Status of the ionization module/model

with Pallavi Bhat (Pune)

Use temperature

```
###                                  -*-Makefile-*-
### Makefile for modular pencil code -- local part
### Included by `Makefile'
###

MPICOMM     =    mpicomm
HYDRO       =    hydro
DENSITY     =    density
ENTROPY     =    temperature_ionization
MAGNETIC    =    magnetic
RADIATION   =    radiation_ray
EOS         =    eos_temperature_ionization
SHOCK       =    shock
FORCING     =    forcing
GRAVITY     =    gravity_simple
REAL_PRECISION = double
```

Useful units, etc

```
! -*-f90-*-  (for Emacs)    vim:set filetype=fortran:  (f
!
! Convection in vertically stratified atmosphere/solar co
! Initialisation parameters
!
&init_pars
  cvsid='$Id: start.in,v 1.1 2014/07/03 07:34:12 palvi Exp
  unit_length=1e8, unit_velocity=1e5, unit_density=1e0, u
  xyz0=-2.,-2., 0.0
  xyz1= 2., 2., 9.0
  lperi= T, T, F
  lwrite_aux=T
  lwrite_ic=F
/
&eos_init_pars
  lss_as_aux=T, lpp_as_aux=T, lcp_as_aux=T, lcv_as_aux=T,
  xHe=0.1, yMetals=1e-4
  !lHminus_opacity_correction=T
  !lconst_yH=T, yH_const=.99
/
&hydro_init_pars
/
&density_init_pars
  initlnrho='exp_zbot', rho_left=2e-3, Hrho=4.
/
&grav_init_pars
  gravz_profile='const', gravz=-274.
/
&entropy_init_pars
/
&magnetic_init_pars
/
&radiation_init_pars
  bc_rad='p:p','p:p','S:0'
  radx=0, rady=0, radz=1, rad2max=1
  opacity_type='Hminus', scalefactor_kappa=1e-5
/
```

```
! -*-f90-*-  (for Emacs)    vim:set filetype=fortran:  (for vim)
!
! Convection in vertically stratified atmosphere/solar convection zone
! Run parameters
!
&run_pars
  cvsid='$Id: run.in,v 1.1 2014/07/03 07:34:12 palvi Exp $'
  nt=5000000, it1=20, isave=10, itorder=3, cdt=.7
  dsnap=50., dvid=100.
  iz=100
  bcz = 's','s','a','a2','f:a2','s','s','a','s'
  lwrite_aux=T
/
&eos_run_pars
  lss_as_aux=T, lpp_as_aux=T, lcp_as_aux=T, lcv_as_aux=T, lgamma_as_aux=T
  lHminus_opacity_correction=T
/
&hydro_run_pars
  tdamp=1.0
  dampu=10.0
  ldamp_fade=T
/
&density_run_pars
  lreinitialize_lnrho=F, initlnrho='rescale', rescale_rho=1.03
  lupw_lnrho=T
/
&forcing_run_pars
/
&grav_run_pars
/
&entropy_run_pars
  chi=1e-6
  lupw_lnTT=T
/
&magnetic_run_pars
  iresistivity='eta-const','eta-shock'
  lweyl_gauge=F
  eta=1e-2, eta_shock=5.
  va2max_jxb=2500., va2power_jxb=4
/
&radiation_run_pars
/
&viscosity_run_pars
  ivisc='nu-const','nu-shock'
  nu=1e-2, nu_shock=5.
/
&shock_run_pars
  lshock_first=F
/
                                                  1,1           All
```

Basic equations

$$
\begin{aligned}
\frac{\mathrm{D}\ln\rho}{\mathrm{D}t} &= -\boldsymbol{\nabla}\cdot\boldsymbol{u}, \\
\rho\frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} &= -\boldsymbol{\nabla}(p+\phi)+\rho\boldsymbol{g}+\boldsymbol{J}\times\boldsymbol{B}+\boldsymbol{\nabla}\cdot(2\rho\nu\mathsf{S}), \\
\rho T\frac{\mathrm{D}s}{\mathrm{D}t} &= -\boldsymbol{\nabla}\cdot\boldsymbol{F}_{\mathrm{rad}}+2\rho\nu\mathsf{S}^2, \\
\frac{\partial\boldsymbol{A}}{\partial t} &= \boldsymbol{u}\times\boldsymbol{B}+\eta\nabla^2\boldsymbol{A},
\end{aligned}
$$

Working with temperature

$$p = \frac{\mathcal{R}}{\mu} T \rho, \quad \mathcal{R} = k_{\rm B}/m_{\rm u}$$

Y=0.24: mass fract
$x_{\rm He}$=0.08: vol fract

$$\mu(\rho, T) = \mu_{\rm Y}/(1 + y_{\rm H} + x_{\rm He})$$

$$\mu_Y = 1/(1 - Y), \quad Y \approx 1/(1 + 1/4x_{\rm He})$$

$$\rho T \frac{{\rm D}s}{{\rm D}t} = \rho \frac{{\rm D}e}{{\rm D}t} + p \boldsymbol{\nabla} \cdot \boldsymbol{u} = \rho c_v T \left(\frac{{\rm D} \ln T}{{\rm D}t} + \frac{\gamma - 1}{\delta} \boldsymbol{\nabla} \cdot \boldsymbol{u} \right)$$

Pressure gradient

$$\frac{1}{\rho}\boldsymbol{\nabla} p = \frac{c_{\mathrm{s}}^2}{\gamma}(\boldsymbol{\nabla}\ln\rho + \delta\boldsymbol{\nabla}\ln T),$$

$$c_{\mathrm{s}}^2 = \gamma p/\rho\alpha$$

$$\alpha = (\partial\ln\rho/\partial\ln p)_T$$

$$\delta = (\partial\ln\rho/\partial\ln T)_p$$

$$c_p = (\partial e/\partial T)_p$$

$$c_v = (\partial e/\partial T)_v$$

$$\gamma = c_p/c_v$$

Saha equation

$$\frac{y_{\rm H}^2}{1-y_{\rm H}} = \frac{\rho_{\rm e}}{\rho}\left(\frac{\chi_{\rm H}}{k_{\rm B}T}\right)^{-3/2} \exp\left(-\frac{\chi_{\rm H}}{k_{\rm B}T}\right)$$

$$\chi_{\rm H} = 13.6\,{\rm eV}$$

$$\rho_{\rm e} = \mu_Y m_{\rm u} (m_{\rm e}\chi_{\rm H}/2\pi\hbar^2)^{3/2}$$

Opacity: either Kramers or Hminus

$$\kappa = \kappa_0 \rho^a T^b$$

$$\kappa = \kappa_0 (y_{\rm H} + x_Z)(1-y_{\rm H}) \frac{\rho}{\rho_{e^-}} \left(\frac{\chi_{\rm H^-}}{k_{\rm B}T}\right)^{3/2} \exp\left(\frac{\chi_{\rm H^-}}{k_{\rm B}T}\right)$$

$$\chi_{\rm H^-} = 0.754\,{\rm eV}, \quad \kappa_0 = \sigma_{\rm H^-}/4m_{\rm u}\mu_Y,$$

$$\sigma_{\rm H^-} = 4\times 10^{-17}\,{\rm cm}^2, \quad x_Z = 10^{-4}$$

$$\rho_{e^-} = \mu_Y m_{\rm u} (m_{\rm e}\chi_{\rm H^-}/2\pi\hbar^2)^{3/2}$$

Thermodynamic coefficients

$$c_p = \left(\frac{5}{2} + A_p B_p^2\right) \frac{\mathcal{R}}{\mu},$$

$$c_v = \left(\frac{3}{2} + A_v B_v^2\right) \frac{\mathcal{R}}{\mu}$$

$$\alpha = A_p / A_v,$$

$$\delta = 1 + A_p B_p$$

where:

$$A_p = \frac{y_{\mathrm{H}}(1 - y_{\mathrm{H}})}{(2 - y_{\mathrm{H}}) x_{\mathrm{He}} + 2}, \qquad B_p = \frac{5}{2} + \frac{\chi_{\mathrm{H}}}{k_{\mathrm{B}} T},$$

$$A_v = \frac{y_{\mathrm{H}}(1 - y_{\mathrm{H}})}{(2 - y_{\mathrm{H}})(1 + y_{\mathrm{H}} + x_{\mathrm{He}})}, \qquad B_v = \frac{3}{2} + \frac{\chi_{\mathrm{H}}}{k_{\mathrm{B}} T}.$$

Run parameters

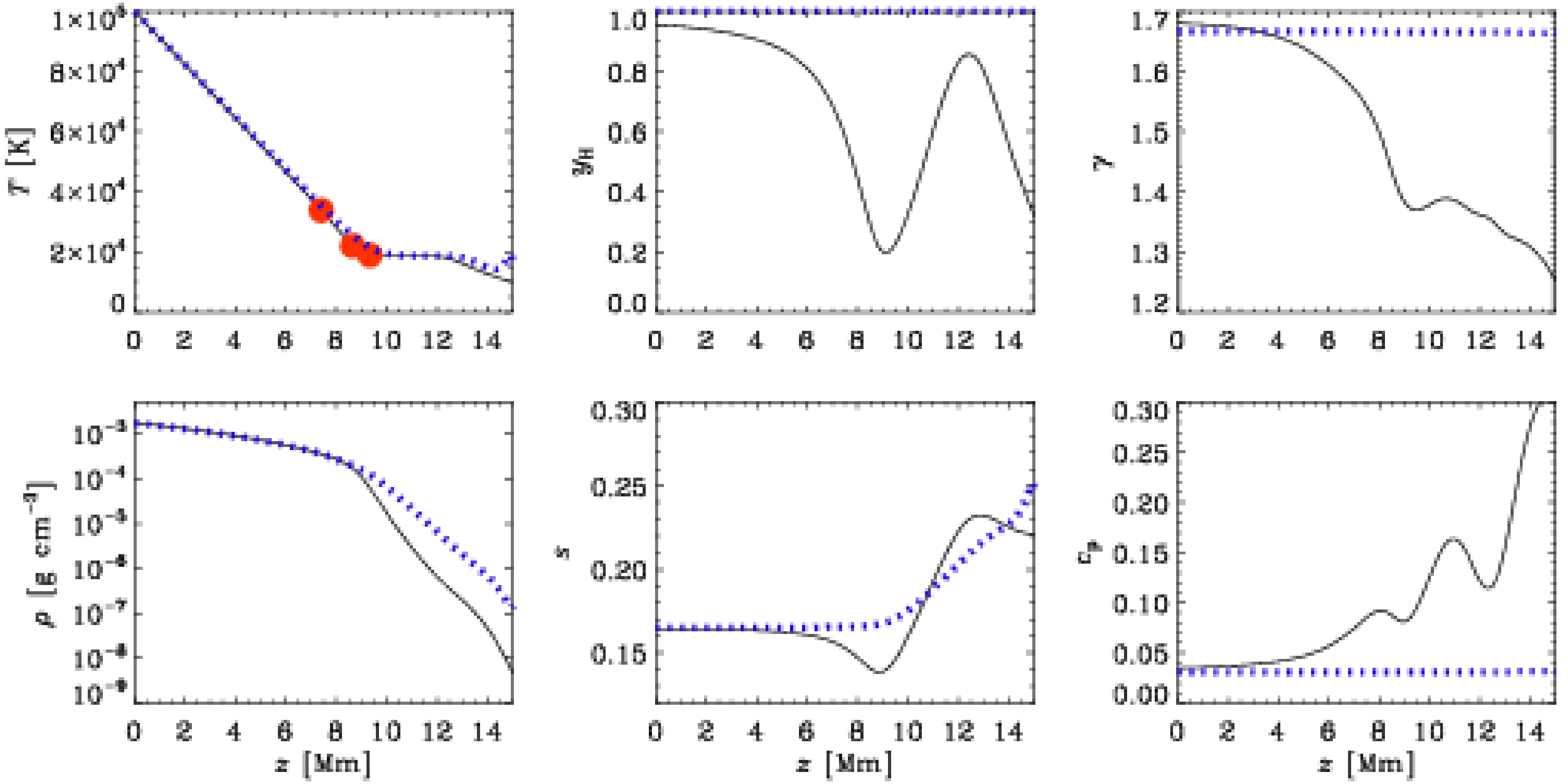
$$g = 274\,\mathrm{km}^2\,\mathrm{s}^{-2}\,\mathrm{Mm}^{-1} = 2.74 \times 10^4\,\mathrm{cm}\,\mathrm{s}^{-2}$$
$$a = 1,\ b = 0,\ \tilde{\kappa}_0 = 10^5\,\mathrm{Mm}^{-1}\,\mathrm{cm}^3\,\mathrm{g}^{-1}$$
$$\nu = \eta = 10^{-3}\,\mathrm{Mm}\,\mathrm{km}\,\mathrm{s}^{-1}\ (10^{10}\,\mathrm{cm}^2\,\mathrm{s}^{-1})$$
$$R = 1\,\mathrm{Mm},\ B_0 = 1\,\mathrm{kG}.$$

suction:

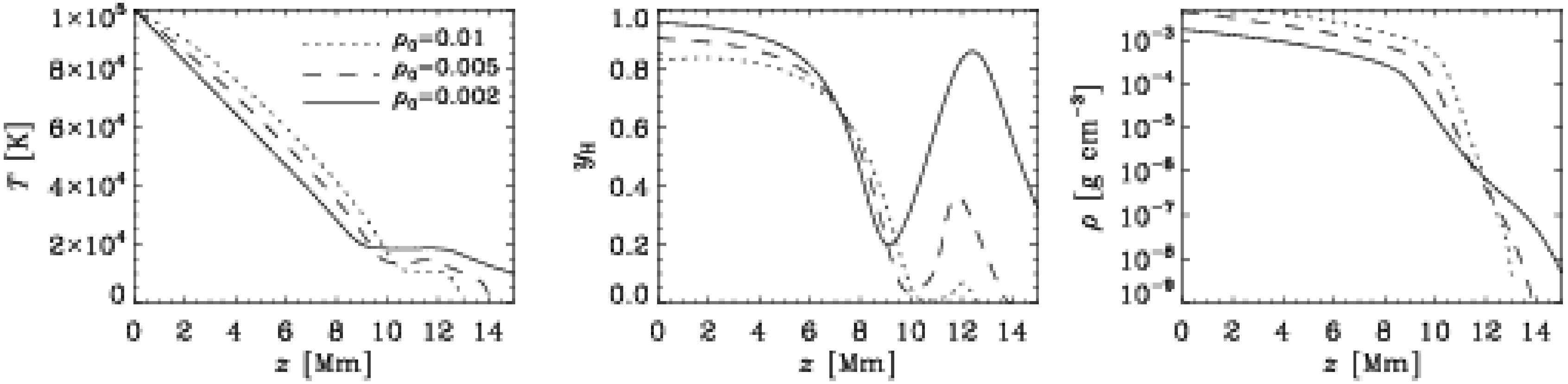
$$\phi = \phi_0 e^{-[x^2+(z-z_0)^2]/2R^2}$$

Run	opacity	z_0	ϕ_0	$p(z_0)$	$\max\lvert u_z\rvert$
F3	(1,0)	3	3×10^{-3}	1	1.1
K3a	(1,0)	3	3×10^{-3}	1	45
K3b	(1,0)	3	3×10^{-4}	1	40
H10	H^-	10	3×10^{-2}	0.07	15

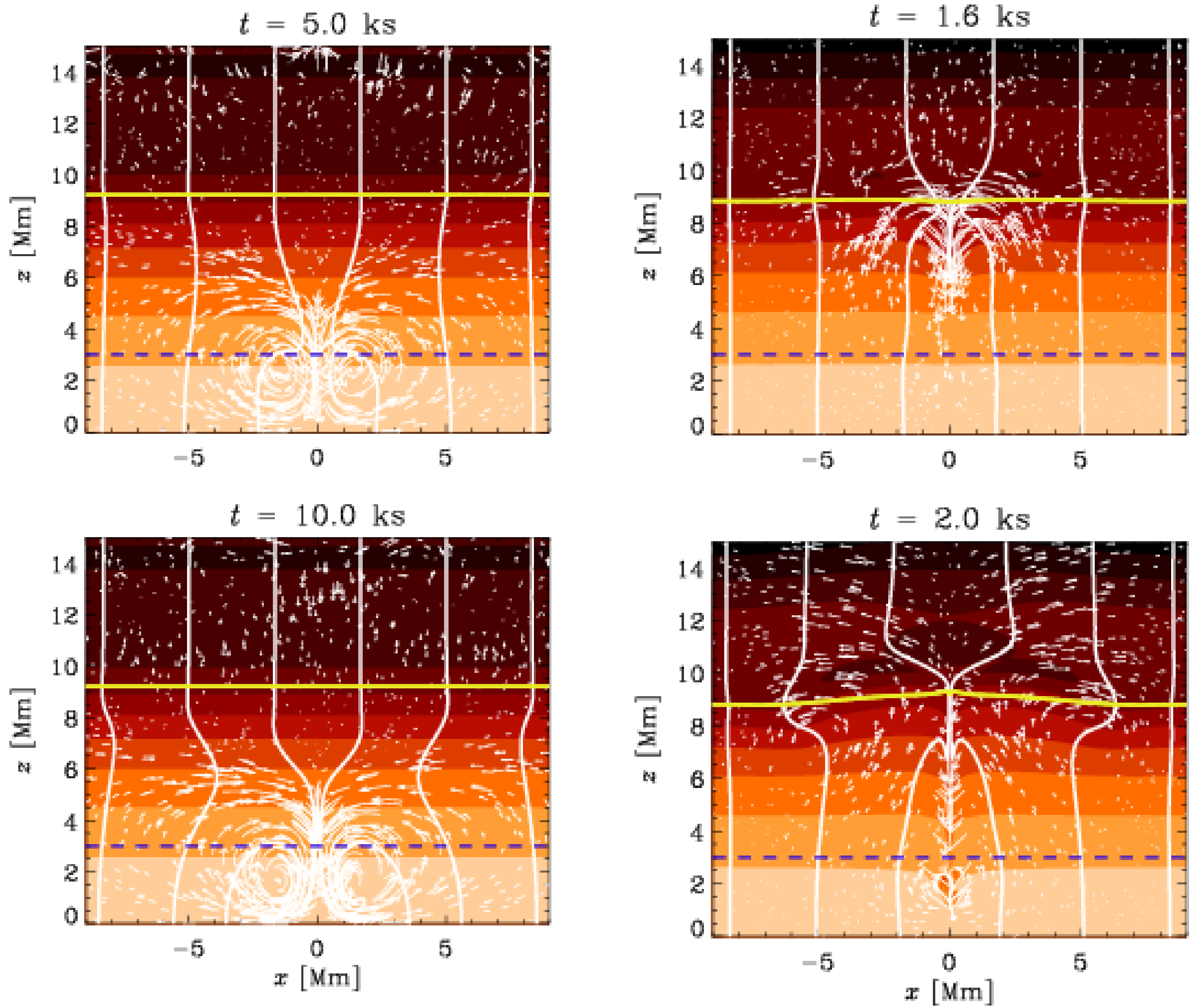
With/without ionization



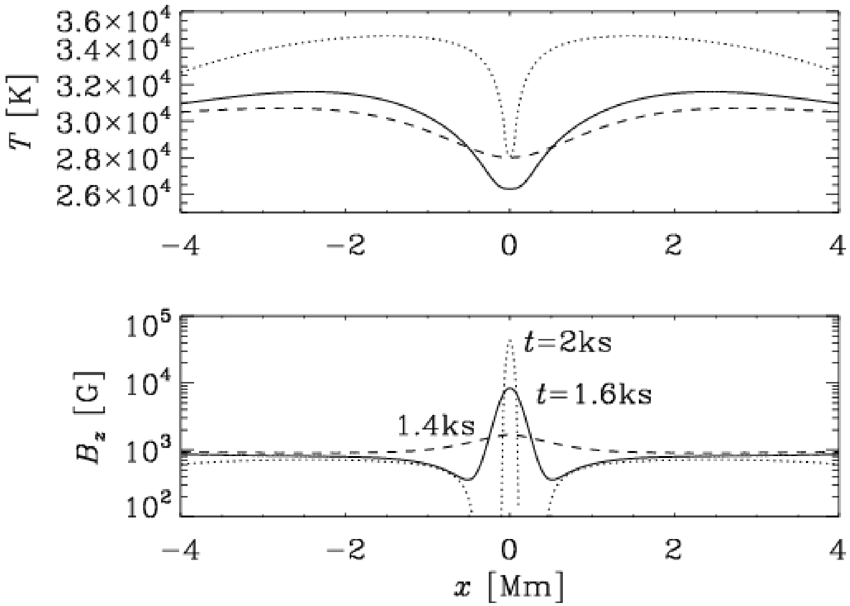
Different bottom density

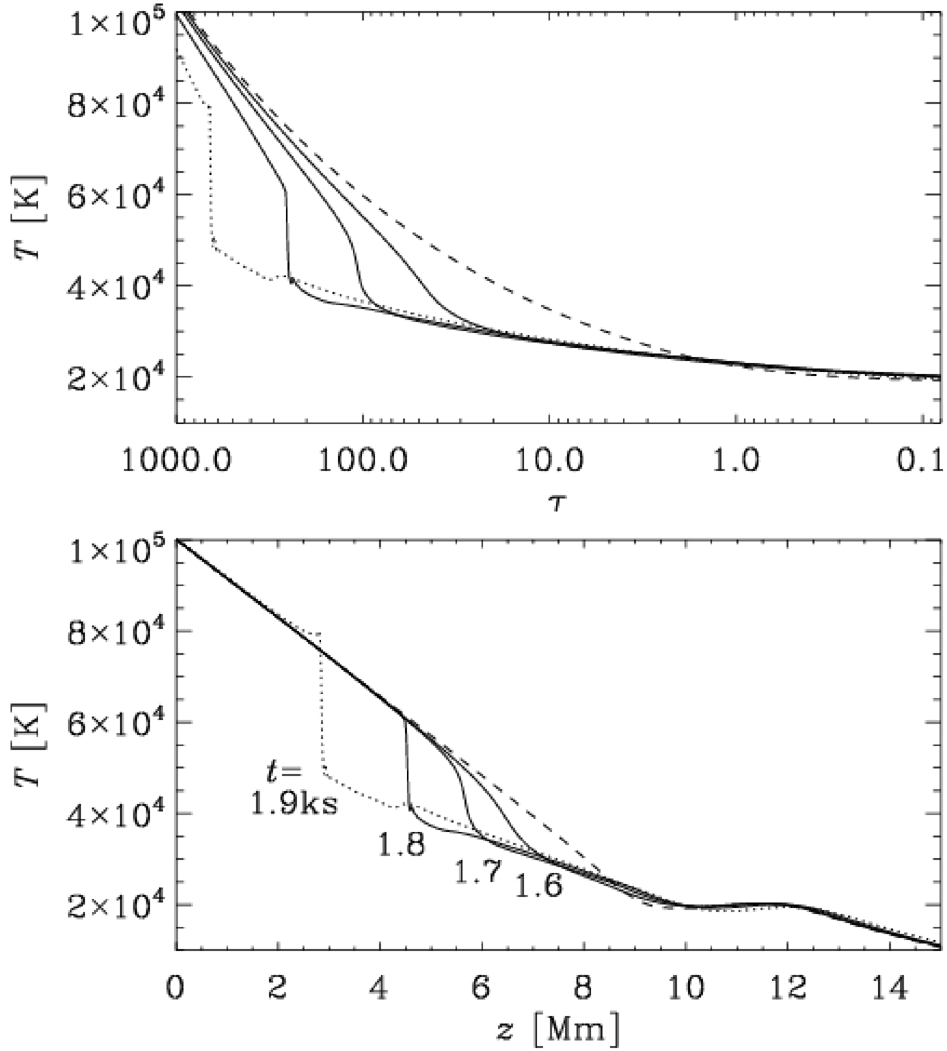


Fixed/variable ionization



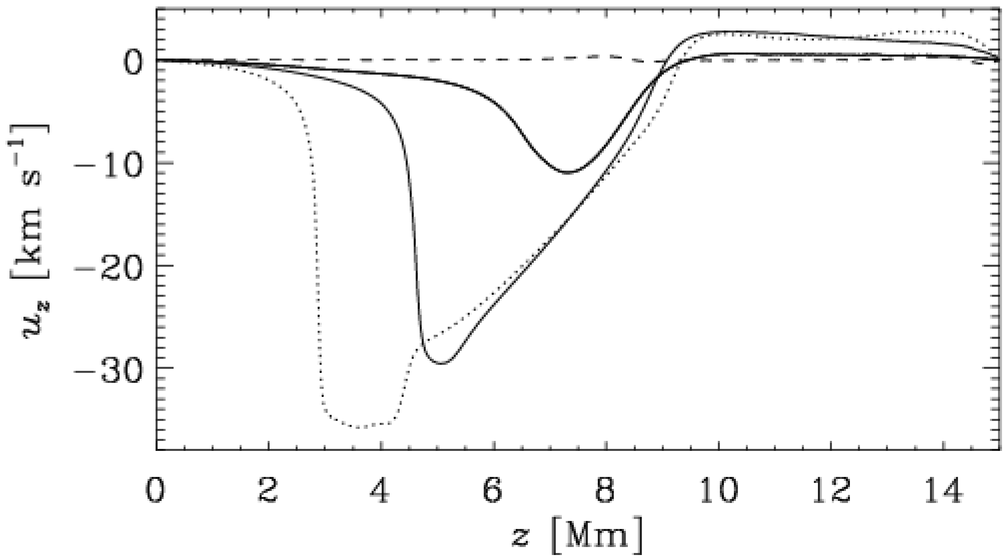
Suction in action



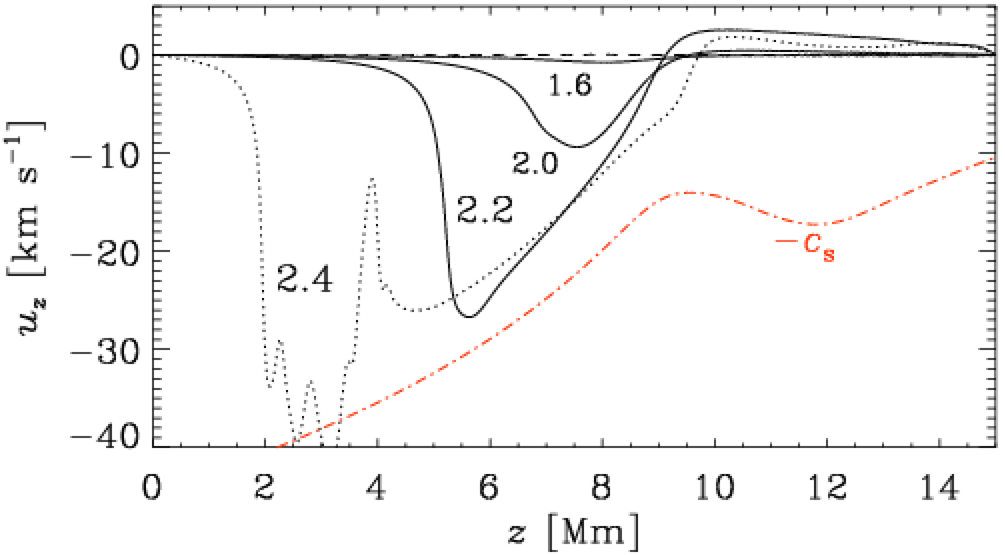


Temperature profils

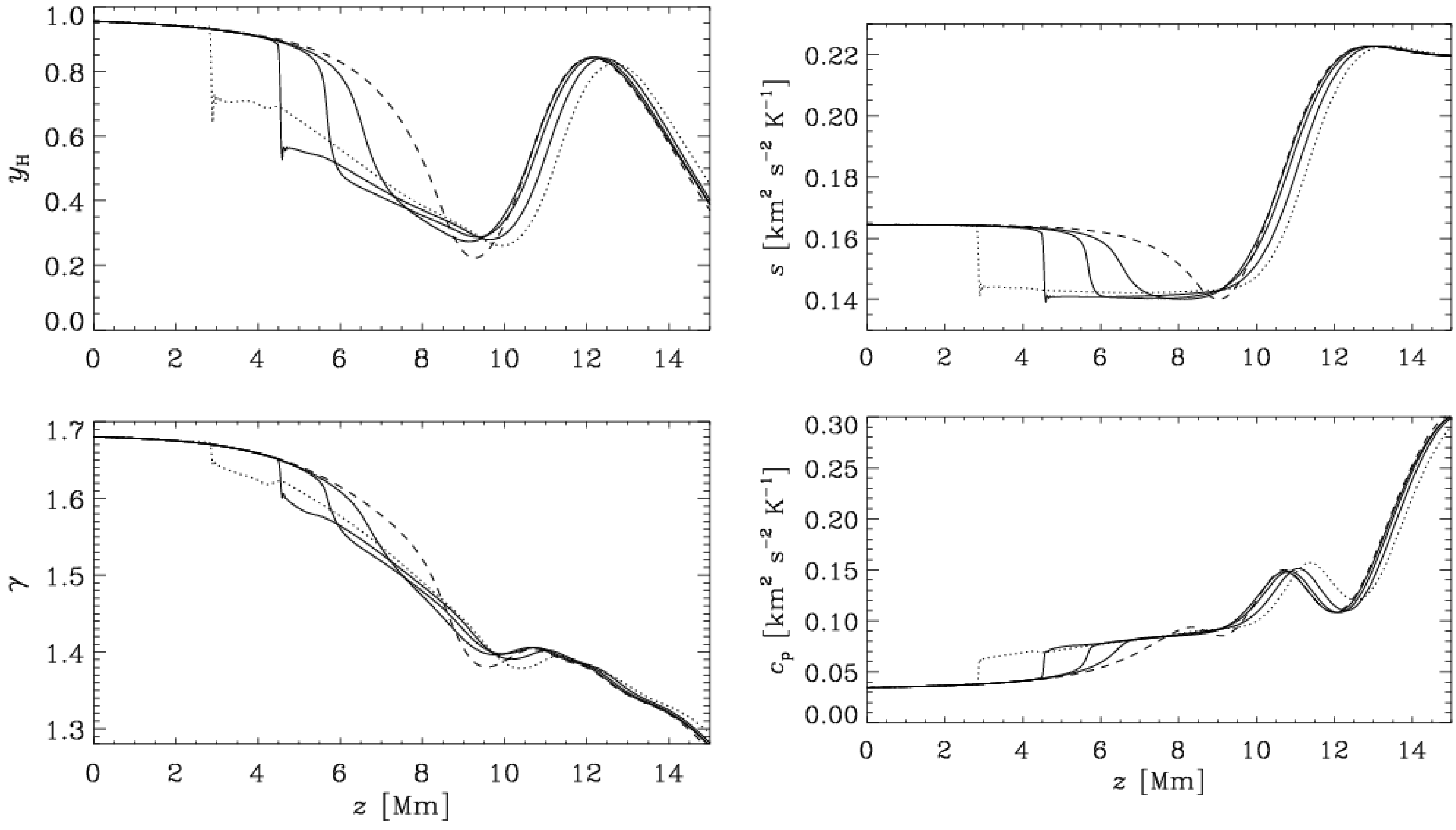
Velocity evolution



Weaker suction and comparison
With sound speed

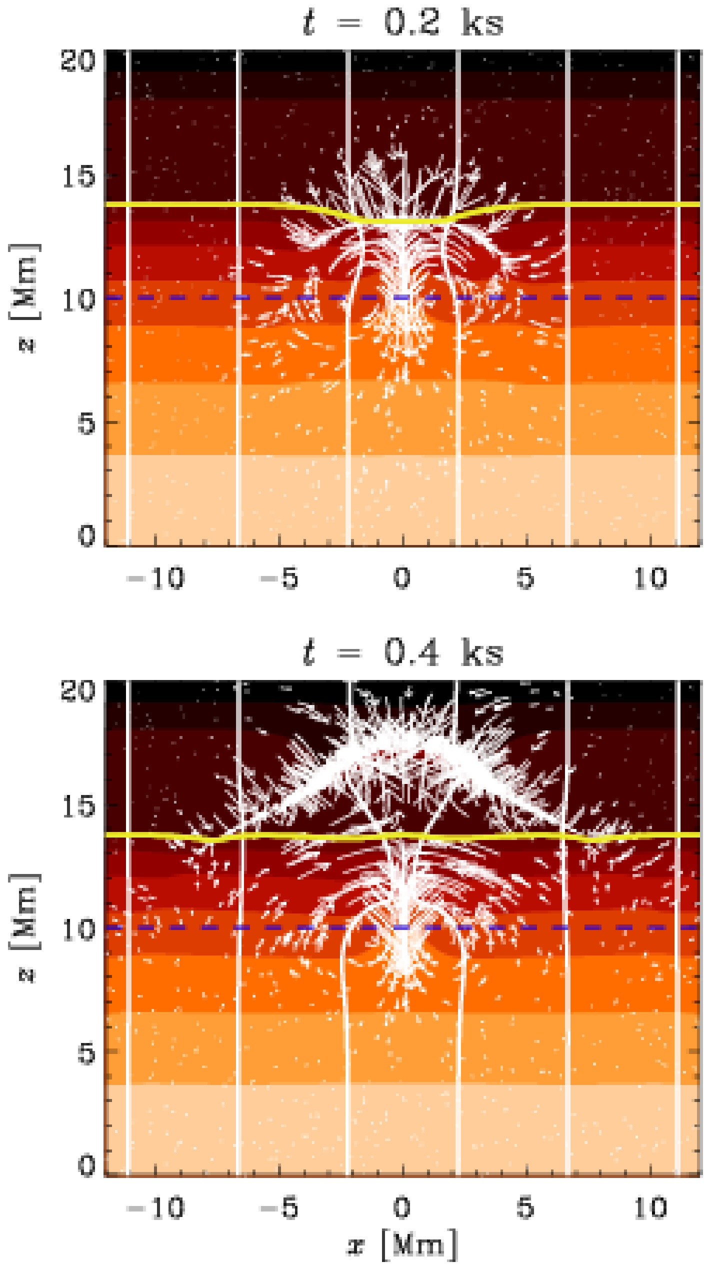


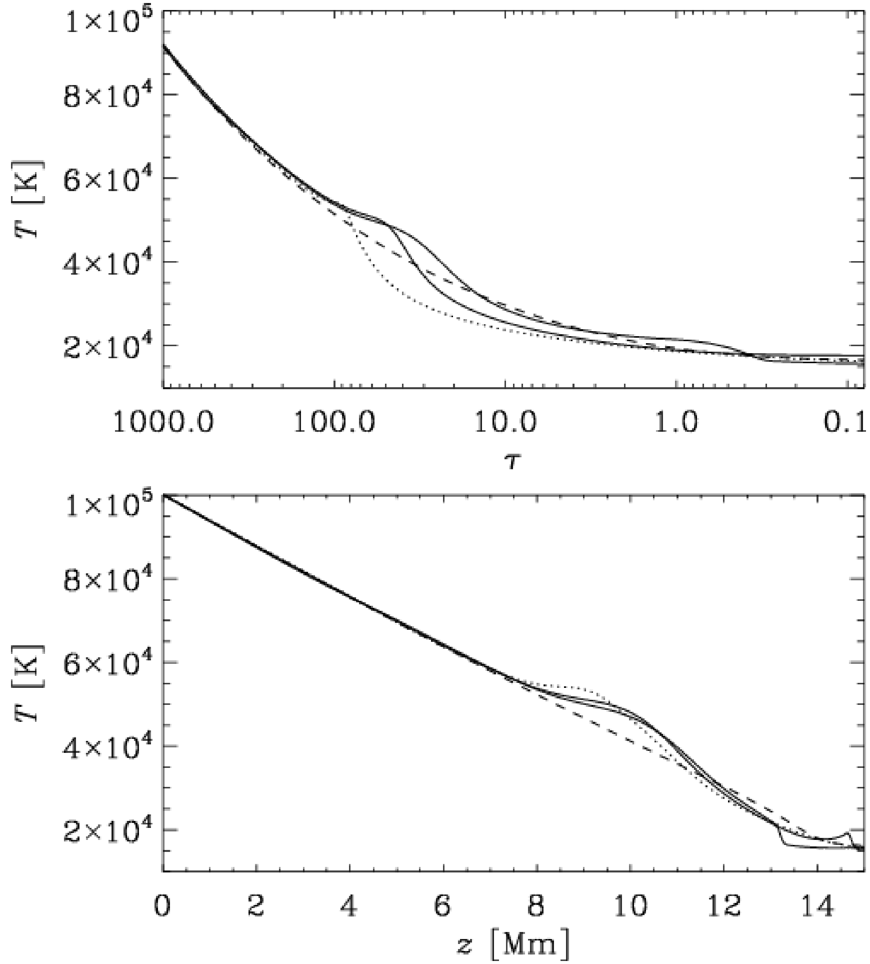
Evolution of thermodynamic coeffients



Carries stuff with it…

Same with Hminus





Stably stratified deeper parts…