/velocity phase

1.5D - cylindrical





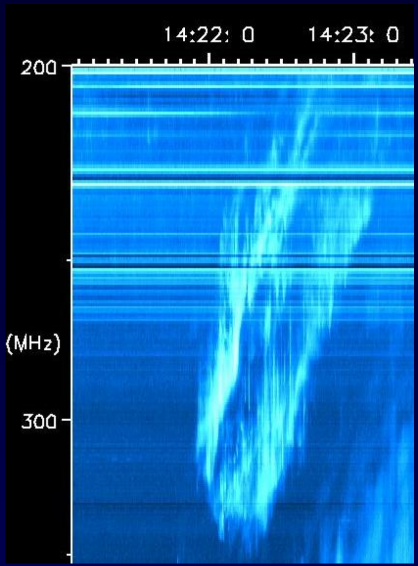


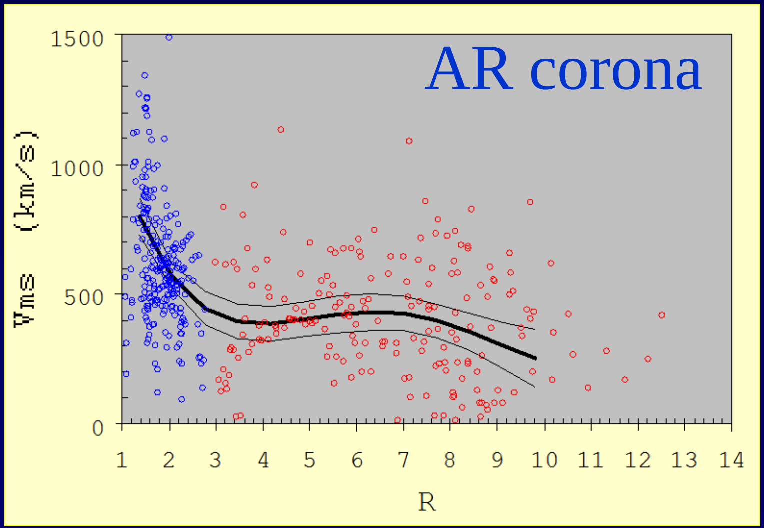


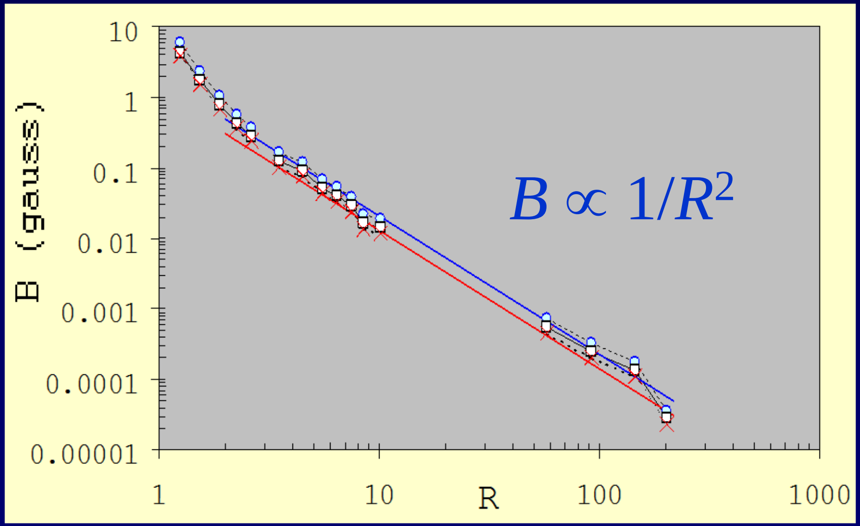
- amplitude growth + steepening → shock formation
- lower amplitude, formation of rarefaction region
- after t~0.08 decreasing amplitude/velocity

Diagnostics

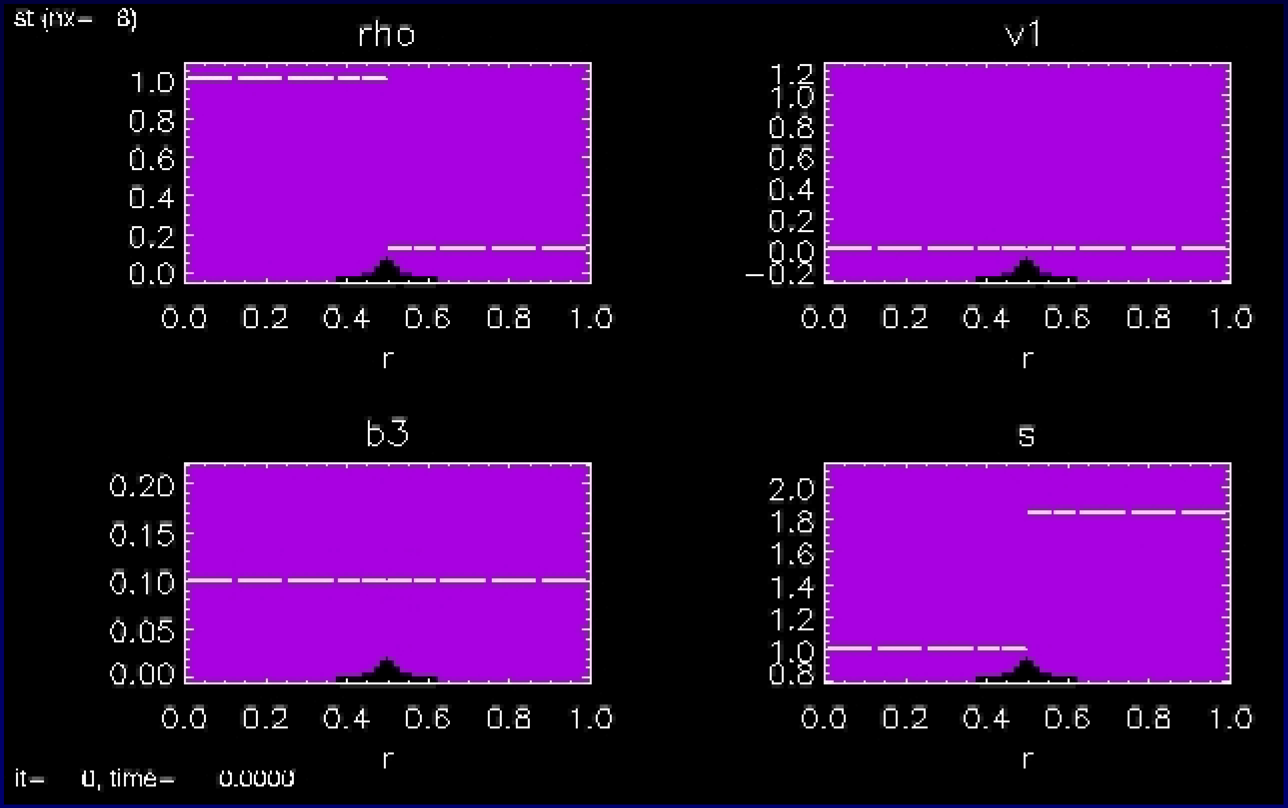
Type IIs:
- IP tracking of CMEs
- UC, IP diagnostics
  (v_A, v_{ms}, B, n, β)







Moreton waves: (quiet sun, low corona) effective v_{ms} = 200-400 km/s


st (nx= 8)
rho
v1
b3
s
r
r
r
r
it= 0, time= 0.0000

X

- XXX