Slow mode waves and quasi-periodic upflows in the multi-temperature solar corona as seen by the SDO

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Talk plan

1. Propagating disturbances (PDs) in coronal loops: brief review
2. Surfing transform (ST) technique and SDO AIA data (AR 11082)
3. Measuring temperature-dependent propagation speeds using ST
4. Spatial dependence of PD in the studied fan loop system
5. Statistical analysis of velocity ratios vs sound wave ratios
6. Examples of low-altitude PDs: downward plasma flows
7. Conclusions and open problems
Slow magnetosponic waves in coronal plumes

(a) Polar plumes over the south pole of the Sun as seen in the EIT 171 A;
(b) Radial dependence of the relative density fluctuation (solid line) obtained from a
numerical solution of MHD equations;
(c) Wave amplitude (relative to the background intensity) dependence on the height,
solid line shows the analytical slow mode fit.
Slow magnetisonic waves in coronal loops

Left: intensity map in the Fe XII 195 A line from Hinode/ EIS. Right: Doppler velocity measurements.

In-phase relation between Doppler shift and intensity oscillations.
Waves or periodic upflows?

Hinode / XRT image of the studied AR NOAA 10942

Temporal evolution of the line peak intensity, Doppler shift, non-thermal width, and R–B asymmetry of the Fe XII195 A line. The arrow points to an isolated strong upflow event.
Longitudinally propagating arc wave in the pre-onset optical aurora


(a) Optical aurora

(b) Magnetotail

(c) Electric field

(d) Plasma beta

(e) Waves signal W(t)
Surfing transform (ST)

\[
a_S(t, v) = \frac{v}{L} \int_t^{t+L/v} a(x = x_S, t') dt'.
\]

- \( t \) — starting time
- \( x_S = v \times (t' - t) \) — averaging path
- \( L \) — propagated distance
- \( v \) — surfing velocity
ST of 1-dimensional harmonic wave oscillation

\[
a_S(t, v) = \frac{v}{L} \int_t^{t+L/v} a_0 \cos \left( k_0 v \times (t' - t) - \omega_0 t' \right) dt'
\]

\[
= \frac{a_0 v}{L(k_0 v - \omega_0)} \left\{ \sin \left( [k_0 v - \omega_0] [t + L/v] - k_0 vt \right) - \sin \left( [k_0 v - \omega_0] t - k_0 vt \right) \right\}
\]

\[
= a_0 \frac{\sin(\xi)}{\xi} \cos \left( \omega_0 t + \xi \right) \quad \text{with} \quad \xi = \frac{L(k_0 v - \omega_0)}{2v},
\]

\[
\text{used the identity } \sin(\alpha) - \sin(\beta) = 2 \sin\left( \frac{\alpha - \beta}{2} \right) \cos\left( \frac{\alpha + \beta}{2} \right)
\]

dispersionless case

phase speed \( v_0 = \omega_0/k_0 \)
velocity detuning parameter \( \xi = L\omega_0(v - v_0)/(2vv_0) \)
\( v \rightarrow v_0 \)
\( \xi \rightarrow 0 \)
\( a_S(t, v) \rightarrow a_0 = \max (a_S) \) \( \text{velocity resonance} \)
ST spectrum

\[ P_S(f, v) = \frac{\nu}{L} \left| \int_{-\infty}^{\infty} \int_{t}^{t+L/v} a(v \times (t' - t), t') e^{-i2\pi ft} dt' dt \right|^2 \]

Velocity spectrogram

\[ P_S(v, f = f_0) = P_0 \text{sinc}^2 \left( \frac{L\omega_0(v - v_0)}{2\nu v_0} \right) \]

reaches maximum at \( v = v_0 \)
(a) Extraction of the ST signal from a position-time plot. Dashed lines show the fronts of a periodic PD described with phase speed $v_0$, solid line is the averaging path defined by the surfing speed $v$ and the starting time $t$, $L$ is the size of the studied region. (b) Position-time plot of the simulated noisy wave signal defined by Eq. (5). (c) Surfing signals obtained using three values of $v$ matching the phase speeds of the wave components. (d) ST spectrum computed using 400 ST signals covering the velocity range $-200 \ldots 200$ km/s. (e) Velocity spectrograms representing horizontal sections of the ST spectrum at $f_0 = 5.00$ mHz (dotted blue line) and $f_0 = 3.3$ mHz (solid black line).

\[
a(x, t) = \sum_{i=1}^{3} a_0 \cos(k_i x - \omega_i t) + \sigma \zeta_{x, t}
\]

\[
[\omega_1, \omega_2, \omega_3]/(2\pi) = [5.00, 3.33, 3.33] \text{ mHz}
\]

\[
[v_1, v_2, v_3] = [-100, 50, 120] \text{ km/s}
\]

\[k_i = \omega_i/v_i\]
(a) A snapshot of the active region NOAA AR 11082 as seen in the 171 A SDO AIA channel at 7:00:00 UT. The dashed white lines show the domain of the most consistent PD activity. The solid green lines outline the region of detectable slow wave activity. (b) Multi-spectral AIA images of the same region obtained at around the same time; temperatures values are for the peaks of the response functions based on the 2013 release of the CHIANTI atomic database (Dere et al. 1997; Landi et al. 2013).
$$a(x, t) = I(x, t) - I(x, t-60s)$$

$$a_s(t, v=v_0)$$

$$P_s(v, f=f_0), \text{ all fronts}$$

$v_0=58\pm3\text{ km/s}$
$L=10\pm1\text{ Mm}$

$v_0=92\pm2\text{ km/s}$
$L=22\pm2\text{ Mm}$

$v_0=114\pm8\text{ km/s}$
$L=20\pm3\text{ Mm}$

$v_0=138\pm21\text{ km/s}$
$L=17\pm8\text{ Mm}$
$v \sim 90-110$ km/s: consistent with previous measurements


3-5 min period: p-mode oscillation?
Velocity ratios measured for the entire wave event and two selected fronts, as compared to the predicted sound speed ratios.

<table>
<thead>
<tr>
<th>Wavelength</th>
<th>All fronts</th>
<th>Selected fronts</th>
<th>Predicted</th>
</tr>
</thead>
<tbody>
<tr>
<td>131 Å</td>
<td>0.63 ± 0.03</td>
<td>0.86 ± 0.04</td>
<td>0.79</td>
</tr>
<tr>
<td>171 Å</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>193 Å</td>
<td>1.23 ± 0.08</td>
<td>1.31 ± 0.06</td>
<td>1.34</td>
</tr>
<tr>
<td>211 Å</td>
<td>1.50 ± 0.23</td>
<td>1.50 ± 0.15</td>
<td>1.42</td>
</tr>
</tbody>
</table>
Example of downwardly propagating PDs

- Wave front
- $v \sim \text{const of a projected distance of } \sim 35 \text{ Mm}$
- Downward fronts or flows, $v \sim 5-10 \text{ km/s}$

- PSD, arb.units
  - $T = 320.0 \text{ s}$
  - $V = 90.0 \text{ km/s}$
  - No detectable PDs for $v < 0$
Conclusions

(1) We have presented a new methodology for measuring parameters of PDs in multi-temperature coronal images based on the ST technique.

(2) The developed methodology has been applied to the analysis of PDs in coronal fan loops in AR 11082 across a range of temperatures covered by four SDO AIA channels.

(3) We found that traveling velocity of the disturbances propagating along the studied system of loops obeys an approximate square root temperature dependence predicted for slow mode magneto-acoustic waves which seems to be the dominating wave mode in the studied loop structures.

(4) Our slow-mode observations extend recent findings by Kiddie et al (Solar Pys 2012) by demonstrating temperature-dependent PD activity simultaneously in four AIA channels in a non-sunspot active region.

(5) Closer to the base of the corona, we observed occasional downwardly directed PDs with a significantly lower velocity, possibly associated with bulk plasma flows.

(6) It remains to be clarified whether or not the magnetosonic wave activity at higher altitudes is driven by (partially undetected) fast plasma flows at the base of the corona as has been proposed by some authors (Tian et al. 2011b,a; Warren et al. 2011; Ugarte-Urra & Warren 2011; Su et al. 2012; Ofman et al. 2012).
The wave - flow dilemma


- **Flows**: Tian et al. 2011b,a; Warren et al. 2011; Ugarte-Urra & Warren 2011; Su et al. 2012; …

- **Wave-flow interaction**: De Pontieu and McIntosh, 2010; Nishizuka & Hara 2011; Ofman et al. 2012; …

- **Counter-propagating flows**: Kamio et al. 2011; Young et al. 2012, …
ST analysis of simulated wave signals in four SDO AIA channels. Left: time-differenced position-time plots of a harmonic wave signal in the 171 °A channel. Right: velocity spectrograms obtained for each channel; the phase speed of the wave is adjusted to the temperature the channel assuming that the wave is slow magnetosonic. Color coding: 131 A - blue, 171 A - red, 193 A - green, 211 A - gray. Black curves are least-square fits using the theoretical model (4), solid (dashed) vertical lines are the measured (predicted) propagation velocities for each channel. The amount of additive noise increases from top to bottom as shown by the provided power signal-to-noise ratios (S/N). The tilted red lines on the left panels show the phase speeds and wave periods measured at 171 °A.
<table>
<thead>
<tr>
<th>#</th>
<th>slices</th>
<th>PD period, s</th>
<th>log f-range</th>
<th>PD velocity, km/s</th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>131A</td>
</tr>
<tr>
<td>0</td>
<td>0-4</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>1</td>
<td>5-9</td>
<td>470</td>
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<td>47 ± 3</td>
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<td>49 ± 6</td>
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<tr>
<td>9</td>
<td>45-49</td>
<td>276</td>
<td>1.2</td>
<td>–</td>
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