Tracing Heliospheric Structures to Their Solar Origin

Robert Wimmer-Schweingruber
wimmer@physik.uni-kiel.de
Christian Albrechts University Kiel
Kiel, Germany
for the Solar Orbiter Team
Tracing Heliospheric Structures to Their Solar Origin

The Problem
What can we measure?
Linkage...
The End
The Problem

How does the Sun create and control the Heliosphere – and why does solar activity change with time?

1) What drives the solar wind and where does the coronal magnetic field originate from?
2) How do solar transients drive heliospheric variability?
3) How do solar eruptions produce energetic particle radiation that fills the heliosphere?
4) How does the solar dynamo work and drive connections between the Sun and the heliosphere?
Remote-sensing windows (10 days each)

High-latitude Observations

Perihelion Observations

High-latitude Observations

What can we measure?

- Magnetic field on the Sun (PHI)
- Hydrogen density (EUI, METIS)
- Helium density (EUI)
- Composition on disk (SPICE)
- LOS flow velocities (SPICE, PHI)
- He/H in corona (EUI & METIS)
- Turbulence in corona (EUI, SoloHI)
- Eruptive events (EUI, METIS, PHI, SoloHI, STIX)
Remote-sensing windows (10 days each)

High-latitude Observations

What can we measure?

TRC (Bonnet et al, 1980)

SDO/AIA

PROBA2/SWAP

H Lyman alpha  121.6nm chromosphere

He II  30.4nm transition region

Fe IX, X, XI ~ 17nm low corona
Remote-sensing windows (10 days each)

EIT | HECOR | SCORE

H Lyman alpha  121.6nm chromosphere
He II  30.4nm transition region
Fe IX, X, XI ~ 17nm low corona

Courtesy F. Auchere  
 Courtesy S. Finesschi
Remote-sensing windows (10 days each)

FSI & METIS: 30.4 @ 0.28 AU

Perihelion Observations

High-latitude Observations

What can we measure?

EUI: SP+
Perihelion Observations

Remote-sensing windows (10 days each)

High-latitude Observations

What can we measure?

- Magnetic field on the Sun (PHI)
- Hydrogen density (EUI, METIS)
- Helium density (EUI)
- Composition on disk (SPICE)
- LOS flow velocities (SPICE, PHI)
- He/H in corona (EUI & METIS)
- Turbulence in corona (EUI, SoloHI)
- Eruptive events (EUI, METIS, PHI, SoloHI, STIX)
Remote-sensing windows (10 days each)

High-latitude Observations

**What can we measure?**

<table>
<thead>
<tr>
<th>Property</th>
<th>remotely</th>
<th>In situ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field</td>
<td>PHI (disk, low corona)</td>
<td>MAG, (SWA)</td>
</tr>
<tr>
<td>H &amp; He density</td>
<td>EUI, METIS (corona)</td>
<td>SWA, (SPC)</td>
</tr>
<tr>
<td>Composition</td>
<td>SPICE (disk)</td>
<td>SWA</td>
</tr>
<tr>
<td>LOS flow velocities</td>
<td>PHI, SPICE (disk)</td>
<td></td>
</tr>
<tr>
<td>Turbulence</td>
<td>EUI, Solo-HI (corona)</td>
<td>MAG, RPW, SWA</td>
</tr>
<tr>
<td>Eruptive events</td>
<td>EUI, METIS, PHI, Solo-HI, STIX</td>
<td>EPD, MAG, RPW, SWA</td>
</tr>
</tbody>
</table>
SPICE, EUI, and PHI-high-res field of view at perihelion
3% of disk at perihelion:
- approx. 18 degrees as seen from Sun center
- apparent solar rotation rate at perihelion is ~ 6°/day
- thus, same source region remains in box for ~ 3 days
- typical travel time: $60 \frac{r_{\text{sun}}}{400 \text{ km/s}} = 1.25 \text{ days}$
- typical travel time: $60 \frac{r_{\text{sun}}}{300 \text{ km/s}} = 1.6 \text{ days}$

Mapping the origin of the solar wind looks feasible if it comes the disk center.
BUT: Does it? Well, that's what Solar Orbiter is all about.
The problem lies in the super-radial expansion of flux tubes.

This is well illustrated by the PFSS 'hairy-ball' model to the left and the coronal funnels shown below.

Tu et al, 2005
Magnetograms from PHI
Coronal Structure from EUI and METIS
The Third “Instrument”: Models

For instance map solar wind back to coronal & chromospheric origin

(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)
The Third “Instrument”: Models

For instance, map solar wind back to coronal & chromospheric origin

(Peleikis et al., SH31B-03
 Kruse et al., SH13A-4080)
The Third “Instrument”: Models

For instance, map solar wind back to coronal & chromospheric origin.

Assumes constant speed from source to observation!

- Horbury and Matteini (SH21B-4097)
The Third “Instrument”: Models

For instance map solar wind back to coronal & chromospheric origin.

Assumes constant speed from source to observation!

- Horbury and Matteini (SH21B-4097)
- Weber and Kasper (SH12A-08)
- Kruse et al. (SH31A-4080)

(Peleikis et al., SH31B-03
Kruse et al., SH13A-4080)
Solar Orbiter works best with all instruments together

PHI, EUI, STIX, SPICE
METIS, Solo-HI
SO & SP+

UV and X-rays

SO

EUI

STIX

6-12 keV (thermal loops)
20-50 keV (HXR footpoints)

radio burst

RPW

MAG, SWA

in-situ observation of escaping ions & electrons

energetic He

energetic electrons

27 keV
40 keV
66 keV
108 keV
181 keV
518 keV

Counts/bin

Mass (AMU)

2 3 4 5
### Processes that affect solar wind composition:

<table>
<thead>
<tr>
<th>Process</th>
<th>Location</th>
<th>Elemental</th>
<th>Ionic</th>
<th>Seen in situ?</th>
<th>Origin understood?</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIP effect</td>
<td>Chromosphere, foot points of loops</td>
<td>yes</td>
<td>?</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Heating</td>
<td>Corona, loops, foot points of loops</td>
<td>Possibly small effect?</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
</tr>
<tr>
<td>Gravitational stratification</td>
<td>Streamers</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Coulomb drag</td>
<td>Coronal expansion</td>
<td>Yes, especially He</td>
<td>no</td>
<td>Yes?</td>
<td>Yes, but does it really act on wind?</td>
</tr>
</tbody>
</table>

Some of these processes can be modeled. Providing simple models, e.g., for FIP, charge states, etc. would be very helpful.
SPICE will provide Doppler-maps for various ions.

(SOHO/SUMER)
Outflow along flux tubes (from coronal models)

Composition (low/high FIP) also from SPICE, compare with SWA (SOHO/SUMER)
Charge states are continuously modified by ionization and recombination. Both are proportional to coronal electron density.

\[
\frac{\partial n_6}{\partial t} + \nabla (n_6 \vec{u}_6) = n_e [n_5 C_5 - n_6 (R_6 + C_6) + n_7 R_7]
\]
Charge states freeze in in the solar wind expansion process.

In situ charge states have lost all memory of what happened in deep corona. They retain memory of their last charge modification (charge states frozen in) in the upper corona.
Charge-state and elemental composition somehow linked.

- Slow wind hot (source?)
- Fast wind cool (coronal hole)

What links chromosphere and corona?

Slow wind strongly FIPped
Fast wind weakly/barely FIPped

Geiss et al. 1995)
Individual streams can be identified in-situ by many independent methods:
- magnetic field
- plasma data
- specific entropy
- composition

Composition is not altered by kinetic processes and remains conserved once it has been set in chromosphere and corona. Excellent tracer!

Composition variable, especially in slow wind.
Composition remains frozen in, i.e., does not change and therefore can be measured at 1 AU.

Expect enhanced time dependence, but also less washing out of kinetic properties. Cleaner boundaries!

Solar Orbiter will go here!
Charge-state and elemental composition somehow linked.

Slow wind hot (source?)
Fast wind cool (coronal hole)

What links chromosphere and corona?

Slow wind strongly FIPped
Fast wind weakly/barely FIPped

Geiss et al.1995)
Charge-state and elemental composition somehow linked.

Slow wind hot (source?)
Fast wind cool (coronal hole)

What links chromosphere and corona?

Slow wind strongly FIPped
Fast wind weakly/barely FIPped

Geiss et al. 1995

Brooks and Warren, 2011
Origin of the Slow Solar Wind?

Edges of Active regions

Edges of Coronal holes

S-web (coronal hole extensions provide open field connection)

Interchange reconnection
Solar Orbiter works best with all instruments together
Information from EPD

3He is preferentially accelerated in flares (probably wave-particle interaction) → flare origin!

Velocity dispersion indicates rapid acceleration and good connection → no time for diffusion!
Velocity dispersion also indicates that particles are flowing towards observer from the source. The flow is anisotropic.

For good connection:
→ $^3\text{He}$, large e/p ratio
→ velocity dispersion
→ anisotropies
→ type III radio emission
→ minimal onset delay

Such events are seen at 1 AU, albeit rarely (e.g., Klassen et al. 2011).
Solar Orbiter & the Heliosphere

Need a strong synoptic program to allow linkage.
Need tools that allow user to easily discriminate:

**Hot and cool coronal regions:**
- provide FIP maps of potential source regions
- provide temperature maps of potential source regions
- do so for more than one Low FIP/High FIP pair.

**Line broadening as measure of ion heating and/or turbulence:**
- Doppler maps
- coronal turbulence maps

**Magnetic connectivity**
- Magnetograms → hairy ball models to trace open field
- Timing, magnetic topology, and locations of eruptive events

**Modeling must be an integrated “instrument” of Solar Orbiter**

Thanks to Solar Orbiter & SP+ Teams, funding agencies, tax payers.