A Multi-Wavelength View on Coronal Rain

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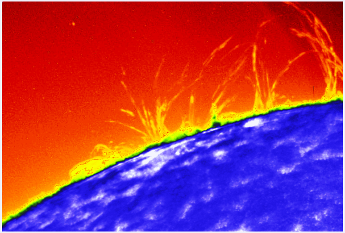
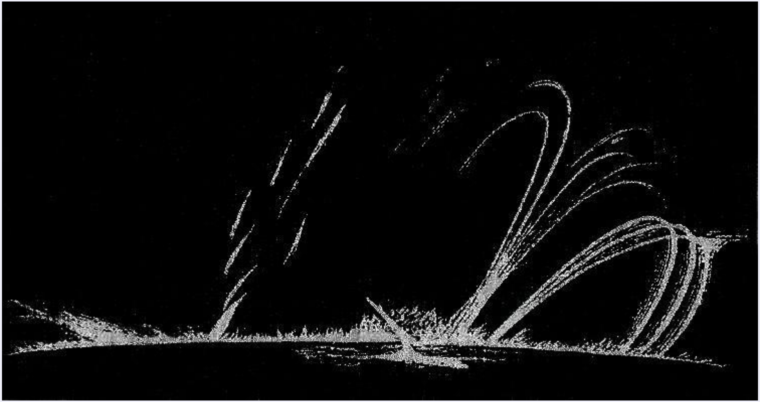


Outline

Contents

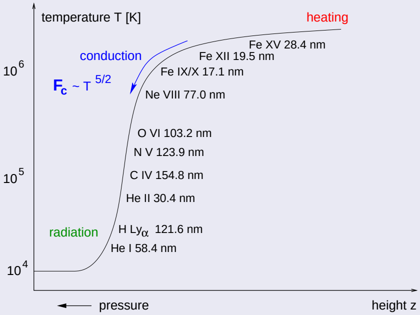
Early Observations of Dynamic Coronal Loops



Coronal loops drawn by A. Secchi from Hα observations on Oct. 5, 1871

Energy Balance in the Solar Transition Region

Temperature Structure



Energy Contributions

conductive flux:

$$F_c = -\kappa_0 T^{5/2} \mathrm{d}T/\mathrm{d}z$$

radiative losses:

$$L_r = n_e n_{ion} \Phi(T)$$

mech. energy flux (prescribed):

$$F_m = F_{m0} \cdot e^{-(z-z_0)/H_m}$$

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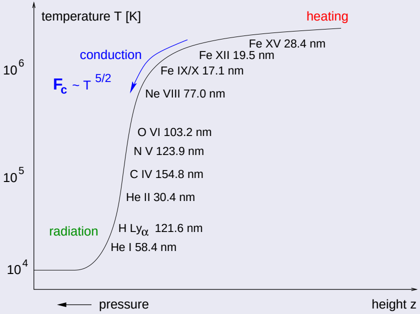

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TTRANZ Code (Hansteen 1993)

- 1-D radiative HD code with adaptive grid
- non-equilibrium rate equations / self-consistent radiative losses

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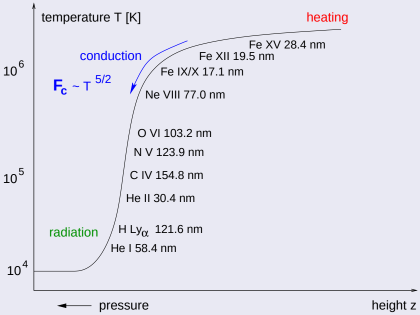

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Important

- $\langle \Phi(T) \rangle$ peaks at $T^* = 2 - 3 \cdot 10^5$ K $\Rightarrow$ local minimum in T will radiatively cool more strongly than surroundings!
- radiative losses $L_r \propto n_e^2$

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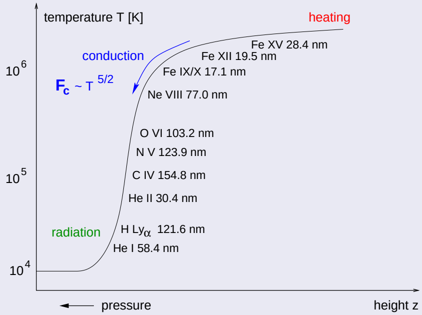

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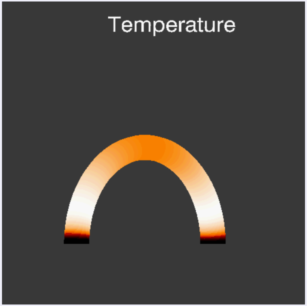
Thermal Instability

How can such an instability occur?

The Evaporation-Condensation Cycle



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Heat Loops in the Lower Corona

DO LOOP

- energy budget in the upper part of the loop becomes negative

END DO

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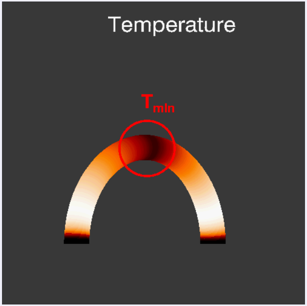

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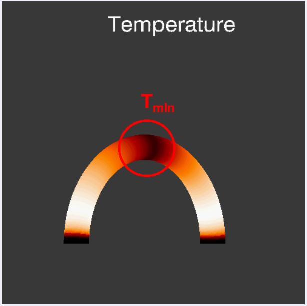

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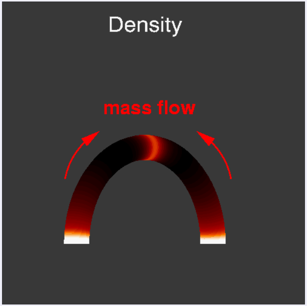

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- mass flow towards pressure minimum

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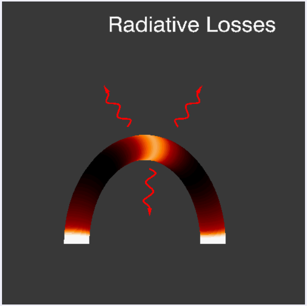

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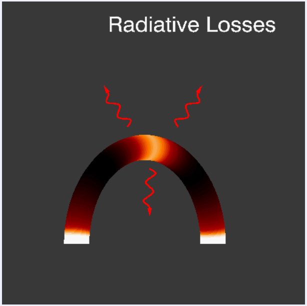

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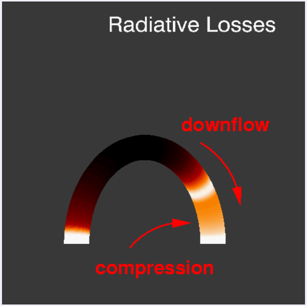

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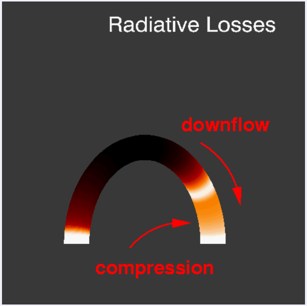

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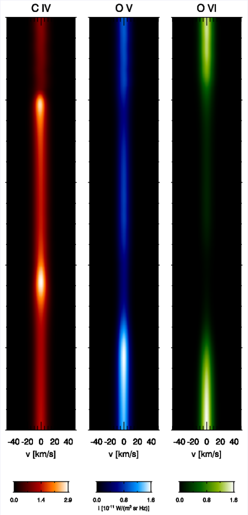
- condensation region is gravitationally unstable
- depleted loop reheats

END DO

Model Predictions



Observational Consequences

- strong intensity variations in transition region lines

(Müller et al. 2003)

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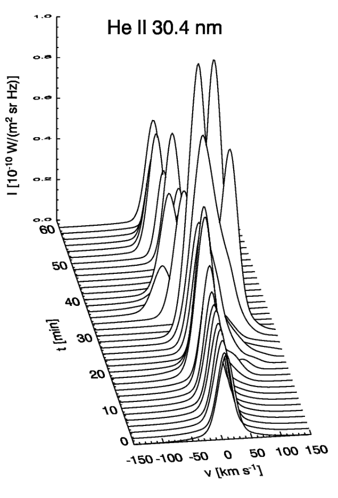

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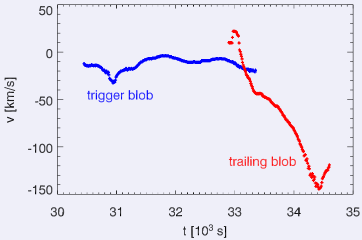

Observational Consequences

- strong intensity variations in transition region lines

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- shocks can trigger further cooling events

  (Müller et al. 2005)

Evaporation & Condensation: Variations on a Theme

Paths to Instability

There are different ways to trigger a thermal instability in a loop :

- heating concentrated in the lower corona (continuous or episodic)
- sudden decrease of heating scale height
- overheating (note: similarity to overheated open coronae!)

Evaporation & Condensation: Variations on a Theme

Paths to Instability

There are different ways to trigger a thermal instability in a loop :

- heating concentrated in the lower corona (continuous or episodic)
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What all mechanisms have in common:

- heating imbalance between lower and upper loop
- chromospheric evaporation increases density in upper part
- evolution can be cyclic

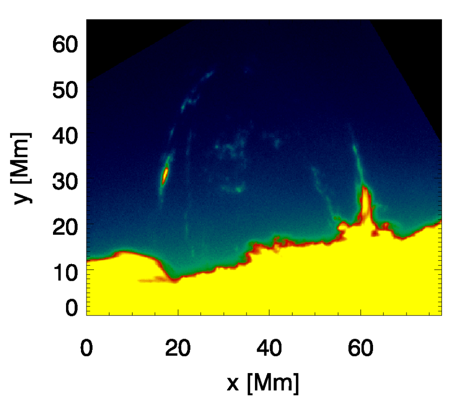
Reality Check

Multi-Wavelength Data of Cooling Loops

Off-limb time series from different instruments:

1. EIT shutterless campaign + Big Bear Hα (previous talk by A. De Groof)
2. Swedish Vacuum Solar Telescope (SVST) +TRACE
   - SVST: blue/red wing of Hα, Ca K
   - TRACE: 160 nm, 17.1 nm, and 19.5 nm data

SVST Hα data



Feature Tracking

1. outline loop structures
2. extract data along loops
3. generate space-time diagrams
4. deduce projected velocities

movie space-time diagrams

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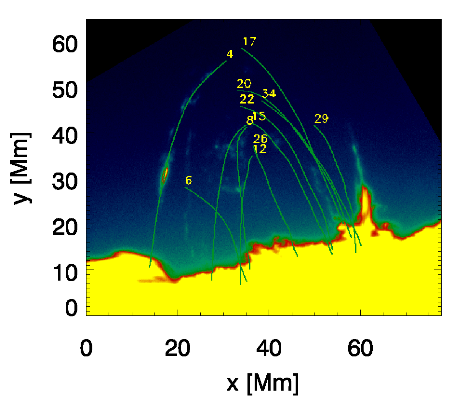

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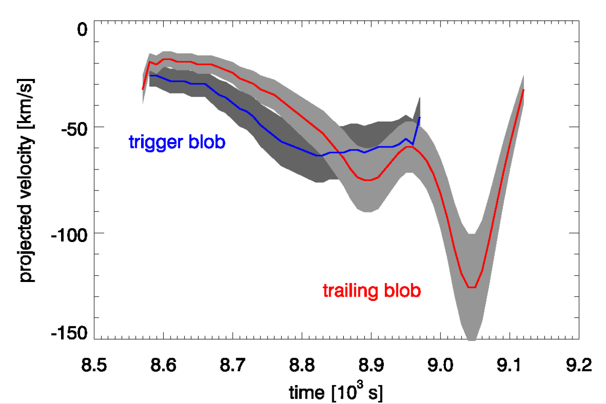
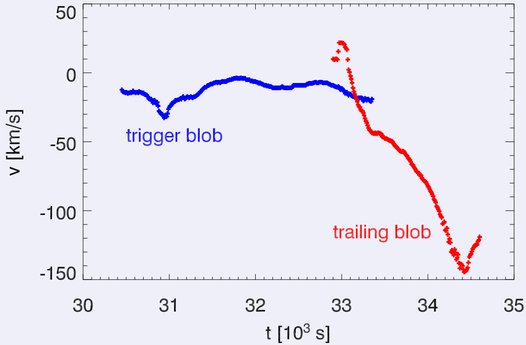
Extracting Velocities: Slow and Fast Blobs

deduced projected velocities (example):



Extracting Velocities: Slow and Fast Blobs

qualitative comparison with model results:



Summary

Conclusions

1. Coronal rain can be naturally explained by thermal instability in loops which are heated in the low corona
2. Many predicted phenomena in good agreement with observations, e.g.
   - Strong brightening seen in “cool” spectral lines
   - Both slow and transonic downflows

Work in progress: use Ca K data to study cooling process down to chromospheric temperatures

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Further Reading

Müller et al., A&A 436, 1064 – 1074 (2005)
De Groof et al., A&A, *in press* (2005) [preprint on A&A web page]

Basic Equations

- mass conservation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial z}(\rho u) = 0$$

- momentum equation

$$\rho \frac{\partial u}{\partial t} + \rho u \frac{\partial u}{\partial z} = -\frac{\partial}{\partial z}(p + \Lambda) - \rho g_{\parallel}$$

- energy equation

$$\frac{\partial}{\partial t}(\rho e) + \frac{\partial}{\partial z}(\rho u e) + (p + \Lambda)\frac{\partial u}{\partial z} = -\frac{\partial F_c}{\partial z} + Q - L_r$$

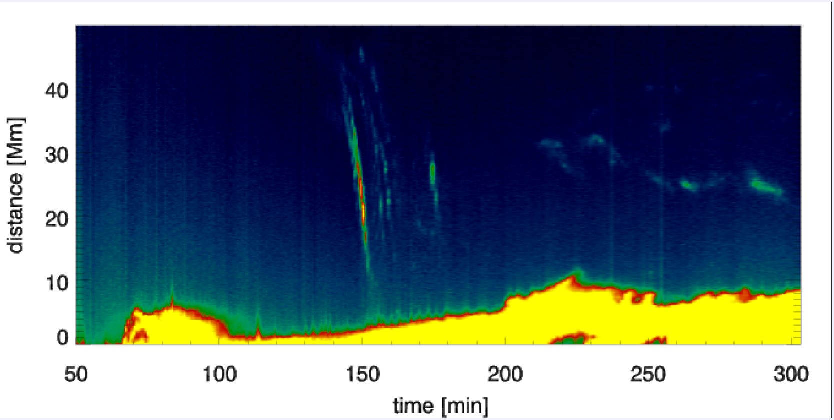
- ionization rate equations

$$\frac{\partial n_{ij}}{\partial t} + \frac{\partial}{\partial z}(n_{ij} u) = n_e \left[n_{ij-1} C_{ij-1} - n_{ij}(C_{ij} + \alpha_{ij}) + n_{ij+1}\alpha_{ij+1} \right]$$

Go back

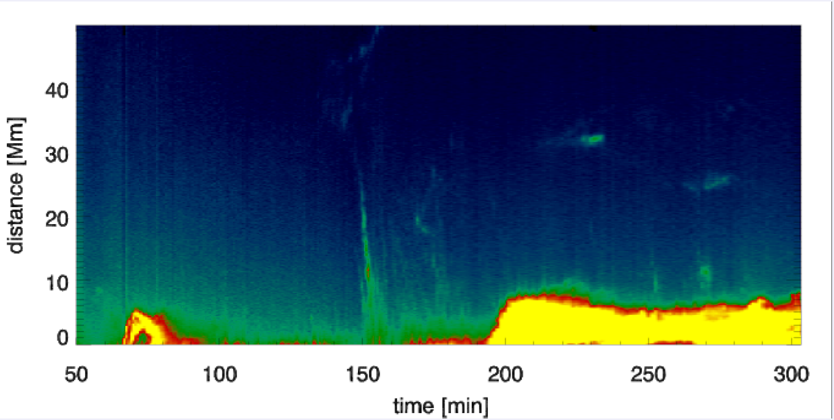
SVST Hα data - Space-Time Diagrams

blue wing: $\lambda_0 - 350\,\text{mÅ}$



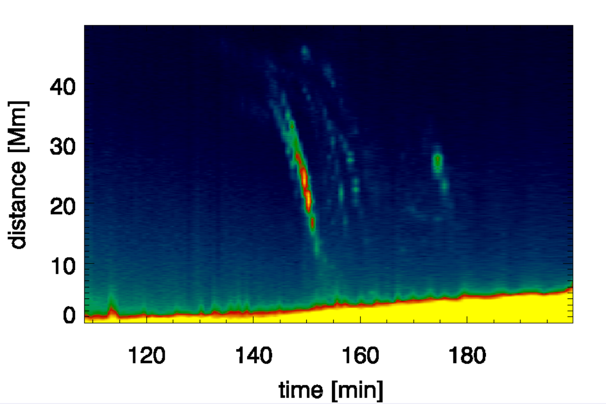
SVST Hα data - Space-Time Diagrams

red wing: $\lambda_0 + 350\,\text{m}\text{Å}$



Extracting Velocities: Slow and Fast Blobs

cutout from $\lambda_0 - 350\,\mathrm{m\AA}$:
slope of tracks = projected velocity, $v = \mathrm{ds}/\mathrm{dt}$



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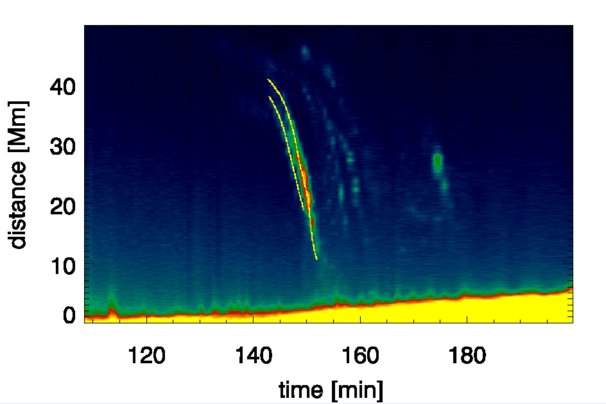

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