Dynamics of rain blobs: fully and partially ionised plasmas

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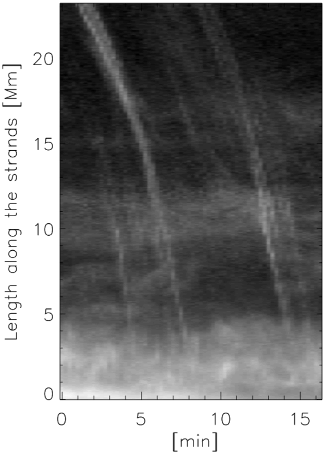
Some observational facts

1. Acceleration typically much smaller than that of gravity (projected along the blob trajectory).
2. Blobs often reach a constant velocity, in the range 40–120 km s^{-1}.
3. De Groof et al. (2005), using Hα and He 304 Å observations: blob made of neutral and ionised fractions that fall together. Strong (dynamical?) coupling between charged particles and neutrals.

We consider a simple configuration and perform hydrodynamic numerical simulations to investigate the kinematics and dynamics of coronal rain blobs.

Some observational facts

- Height-distance diagram.
- Very common trajectory:
  - Antolin et al. (2010, 2012a, b).
  - Chae (2010, ApJ, 714, 618): descending knots in a hedgerow prominence.
  - Vissers's talk about flocculent flows this morning.



Antolin et al. (2010)

Model: assumptions (FIP)

We include:

- Fully ionised plasma (FIP) made of H,
- hydrodynamic time evolution of a formed blob in the loop environment,
- vertical motions,
- adiabatic changes of state.

We do not include:

- The neutral fraction of the plasma,
- the blob formation process,
- path curvature,
- radiation, conduction, cooling,
- transition region and chromosphere,
- magnetic field.

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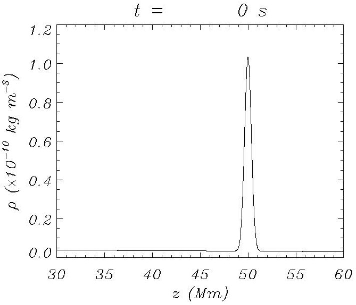
Model: initial state

- Background: isothermal loop, vertically stratified by gravity:

$$p(z,t=0) = p_0 e^{-z/H}, \quad \rho(z,t=0) = \rho_0 e^{-z/H}, \quad H = \frac{2RT_0}{g}$$

- z-axis is vertical; T_0 is the loop temperature; $R = k_B/m_p$ is the gas constant.
- The blob is represented by a localised density enhancement.
- In the initial state the vertical speed is zero.



Parameter values:
$H = 120$ Mm
$\rho_0 = 5\times10^{-12}$ kg m^{-3}
$\rho_{b0} = 10^{-10}$ kg m^{-3}
$z_0 = 50$ Mm

Model: equations

- Three unknowns ρ, p, v.
- The unknowns only depend on t and z.

- Mass continuity:

$$\frac{\partial \rho}{\partial t} = -v\frac{\partial \rho}{\partial z} - \rho\frac{\partial v}{\partial z}$$

- z-component of the momentum equation:

$$\rho\frac{\partial v}{\partial t} = -\rho v\frac{\partial v}{\partial z} - \frac{\partial p}{\partial z} - g\rho$$

- Energy equation:

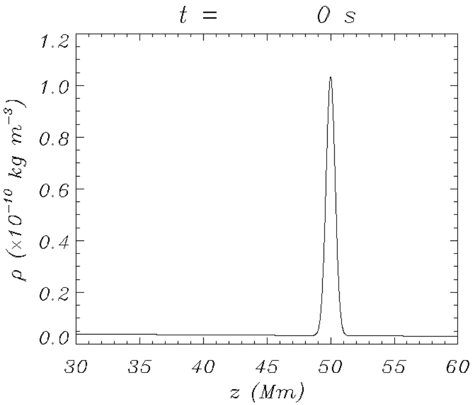
$$\frac{\partial p}{\partial t} = -v\frac{\partial p}{\partial z} - \gamma p\frac{\partial v}{\partial z}$$

Model: numerical method

- The time-dependent PDEs are solved using the PDE2D code with Galerkin's method.
- We are interested in the height range $0 \leq z \leq 60$ Mm.
- Open boundaries at the top and bottom of the system.
- No artificial viscosity/dissipation added.
- Grid spacing $\simeq$ 10 km.
- Simulation time: 1000 s.

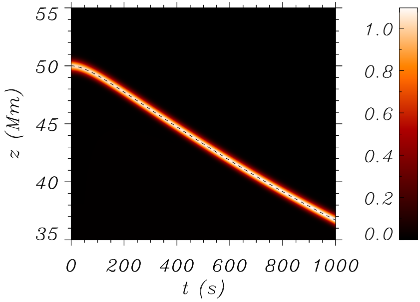
Density

- The condensation keeps its density and shape as it falls.
- If the blob were to fall with the acceleration of gravity, it would reach $z = 0$ at $t \simeq 540$ s.



Blob height

- Height–time diagram of density (colour scale in units of 10^{-10} kg m^{-3}).
- Initial acceleration phase followed by constant speed phase.



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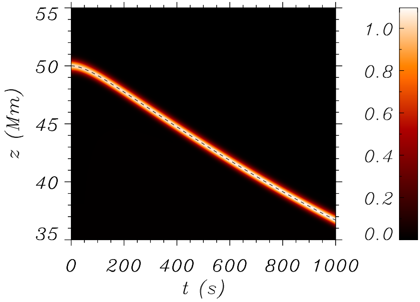
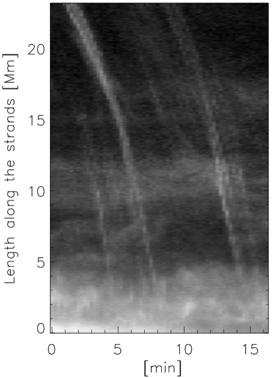
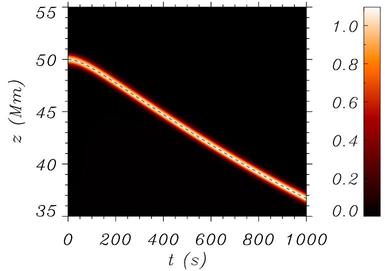
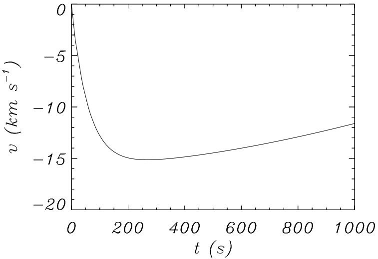




Antolin et al. (2010)

Height and blob velocity

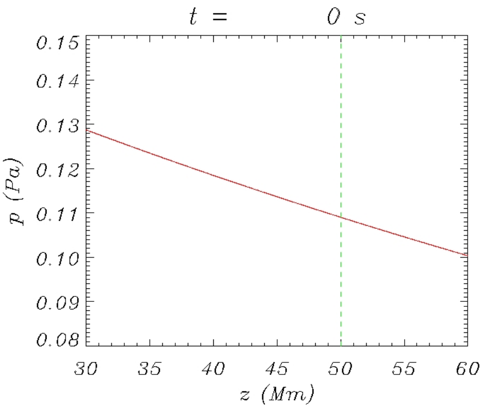




- Initial acceleration phase lasts $\simeq 200$ s.
- Blob then attains a roughly constant speed $\simeq 15$ km s^{-1}.

Pressure

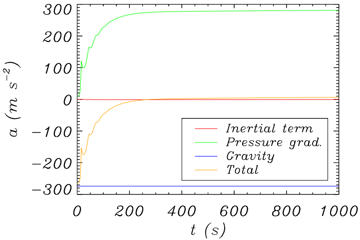
- Sound wave generated at the initial blob position (sound speed $\simeq 235$ km s^{-1}).
- A strong pressure gradient is generated at the blob position.
- Established pressure gradient travels with the blob (its position is given by the green line).

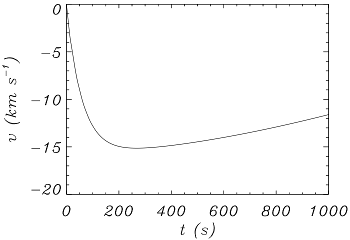


- Pressure structure under and above the blob is rearranged.

Blob acceleration

$$\rho\frac{\partial v}{\partial t} = -\rho v\frac{\partial v}{\partial z} - \frac{\partial p}{\partial z} - g\rho \quad \Rightarrow \quad \frac{\partial v}{\partial t} = -v\frac{\partial v}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial z} - g$$





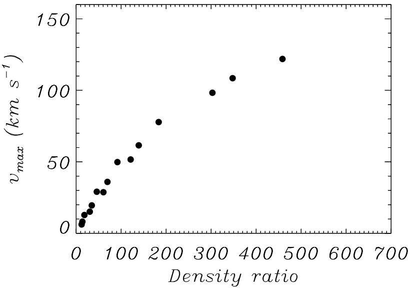
- Inertial term is negligible.
- Pressure gradient builds up and counteracts gravity at $t \simeq 200$ s.

Maximum descending speed

Similar dynamics are obtained for other parameter values.

- The density ratio (initial blob density to local loop density) determines the maximum falling speed.
- The local loop density depends on
  - initial blob height (z_0),
  - density at base of loop (ρ_0),
  - the vertical scale height ($H \propto T_0$).

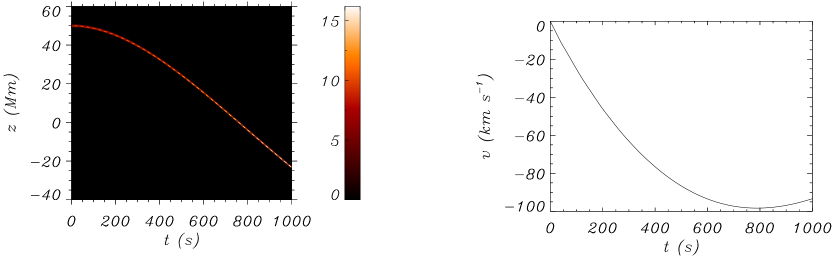
$$\rho(z, t = 0) = \rho_0 e^{-z/H}$$



- Observed blob velocities require blob to loop density ratios as large as 500 or more.

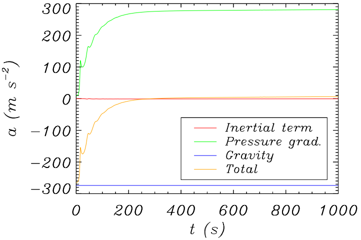
Larger blob density: height and velocity

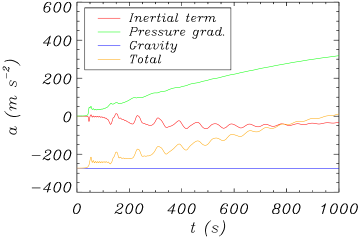
- Blob density is 10 times larger.
- Height–time diagram is much more parabolic.



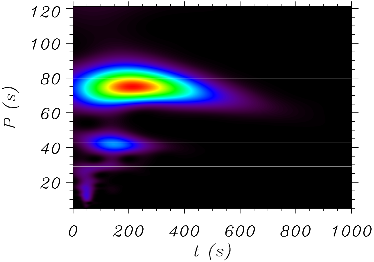
- Initial acceleration phase lasts much longer ($\simeq 800$ s compared to $\simeq 200$ s).
- Maximum falling velocity is much higher ($\simeq 100$ km s^{-1} compared to $\simeq 15$ km s^{-1})

Larger blob density: acceleration



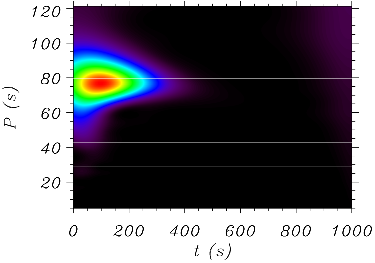


- Oscillations in the inertial term acceleration: $v\dfrac{\partial v}{\partial z}$.
- Wavelet diagram of $\dfrac{\partial v}{\partial z}$.
- Periods: $\simeq 75$ s, $\simeq 42$ s, $\simeq 28$ s.

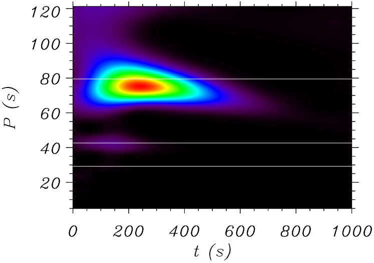


Larger blob density: sound wave emission

- Blob density and velocity also display damped oscillations.
- These oscillations in ρ and v are revealed after fitting and subtracting a third degree polynomial + wavelet analysis.
- Horizontal lines: theoretical periods of leaky sound waves of static blob with $g = 0$.



Blob velocity



Blob density

Model: assumptions (PIP)

We include:

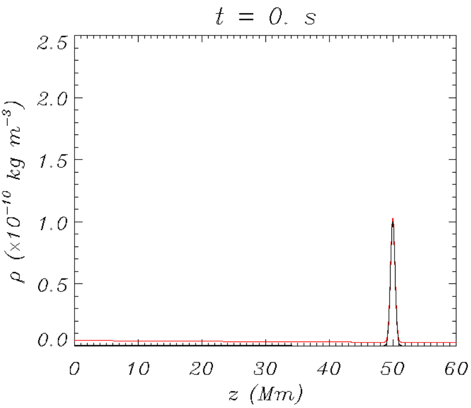
- The blob is partially ionised.
- The loop also contains a small fraction of neutrals (to avoid numerical problems).
- Hydrodynamic equations for the time evolution of two fluids (charged particles and neutrals) coupled by friction.

We do not include:

- Ionisation and recombination.

Model: initial state

- Red = charged particles, black = neutrals.



Model: initial state

- Background: isothermal loop, vertically stratified by gravity:

$$p_{ie}(z,t=0) = p_{ie0}\, e^{-z/H_i}, \qquad \rho_i(z,t=0) = \rho_{i0}\, e^{-z/H_i}, \qquad H_i = \frac{2RT_0}{g}$$

$$p_n(z,t=0) = p_{n0}\, e^{-z/H_n}, \qquad \rho_n(z,t=0) = \rho_{n0}\, e^{-z/H_n}, \qquad H_n = \frac{RT_0}{g}$$

- Parameter values:

$$H_i = 120 \text{ Mm} \qquad H_n = 60 \text{ Mm}$$

$$\rho_{i0} = 4.5 \times 10^{-12} \text{ kg m}^{-3} \qquad \rho_{n0} = 0.5 \times 10^{-12} \text{ kg m}^{-3}$$

$$\rho_{bi0} = 10^{-10} \text{ kg m}^{-3} \qquad \rho_{bn0} = 10^{-10} \text{ kg m}^{-3}$$

$$z_0 = 50 \text{ Mm}$$

Model: equations

- Six unknowns ρ_i, p_{ie}, v_i and ρ_n, p_n, v_n.

- Mass continuity equations:

$$\frac{\partial \rho_i}{\partial t} = -v_i \frac{\partial \rho_i}{\partial z} - \rho_i \frac{\partial v_i}{\partial z} \qquad \frac{\partial \rho_n}{\partial t} = -v_n \frac{\partial \rho_n}{\partial z} - \rho_n \frac{\partial v_n}{\partial z}$$

- z-component of the momentum equations:

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

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

- Energy equations:

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

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

Model: equations

- Q_i^{in} = heating of ions due to collisions with neutrals.

$$Q_i^{in} = \alpha_{in}\left[\frac{1}{2}(v_n - v_i)^2 + 3R(T_n - T_i)\right]$$

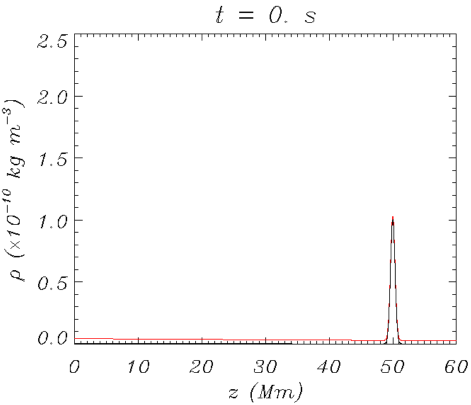
- The temperatures of ions and neutrals are obtained from the perfect gas law

$$p_{ie} = 2\rho_i R T_i \qquad p_n = \rho_n R T_n$$

- The friction coefficient α_{in} depends on the density and temperature of charged particles and neutrals. It must be computed at each position at each time step.

Density

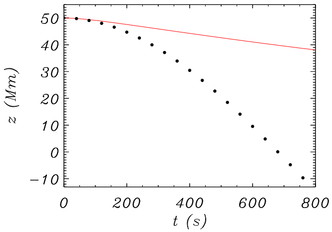
- No friction force ($\alpha_{in} = 0$).
- The neutral fraction of the blob (black line) falls faster than the ionised fraction because of its larger density ratio.

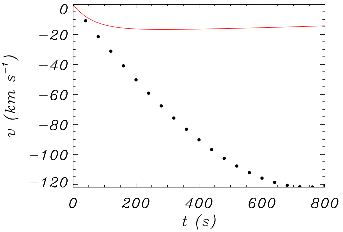


Height vs. time and velocity

Black = neutrals; red = ions.

$$\alpha_{in} = 0$$





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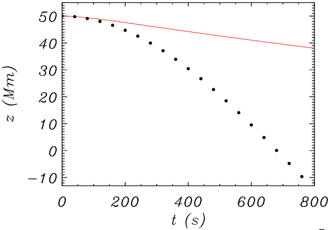
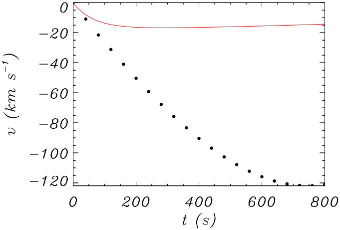
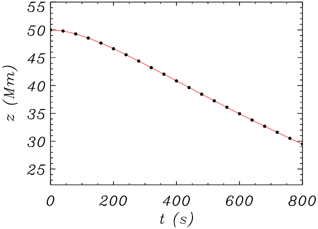
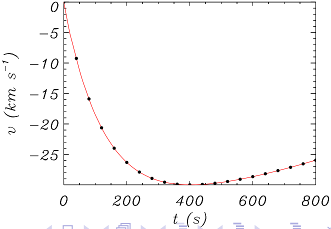


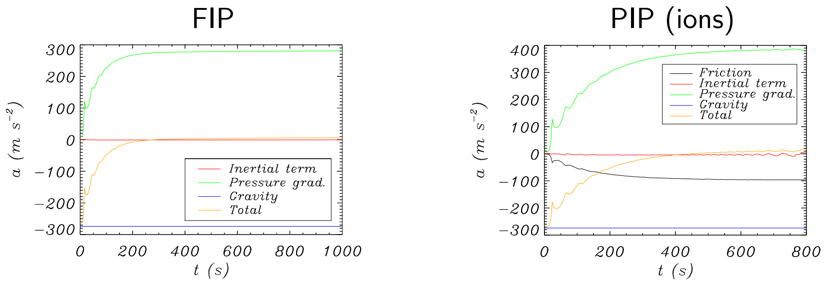


$$\alpha_{in} \neq 0$$





Acceleration

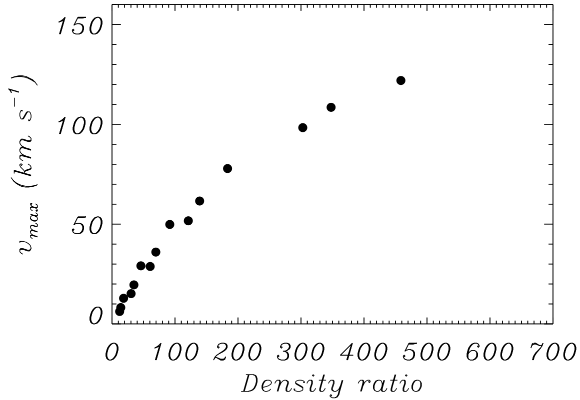


- Friction with neutrals gives rise to downward force that accelerates ions.

Maximum descending speed

Black circles = fully ionised plasma.

Blue squares = partially ionised plasma.



- The density ratio still determines the maximum falling speed.

Maximum descending speed

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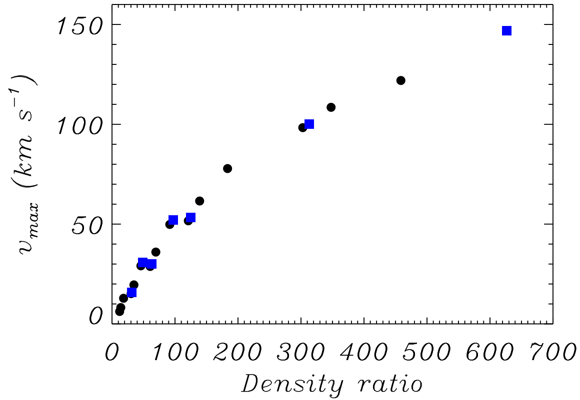

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Conclusions

- Strong dynamical coupling of charged particles and neutrals. Main results do not change when going from FIP to PIP.

- Presence of mass condensation leads to a pressure gradient that opposes gravity.
- "Small" density ratio: acceleration phase followed by more or less constant speed.
- "Large" density ratio: acceleration phase lasts much longer.
- Maximum falling speed increases with density ratio. Very good correlation between the two quantities.
- Damped oscillations because of sound wave emission. Detectable as periodic changes of the blob density and velocity?