Helios Observations of Quasiperiodic Density Structures in the Slow Solar Wind at 0.3, 0.4, and 0.6 AU

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Solar wind formation is chunky and quasiperiodic
Quasiperiodic density structures below and above sonic and Alfvénic transitions

Acceleration proportional to expansion => periodicity is the same at all heights
The density in the upper corona is highly structured in space and time.

COR2 deep field exposures show quasiperiodic density structures released on smaller timescales too - scales that have been identified in L1 solar wind data. [e.g. Viall et al. 2008; Viall et al. 2009; Kepko et al. 2002]
Magnetic reconnection at the open-closed boundary of the corona is one source of time dynamics in the solar wind
Magnetic reconnection at the open-closed boundary creates magnetic structures and flux ropes.
Solar wind density structures formed in the corona are associated with magnetic field boundaries. Density is what we see in white light and what drives magnetosphere.
90-minute quasiperiodic at L1 was formed by reconnection in corona has 20-minute embedded periodicity
Dynamic pressure drives global magnetospheric oscillations at the same frequencies

Kepko et al 2016
‘Quiescent’ Solar Wind has Quasiperiodic Density (Dynamic Pressure) changes that drive Periodicities in Earth’s Magnetic Field (half of time)

Magnetospheric oscillations -> radiation belt dynamics (e.g. Mann et al. 2016), precipitating electrons (Kepko et al. 2002). Now a GEM working group to look into this.
If the structures at L1 are the same as those released at Sun (at least sometimes they are), then we should see them inside of 1 AU in Helios (Di Matteo et al, 2019; Stansby & Horbury 2018; Stansby et al. 2018)
<table>
<thead>
<tr>
<th>Event</th>
<th>Periodicity (Frequency) Visual Inspection</th>
<th>Frequency (Periodicity) MTM</th>
<th>Source region</th>
<th>HCS crossing/ Mapped to HCS</th>
<th>Temperature</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>≈31 min (≈0.54 mHz)</td>
<td>≈0.53 mHz (≈31.5 min)</td>
<td>AR and CH extension</td>
<td>No/Near</td>
<td>Hotter ($T_{ij}$)</td>
<td>/</td>
</tr>
<tr>
<td>2</td>
<td>≈120 min (≈0.14 mHz)</td>
<td>≈0.16 mHz (≈104 min)</td>
<td>CH</td>
<td>Yes/Yes</td>
<td>Hotter (both)</td>
<td>/</td>
</tr>
<tr>
<td>3</td>
<td>≈112 min (≈0.15 mHz)</td>
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<td>AR and CH extension</td>
<td>No/Near</td>
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</tr>
<tr>
<td>4</td>
<td>≈74 min (≈0.23 mHz)</td>
<td>≈0.20 mHz (≈83 min)</td>
<td>Lacking source data</td>
<td>Yes/Yes</td>
<td>Hotter (both)</td>
<td>Flux rope</td>
</tr>
<tr>
<td>5</td>
<td>≈5.8 hr (≈0.05 mHz)</td>
<td>Lacking continuous data</td>
<td>AR and CH extension</td>
<td>No/Far</td>
<td>Hotter (both)</td>
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</tbody>
</table>

**October 18 1975**

**April 14 1977**

**May 3 1980**

**June 9 1980**

**June 1981**

<table>
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<tr>
<th>Date</th>
<th>Values</th>
<th>Hotter/Flux rope</th>
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<tbody>
<tr>
<td>October 18 1975</td>
<td>0.59</td>
<td></td>
</tr>
<tr>
<td>April 14 1977</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>May 3 1980</td>
<td>0.58</td>
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<tr>
<td>June 9 1980</td>
<td>0.39</td>
<td></td>
</tr>
<tr>
<td>June 1981</td>
<td>0.30</td>
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Periodic density structures (100-minute 12-minute) in Helios data at 0.37 AU are created in solar corona

Density changes concurrent with B field changes (often pressure balance structures) and temperature changes, which are washed out by 1 AU
Periodic density structures (80-minute 30-minute) in Helios data at 0.39 AU are created in solar corona

Flux rope and at HCS like the simulation predictions
Periodic density structures (5-hr 120-minute) in Helios data at 0.31 AU are created in solar corona

Away from the HCS, prediction of S-web/interchange reconnection (Antiochos et al. 2011) T anisotropies in both directions of a factor of a few
Tpar/Tperp large - approaching 10
Pressure balance structures

Sam Wallace
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<tr>
<td>2</td>
<td>≈120 min (=0.14 mHz) ≈33 min (=0.51 mHz)</td>
<td>≈0.16 mHz (=104 min) ≈1.47 mHz (=11 min) ≈3.58 mHz (=4.7 min)</td>
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<td>3</td>
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<td>≈0.13 mHz (=128 min) ≈1.83 mHz (=9 min)</td>
<td>AR and CH extension</td>
<td>No/Near</td>
<td>Hotter ($T_{ij}$)</td>
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<td>May 3 1980</td>
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<td>≈0.20 mHz (=83 min) ≈0.57 mHz (=29 min) ≈1.55 mHz (=11 min)</td>
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<td>Hotter (both)</td>
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Temperature: Hotter ($T_{ij}$)

Other: Flux rope
The Magnetosphere exhibits global oscillations under ‘quiescent’ solar wind conditions that are directly caused by how the solar wind was released four days earlier.

Cannot observe dynamic evolution in this range.

Everything is to scale on this chart.
Questions for PSP:

- Trains of quasiperiodic density structures in which many of the boundaries will have alpha, T, or T anisotropy, or B changes. Not often are all present for the entire train of structures. Even at Helios, this could be an evolution effect, so:

  - What do these look like (alphas, T, T anisotropy, B, V) when they first come out?!
  - How rapidly do they evolve, and which parameters evolve (e.g. proton density is responding to pressure balance but alphas and B rotations don’t have to)?
  - How much of first two is due to the physics of release (magnetic reconnection) vs the physics of acceleration?
  - How does white light ‘density structure’ compare to in situ ‘density structure’
  - How much of the solar wind is filled with reconnection-released solar wind?
Extra
- Periodic radial length-scales in solar wind number density appear at different frequencies, depending on solar wind speed

- Bimodal velocity distribution (solar min) or continuum (solar max) leads to occurrence enhancements at particular frequencies

- Occurrence enhancements near $f = 0.7, 1.4, 2.0,$ and $4.8$ mHz are statistically significant at the three-sigma level for the majority of the SW intervals

- Occurrence enhancements near $f = 1.0, 1.5, 1.9, 2.8, 3.3$ and $4.4$ mHz are statistically significant in a majority of the magnetospheric intervals

- We find occurrence enhancements near $f = 2, 3$ and $4.8$ mHz in the majority of both our solar wind and our magnetospheric occurrence distributions

- The magnetosphere oscillates through many mechanisms; these results suggest that one important mechanism is solar wind direct driving
- Proton density: 5-10 cm\(^{-3}\)
- Medium speed: 450-500 km/s
- Magnetic field direction is highly variable
- Ortho-Parker Spiral during event – green horizontal lines indicate Parker spiral angle
- \(A_{\text{He}}\) is overabundant: Predicted value is \(\sim 4\%\); 6-10\% is observed
- Empirical \(A_{\text{He}}\) relation does not predict periodicities in \(A_{\text{He}}\) during this event; in other words, the proton speed is nearly constant