Hydraulic effects in a partially ionized radiative atmosphere

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Outline

- Motivational Background
- Simulation setup
- 1D simulations results : Setting up the atmosphere
- 2D simulations results : Hydraulic flux formation.
- Summary and future work.

Background

In a series of papers, Parker (1974, 1976, 1978) introduced the idea of hydraulic flux concentrations at the solar surface.

A common feature in such hydraulic models is downward flows inside the sunspots.
(Also identified as driving mechanism in NEMPI.)
It is important to assess the effects of thermodynamics and radiation on the formation of such flux concentrations.

Goal : study the effects of partial ionization near the radiative surface on the formation of such magnetic flux concentrations.

Simulation Plan

- construct hydrostatic and thermal equilibrium 1D solutions
  - radiative transfer
  - partial ionization
- 1D solutions as initial condition in 2D models
  - localized underpressure as ”forcing”
  - drives flows by suction
- compare with and without partial ionization.
- Used the PENCIL CODE.

1D models

Initial condition: Isothermal solution in hydrostatic equilibrium
But no thermal equilibrium

Energy equation :

$$\rho T \frac{\mathrm{D}s}{\mathrm{D}t} = -\boldsymbol{\nabla} \cdot \boldsymbol{F}_{\mathrm{rad}} + 2\rho\nu\mathbf{S}^2 + \eta\mu_{\mathrm{M}}\boldsymbol{J}^2,$$

For Equilibrium solution,

$$\rho T \frac{\mathrm{D}s}{\mathrm{D}t} = 0, \quad \boldsymbol{\nabla} \cdot \boldsymbol{F}_{\mathrm{rad}} = 0 \tag{1}$$

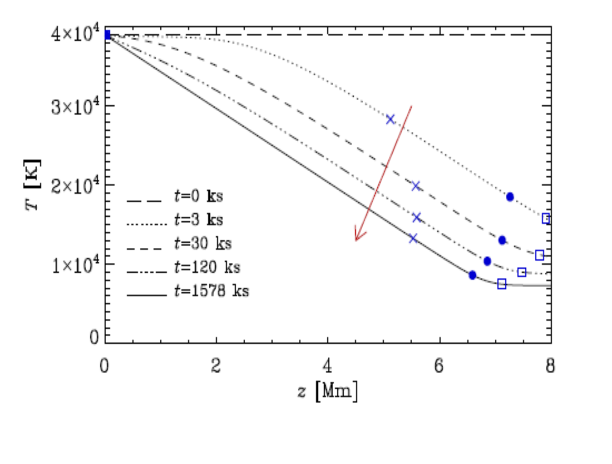
Radiative transfer equation,

$$-\boldsymbol{\nabla} \cdot \boldsymbol{F}_{\mathrm{rad}} = \kappa\rho \oint_{4\pi} (I - S)\, \mathrm{d}\Omega,$$

where $S = (\sigma_{\mathrm{SB}}/\pi)T^4$.

1D models

The temperature profile relaxes as it radiatively cools to an equilibrium solution. (Barekat and Brandenburg, 2014)
We fix temperature at the bottom, $T = T_0 \quad \text{on } z = 0$



Opacity

- Kramer's opacity: $\kappa = \kappa_0 \rho^a T^b$
- In $\tau \gg 1$ (opt. thick), $\boldsymbol{F}_{\rm rad} = -K \nabla T$ (diffusion approx.)

$$K(\rho, T) = \frac{16\sigma_{\rm SB} T^3}{3\kappa\rho} = \frac{16\sigma_{\rm SB} T^{3-b}}{3\kappa_0 \rho^{a+1}}.$$

$$n = \frac{3-b}{1+a}$$

  where n is the polytropic index as in $\rho \propto T^n$.
- H^- Opacity: (from Kippenhahn and Weigert, 1990)

$$\kappa = \kappa_0 y_{\rm H}(1 - y_{\rm H}) \frac{\rho}{\rho_{e^-}} \left(\frac{T_{\rm H^-}}{T} \right)^{3/2} \exp\left(\frac{T_{\rm H^-}}{T} \right),$$

Partial Ionization

- Equation of state: perfect gas, $p = (\mathcal{R}/\mu)T\rho$

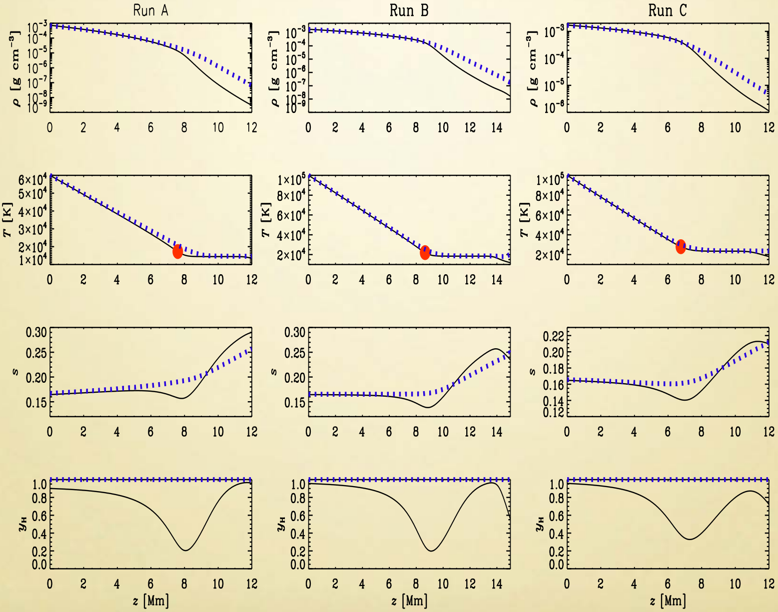
$$\mu(\rho, T) = (1 + 4x_{\mathrm{He}})/(1 + y_{\mathrm{H}} + x_{\mathrm{He}}),$$

- Saha Ionization equation, (only hydrogen)

$$\frac{y_{\mathrm{H}}^2}{1 - y_{\mathrm{H}}} = \frac{\rho_{\mathrm{e}}}{\rho}\left(\frac{T_{\mathrm{H}}}{T}\right)^{-3/2} \exp\left(-\frac{T_{\mathrm{H}}}{T}\right),$$

where $\rho_{\mathrm{e}} = \mu_0 m_{\mathrm{u}}(m_{\mathrm{e}}\chi_{\mathrm{H}}/2\pi\hbar^2)^{3/2}$ is the electron density.

Kramer's opacity: 1D profiles (Bhat and Brandenburg)



Correspondence between entropy profile and $y_{\rm H}$ profile

For the case of $\tau \gg 1$,

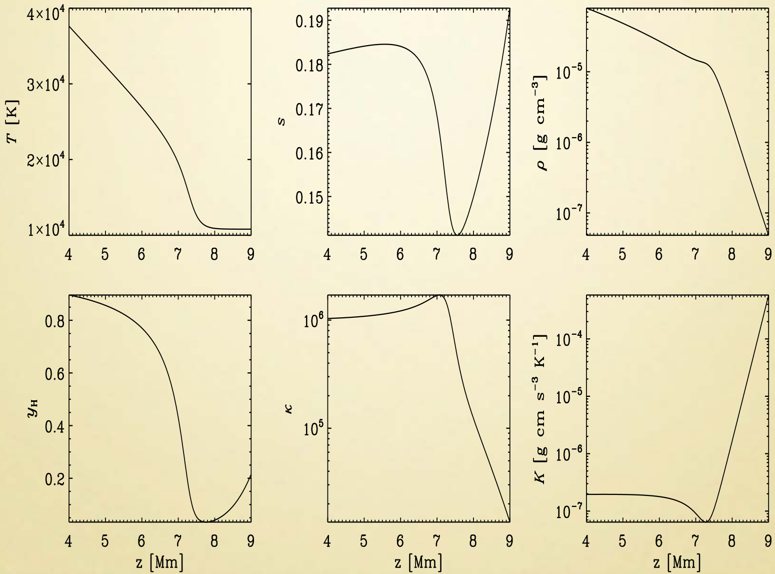
$$\mathrm{d}s = \mathrm{d}y_{\rm H} \frac{\mathcal{R}}{\mu_0} \left[\frac{1}{A_v} \frac{(n-3/2)}{(n+3/2)} - B_v \right],$$

In the case of $\tau \ll 1$, we have

$$\mathrm{d}s = \mathrm{d}y_{\rm H} \frac{\mathcal{R}}{\mu_0} \left[\frac{1}{A_v} - B_v \right]$$

where A_v and B_v are functions of ρ and T.

H^- opacity: 1D profiles



2D models

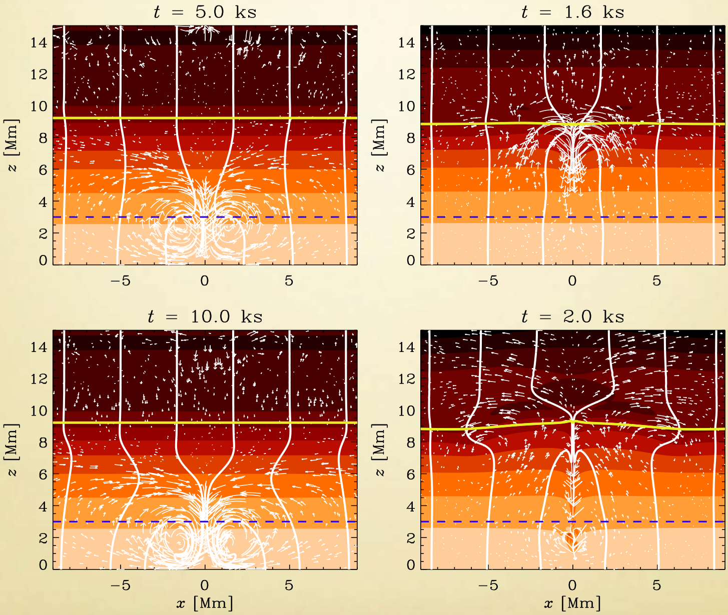
- ϕ : continuous suction forcing on RHS of momentum equation,

$$\rho \frac{\mathrm{D}\boldsymbol{u}}{\mathrm{D}t} = -\boldsymbol{\nabla}(p+\phi) + \rho\boldsymbol{g} + \boldsymbol{J}\times\boldsymbol{B} + \boldsymbol{\nabla}\cdot(2\rho\nu\mathbf{S}),$$

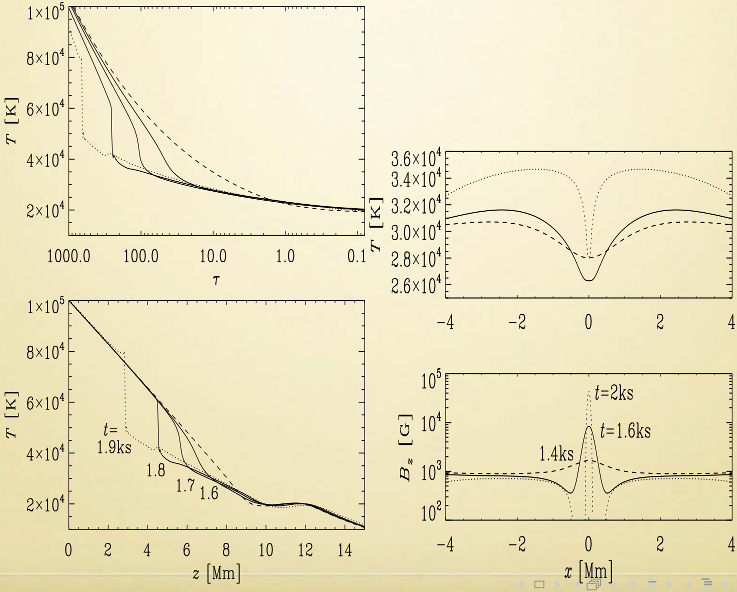
$$\phi = \phi_0 e^{-[x^2+(z-z_0)^2]/2R^2}, \tag{2}$$

  - ϕ_0 is the amplitude with a negative value
  - R the radius of the blob-likes structure
  - z_0 is the height where its placed.
- This underpressure could be caused by ”negative effective magnetic pressure” (As seen in Sarah’s talk or see Dhruba’s poster).

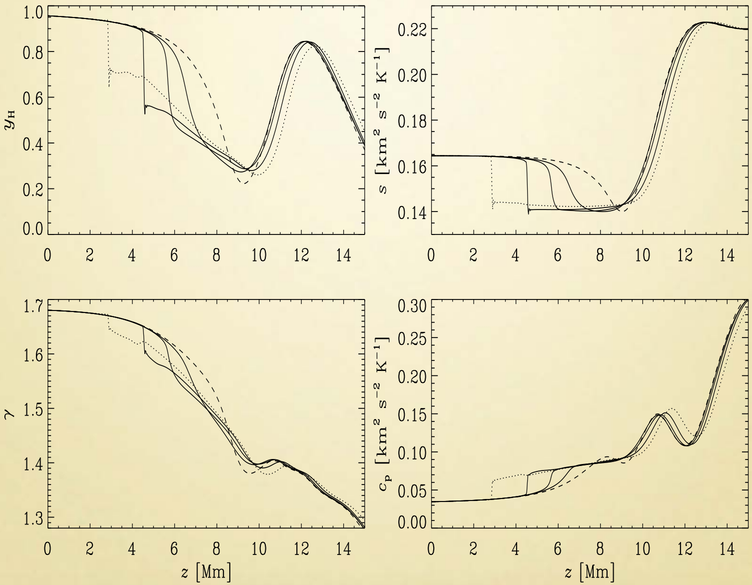
2D models: without (LHS) and with (RHS) partial ionization



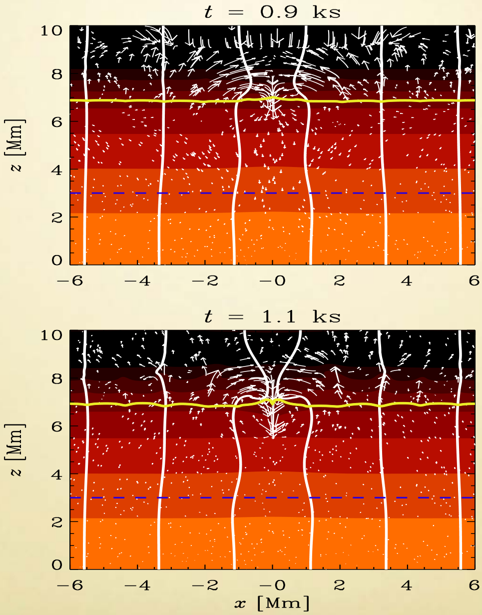
2D models with partial ionization : Temperature evolution



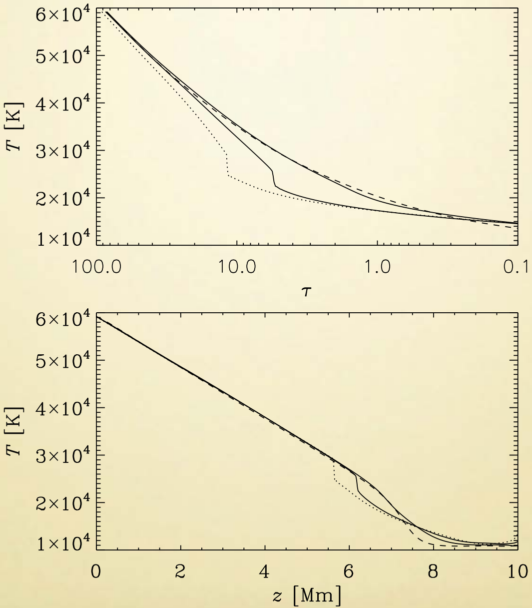
2D models with partial ionization: evolution of $s, y_\mathrm{H}, \gamma, c_p$



2D models: H^- Opacity



2D models: H^- Opacity: evolution of temperature



Summary

- In 1D models, due to partial ionization, an unstable stratification forms always near $\tau = 1$. The extrema in specific entropy profile corresponds to the extrema in degree of ionization.
- In 2D models, the artificially produced downflows lead to formation of strong flux concentrations.
- 2D Models that including partial ionization, the flux concentrations form at $\tau = 1$ as compared to models without partial ionization.
- The effects of partial ionization and resulting stratification are important for the production of strong magnetic flux amplifications at $\tau = 1$.
- To apply to sunspots, important to consider the effects of turbulent convection.

B.Cs

We assume the gas to be stress-free in the z direction at $z = 0$ and L_z,

$$\partial u_x/\partial z = \partial u_y/\partial z = u_z = 0. \quad \text{on } z = 0, L_z. \tag{3}$$

We have periodic BCs in the x direction.