Predicting observational signatures of coronal heating by Alfvén waves and nanoflares

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Grotrian, Edlén (1943): correct interpretation of coronal lines
T > 1 MK
>200 times hotter than photosphere

Coronal heating problem

The solar corona

Hinode/XRT
Heating mechanisms

• Alfvén wave model (Alfvén 1947, Uchida & Kaburaki 1974, Wenzel 1974).

  - Alfvén waves can carry enough energy to heat and maintain a corona (Hollweg et al. 1982, Kudoh & Shibata 1999)

  - Waves may be created by sub-photospheric motions or by magnetic reconnection events. They propagate into the corona and dissipate their energy (linear & nonlinear mechanisms)

  - Mode conversion: Alfvén waves convert into longitudinal modes during propagation, which can steepen into shocks and heat the plasma (Moriyasu et al. 2004)
Heating mechanisms

- Both models may explain observed intermittency and spiky intensity profiles of coronal lines (Parnell & Jupp 2000, Katsukawa & Tsuneta 2001, Moriyasu et al. 2004).

How to recognize both mechanisms when they operate in the corona?
Observational facts

- Energy release processes in the Sun, from solar flares down to microflares are found to follow a power law distribution in frequency (Lin et al. 1984; Dennis 1985).

\[
\frac{dN(I)}{dI} \propto I^{-\delta}
\]

- Main contribution to the heating may come from smaller energetic events (nanoflares) if these distribute with a power law index \( \delta > 2 \) (Hudson 1991).

- Studies of small-scale brightenings have shown a power law both steeper and shallower than 2 (Krucker & Benz 1998, Aschwanden & Parnell 2002).

\( \delta \sim 1.4 - 1.6 \)
Purpose

• Propose unique observable signatures of Alfvén wave heating and nanoflare-reconnection heating.
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  convective motions

  reconnection events
Propose unique observable signatures of Alfvén wave heating and nanoflare-reconnection heating. Different characteristics of wave modes along magnetic flux tubes:

- Convective motions
- Reconnection events
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  Different characteristics of wave modes along magnetic flux tubes
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  Different distribution of shocks and strengths in the tubes
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- Different characteristics of wave modes along magnetic flux tubes
- Convective motions
- Reconnection events
- Different distribution of shocks and strengths in the tubes
- Distinctive flow patterns along the tubes
- Distinctive X-ray intensity profiles
- Distinctive frequency distribution of heating events between the models: distinctive power law index
Numerical model

• Initial conditions
  - $T_0 = 10^4$ K, constant
  - $\rho_0 = 2.5 \times 10^{-7}$ g cm$^{-3}$
  - $p_0 = 2 \times 10^5$ dyn cm$^{-2}$
  - $B_0 = 2300$ G, with apex to base area ratio of 1000
  - Hydrostatic pressure balance up to 800 km height. After $\rho \propto (\text{height})^{-4}$ (Shibata et al. 1989)

• 1.5-D MHD code


• Torsional Alfvén waves created by a random photospheric driver. Also monochromatic waves
Nanoflare heating function

\[ \mathcal{H}_i(t, s) = E_0 \sin \left( \frac{\pi (t - t_i)}{\tau_i} \right) \exp \left( -\frac{|s - s_i|}{s_h} \right) \]

\[(t_i < t < t_i + \tau_i)\]

- Artificial injection of energy: we assume only slow modes are created
- Heating events can be:
  - Uniformly distributed along loop
  - Concentrated towards footpoints
- Energies of heating events can follow
  - A uniform distribution
  - A power law distribution
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\[ \frac{dN(E_0)}{dE_0} \propto E_0^{-\alpha} \]

\( \alpha = 1.5 \)
Nanoflare heating function

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Results
Alfvén wave heating

Loop heated uniformly
Satisfies RTV scaling law
(Moriyasu et al. 2004)
Strong slow/fast shocks are ubiquitous in the corona.

Spicules easily created (Kudoh & Shibata 1999)
Alfvén wave heating

High speed flows are obtained

\[ \langle v \rangle \sim 50 \text{ km/s} \]

\[ v_{\text{max}} > 200 \text{ km/s} \]
Alfvén wave heating

Doppler velocities calculated from Fe XV emission line, using CHIANTI atomic database

Red shifts observed at footpoints

Agreement with observations in QS?
Alfvén wave heating

For $<v_{\phi}^2>^{1/2} \gtrsim 1.3$ km/s a corona is created
Alfvén wave heating

- The 100 - 150 s range is the more efficient
- Shorter periods do not carry sufficient energy into the corona (large dissipation)
- Larger periods produce too strong shocks that disrupt energy balance in the corona
Nanoflare heating

**Footpoint**

- Temperature vs. Length along the loop (x 10000 km)
- Time = 0.00 min

**Uniform**

- Temperature vs. Length along the loop (x 10000 km)
- Time = 0.00 min

**Mean Temperature**

- Graph showing mean temperature over length along the loop (x 1000 km)
Nanoflare heating

![Diagram showing temperature and energy flux relationship in Nanoflare heating](image-url)
Nanoflare heating
Nanoflare heating

![Diagram illustrating nanoflare heating](image)

**Graph: Nanoflare heating**

- **Y-axis:** \(<T> \text{ [K]}\)
- **X-axis:** \(<\text{Energy flux}> \text{ [erg cm}^{-2} \text{s}^{-1}]\)

- Scale: Logarithmic

- Data points: Symbols indicate measured values.
Nanoflare heating

<Energy flux> [erg cm\(^{-2}\) s\(^{-1}\)]

\(<T> [K]\)

10 Mm

20 Mm
Nanoflare heating

Conductive flux

\[ F \sim \frac{\kappa_0 T^{7/2}}{S_h} \Rightarrow \frac{T}{T_b} = \left( \frac{S_h}{S_h'} \right)^{2/7} \approx 2 \]
Nanoflare heating

Poloidal Velocity

Footpoint

$\langle v \rangle \sim 15 \text{ km/s}$

$v_{\text{max}} > 200 \text{ km/s}$

Uniform

$\langle v \rangle \sim 5 \text{ km/s}$

$v_{\text{max}} < 40 \text{ km/s}$
Nanoflare heating

Doppler velocities from Fe XV emission line (CHIANTI):

**Footpoint**

**Uniform**

blue shifts at footpoints

Agreement with observations in AR (Hara et al. 2008)
Simulating observations with Hinode/XRT

**Alfvén wave**

**Top of TR**

**Apex**

Ubiquitous strong slow and fast shocks

Height = 12820 km

Height = 31565 km
Simulating observations with Hinode/XRT

Nanoflare footpoint

Small peaks are leveled out

Top of TR

Apex

Height = 8473 km

Height = 31565 km
Simulating observations with Hinode/XRT

Nanoflare uniform

Flattening by thermal conduction

Top of TR

Apex

Height = 8473 km

Height = 31565 km
Intensity histograms

Height = 31565 km
Intensity histograms

Alfvén wave

\[ \frac{dN(I)}{dI} \propto I^{-\delta} \]

Top of TR

\[ \delta = 2.53 \]

\[ \langle \delta \rangle \gg 2 \]
• heating from small dissipative events
• \( \delta \sim \) constant in the corona

Height = 12820 km
Intensity histograms

Nanoflare footpoint

Output: \( \frac{dN(I)}{dI} \propto I^{-\delta} \)

Input: \( \frac{dN(E)}{dE} \propto E^{-\alpha} \)

- \( 1.5 < \langle \delta \rangle < 2 \)
- \( \delta \sim \alpha \) close to footpoints

Top of TR

\( \delta = 1.86 \)

\( \alpha = 1.8 \)

Height = 8473 km
Intensity histograms

Nanoflare uniform

\[ \frac{dN(I)}{dI} \propto I^{-\delta} \]

Top of TR

- \( <\delta> \approx 1 \)
- \( \delta \) decreases approaching apex due to fast dissipation of slow modes & to thermal conduction

\[ \delta = 2.66 \]

\[ <\delta> = -0.78 \]

\[ <T> \approx 1 \times 10^6 \text{ K} \]
# Conclusions

Alfvén wave heating / uniform heating $\rightarrow$ QS loops?

Nanoflare-footpoint heating $\rightarrow$ AR loops?

## Observational signatures

<table>
<thead>
<tr>
<th>Heating model</th>
<th>Mean &amp; max velocities(km/s)</th>
<th>Doppler vel. (Fe XV)</th>
<th>Intensity flux</th>
<th>Mean power law</th>
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</thead>
<tbody>
<tr>
<td>Alfvén wave</td>
<td>$&lt;v&gt; \sim 50$  $v_{\text{max}} &gt; 200$</td>
<td>red shifts $\sim 10$ km/s</td>
<td>bursty everywhere</td>
<td>$&lt;\delta&gt; \sim 2$ constant</td>
</tr>
<tr>
<td>Nanoflare footpoint</td>
<td>$&lt;v&gt; \sim 15$  $v_{\text{max}} &gt; 200$</td>
<td>blue shifts $\sim 30$ km/s</td>
<td>bursty close to TR</td>
<td>$2 &gt; &lt;\delta&gt; \sim 1.5$ decreases</td>
</tr>
<tr>
<td>Nanoflare uniform</td>
<td>$&lt;v&gt; \sim 5$  $v_{\text{max}} &lt; 40$</td>
<td>blue shifts $\sim 10$ km/s</td>
<td>Flat everywhere</td>
<td>$&lt;\delta&gt; \sim 1$ decreases</td>
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Antolin et al. (2008), ApJ 687