NAS Space Weather Workshop

Solar Wind

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To significantly advance basic understanding of the corona and solar wind, it is essential to have continuous monitoring of the

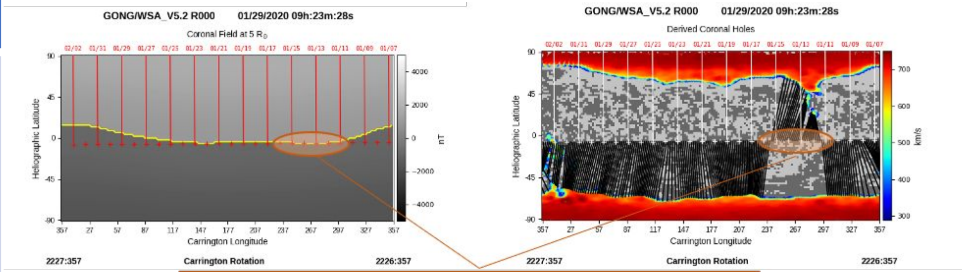
- **Sun's global magnetic field distribution.**
- **Sun in Extreme Ultraviolet (EUV) and white light (WL).**
- **Solar wind (in situ + heliospheric imaging) from multiple and widely spaced vantage points (e.g., in/out of the ecliptic plane).**

Observations Issues, Problems, & Impacts Resulting From the Lack of Global Solar Magnetic Field Observations*

Observational Issue	Problems	Impact
Missing solar far-side magnetic field measurements	ARs on solar far-side not included or partially included in photospheric magnetic field maps	· ARs affect global magnetic field configuration · Partial incorporation of ARs at limb produce nonphysical magnetic monopoles and time-dependent effects in coronal/SW models
Large uncertainties in magnetic field measurements near limb	Unreliable polar magnetic field estimates	· Coronal/SW model solutions highly sensitive to polar fields · Monopole moments introduced into maps

Abbreviations: ARs, active regions; SW, solar wind *Posner et al., 2021*

Coronal model solutions (used to drive solar wind models) are extremely sensitive to the strengths of the Sun's polar magnetic fields



A small uncertainty in the strengths of the polar fields can easily change the *predicted* source of the solar wind at a spacecraft

(Left) WSA coronal magnetic field at 5Rs with light (dark) gray indicating positive (negative) field polarity. The yellow line shows the heliospheric current sheet. The red crosses indicate the daily sub-earth points. (Right) WSA derived coronal holes (colored regions). See Posner et al., 2021 for details.

Solution: Greater observational (magnetograph, helioseismic) coverage (e.g., L4, L5, far-side, out of plane/poles) is needed to improve solar magnetic field maps.

Critical Data Products Needed To Improve, Validate, and Constrain Coronal & Solar Wind Models

Critical Data Product	Impact	Current & Needed Observational Instrumentation (Space Based)
Global synchronic magnetic field maps	Improved B.C. used to drive coronal & SW models, especially time-dependently	SDO/HMI & SolO/PHI ***Missing: Out of plane (polar?) imagers, continuous far-side imaging (direct & helioseismic)***
Global synchronic EUV maps	Coronals holes identified in EUV maps can be used to V&C coronal models	STEREO A, SDO, SolO ***Missing: Polar imager, continuous far-side imaging***
Coronal 3D Ne & plane of the sky magnetic field reconstructions	3D WL electron density (Ne) tomographic reconstructions & plane of the sky WL images segmented to surmise the coronal magnetic field observationally -Used to V&C models -Multiple viewpoints improve V&C	STEREO A, SOHO, SolO, CODEX, PUNCH ***Missing: Out of the plane & widely spaced, strategically located imaging***
Multi-vantage-point in situ plasma observations	SW plasma observations* from multiple, widely spaced vantage points used to V&C SW models.	L1 (ACE, WIND, DSCVR), STEREO A, PSP, SolO ***Missing: Out of the plane & widely spaced, strategically located imaging***

Abbreviations: B.C., boundary conditions; EUV, extreme ultraviolet; Ne, electron density; SW, solar wind; V&C, validate & constrain; WL, white light

* Standard in situ plasma measurements (e.g., speed, magnetic field, density, temperature, *composition, charge state*., etc.)

Operational (OPS) considerations for improved forecasting of space weather events

As stated earlier, key goal is global, synchronic observations of solar surface magnetic field to provide the basis for both simple WSA-like and full-MHD models

Current plans exist for wider longitudinal spread of magnetograph observations
- e.g., L5/L4 missions, SWFO_next (NOAA, ~5 years hence)

Requires methodology for consistently incorporating multi-view magnetograph data
- spatial and spectral resolution, lines observed, differing optics, etc.

Even with these advances, many impediments remain to a full-MHD solar model for OPS
(e.g., no means to quantitatively measure on-disk $\mathbf{B}_{CME}$ above $1R_s$)

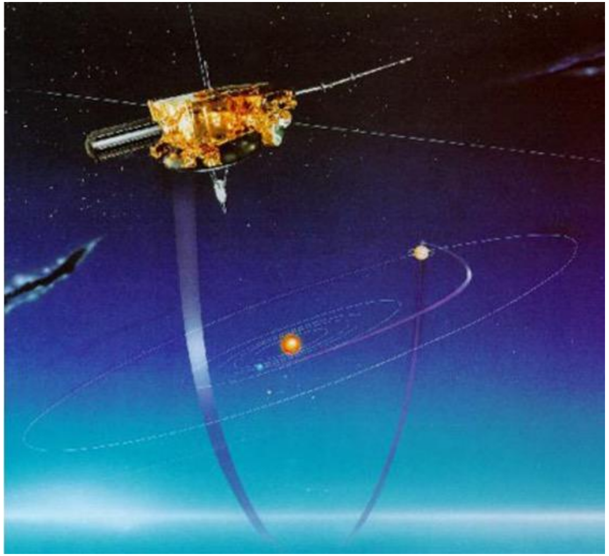
In interim, Is there a way to upgrade/replace WSA with a more realistic "enough" model?

But all that leaves open 2 crucial issues in terms of potential for OPS forecasting

1) Direct observations of high-latitude ($\gtrsim 45^\circ$) solar surface magnetic fields is problematic
2) In-ecliptic views of CMEs (as with STEREO) have strong limitations (not tomography)

So what to do, keeping in mind that OPS forecasting done with relatively crude data?

Major advance in observing polar fields <u>and</u> in tracking CMEs could come from polar view



A polar OPS mission, *similar* to Ulysses, could do the trick ⇒
Would enable:

- Direct in-situ measurement of high-lat SW plasma plus magnetograph observations of solar polar surface fields
- OPS coronagraph/HI triangulation of CMEs, in conjunction with in-ecliptic observations

- Min practical number of high-latitude s/c to provide continuous views of both poles is **4**
- Off-ecliptic imaging would also enable tracking non-steady large-scale ambient evolution (HS streams typically <u>not</u> perfect spirals)
- Practical issues include launch and orbital dynamics, propulsion, deep-space telemetry, s/c lifetimes, etc., -- and COST

Polar OPS mission thus demands robust architecture ("Jeep" vs "Lamborghini"), with very specifically defined goals and expectations

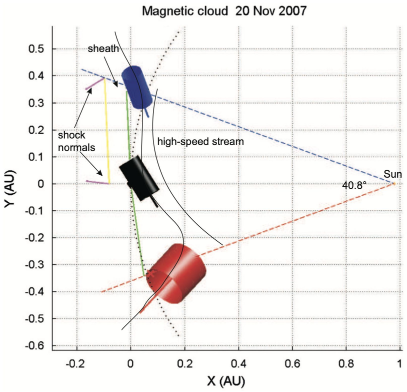
What do we need to improve our understanding of solar eruptive phenomena (CMEs, SEPs) in the solar wind?

Observations:

- Remote sensing: 2–3 views on the ecliptic, plus at least 1 out-of-ecliptic view (incl. poles)
- In situ: Multiple spacecraft covering various heliolatitudes & heliolongitudes
    - CMEs: mag, plasma, composition, particles, …
    - SEPs: proton, electrons, heavy ions, from thermal to energetic particles

Modeling:

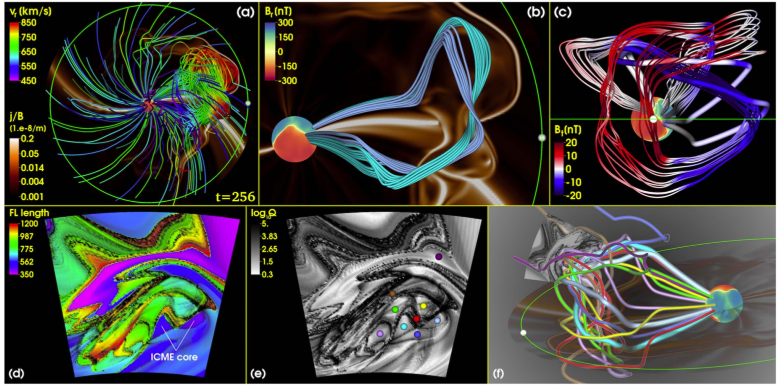
- Both CMEs & SEPs propagate / are transported within and interact with the solar wind ⇒ improvement of solar wind models
- Towards more realistic CME–solar wind and CME–CME interactions (e.g., CMEs as magnetized structures, …)
- Towards holistic Sun-to-heliosphere models (e.g., multi-domain simulations, …)



From Farrugia et al. [2011]

These two aspects go together!

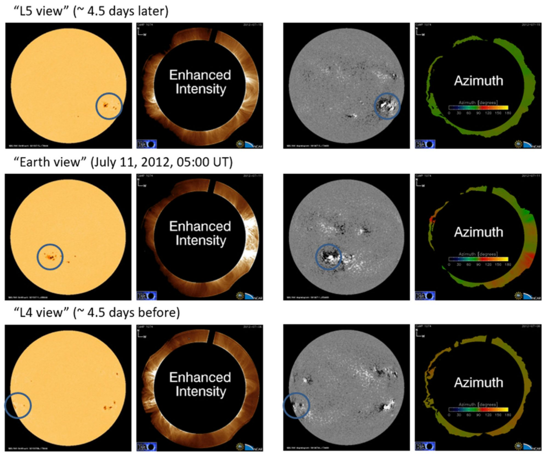
From Török et al. [2018]



What do we need to improve forecasts of solar eruptive phenomena (CMEs, SEPs) in the solar wind?

Observations:

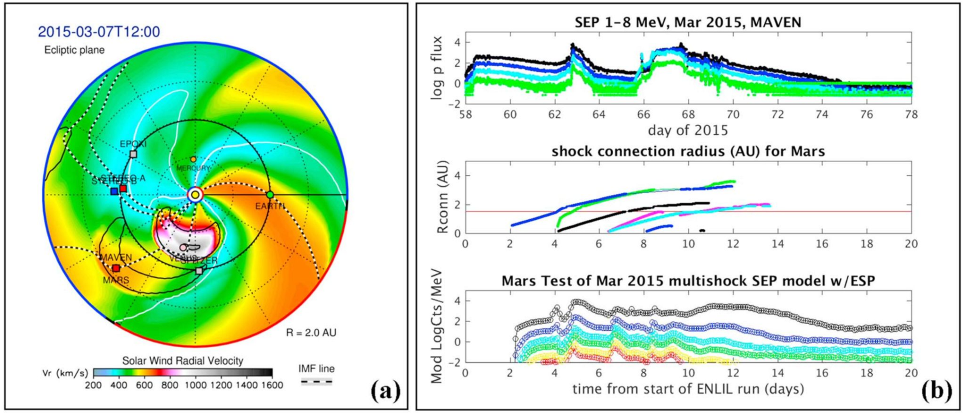
- Remote sensing: views from L1–L4–L5
- In situ: CMEs deflect/rotate/deform/interact once they have left the Sun, intermediate measurements between the Sun and L1 would greatly improve forecast accuracy



From Bemporad et al. [2021]

Modeling:

- Key goal for forecasts: modeling/predicting CME magnetic fields → gaining momentum in research, next step: real-time applications
- Some SEP models currently have real-time capabilities → these need to be benchmarked and their feasibility for real-time forecasts has to be tested



From Luhmann et al. [2017]

The Solar Wind that Hits an L1 Monitor Is Not the Solar Wind that Hits the Earth

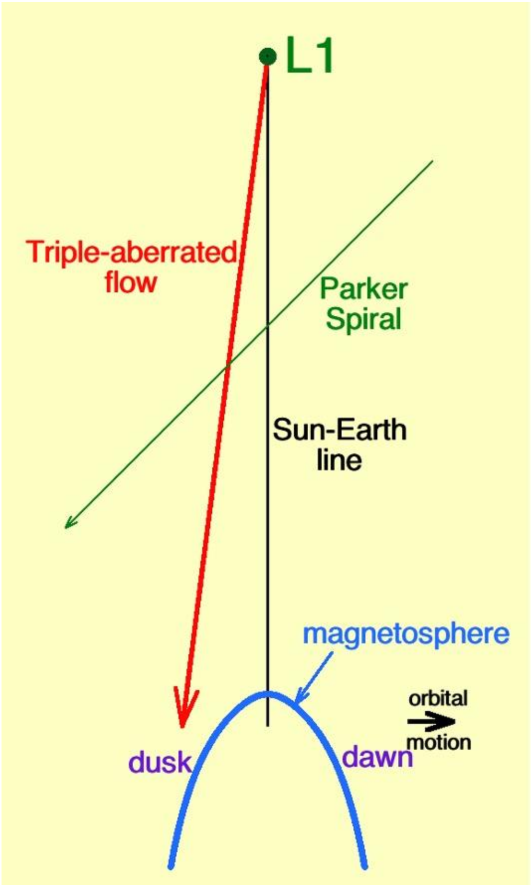
The velocity vector of the solar wind varies with time by about ±5°

$\Rightarrow$ ±20 R_E at Earth

There is a triple aberration of the solar wind:

1. The motion of the Earth around the Sun.
2. The solar-wind flow is not radial.
3. Magnetic structure propagates outward along Parker spiral faster than the plasma flow.

Streamline can pass 30 R_E duskward (or worse).

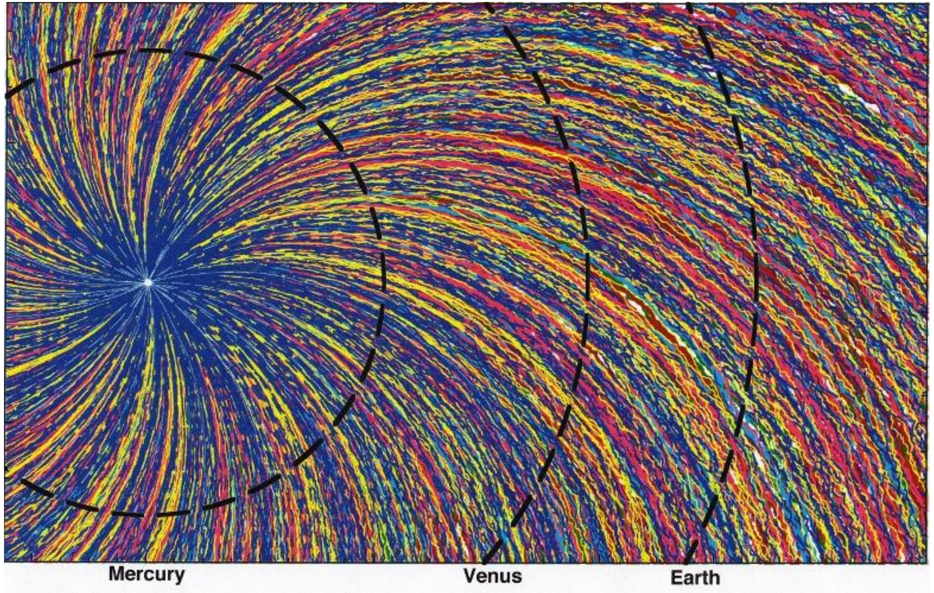


The size of the errors obtained from L1 monitoring are on the order of the background solar-wind structure sizes.

When using data analysis to uncover or confirm how the solar wind drives the Earth, errors in the solar wind variables change the “best fit” answers.

The background fine-structured solar wind is where most of the data is, and this is where we learn how the solar wind drives the Earth.

⇒ Need solar-wind monitors closer to Earth than L1 to get this correct.



Supplemental Information & References

Supplemental Information 1*

- Current photospheric magnetic field maps (i.e., based on measurements only available at Earth) lack upwards of 220° longitude (~61% of the total map!) in new and simultaneous observations. Measurements in these maps can therefore be as old as ~17 days. If measurements included those from Earth and from L4 *or* L5, then the longitudinal span in the maps missing simultaneous observation is reduced to ~160° or roughly 12 days. If measurements from L1, L4, and L5 were all available, then the missing observations would only span about 100° in heliographic longitude, except for the polar regions. In such a map, no data would be older than about 8 days, with the oldest data residing at the eastern edge of the Sun as viewed from an L5 observatory. While flux transport models do not account for the emergence of active regions, they would be able to manage these narrower gap regions much more effectively.*

- Helioseismic holography (Gizon et al., 2018; Liewer et al., 2014; Lindsey & Braun, 2000; Yang, 2018) and time-distance helioseismology (Duvall et al., 1993; Zhao et al., 2019) enable the detection and specification of active regions on the far side of the Sun. They can thus be monitored and even inserted into photospheric maps before they enter the field-of-view as seen from L5, which would further improve SWx predictions. In fact, Arge et al. (2013) demonstrated that this approach can improve solar wind forecasts.*

- Combining magnetogram data from different instruments is generally non-trivial due to differences in the instrumentation (e.g., wavelengths used, resolutions, etc.) and the complexities of intercalibration BUT simultaneous overlapping observations should help to overcome this problem.*

* *Note: Text taken directly from Posner et al., 2021 and slightly modified in places (co-author Arge wrote much of the original text).*

Supplemental Information 2

- An interesting simulation of the effects of adding in-ecliptic magnetograph views from L4/L5 can be found in
  A. Pevtsov, G. Petrie , P. MacNeice , and I. I. Virtanen, "Effect of Additional Magnetograph Observations From Different Lagrangian Points in Sun-Earth System on Predicted Properties of Quasi-Steady Solar Wind at 1 AU", **SWJ**, 10.1029/2020SW002448.

- Our operational experience with CMEs at SWPC suggests that multi-coronagraph views in the ecliptic show that the practical uncertainty it determining the east-west pointing in any given event is about 15-20 degrees, whereas the north-south component is more like 10 degrees. This applies mainly to weaker, localized events, such as those stemming from streamer blowouts. For really explosive events (like 10 Sept 2017) seen head-on off-limb the uncertainty can be somewhat greater. CME images taken from high solar latitudes would reduce the east-west point uncertainty greatly.

- Whether 2 s/c might suffice for collecting polar info has to do with the phasing of the s/c and the desire to keep one at high latitudes in each hemisphere to optimize the magnetograph observations. For CMEs, it probably does not matter so much, for surface field 2 s/c may suffice if you accept more uncertainty in one of the poles. The shape (circular or elliptical, range and eccentricity) could have an influence.

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