Travel-time Magnetoseismology

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Acknowledgments: MHD simulation results are provided by Dong-Hun Lee.
The Scientific Question

- How do the impulse-induced perturbations propagate in the magnetosphere?
- How can such knowledge help us estimate the state of the magnetosphere?
# Three Seismologies, Two Methods

<table>
<thead>
<tr>
<th></th>
<th>Seismology</th>
<th>Helioseismology</th>
<th>Magnetoseismology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Travel-time</strong></td>
<td><img src="image1" alt="Earthquake" /></td>
<td><img src="image2" alt="Sunspot data" /></td>
<td><img src="image3" alt="Impulsive Events" /></td>
</tr>
<tr>
<td><strong>Normal-mode</strong></td>
<td><img src="image4" alt="Globes" /></td>
<td><img src="image5" alt="Normal-mode" /></td>
<td><img src="image6" alt="Field Line Resonances" /></td>
</tr>
</tbody>
</table>

*Figure: Travel-time normal-mode seismology, showing Earthquake and Sunspot data.*
### Scale Lengths Associated with Magnetoseismology

#### Dayside impulses

![Dayside impulses](image1)

#### Scale Comparison

<table>
<thead>
<tr>
<th></th>
<th>Earth &amp; Seismic Waves</th>
<th>Magnetosphere &amp; MHD Waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radius</td>
<td>6400 km</td>
<td>~64,000 km (sunward)</td>
</tr>
<tr>
<td>Wave speed</td>
<td>1-14 km/s</td>
<td>300-10,000 km/s</td>
</tr>
<tr>
<td>Wave-length</td>
<td>~10^0 km</td>
<td>10^4-10^5 km</td>
</tr>
<tr>
<td>Scale length of ∇V</td>
<td>Typically ≥ 10^3 km</td>
<td>Typically ≤ 2×10^4 km</td>
</tr>
</tbody>
</table>

Can’t use ray tracing in magnetoseismology !!!
Tamao’s Model of Impulse Propagation via MHD Waves

**Compressional Mode:**
- Propagates in all directions
- Suffers geometrical attenuation (~ 1/r)

**Alfven Mode:**
- Propagates along magnetic field line
- Wave energy conserved

“Tamao travel path” : preserves most wave energy

Tamao [1964a]
Impulse Travel Time Predicted by Tamao’s Model
Simulation of Sudden Impulse Propagation via MHD Waves

Alfvén speed

$\delta B_v$

Arrival Time & Onset Time

(Simulation made by Dong-Hun Lee)
Currents Associated with the Compression

MHD waves

Tamao [1964b]

Kikuchi and Araki [1979]; Kikuchi et al. [1996]
Propagation of Impulse Front (Onset)

- It is argued that the Earth-ionosphere waveguide model is evidenced by the simultaneous onset time seen on the ground across all latitudes.

\[ \delta B \]

Onset will be seen across all latitudes on the ground within \(~10\) sec (without the need of Earth-ionosphere wave guide)!
Propagation of Impulse

Conventional (static) View

Dynamics View

(a) t ~ 40 sec

(b) t ~ 90 sec
MHD Simulation on Ionospheric Currents due to Impulse

Plasmapause Latitude
Tremors (quakes) in space

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Density Model and Inversion

Tamao Model of Wave Propagation

\[ t_{Tamao} \equiv \int_{\text{shortest path to field line}} \frac{ds}{V_f(r)} + \int_{\text{field-aligned}} \frac{ds}{V_A(r)} \]

Density Function

\[ n = \begin{cases} 
  n_{mp} \left( \frac{L_{mp} R_E}{r} \right)^{m_1} & \text{if } L > L_{pp}, \\
  n_{pp} \left( \frac{L_{pp} R_E}{r} \right)^{m_2} & \text{if } L \leq L_{pp} 
\end{cases} \]

Nonlinear optimization

\[ \chi^2 = \sum_i \left( \frac{t_{i, \text{observed}} - t_0 - t_{i, \text{Tamao}}}{\sigma_i} \right)^2 \]

Parameters to solve: \( (t_0, n_{mp}, m_1, L_{pp}, n_{pp}, m_2) \)

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Density Profile Estimated through Magnetoseismic Inversion

In situ observations by Akebono also suggest that the plasmapause $L_{pp} \sim 3.5$ prior to the SI event.
Polar’s Observation of Impulse Time

- Estimated Start time: **2344:20 UT**
- Calculated travel time from impact location to Polar: **48.4 sec**
- Observed arrival time at Polar: **2345:08 UT**
Tamao’s travel path:
1. From low L to high L
2. From high L to low L
Test of Inversion: Using Artificial Data

Artificial Data:
- 10 imaginary observations equally spaced between 6 and 24 in L-value (all outside the plasmasphere)
- Timing uncertainty: 5 sec
- Arrival time consistent with Tamao travel time

Models:
- Magnetic Field: T89
- Plasma:
  \[ n = \frac{n_{sh}}{1 - \exp^{-L/12}} \]
  \[ T = \frac{T_{sh}}{1 - 0.5 \exp^{-L/12}} \]

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<tr>
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<th>True Value</th>
<th>Estimation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_0 ) [sec]</td>
<td>0.0</td>
<td>0.2 ± 10.0</td>
</tr>
<tr>
<td>( L_S )</td>
<td>15.0</td>
<td>15 ± 0.1</td>
</tr>
<tr>
<td>( n_{sh} ) [a.m.u./cm^3]</td>
<td>0.60</td>
<td>0.60 ± 0.09</td>
</tr>
<tr>
<td>( T_{sh} ) [eV]</td>
<td>3000</td>
<td>2980 ± 800</td>
</tr>
</tbody>
</table>
Polar-THEMIS Joint Observations for Magnetoseismic Studies

- THEMIS will deploy five satellites near the equatorial plane.
- Magnetoseismic inversion can take advantage of all satellite observations, but it favors the observations distributed across different regions.
- Polar can provide joint observations at high latitudes, giving critical timing records for Alfvén wave propagation.