Temperature inversion in a gravitationally bound plasma: case of the solar corona

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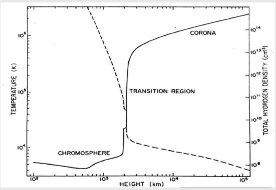
Temperature inversion in the solar atmosphere

The temperature of the solar atmosphere increases from thousands to millions of degrees moving from the lower layer (the chromosphere) to the outermost one (the corona), while the density drops accordingly: this is referred to as temperature inversion. The two layers are connected by the transition region, a very thin interface that sees temperature and density variations of orders of magnitude. The mechanism behind the coronal heating is still largely unknown.



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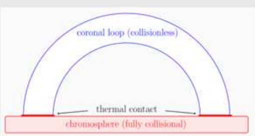
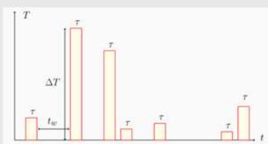
- **Standard approach (thermal equilibrium approach) :** Assuming local thermodynamic equilibrium, a hot corona can form only upon the local deposition of heat in the upper layer. The energy coming from the Sun is enough to heat the whole corona, bringing on how to dissipate the energy at coronal heights.

- **Scudder approach (non-equilibrium approach) :** In Scudder (1992a,b) has been shown that if the velocity distribution functions of electrons and ions in the chromosphere are non-Maxwellian with suprathermal tails, then temperature must increase with height: faster particles are able to climb higher in the Sun's gravity well and temperature increases thanks to "gravitational velocity filtration." However, non-thermal distributions in the highly collisional chromospheric plasma are difficult to justify, and Scudder's model produces a linear increase of the temperature with height without a transition region.

The coronal Loop scheme

We model a coronal loop as a collisionless plasma in contact with a thermostat mimicking the collisional high chromospheric plasma.





If the thermostat (chromosphere) temperature is constant, the coronal loop is isothermal, at the same temperature T_0 of the thermostat. But the chromosphere is a very dynamic environment, therefore we assume that its temperature fluctuates due to random heating events of amplitude ΔT and duration τ, separated by waiting times t_w during which the temperature of the thermostat switches back to T_0.

We keep τ fixed and we draw ΔT and t_w from exponential probability distributions with given $\langle \Delta T \rangle$ and $\langle t_w \rangle$. If

$$\tau < t_R \qquad \langle t_w \rangle < t_R$$

where t_R is the relaxation time in the corona, the coronal plasma never relaxes to thermal equilibrium: it rather reaches a non-equilibrium stationary state with suprathermal tails in the particles velocity distribution functions, always exhibiting inverted temperature and density profiles due to velocity filtration.

Numerical model

We use a mean-field approximation for the electrostatic interaction between the particles of the coronal plasma, which are subjected to a constant downward gravity and to the Pannekoek-Rosseland field which ensures charge neutrality, whose combined effect is proportional to $(M_i + M_e)/2$. The equations of motion are

$$M_\alpha \ddot{x}_{j,\alpha} = e_\alpha E(x_{j,\alpha}) + g\frac{M_e + M_i}{2}\sin\left(\frac{\pi x_{j,\alpha}}{2L}\right)$$

where $x \in [-L, L]$ is the coordinate along the loop, $j = 1, \ldots 2N$ numbers the particles, $\alpha = e, i$ denotes the species, $g = GM_\odot/R_\odot^2$ is the Sun's gravity,

$$E(x) = 8\frac{|e_\alpha|}{S}N\left(q_i - q_e\right)\sin\left(\frac{\pi x}{L}\right)$$

is the self-consistent electric field, with

$$q_\alpha = \frac{1}{2N}\sum_{j=1}^{2N}\cos\left(\frac{\pi x_{j,\alpha}}{L}\right)$$

the "stratification parameter" for each species: $q_\alpha = 0$ corresponds to a uniform distribution of particles, $q_\alpha = -1$ to a distribution concentrated at the base of the loop. The difference $q_i - q_e = 0$ measures the charge imbalance giving rise to the electric field.

We solve the equations of motions coupled to the fluctuating thermostat and find that the value of electrostatic unit "e"does not affect the results in the non-equilibrium stationary state. Therefore we use "e" much smaller than a realistic value to avoid prohibitively small time steps. For all the other parameters we choose realistic values, i.e., $M = 1836$ $n = 2.5 \cdot 10^9 cm^{-3}$ $L = \pi \cdot 10^4 km$ $T_0 = 10^4 K$.

Analytical/theoretical model

We show that in the regime in which the system reaches the non-equilibrium stationary state (i.e. the temperature inversion) we can describe the system with time-average distribution functions such that

$$\tau, \langle t_w \rangle < \tilde{t} < t_R \qquad \tilde{f}_\alpha = \frac{1}{\tilde{t}}\int_{\tilde{t}} f_\alpha dt$$

Whose dynamics obeys to a time-average Vlasov dynamics with a time-average distribution at its base

$$\frac{\partial \tilde{f}_\alpha}{\partial t} + \frac{p}{M_\alpha}\frac{\partial f_\alpha}{\partial x} + F[\tilde{f}_\alpha]\frac{\partial \tilde{f}_\alpha}{\partial p} = 0 \qquad \tilde{f}_{0,\alpha}(p) = A\int_{T_0}^{+\infty} dT\frac{f(T)}{TM_\alpha}e^{-\frac{p^2}{2M_\alpha k_B T}} + (1-A)\frac{e^{-\frac{p^2}{2M_\alpha k_B T_0}}}{M_\alpha T_0}$$

$$\tilde{f}_{0,\alpha}(p) \quad \text{at the base} \qquad A = \frac{\tau}{\tau + \langle t_w \rangle}$$

The stationary solution can be computed analytically and we get

$$\tilde{f}_{\alpha,SS}(x,p) = \mathcal{N}_\alpha\left(A\int_{T_0}^{+\infty} dT\frac{f(T)}{T}e^{-\frac{H_\alpha}{k_B T}} + (1-A)\frac{e^{-\frac{H_\alpha}{k_B T_0}}}{T_0}\right)$$

Where N_α is a normalization, H_α is the single-particle Hamiltonian of each species and γ is the probability distribution of the temperature increments in the thermostat. This result shows that the stationary distribution function is given by a thermal distribution at temperature $T = T_0$ plus a non-thermal contribution arising from the average of thermal distributions at $T \neq T_0$ over the probability distribution of the temperature fluctuations.

The weight of the non-thermal contribution is proportional to A. The thermal population dominates at small heights z, and is depressed by the gravity term in H_α when increasing z; conversely, the non-thermal contribution becomes more and more relevant at larger z due to velocity filtration, because faster particles can climb higher in the potential well, showing up as suprathermal tails in the distribution (see the figure in the next column).

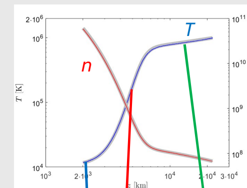
The solar atmosphere

Constraints on the thermostat temperature fluctuations:

- $A \ll 1 \rightarrow \tau \ll \langle t_w \rangle$ to have $T \cong T_0$ at chromospheric heights.
- $\langle \Delta T \rangle = 10^2 T_0$ to have a million-Kelvin corona

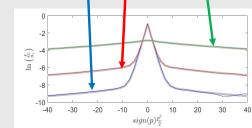
Rapid, intermittent strong heating events can produce a one-million degree corona.

Inverted temperature-density profiles



Barbieri, L., et al. A&A 681, L5 (2024).

Velocity distribution functions



- Theoretical profiles (in grey) are similar to the numerical ones (the colored ones) with a transition region followed by a corona.
- The velocity distribution functions have a pronounced central thermal core that gradually disappear passing through the transition region and is finally filtered out in the corona where there are only suprathermal tails.
- $t_R \sim 10s$, $\langle t_w \rangle \sim 1s$, $\tau \sim 10^{-2}s$ Currently unresolved fluctuations, yet compatible with average chromospheric temperature 11000K.

Conclusions and perspectives

Temperature fluctuations in the chromosphere are able to produce a (thick) transition region and a one-million Kelvin corona.

- **At variance with the standard approach:** there is no local deposition of heat in the upper layers.
- **At variance with the Scudder approach:** suprathermal tails are not imposed in the chromosphere but are produced by the thermostat temperature fluctuations.
- **We have to:** find physical processes yielding sufficiently fast and intense heating events in the chromosphere.
- **We have to:** Include collisions in the corona.

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