Downflowing dynamics of vertical prominence threads

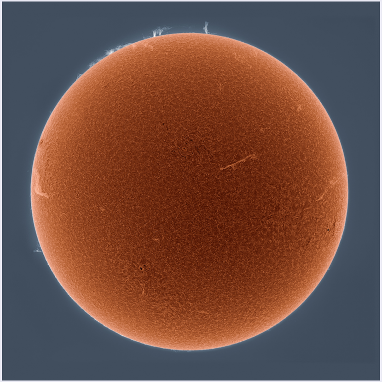
R. Oliver, R. Soler, T. Zaqarashvili, J. Terradas

Physics Department,
University of the Balearic Islands,
Spain

Solar prominences

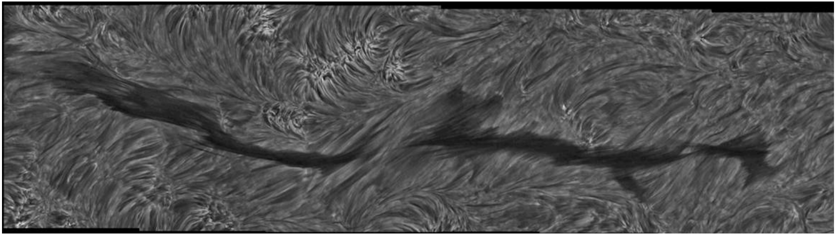
Filaments and prominences

- Quiescent prominences are long, thin and tall.
- Cool and dense objects ($T \simeq 10^4$ K, $n \simeq 10^{10}$ cm^{-3}) embedded in the hotter and rarer solar corona ($T \simeq 10^6$ K, $n \simeq 10^8$ cm^{-3}).



http://www.avertedimagination.com (Hα)

Horizontal threads



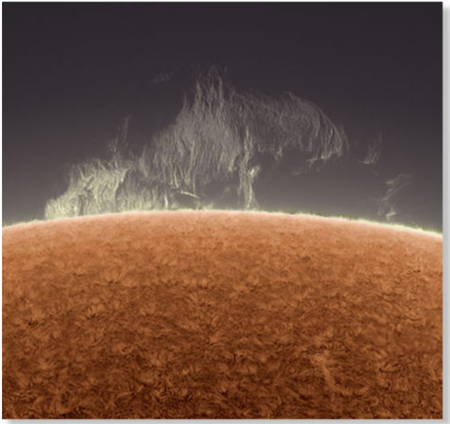
Dutch Open Telescope (Hα)

- Seen from above, prominences display many thin threads aligned close to the direction of the filament axis.
- These threads are presumably cool condensations at the central part of large magnetic tubes anchored in the photosphere.
- The threads probably sit in a magnetic field dip.

Vertical threads

BUT...

Large quiescent prominences observed on the limb often display vertical fine structures.



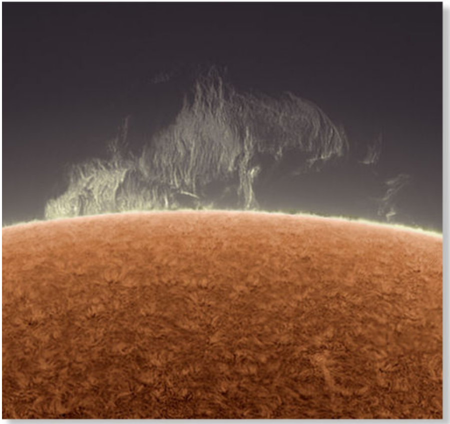
http://www.avertedimagination.com (Hα)

Vertical threads

BUT...

Large quiescent prominences observed on the limb often display vertical fine structures.

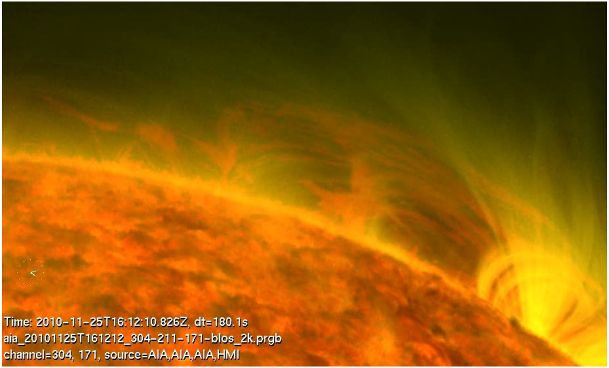
How can one reconcile horizontal and vertical threads?



http://www.avertedimagination.com (Hα)

Vertical threads: Liu et al. (2012)

- Prominence formation observed with AIA on SDO.
- Composite 171 Å & 304 Å images ($\simeq$ 800,000 K & $\simeq$ 80,000 K).
- FOV size: $\simeq$ 400 Mm $\times$ $\simeq$ 200 Mm. Duration: $\simeq$ 10 hours.
- Prominence forms by condensation of hotter material.
- Vertical threads and downflows.

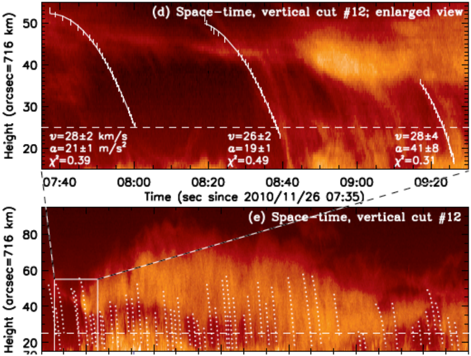


Liu et al. (2012) (304 Å & 171 Å)

Liu et al. (2012)

- Prominence mass is not static, but maintained by balance of condensation (at a rate of 1.2×10^{10} g s^{-1}) and drainage (at a rate of 1.1×10^{10} g s^{-1}).
- Drainage rate enough to dissolve the prominence in $\simeq 2.5$ hours.

Liu et al. (2012): high density, falling blobs



- Space-time diagram along a vertical thread.

- Mass drains down along vertical threads in the form of bright blobs.
- Liu et al. (2012) studied 874 downflowing trajectories:
  - Typical event lasts between a few min and 30 min.
  - The descending mass blob starts at a height between 25" and 60".
  - Blob accelerations between 10 and 200 m s $^{-2}$ (mean: 46 m s $^{-2}$).
  - Blob speeds 25" above the surface: $\simeq$ 30km s $^{-1}$.

Aims of this work

Aims

- To investigate the dynamics of gas condensing in the corona.
- To estimate the importance of partial ionisation effects.

Outline

Model: assumptions and equations

We concentrate in the dynamics of the falling material after it has condensed. The condensation process is not reproduced.

Model: assumptions and equations

We concentrate in the dynamics of the falling material after it has condensed. The condensation process is not reproduced.

- Ionisation/recombination ignored.
- Conduction, cooling, Joule heating ignored.
- Collisions between electrons and neutrals discarded in momentum and energy equations.
- Pure H gas: species are H^+, e^- and H.
- Magnetic field is horizontal: no magnetic tension, but magnetic pressure is included.
- Mass motions in the vertical direction only.

Model: assumptions and equations

We concentrate in the dynamics of the falling material after it has condensed. The condensation process is not reproduced.

- Ionisation/recombination ignored.
- Conduction, cooling, Joule heating ignored.
- Collisions between electrons and neutrals discarded in momentum and energy equations.
- Pure H gas: species are H^+, e^- and H.
- Magnetic field is horizontal: no magnetic tension, but magnetic pressure is included.
- Mass motions in the vertical direction only.

- Two-fluid equations presented yesterday by T. Zaqarashvili.
- To emulate the mass condensation a source term is added to the mass continuity equations of charged particles and neutrals.

One-dimensional equations

- z-axis is vertical, x-axis along magnetic field.
- Magnetic field: $\mathbf{B} = B\,\widehat{\mathbf{e}}_x$.
- Charged particles: density ρ_i, pressure $p_{ie} = p_i + p_e$, velocity $\mathbf{v}_i = v_i\widehat{\mathbf{e}}_z$.
- Neutral particles: density ρ_n, pressure p_n, velocity $\mathbf{v}_n = v_n\widehat{\mathbf{e}}_z$.

One-dimensional equations

- z-axis is vertical, x-axis along magnetic field.
- Magnetic field: $\mathbf{B} = B\widehat{\mathbf{e}}_x$.
- Charged particles: density ρ_i, pressure $p_{ie} = p_i + p_e$, velocity $\mathbf{v}_i = v_i\widehat{\mathbf{e}}_z$.
- Neutral particles: density ρ_n, pressure p_n, velocity $\mathbf{v}_n = v_n\widehat{\mathbf{e}}_z$.

- Seven unknowns ρ_i, p_{ie}, v_i, B, ρ_n, p_n, v_n.
- The unknowns only depend on z and t.

One-dimensional equations

$$\frac{\partial \rho_i}{\partial t} = -v_i \frac{\partial \rho_i}{\partial z} - \rho_i \frac{\partial v_i}{\partial z} + r_i(z,t)$$

$$\frac{\partial \rho_n}{\partial t} = -v_n \frac{\partial \rho_n}{\partial z} - \rho_n \frac{\partial v_n}{\partial z} + r_n(z,t)$$

$$\rho_i \frac{\partial v_i}{\partial t} = -\rho_i v_i \frac{\partial v_i}{\partial z} - \frac{\partial p_{ie}}{\partial z} - g\rho_i - \frac{1}{\mu} B \frac{\partial B}{\partial z} - \alpha_{in}(v_i - v_n)$$

$$\rho_n \frac{\partial v_n}{\partial t} = -\rho_n v_n \frac{\partial v_n}{\partial z} - \frac{\partial p_n}{\partial z} - g\rho_n + \alpha_{in}(v_i - v_n)$$

$$\frac{\partial p_{ie}}{\partial t} = -v_i \frac{\partial p_{ie}}{\partial z} - \gamma p_{ie} \frac{\partial v_i}{\partial z} + (\gamma - 1)\alpha_{in}(v_i - v_n)v_i$$

$$\frac{\partial p_n}{\partial t} = -v_n \frac{\partial p_n}{\partial z} - \gamma p_n \frac{\partial v_n}{\partial z} - (\gamma - 1)\alpha_{in}(v_i - v_n)v_n$$

$$\frac{\partial B}{\partial t} = -v_i \frac{\partial B}{\partial z} - B \frac{\partial v_i}{\partial z} + \frac{\partial}{\partial z}\left(\eta \frac{\partial B}{\partial z}\right)$$

Static coronal equilibrium

- In the initial state ($t = 0$) the vertical speed of charges and neutrals is zero: $v_i = v_n = 0$.
- The initial temperature is assumed uniform and identical for all species: T_0. Thus, $p_{ie} = 2\rho_i R T_0, p_n = \rho_n R T_0$.
- The following vertically stratified solution is adopted:

$$\rho_i(z, t=0) = \rho_{i0} e^{-z/H_i} \qquad \rho_n(z, t=0) = \rho_{n0} e^{-z/H_n}$$
$$p_{ie}(z, t=0) = p_{ie0} e^{-z/H_i} \qquad p_n(z, t=0) = p_{n0} e^{-z/H_n}$$
$$B(z, t=0) = B_0 e^{-z/2H_i}$$

- ρ_{i0}, p_{ie0}, B_0, ρ_{n0} and p_{n0} are the values of the variables at the coronal base.
- H_i and H_n are the ions and neutrals vertical scale heights.

Static coronal equilibrium

- In the initial state ($t = 0$) the vertical speed of charges and neutrals is zero: $v_i = v_n = 0$.
- The initial temperature is assumed uniform and identical for all species: T_0. Thus, $p_{ie} = 2\rho_i R T_0, p_n = \rho_n R T_0$.
- The following vertically stratified solution is adopted:

$$\rho_i(z, t=0) = \rho_{i0} e^{-z/H_i}$$

$$p_{ie}(z, t=0) = p_{ie0} e^{-z/H_i}$$

$$B(z, t=0) = B_0 e^{-z/2H_i}$$

$$\rho_n(z, t=0) = \rho_{n0} e^{-z/H_n}$$

$$p_n(z, t=0) = p_{n0} e^{-z/H_n}$$

- ρ_{i0}, p_{ie0}, B_0, ρ_{n0} and p_{n0} are the values of the variables at the coronal base.
- H_i and H_n are the ions and neutrals vertical scale heights.

Mass condensation

- Mass condensation modeled by the terms r_i and r_n in the mass continuity equations, taken as follows

$$r_i(z,t) = r_{i0} \exp\left[-\left(\frac{z-z_0}{\Delta}\right)^2\right]\left[1-\exp\left(-\frac{t}{\tau_0}\right)\right]$$

$$r_n(z,t) = r_{n0} \exp\left[-\left(\frac{z-z_0}{\Delta}\right)^2\right]\left[1-\exp\left(-\frac{t}{\tau_0}\right)\right]$$

- Condensation is localised in space about a height $z = z_0$, has a characteristic vertical size 2Δ and grows smoothly in time until it reaches its full amplitude after a time $t \simeq 6\tau_0$ has elapsed. We consider $\tau_0 = 10$ s.
- Parameter values adjusted from the observations of Liu et al. (2012): $z_0 = 35$ Mm, $\Delta = 0.5$ Mm, $r_{i0} + r_{n0} = 4 \times 10^{-13}$ kg m^{-3} s^{-1}.

Outline

Fully ionised plasma, $B = 0$, no mass condensation

- No neutrals, no magnetic field.
- Density enhancement added to the coronal equilibrium at $t = 0$.
- No mass condensation for $t > 0$.
- Only the evolution equations of charged particles need to be considered:

$$\frac{\partial \rho_i}{\partial t} = -v_i \frac{\partial \rho_i}{\partial z} - \rho_i \frac{\partial v_i}{\partial z} + \cancel{r_i(z,t)}$$

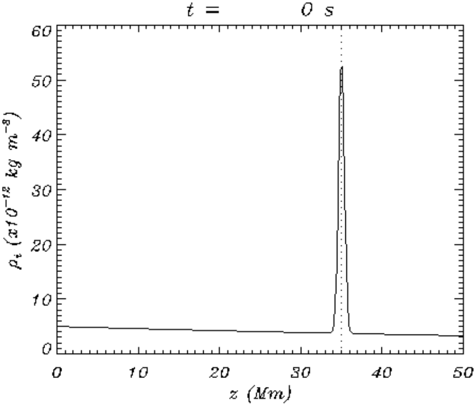
$$\rho_i \frac{\partial v_i}{\partial t} = -\rho_i v_i \frac{\partial v_i}{\partial z} - \frac{\partial p_{ie}}{\partial z} - g\rho_i - \cancel{\frac{1}{\mu} B \frac{\partial B}{\partial z}} - \cancel{\alpha_{in}(v_i - v_n)}$$

$$\frac{\partial p_{ie}}{\partial t} = -v_i \frac{\partial p_{ie}}{\partial z} - \gamma p_{ie} \frac{\partial v_i}{\partial z} + \cancel{(\gamma - 1)\alpha_{in}(v_i - v_n) v_i}$$

Fully ionised plasma, $B = 0$, no mass condensation: density

Equilibrium: $\rho_{i0} = 5 \times 10^{-12}$ kg m^{-3}, $T_0 = 2 \times 10^6$ K.

- Density enhancement of 5×10^{-11} kg m^{-3}.
- The blob falls and spreads, so its density decreases.
- If the blob were to fall with the acceleration of gravity, it would reach $z = 0$ at $t \simeq 500$ s.

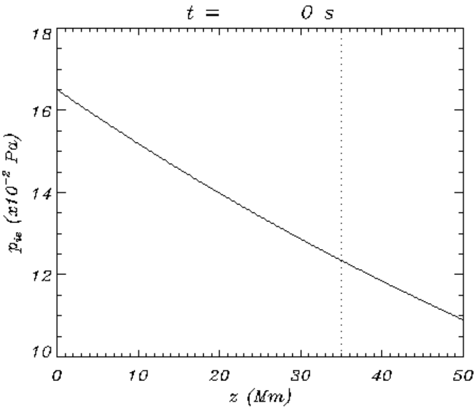


The blob has almost no acceleration! $v \simeq 5$ km s^{-1}.

Fully ionised plasma, $B = 0$, no mass cond.: pressure

Temporal evolution of plasma pressure in the first 200 s.

- The initial perturbation generates a sound wave that moves at a speed of $\simeq 235$ km s^{-1} and perturbs the coronal medium.
- This causes a rearrangement of the pressure such that its gradient opposes the pull of gravity.



Outline

1. Introduction
2. Model
3. Results
   - Fully ionised plasma, no mass condensation
   - Fully ionised plasma
     - Fully ionised plasma, no magnetic field
     - Fully ionised plasma, magnetic field
   - Neutral gas
   - Partially ionised plasma
4. Conclusions

Fully ionised plasma, $B = 0$

- No neutrals, no magnetic field.
- Coronal equilibrium at $t = 0$ (no density enhancement added).
- Mass condensation for $t \geq 0$.
- Only the evolution equations of charged particles need to be considered:

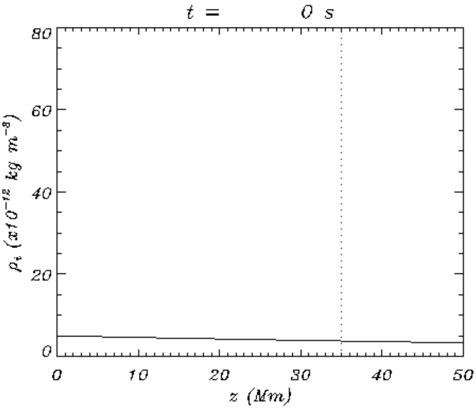
$$\frac{\partial \rho_i}{\partial t} = -v_i \frac{\partial \rho_i}{\partial z} - \rho_i \frac{\partial v_i}{\partial z} + r_i(z,t)$$

$$\rho_i \frac{\partial v_i}{\partial t} = -\rho_i v_i \frac{\partial v_i}{\partial z} - \frac{\partial p_{ie}}{\partial z} - g\rho_i - \cancel{\frac{1}{\mu} B \frac{\partial B}{\partial z}} - \cancel{\alpha_{in}(v_i - v_n)}$$

$$\frac{\partial p_{ie}}{\partial t} = -v_i \frac{\partial p_{ie}}{\partial z} - \gamma p_{ie} \frac{\partial v_i}{\partial z} + \cancel{(\gamma - 1)\alpha_{in}(v_i - v_n)v_i}$$

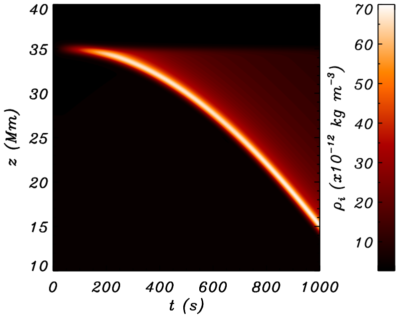
Fully ionised plasma, $B = 0$: density

- Blob forms at the mass condensation position in less than 200 s.
- Blob moves downwards faster than in the previous case (without mass condensation).
- Blob leaves a trail of material behind.
- This trail is formed by the continuous mass injection.



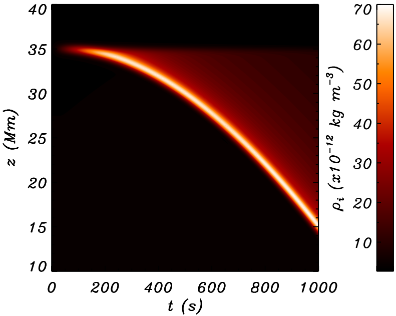
Fully ionised plasma, $B = 0$: acceleration

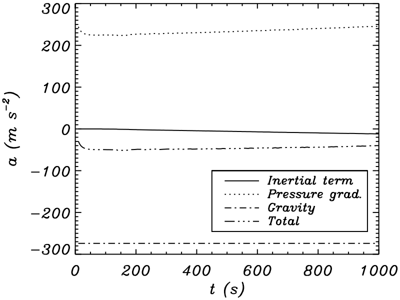
- Blob formation and acceleration. Trailing material.
- A second-order polynomial fit to the maximum density positions yields $a = -40$ m s $^{-2}$.



Fully ionised plasma, $B = 0$: acceleration

- Blob formation and acceleration. Trailing material.
- A second-order polynomial fit to the maximum density positions yields $a = -40$ m s $^{-2}$.

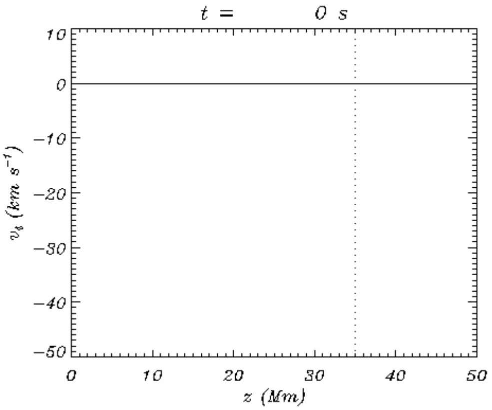




- Accelerations: the inertial term is irrelevant.
- The mass condensation grows smoothly and so a strong pressure gradient can develop from $t = 0$.
- The blob acceleration is not constant: it decreases in time from roughly 50 m s $^{-2}$ to 40 m s $^{-2}$.

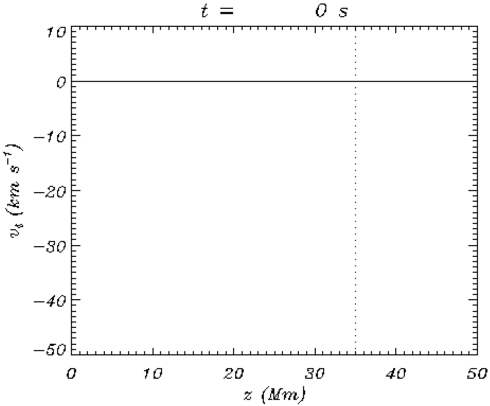
Fully ionised plasma, $B = 0$: dynamics

- Ions velocity distribution as a function of time.
- The condensing mass pulls down material from above and pushes down material below.
- The whole corona falls at a speed that grows in time.



Fully ionised plasma, $B = 0$: dynamics

- Ions velocity distribution as a function of time.
- The condensing mass pulls down material from above and pushes down material below.
- The whole corona falls at a speed that grows in time.



Fully ionised plasma, $B \neq 0$

Same parameters as before, but now $B \neq 0$.
$\beta_0 = 0.1 \rightarrow$ initial magnetic field at $z = 0$ is $B_0 = 20.4$ G.

- Blob formation and dynamics are completely analogous to those of the case $B \neq 0$.
- Total pressure at the mass condensation position is much larger than in the case $B \neq 0$.
- A strong magnetic pressure gradient develops that slows down the blob fall.
- The blob acceleration is $a = -12$ m s $^{-2}$.
- Magnetic diffusion is irrelevant.

Fully ionised plasma, $B \neq 0$

Same parameters as before, but now $B \neq 0$.
$\beta_0 = 0.1 \rightarrow$ initial magnetic field at $z = 0$ is $B_0 = 20.4$ G.

- Blob formation and dynamics are completely analogous to those of the case $B \neq 0$.
- Total pressure at the mass condensation position is much larger than in the case $B \neq 0$.
- A strong magnetic pressure gradient develops that slows down the blob fall.
- The blob acceleration is $a = -12$ m s $^{-2}$.
- Magnetic diffusion is irrelevant.

Fully ionised plasma, $B \neq 0$

Same parameters as before, but now $B \neq 0$.
$\beta_0 = 0.1 \rightarrow$ initial magnetic field at $z = 0$ is $B_0 = 20.4$ G.

- Blob formation and dynamics are completely analogous to those of the case $B \neq 0$.
- Total pressure at the mass condensation position is much larger than in the case $B \neq 0$.
- A strong magnetic pressure gradient develops that slows down the blob fall.
- The blob acceleration is $a = -12$ m s $^{-2}$.
- Magnetic diffusion is irrelevant.

Outline

Neutral gas

- The time dependent equations for ρ_n, p_n and v_n are identical to those of ρ_i, p_{ie} and v_i.
- But the initial configuration is slightly different...

$$\rho_i(z, t=0) = \rho_{i0} e^{-z/H_i} \qquad \rho_n(z, t=0) = \rho_{n0} e^{-z/H_n}$$

$$p_{ie}(z, t=0) = p_{ie0} e^{-z/H_i} \qquad p_n(z, t=0) = p_{n0} e^{-z/H_n}$$

- ...because p_{ie} includes p_i and p_e:

$$p_{ie0} = 2\rho_{i0} R T_0 \qquad p_{n0} = \rho_{n0} R T_0$$

- The scale heights are also different: $H_i = 2\frac{RT_0}{g}$, $\quad H_n = \frac{RT_0}{g}$.

Neutral gas

- The time dependent equations for ρ_n, p_n and v_n are identical to those of ρ_i, p_{ie} and v_i.
- But the initial configuration is slightly different...

$$\rho_i(z, t=0) = \rho_{i0} e^{-z/H_i}$$

$$p_{ie}(z, t=0) = p_{ie0} e^{-z/H_i}$$

$$\rho_n(z, t=0) = \rho_{n0} e^{-z/H_n}$$

$$p_n(z, t=0) = p_{n0} e^{-z/H_n}$$

- ...because p_{ie} includes p_i and p_e:

$$p_{ie0} = 2\rho_{i0} R T_0 \qquad p_{n0} = \rho_{n0} R T_0$$

- The scale heights are also different: $H_i = 2\frac{RT_0}{g}$, $\quad H_n = \frac{RT_0}{g}$.

Neutral gas

- The time dependent equations for ρ_n, p_n and v_n are identical to those of ρ_i, p_{ie} and v_i.
- But the initial configuration is slightly different...

$$\rho_i(z, t = 0) = \rho_{i0} e^{-z/H_i}$$

$$p_{ie}(z, t = 0) = p_{ie0} e^{-z/H_i}$$

$$\rho_n(z, t = 0) = \rho_{n0} e^{-z/H_n}$$

$$p_n(z, t = 0) = p_{n0} e^{-z/H_n}$$

- ...because p_{ie} includes p_i and p_e:

$$p_{ie0} = 2\rho_{i0} R T_0 \qquad p_{n0} = \rho_{n0} R T_0$$

- The scale heights are also different: $H_i = 2\frac{RT_0}{g}, \quad H_n = \frac{RT_0}{g}$.

- The blob moves in an environment with smaller pressure and thus a smaller pressure gradient arises.
- Using the same values as in the fully ionised case (i.e. $\rho_{n0} = 5 \times 10^{-12}$ kg m^{-3}, $T_0 = 2 \times 10^6$ K): $a = -56$ m s $^{-2}$.

Outline

Partially ionised plasma, $B = 0$

Equilibrium density

- To reproduce the observations of Liu et al. (2012) we should consider a fully ionised coronal environment at $t = 0$, that corresponds to $\rho_{n0} = 0$.
- This leads to numerical problems, so a small amount of neutrals is included in the equilibrium.
- We choose the same mass density at the base of the corona as before: 5×10^{-12} kg m^{-3}.
- 90% of the mass at $z = 0$ is in the form of charged particles.
- The temperature is also unchanged: $T_0 = 2 \times 10^6$ K.

Mass condensation

- The total mass condensation rate is the same as before.
- 90% of the mass condenses as neutrals.
- 10% of the mass condenses as ions.

Partially ionised plasma, $B = 0$

Equilibrium density

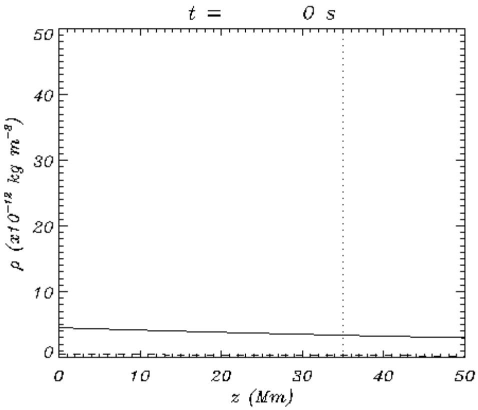
- To reproduce the observations of Liu et al. (2012) we should consider a fully ionised coronal environment at $t = 0$, that corresponds to $\rho_{n0} = 0$.
- This leads to numerical problems, so a small amount of neutrals is included in the equilibrium.
- We choose the same mass density at the base of the corona as before: 5×10^{-12} kg m^{-3}.
- 90% of the mass at $z = 0$ is in the form of charged particles.
- The temperature is also unchanged: $T_0 = 2 \times 10^6$ K.

Mass condensation

- The total mass condensation rate is the same as before.
- 90% of the mass condenses as neutrals.
- 10% of the mass condenses as ions.

Partially ionised plasma, $B = 0$, $\alpha_{in} = 0$: density

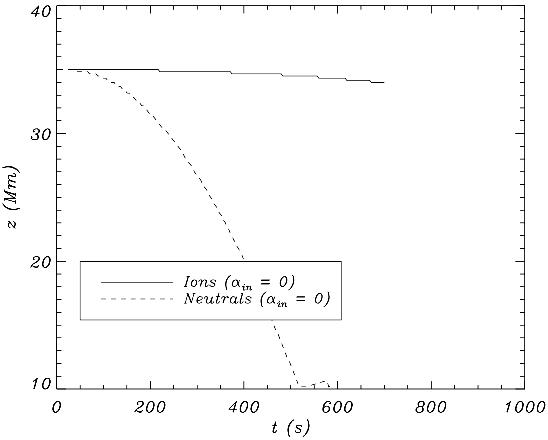
We start by setting $\alpha_{in} = 0$: charges and neutrals evolve independently from each other, as in a fully ionised and in a fully neutral medium.



- Ions fall very slowly, while neutrals have a strong acceleration.
- Reason: small mass condensation of ions, large mass condensation of neutrals in a rare environment.

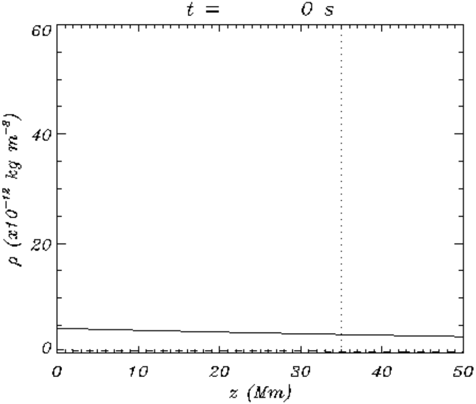
Partially ionised plasma, $B = 0$, $\alpha_{in} = 0$: blob position

- This figure is similar to the density space-time diagram, but only the positions of both blobs are displayed.
- Ions: $a = -5$ m s $^{-2}$, neutrals: $a = -175$ m s $^{-2}$.



Partially ionised plasma, $B = 0$: density

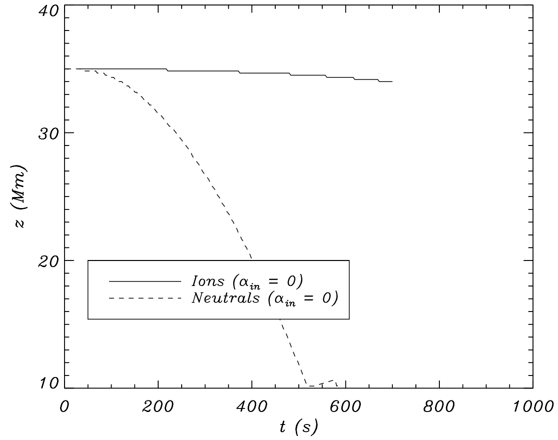
Temporal evolution of density.



- Two blobs form and trail of material above them.
- Friction couples very quickly the dynamics of charges and neutrals and causes the charged and neutral blobs to fall together.

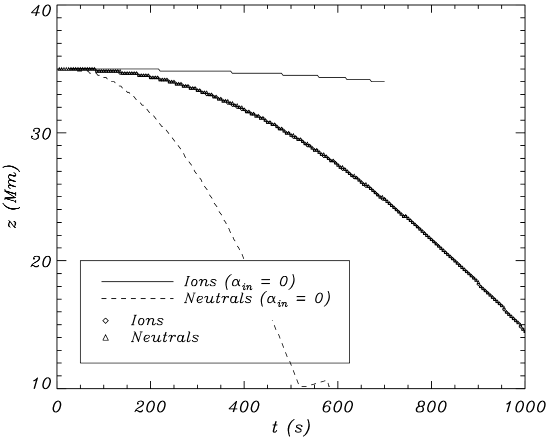
Partially ionised plasma, $B = 0$: blob position

- $\alpha_{in} = 0$. Ions: $a = -5$ m s $^{-2}$, neutrals: $a = -175$ m s $^{-2}$.
- $\alpha_{in} \neq 0$. Ions and neutrals: $a = -41$ m s $^{-2}$.

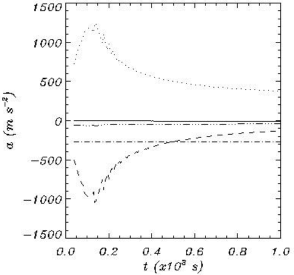


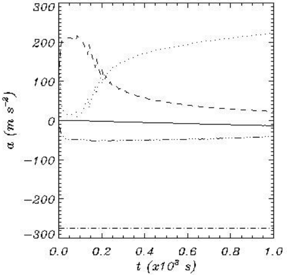
Partially ionised plasma, $B = 0$: blob position

- $\alpha_{in} = 0$. Ions: $a = -5$ m s $^{-2}$, neutrals: $a = -175$ m s $^{-2}$.
- $\alpha_{in} \neq 0$. Ions and neutrals: $a = -41$ m s $^{-2}$.



Partially ionised plasma, $B = 0$: blob acceleration





- Friction force drags ions downwards. Pressure gradient points upwards.
- The neutrals pressure gradient and friction force are upwards.
- The friction and pressure gradient accelerations of ions are much larger than those of neutrals, but when combined together with gravity they yield the same total acceleration.

Conclusions

- In the absence of a mass source, the blob falls at a constant speed.
- A mass condensation gives rise to the formation and subsequent acceleration of the blob.
  - Values of acceleration range from 10 to 175 m s^{-2}.
- Environment with high pressure makes easier to create a large pressure gradient, which results in smaller acceleration.
  - Higher pressure can be caused by: higher temperature, higher base density, magnetic field.
- Smaller mass condensation rate and large pressure lead to same results.
- The dynamical coupling between charged particles and neutrals is extremely fast.

Conclusions

- Gilbert et al. (2002) studied the vertical motions in a steady-state, uniform prominence model with horizontal and uniform magnetic field.
- Besides H^+, e^- and H, these authors also included He^+ and He.
- Pressure gradient is neglected.
- They computed the velocity of the 5 species. No acceleration: the speeds are uniform over the whole prominence height.
- Conclusion #1: charges and neutrals drain at different speeds.
- Conclusion #2: neutrals drain across the magnetic field.

Conclusions

It is hard to see the distinctive trail of plasma in Liu et al.'s figure.