Closed vs. Open Fields

Coronal Holes

Corona = low beta plasma
$\beta \ll 1$
Magnetically dominated region

$\beta = \frac{nKT}{B^2/2\mu_0} = \frac{\rho_{gas}}{\rho_{mag}}$
Closed vs. Open Fields

Closed Field: Streamer Belt

Total Solar Eclipse: August 21st, 2017
Image Credit: Shadia Habbal, Peter Aniol
Image Processing: Milos Druckmuller
Fast Solar Wind

**Speed:** \( v > 600 \text{ km/s} \) (approx.)

**Origin (well established):** Open Field, Coronal Holes (e.g., McComas+ 2003)

**Acceleration:** Accelerated by gradients in the Alfvén wave pressure and heated by Alfvén wave dissipation (van der Holst+ 2014 and references therein)

Traditional bimodal classification based on speed: Fast or slow
Traditional bimodal classification based on speed: Fast or slow

Solar Wind: Origin & Acceleration

**Slow** Solar Wind
**Speed:** \( v < 500 \text{ km/s} \)
**Origin (debated):** Closed field corona? Coronal Hole boundaries?
The debated origin of the slow solar wind has resulted in different theories for how it is accelerated.
Challenging the traditional bimodal paradigm of solar wind: Separating populations of solar wind based on origin and composition, rather than speed.
“Fast” solar wind

In situ observations show:

- Approximately steady, some Alfvénic turbulence
- Low electron temperature and density
- Low Fe/O – similar to that observed in photosphere
- **No FIP effect:** i.e., has more elements with high First Ionization Potential (elements that are not easily ionized, i.e., C)

**Speed:** $v < 600$ km/s
**Origin:** Coronal holes (e.g., McComas+ 2003)
"Slow" solar wind

In situ observations show:

- Not steady!
- Generally found surrounding HCS
- High electron temperature and density
- High Fe/O – similar to corona
- **FIP effect**: i.e., slow wind has more elements with low First Ionization Potential (elements that are easily ionized, i.e., Mg, Fe)

**Speed**: $v < 500 \text{ km/s}$ (approx.)

**Origin**: Closed field corona (Antiochos+ 2011)

![Image of solar wind](SDO AIA Fe XII 193 Å)
In situ observations show:

- Low electron temperature and density
- Low to intermediate Fe/O
- **No FIP effect:** i.e., has more elements with **high** First Ionization Potential (elements that are not easily ionized, i.e., C)

**Speed:** \( v < 600 \text{ km/s} \)

**Origin:** Coronal Hole Boundaries (Stakhiv+ 2015, 2016)
Solar Wind: Origin & Acceleration

- **Origin**: Deep inside coronal holes – continuously open magnetic field lines
- **Composition**: Fe/O ~ 1 (low), no FIP effect, similar to photosphere
- **Speed**: “Fast” \( v > 600 \text{ km/s} \)
- **Acceleration**: Accelerated by gradients in the Alfvén wave pressure and heated by Alfvén wave dissipation (van der Holst+ 2014 and references therein)
Solar Wind: Origin & Acceleration

**Origin:** Closed field corona

**Composition:** Fe/O ~ 3-4 (high), **FIP effect**, similar to corona

**Speed:** “Slow” $v < 500$ km/s

**Acceleration:** Slow wind is released (and accelerated) by opening of closed flux, interchange reconnection along **S-web arcs** (Fisk 2003, Antiochos+ 2011), but evidence for wave acceleration (Stakhiv+ 2016)
Solar Wind: Origin & Acceleration

Origin: Coronal hole boundaries
Composition: no FIP enhancement
Speed: Large range (Stakhiv+ 2015, 2016)! $v < 600 \text{ km/s}$
Acceleration: Same mechanism as fast solar wind (since open field lines) – Alfvén wave pressure gradients. Wind at the boundary is slowed down by field line expansion, measured by magnetic expansion factor (Wang & Sheeley, 1990, 1996)
Magnetic Expansion Factor - \( f_s \)

Measures the rate at which an Earth-directed flux tube expands in cross section between the photosphere and the source surface, as compared with a purely radial \((1/r^2)\) expansion.

\[
\begin{align*}
    f_s &= \left( \frac{R_\odot}{R_s} \right)^2 \left( \frac{B^P(R_\odot)}{B^P(R_s)} \right) \\
    B^P(R_\odot) &: \text{field strength at point P at photosphere} \\
    B^P(R_s) &: \text{field strength at point P at source surface}
\end{align*}
\]

\( R_s = 2.5 \)

\( R_\odot = 1 \)

WS (Wang & Sheeley) Model

\[
V_{WS} = 285 + \frac{650}{f_s^{5/9}}
\]

Derived solar wind speed based solely on magnetic expansion factor
Magnetic expansion factor \((f_s)\) and solar wind speed \((v_{sw})\) are inversely related.

Deep inside coronal holes:
Low \(f_s\), high \(v_{sw}\)

At coronal hole boundaries:
High \(f_s\), low \(v_{sw}\)

Wang & Sheeley, 1990

Figure from: Banaszkiewicz+ 2004
**Input:** Observed Photospheric Field

**Output:** Derived Coronal Holes (1.0 Rs), Solar wind speed, etc.

Updated solar wind velocity relation:

$$ V(f_s, \theta_b) = 285 + \frac{625}{(1 + f_s)^2} \left[ 1.0 - 0.8e^{-(\theta_b/2)^2} \right]^3 $$

where $\theta_b$ is the minimum angular distance that an open field footpoint lies from the nearest coronal hole boundary.

**WSA model**

Problems with $f_s$?

Recent research questions the physical role played by $f_s$ inside pseudostreamers.

(Riley+ 2015, Riley & Luhmann 2012)

Pseudostreamer:
Formed between coronal holes of same magnetic polarity – can limit field line expansion.
It is unclear whether $f_s$ plays a *physical* role in solar wind acceleration in the open field corona, or serves as a *proxy* that distinguishes between slow and fast solar wind.

**Project:**

1) Does the magnetic expansion factor ($f_s$) play a role in acceleration of the solar wind that emerges from the open field corona?
   
   a) Near coronal hole boundaries (boundary wind)
   
   b) Future work: Deep inside coronal holes (fast wind)

**Approach:**

1) Identify periods where spacecraft (ACE, STEREO A & B) are magnetically connected to pseudostreamerms using WSA.

2) Perform a statistical analysis comparing $f_s$ with observed solar wind speed.
Methodology: Identifying Pseudostreamers

1) Use WSA output to identify periods when satellites are magnetically connected to pseudostreamers.

2) Look for periods where the model-predicted and observed solar wind speed match well.

CR 2062: Oct – Nov. 2007
WSA model output derived from ADAPT-VSM photospheric maps

Derived Coronal Holes

- Polarity
  - Outward (+)
  - Inward (-)

- Solar wind from pseudostreamer leaves Sun on 11/03/2007
- Solar wind arrives at Earth on 11/8/2007
Methodology: Identifying Pseudostreamers

3) Identify the pseudostreamer and obtain the footpoint location, latitude $= \theta_{ph}$, longitude $= \phi_{ph}$, of the field lines.

Using this information, we can track the exact parcel of solar wind that left the pseudostreamer, and obtain the date/arrival time of solar wind at the specified spacecraft.
Magnetic topology of pseudostreamers can vary from one side of the cusp to the other.

<table>
<thead>
<tr>
<th>Field line NOT grounded in active region</th>
<th>Field line grounded in active region</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time of solar wind arrival at STEREO-A</strong></td>
<td><strong>Time of solar wind arrival at STEREO-A</strong></td>
</tr>
<tr>
<td>July 17th, 2014 10:03:04 am</td>
<td>July 17th, 2014 12:56:44 pm</td>
</tr>
<tr>
<td><strong>v_s</strong> (km/s)</td>
<td>321</td>
</tr>
<tr>
<td><strong>f_s</strong></td>
<td>14.8750</td>
</tr>
<tr>
<td>**</td>
<td>B</td>
</tr>
</tbody>
</table>

\[ f_s = \left( \frac{R_\odot}{R_s} \right)^2 \left( \frac{B^p(R_\odot)}{B^p(R_s)} \right) \]
Solar wind speed vs. $f_s$ for individual field lines forming pseudostreamer cusps

Pearson Correlation Coef: -0.0672
Field lines not grounded in an active region

\[ |B| < 20 \text{ G} \]

Pearson Correlation Coef: 0.0795
Current Results & Future Work

<table>
<thead>
<tr>
<th>Pearson Correlation Coefficient</th>
<th>Sample size (# of field lines)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Field Lines</td>
<td>-0.0672</td>
</tr>
<tr>
<td>Active Region</td>
<td>-0.3594</td>
</tr>
<tr>
<td>No Active region</td>
<td>0.0795</td>
</tr>
</tbody>
</table>

- Sampled 37 pseudostreamers in total
- There appears no correlation between $f_s$ and $v_{sw}$ at coronal hole boundaries.
- The inverse $f_s - v_{sw}$ relationship may not be wrong, but just not applicable at coronal hole boundaries.
- **Future work:** Look at compositional signatures of pseudostreamers
- **Future work:** Correlation of $f_s$ and $v_{sw}$ for solar wind emerging along continuously open magnetic field lines *deep inside* a coronal hole.
Thank you!

Questions?
Extra slides
Stakhiv+ 2016

Elemental Abundance: Fe/O

Differential Velocities

Temperature Ratio

Proton Density

Proton Specific Entropy

ACE observations

SLOW

v < 500 km/s

FAST

v < 500 km/s

Closed Corona

Short Lived Loops

OPEN: Coronal Hole Boundaries

OPEN: Deep Inside Coronal Holes

High FIP

Intermediate FIP

Low FIP