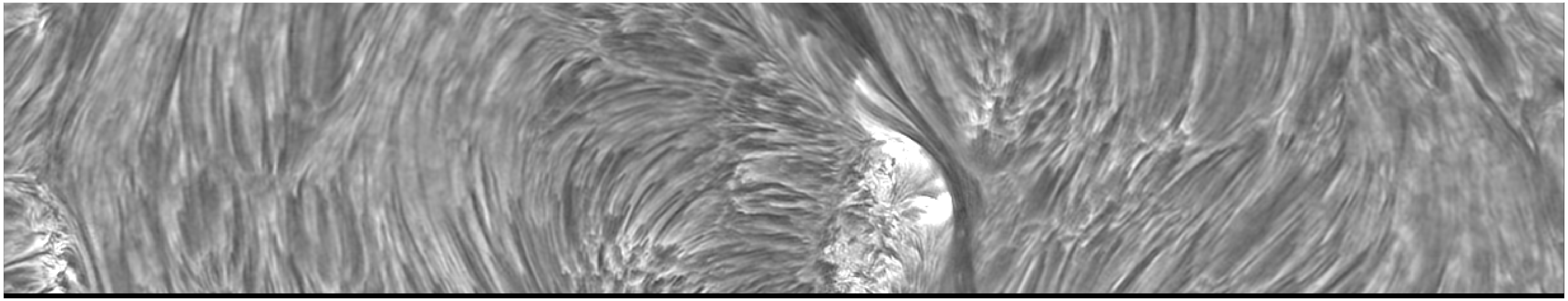


Chromospheric heating by ambipolar diffusion

Elena Khomenko & Manuel Collados

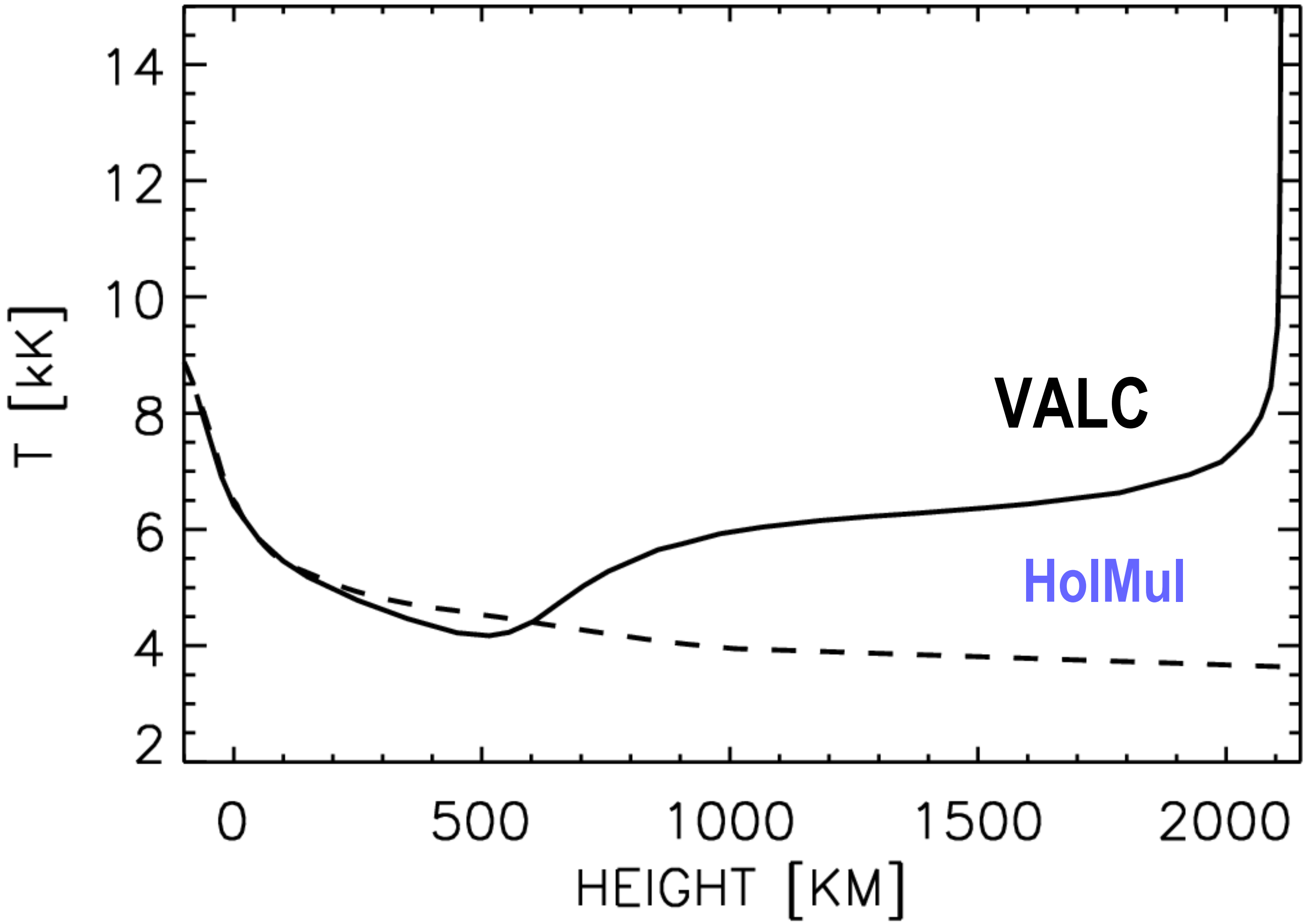
Departamento de Astrofísica, Universidad de La Laguna
and *Instituto de Astrofísica de Canarias (IAC),*

La Laguna, Tenerife (Spain).

SPIA
Solar Partially Ionized Atmosphere

http://www.iac.es/proyecto/spia/

Temperature in solar models



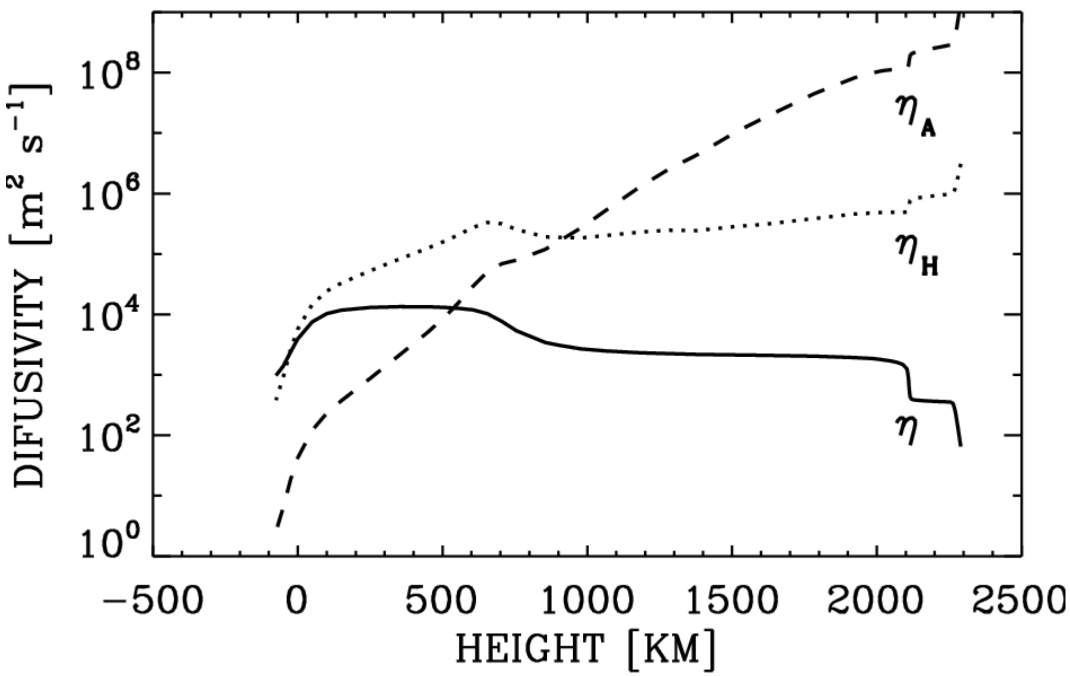
Chromospheric T increases

Radiative equilibrium: T decreases

Elena Khomenko

Generalized Ohm's law

$$\vec{E}^* = \left[\vec{E} + \vec{u} \times \vec{B}\right] = \eta \vec{J} + \eta_H \left[\vec{J} \times \vec{b}\right] - \eta_A \left[(\vec{J} \times \vec{b}) \times \vec{b}\right]$$
$$+ \frac{\varepsilon \vec{G} - \vec{\nabla} \hat{\mathbf{p}}_{\mathbf{e}}}{e n_e} + \frac{\xi_n}{\alpha_n} \left[\vec{G} \times \vec{B}\right] + \frac{\xi_n^2 \rho_e}{\alpha_n} \vec{g} \times \vec{B} + \frac{m_e}{e}(1 + \xi_n \epsilon)\vec{g}$$

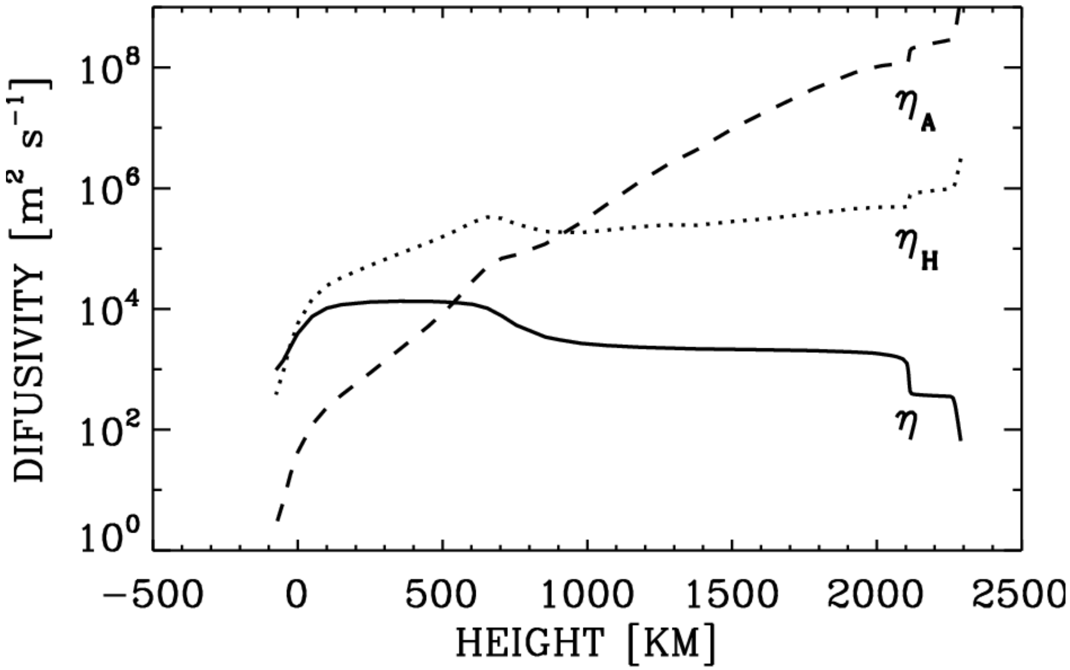


Elena Khomenko

Generalized Ohm's law

$$\vec{E}^* = \left[\vec{E} + \vec{u} \times \vec{B}\right] = \boxed{\eta \vec{J}} + \eta_H \cancel{\left[\vec{J} \times \vec{b}\right]} \boxed{- \eta_A \left[(\vec{J} \times \vec{b}) \times \vec{b}\right]}$$

$$+ \cancel{\frac{\varepsilon \vec{G} - \vec{\nabla} \hat{\mathbf{p}}_{\mathbf{e}}}{e n_e}} + \frac{\xi_n}{\alpha_n} \cancel{\left[\vec{G} \times \vec{B}\right]} + \cancel{\frac{\xi_n^2 \rho_e}{\alpha_n} \vec{g} \times \vec{B}} + \cancel{\frac{m_e}{e} (1 + \xi_n \epsilon) \vec{g}}$$



Elena Khomenko

Energy conservation equation

$$\frac{De_{\mathrm{int}}}{Dt} + \gamma e_{\mathrm{int}} \vec{\nabla} \vec{u} = \boxed{\eta \vec{J}^2} + \boxed{\eta_A J_{\perp}^2}$$

Ohmic term

Ambipolar term

Since Ambipolar diffusivity is **5 orders of magnitude** larger than the Ohmic diffusivity, we expect **important heating** due to current dissipation.

Conversion of magnetic to thermal energy

1) $$\frac{B^2}{2\mu} + e_{\mathrm{int}} = \mathrm{constant}$$

2) $$\frac{B_0^2}{2\mu} + e_{\mathrm{int0}} = \frac{(B_0 - \Delta B)^2}{2\mu} + e_{\mathrm{int0}} + \Delta e_{\mathrm{int}}$$

3) $$\frac{B_0 \Delta B}{\mu} = \Delta e_{\mathrm{int}} = \frac{nk\Delta T}{(\gamma - 1)}$$

$$\boxed{\Delta T = \frac{(\gamma - 1)}{nk\mu} B_0 \Delta B}$$

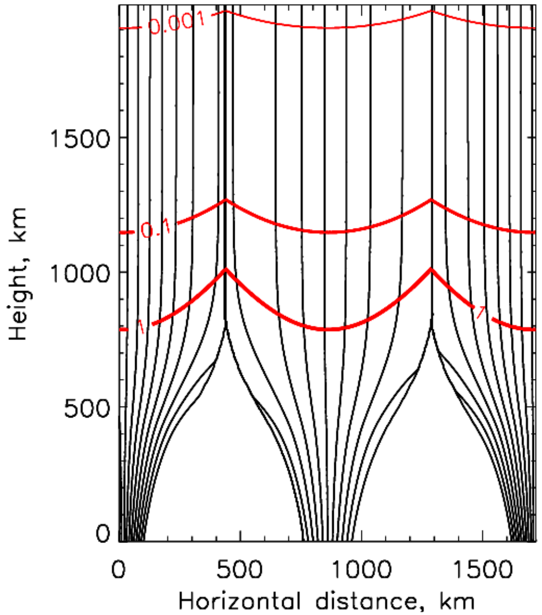
SPIA

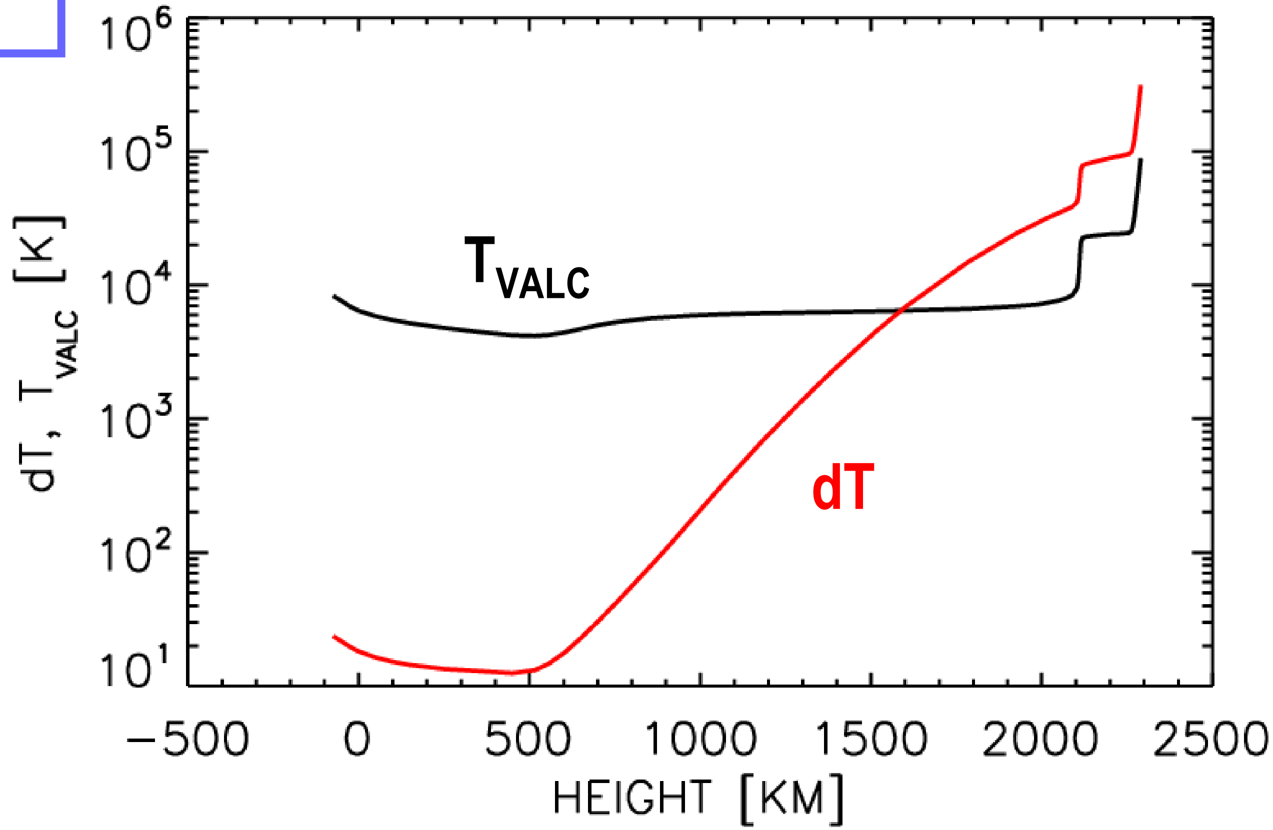
Conversion of magnetic to thermal energy

$$\Delta T = \frac{(\gamma - 1)}{nk\mu} B_0 \Delta B$$

Dissipation of

$$\Delta B = 0.01 B_0$$





Pneuman et al. (1986)

Elena Khomenko

Quasi-MHD equations

$$
\begin{aligned}
\frac{\partial \rho}{\partial t} + \vec{\nabla}\left(\rho \vec{u}\right) &= 0 \\
\rho \frac{D\vec{u}}{Dt} &= \vec{J} \times \vec{B} + \rho \vec{g} - \vec{\nabla} p \\
\frac{De_{\mathrm{int}}}{Dt} + \gamma e_{\mathrm{int}} \vec{\nabla} \vec{u} &= \eta \vec{J}^2 + \eta_A \vec{J}_{\perp}^2 + Q_{\mathrm{rad}} \\
\frac{\partial \vec{B}}{\partial t} &= \vec{\nabla} \times \left[(\vec{u} \times \vec{B}) - \eta \vec{J} - \eta_A \vec{J}_{\perp} \right]
\end{aligned}
$$

Numerical simulations of heating

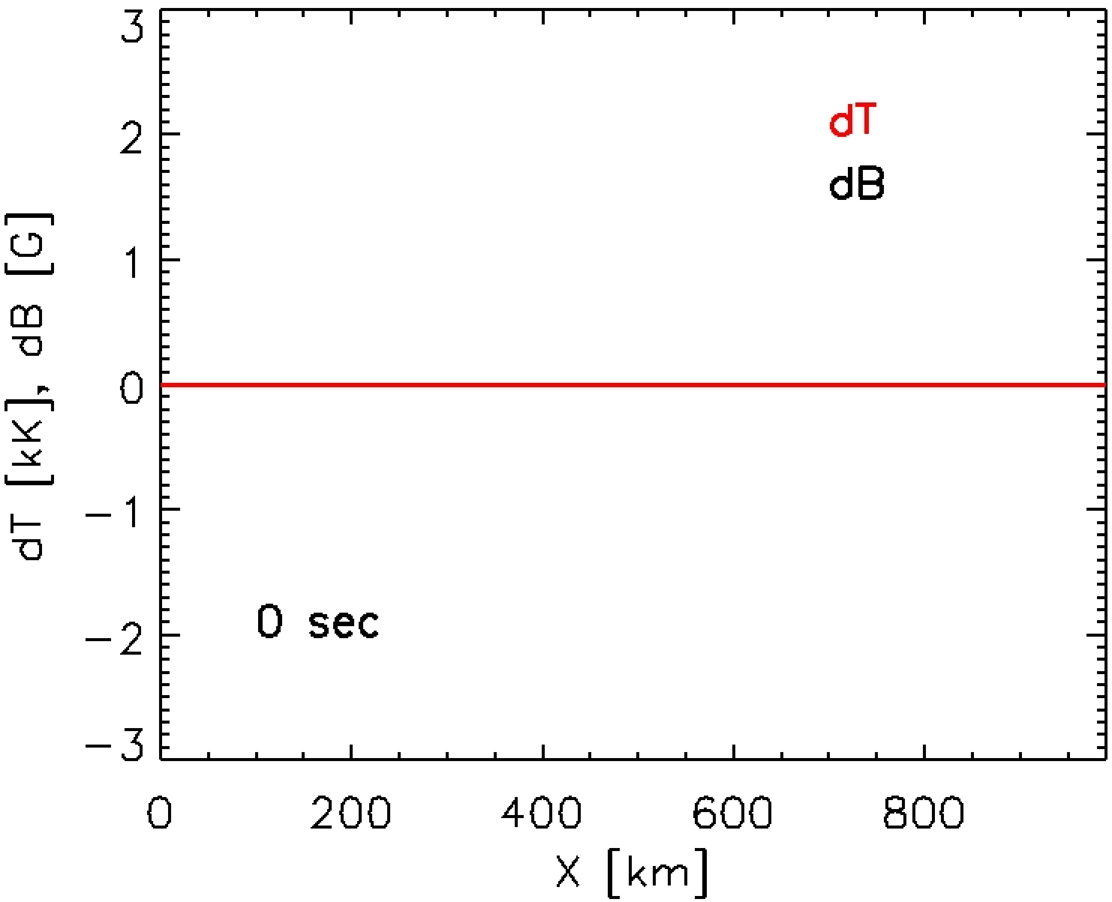
Test case:

No gravity

T, P, ρ from VAL-C
at Z=1000 km

$$B_Z(x) = B_0 \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right)$$

$$B_0 = \sqrt{2\mu P} \times 0.9 = 18\mathrm{G}$$



Elena Khomenko

Numerical simulations of heating

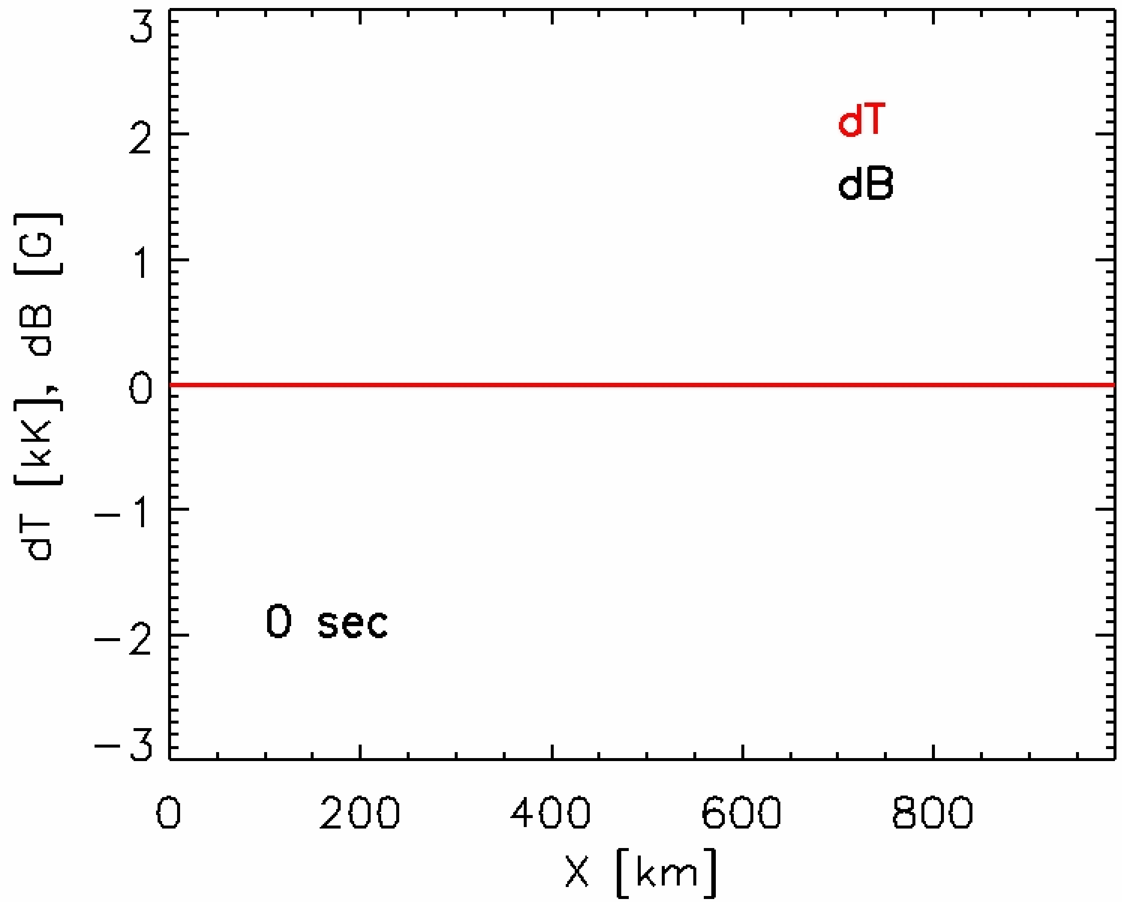
Test case:

No gravity

T, P, ρ from VAL-C
at Z=1000 km

$$B_Z(x) = B_0 \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right)$$

$$B_0 = \sqrt{2\mu P} \times 0.9 = 18\text{G}$$



Numerical simulations of heating

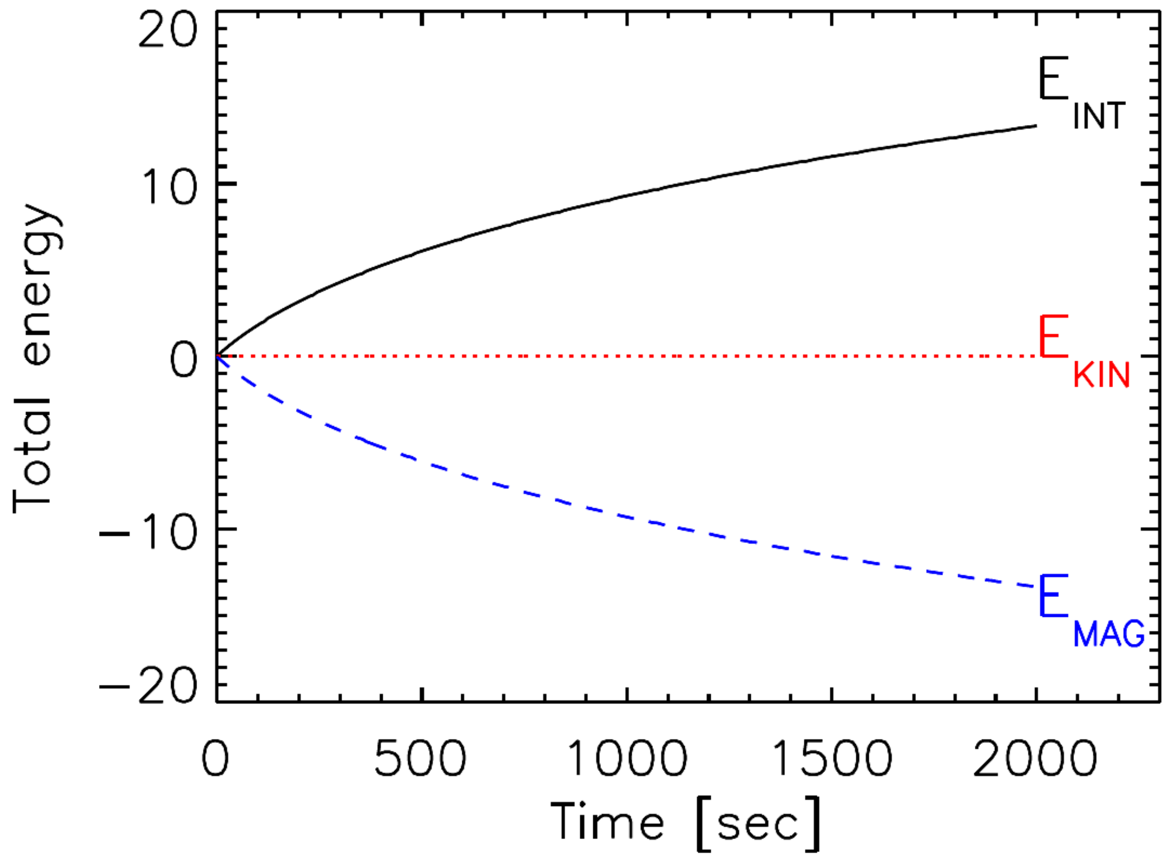
Test case:

No gravity

T, P, ρ from VAL-C
at Z=1000 km

$$B_Z(x) = B_0 \exp\left(-\frac{(x-x_0)^2}{2\sigma^2}\right)$$

$$B_0 = \sqrt{2\mu P} \times 0.9 = 18\mathrm{G}$$



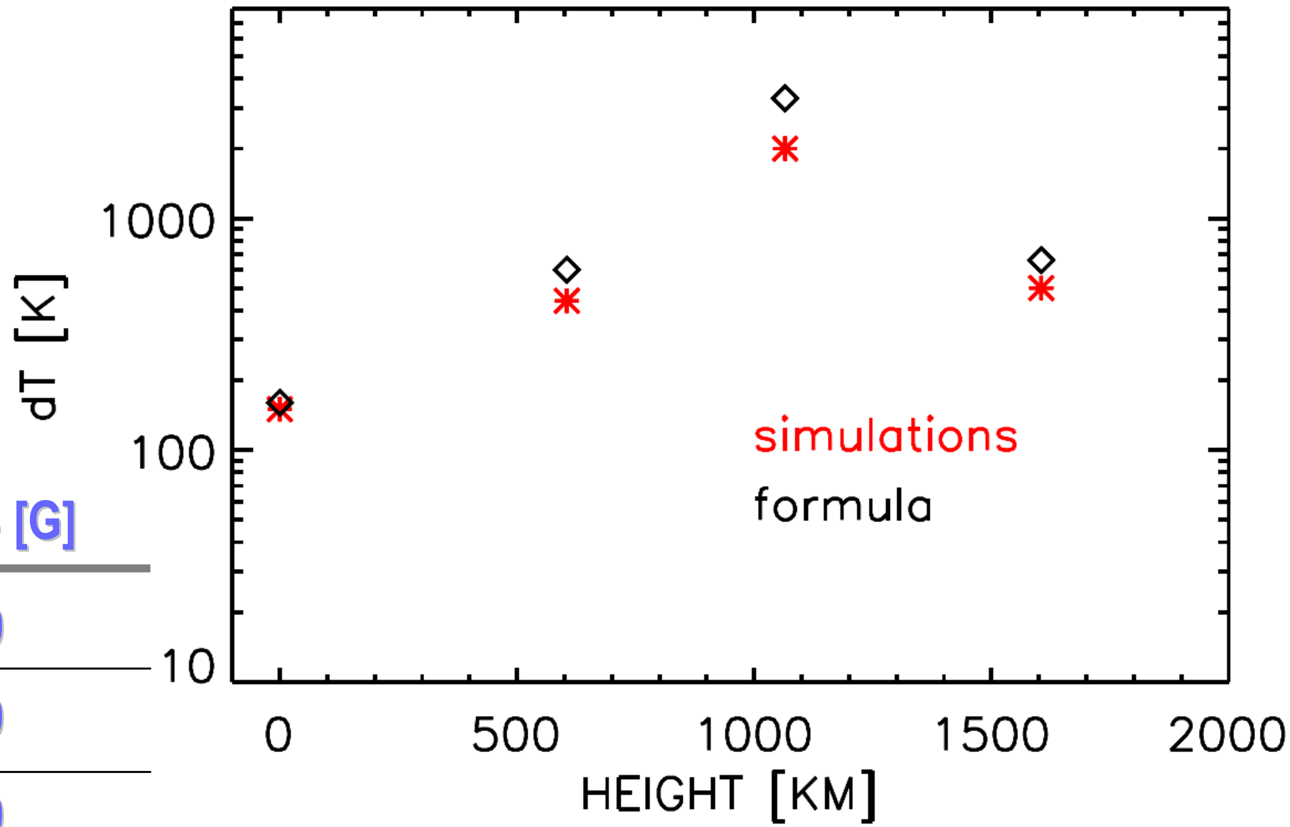
Numerical simulations of heating

Test case:

No gravity

T, P, ρ from VAL-C

Z [km]	B_0 [G]	dB [G]
0	1500	9.0
600	100	5.0
1000	18	2.0
1600	3	0.2



SPIA

Elena Khomenko

Simulation cases

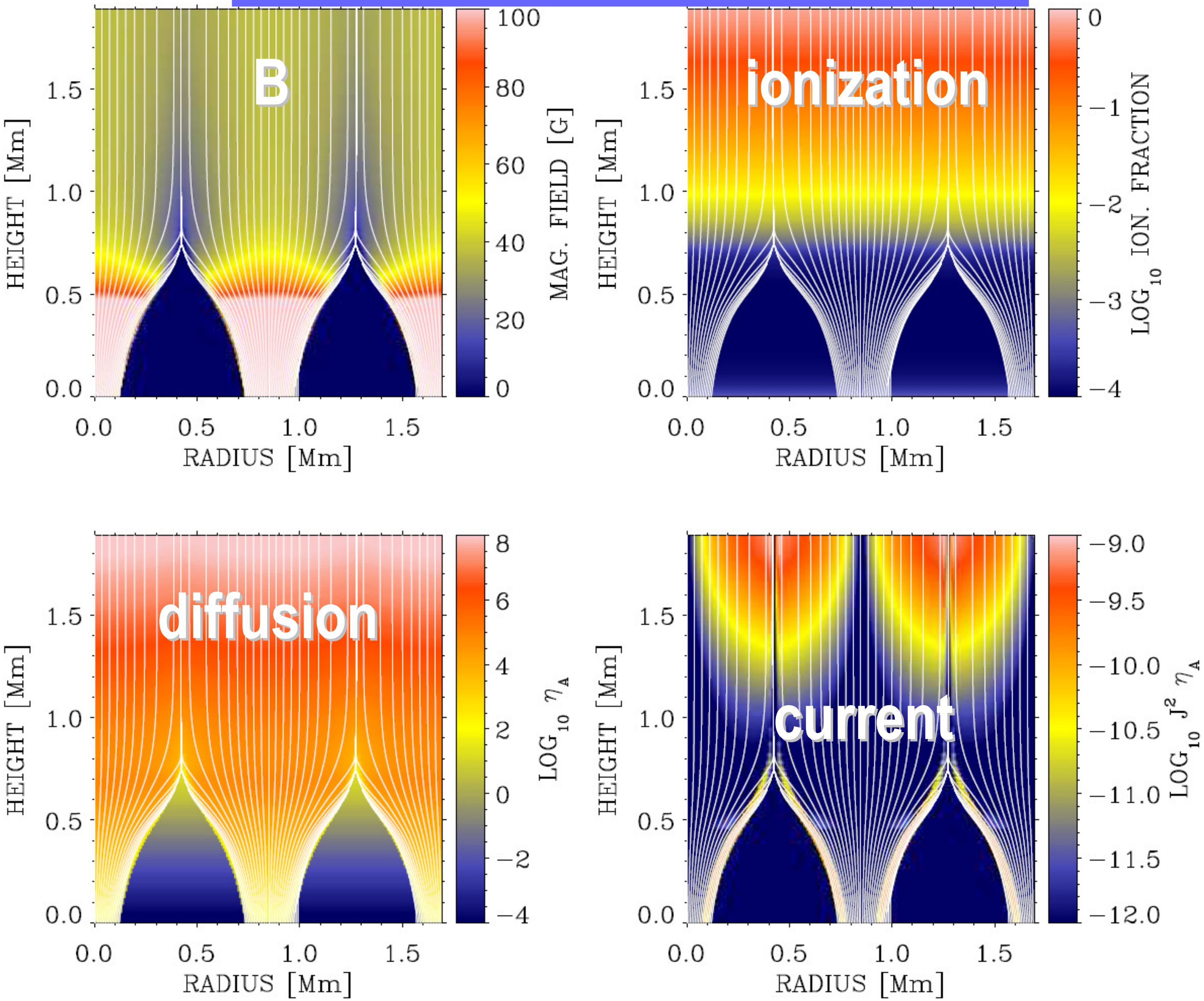
RT \ model	VALC	HolMul
No	+	+
Yes	+	+

SPIA

Elena Khomenko

Flux tube parameters

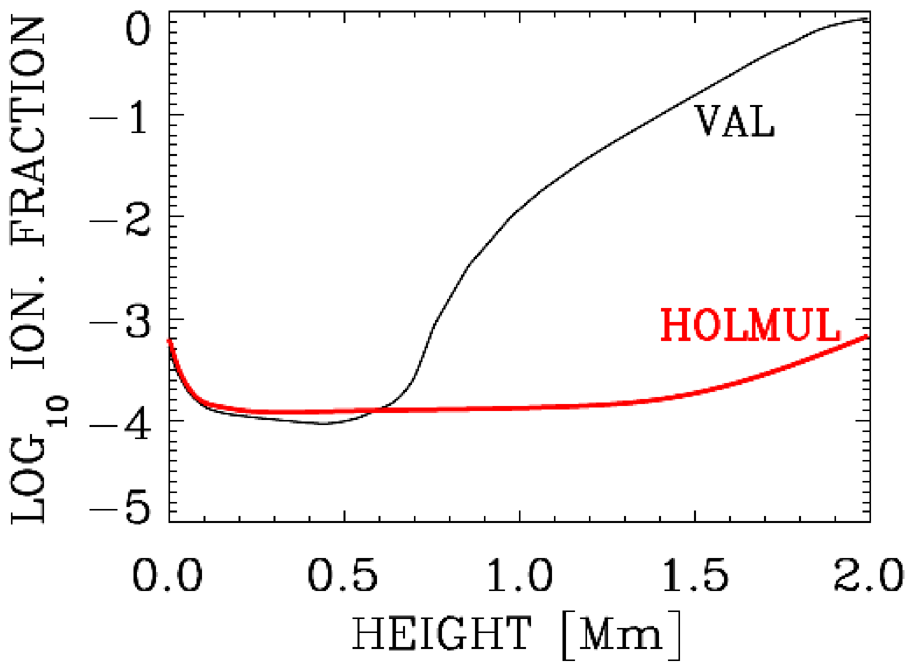
Pneuman et al. (1986), VALC-based

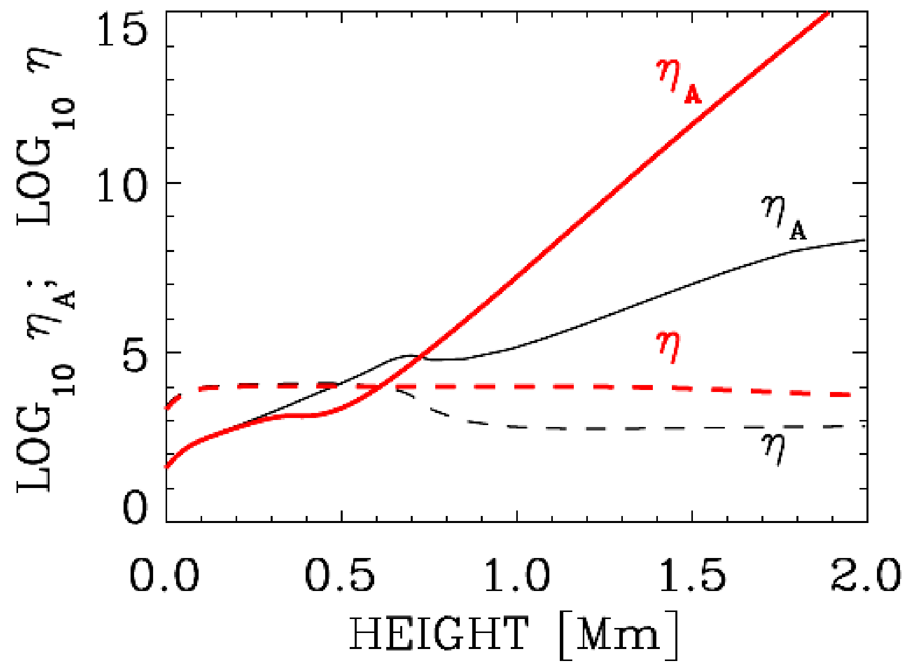


SPIA

Elena Khomenko

Flux tube parameters



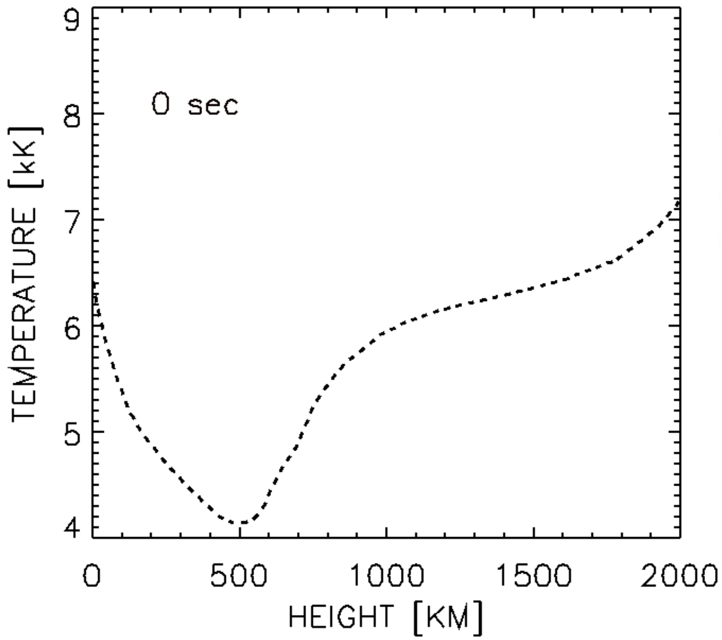


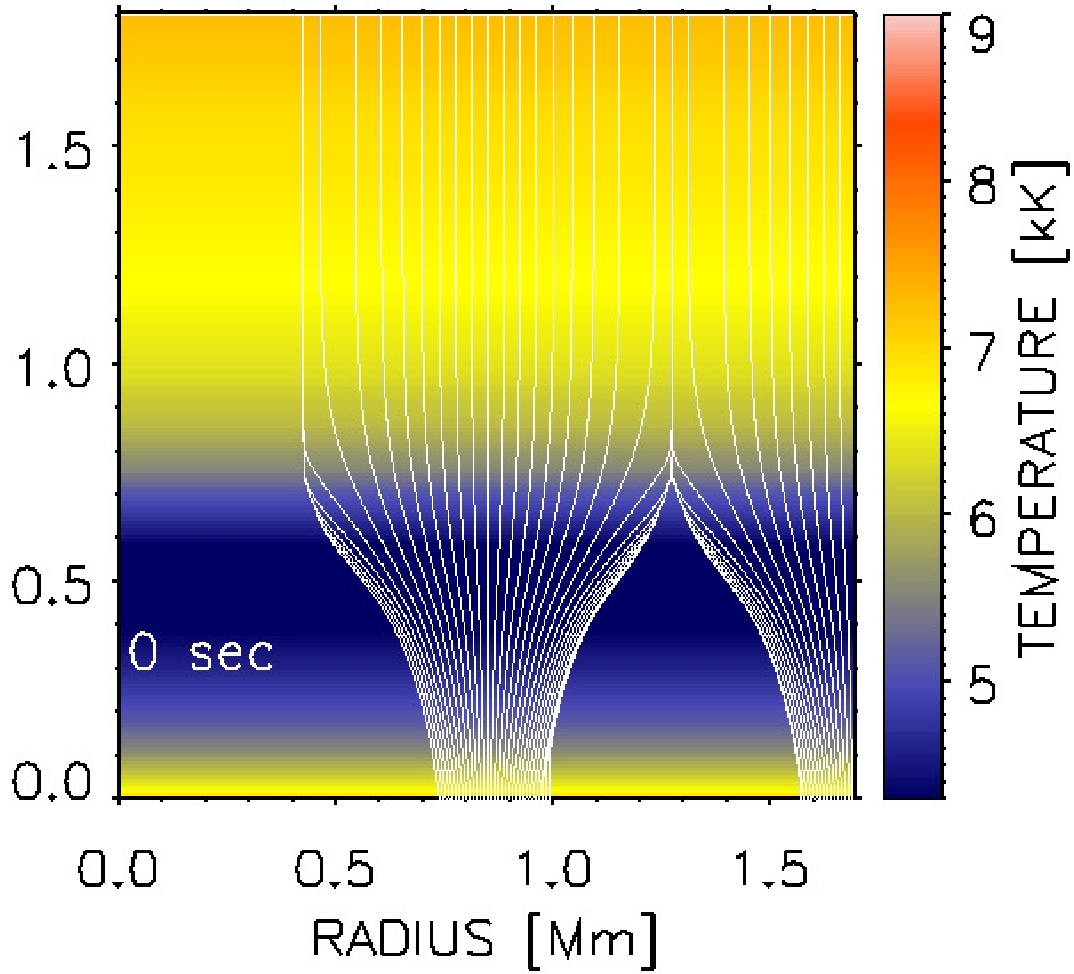
Ionization fraction and diffusion coefficients:
VALC-based vs. HolMul-based

SPIA

Elena Khomenko

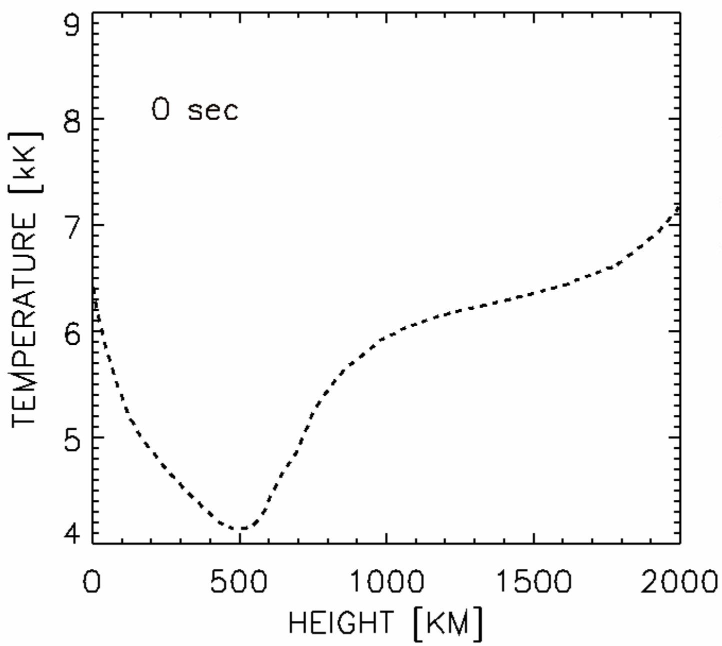
VALC-based, no radiative losses

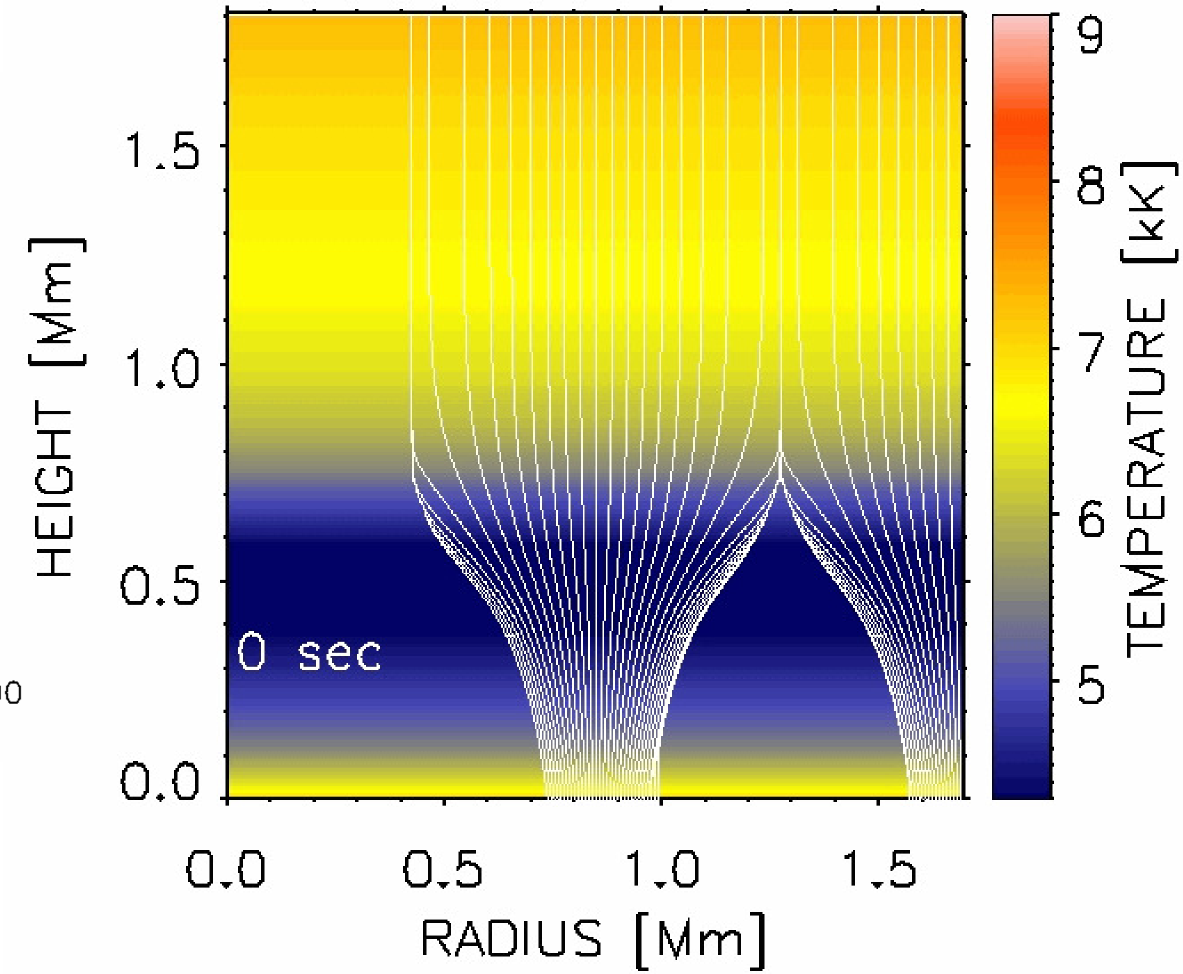




Elena Khomenko

VALC-based, no radiative losses

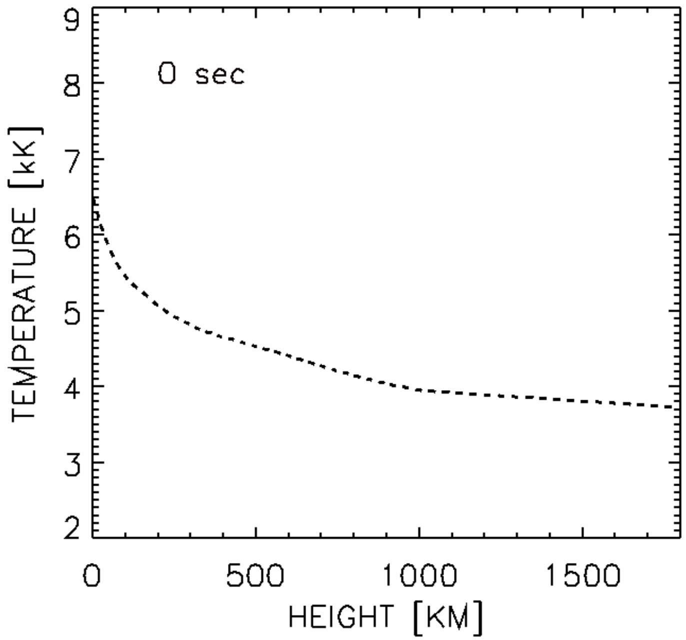


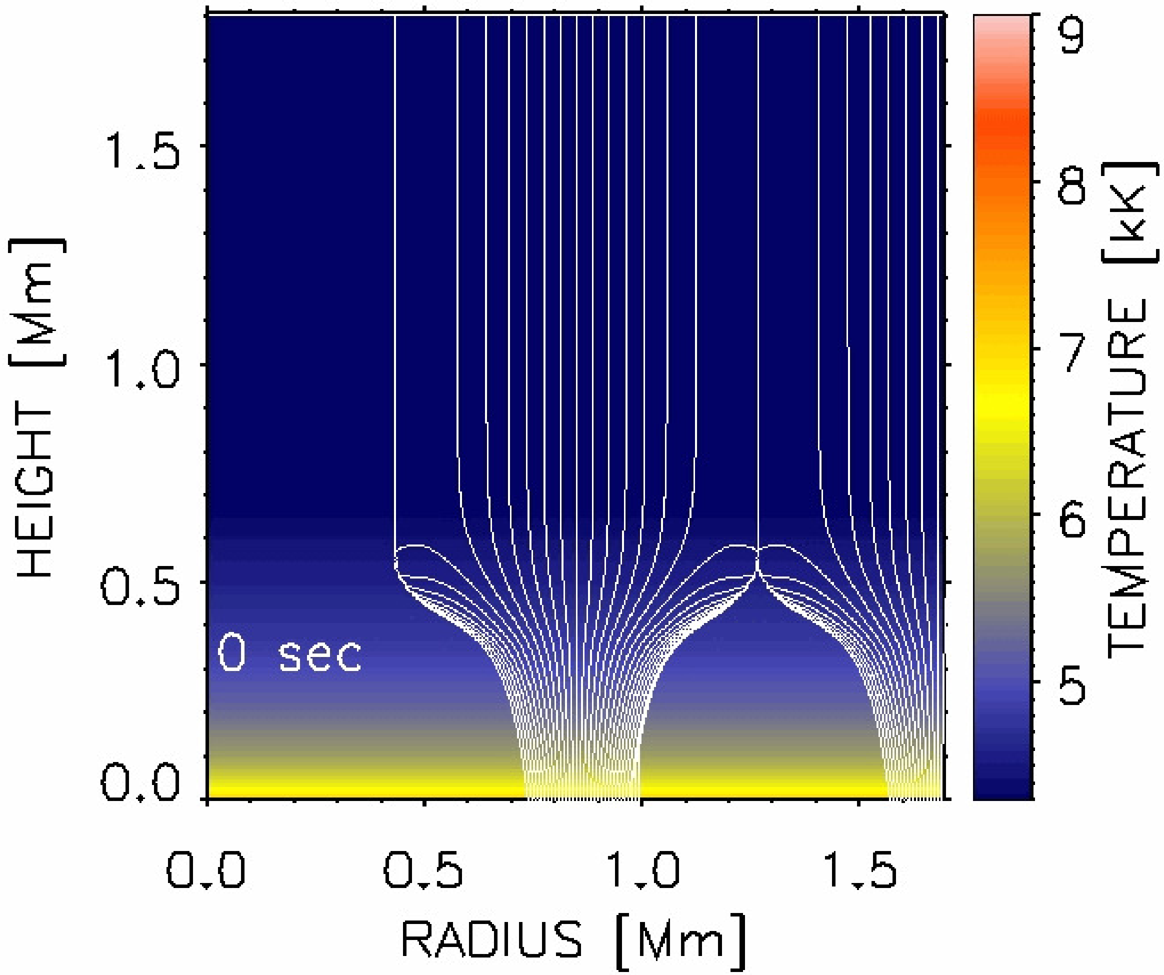


SPIA

Elena Khomenko

HolMul-based, no radiative losses

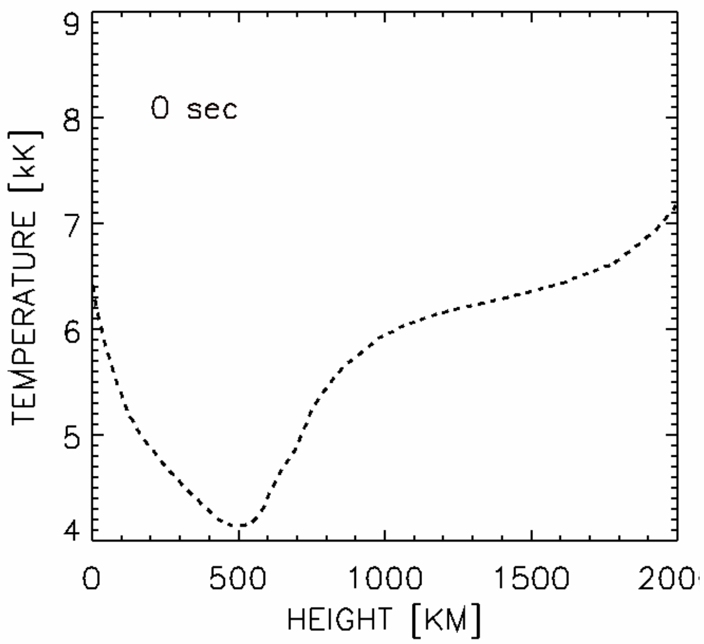


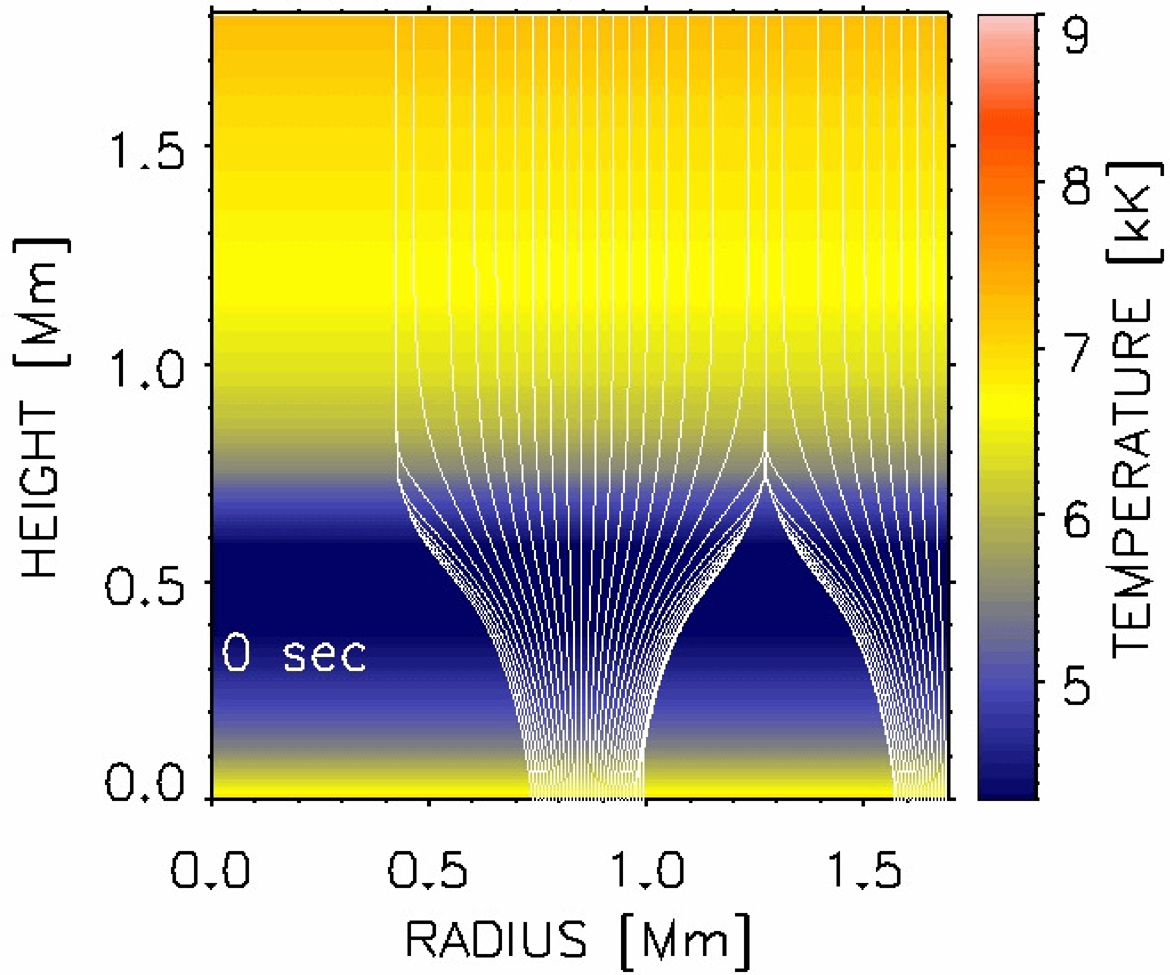


SPIA

Elena Khomenko

VALC-based, radiative losses included

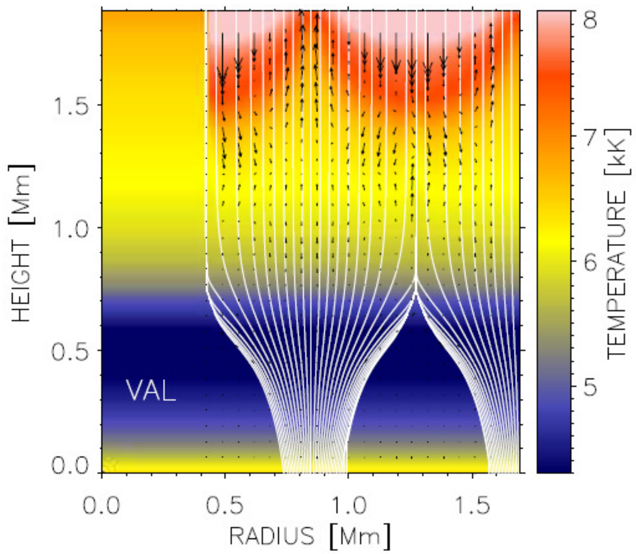




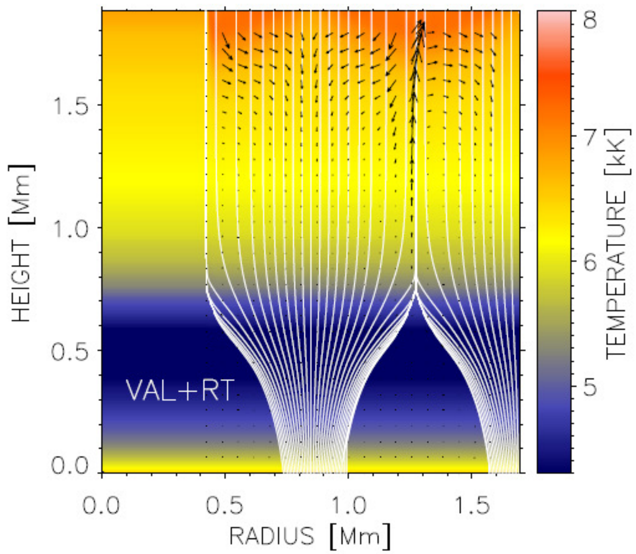
SPIA
Elena Khomenko

All simulation cases after 800 sec

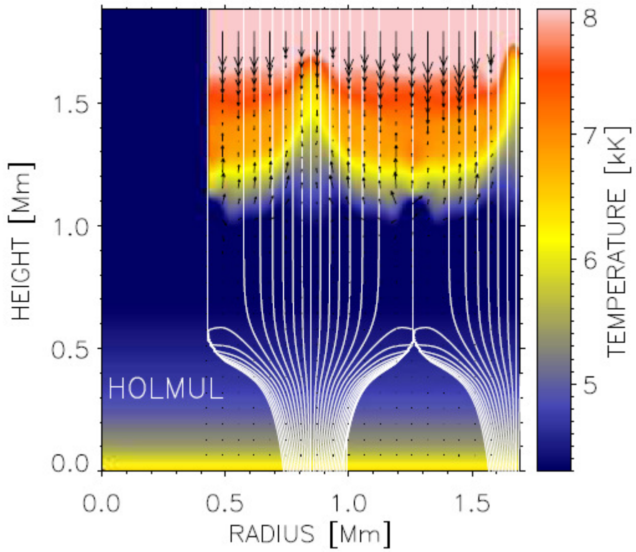
VALC



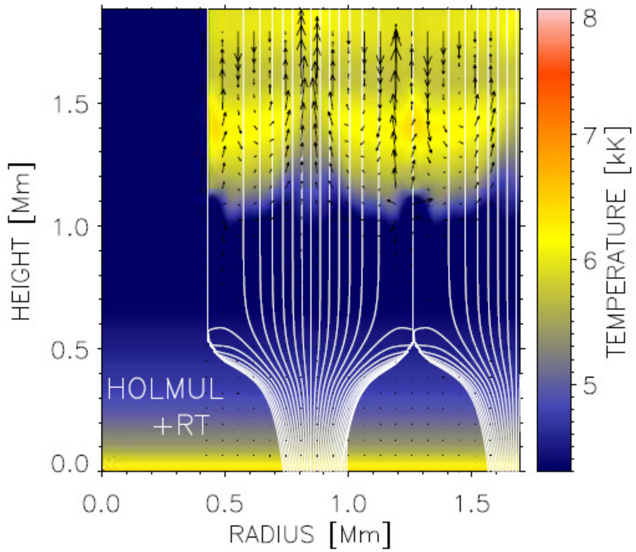
VALC + RT



HolMul



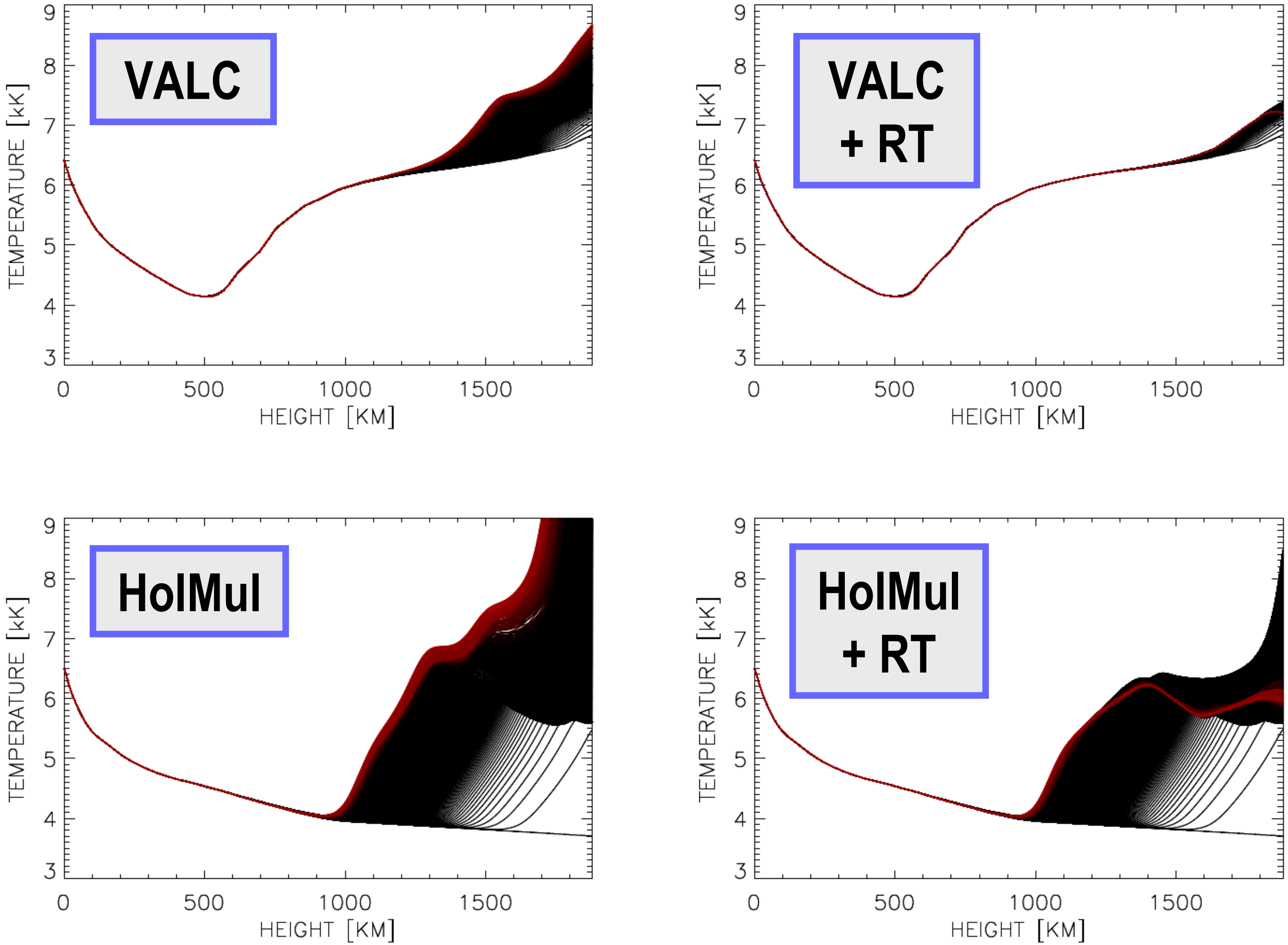
HolMul + RT



SPIA

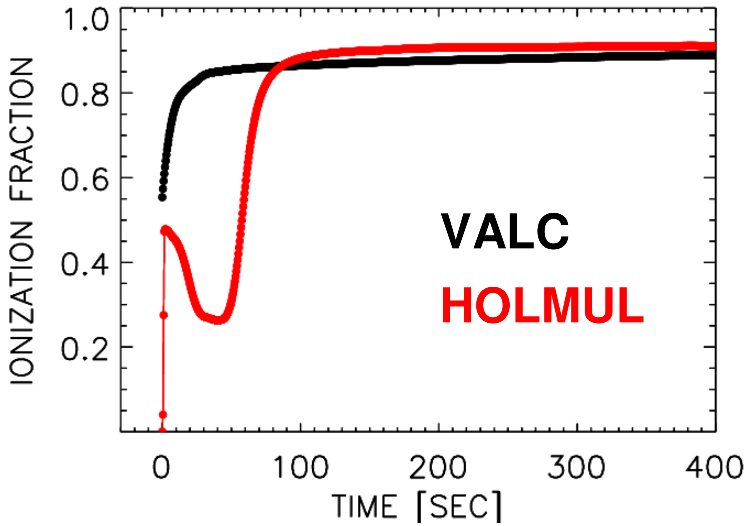
Elena Khomenko

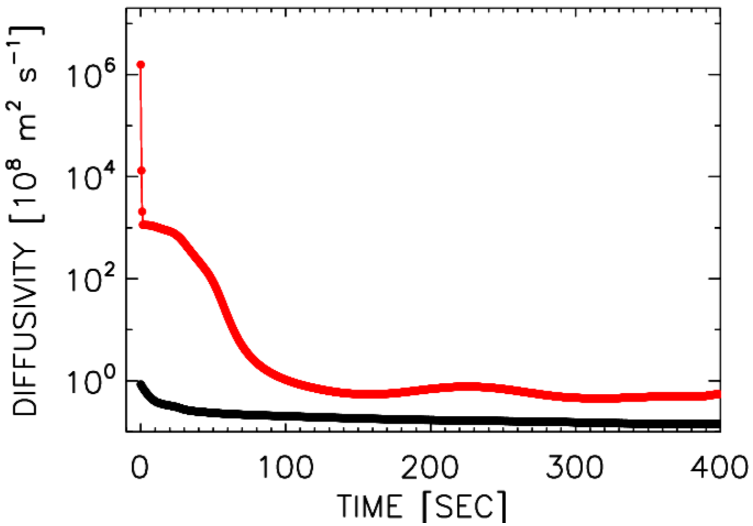
All simulation cases after 800 sec

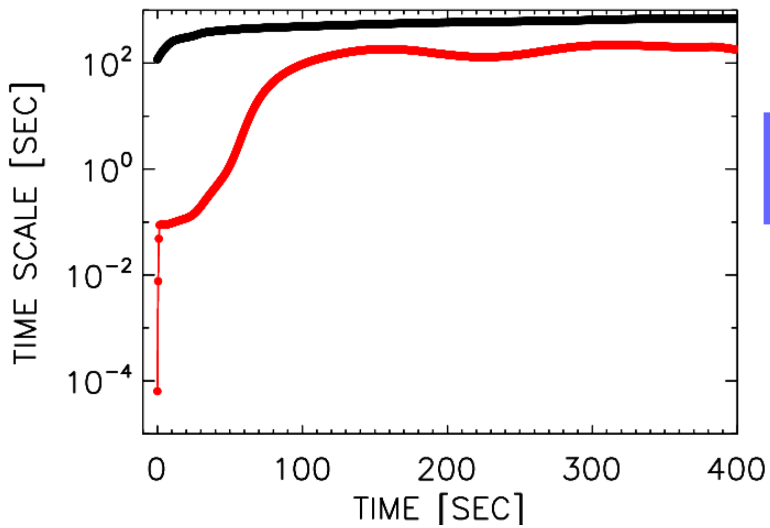


Khomenko

Time evolution, no radiative losses





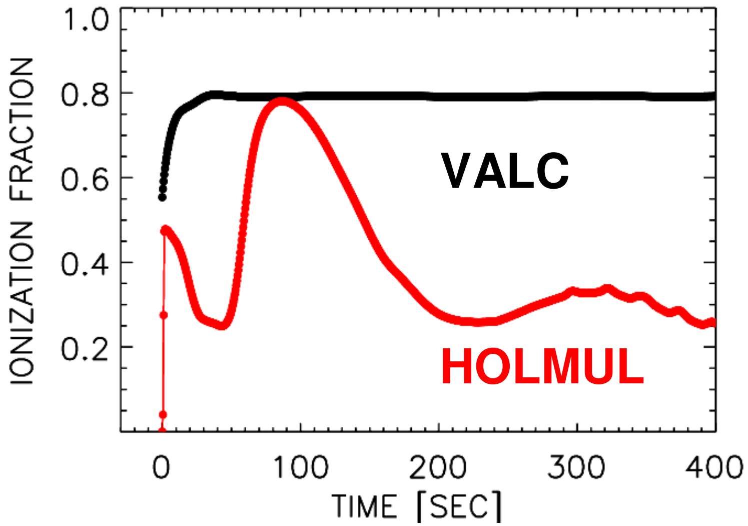


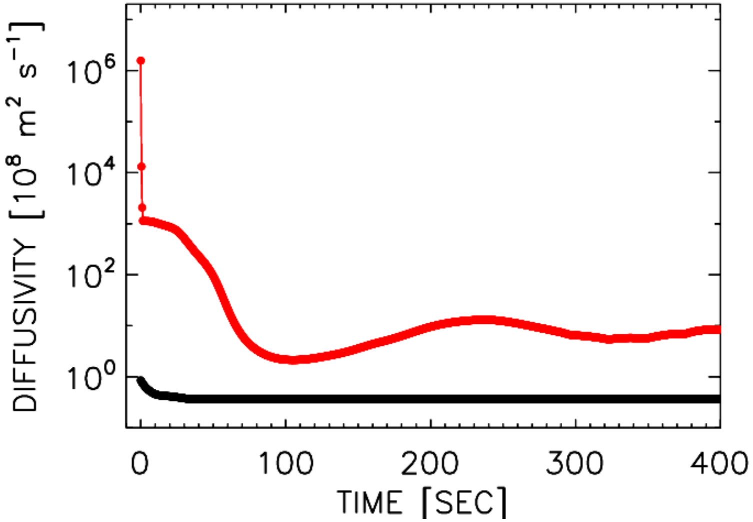
Z=1.8 Mm, X=0.6 Mm

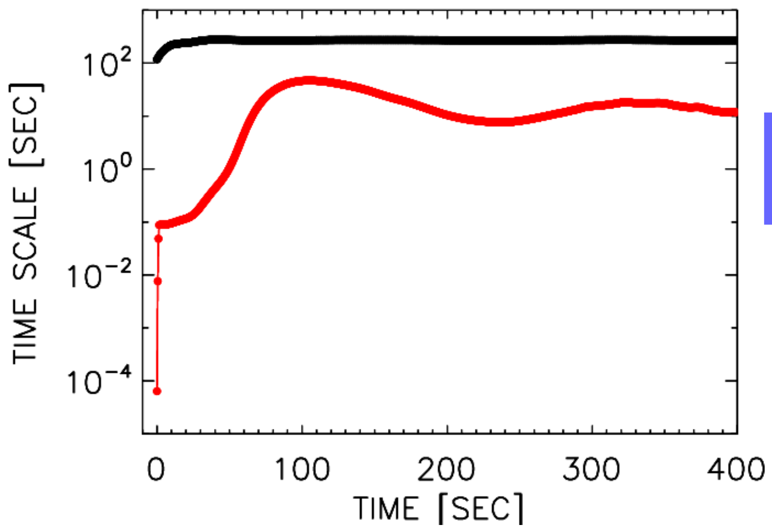
SPIA

Elena Khomenko

Time evolution, radiative losses included



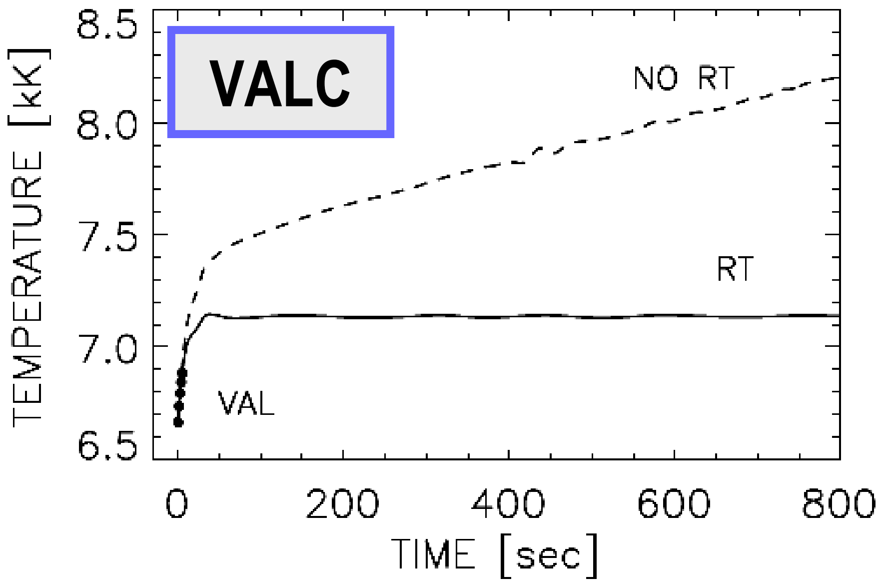


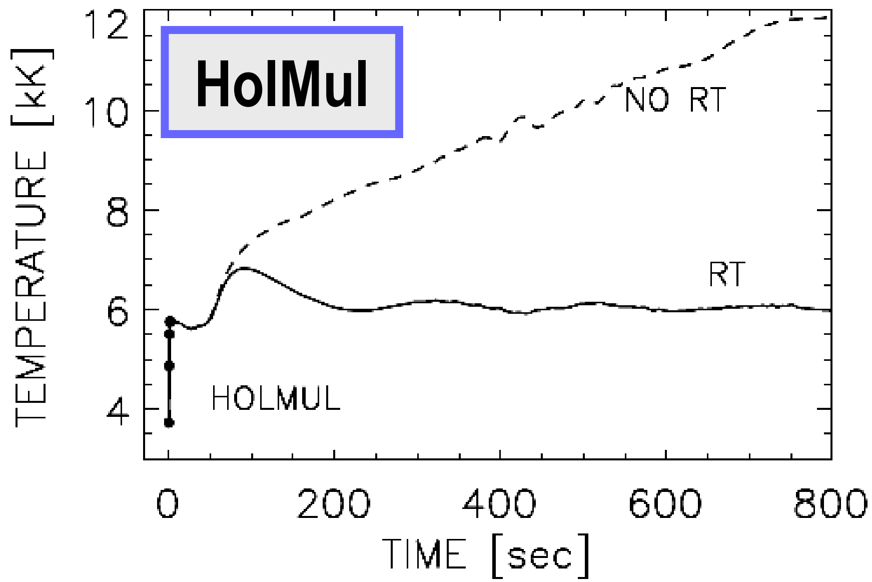


Z=1.8 Mm, X=0.6 Mm

Elena Khomenko

Radiative losses included/ excluded





Z=1.8 Mm, X=0.6 Mm

SPIA

Elena Khomenko

Conclusions

Partial ionization effects are essential in the low **chromosphere**.

Current dissipation due to relative motion between neutrals and ions - **Ambipolar diffusion** - can be an important source of **chromospheric heating**.

- The amount of heating and its time scale depend on the initial temperature of chromospheric magnetic structures, varying from few seconds to minutes.

- The Joule heating by ambipolar diffusion may be able to balance radiative losses of the chromosphere. After a period of damped oscillations, the temperature stabilizes at 6-7 kK at 1.8 Mm.