

New Architectures: Solar and Heliosphere Panel

Key questions:

- 1. What are the novel observational/model architectures/technologies that we are not utilizing as yet?
- 2. What do we need to build a fluently operating architecture from the multi-source / multi-organization observational base we have?
- 3. What are the government/private resources (data/platforms) that we could utilize but are not doing so right now?

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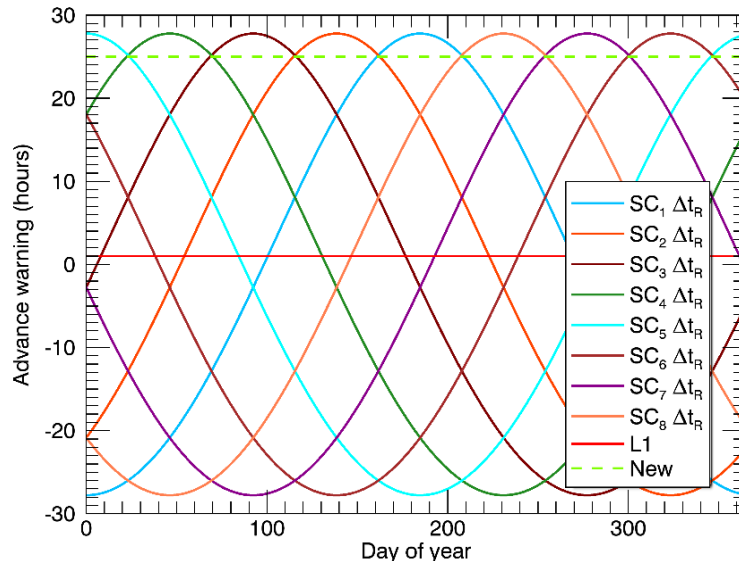
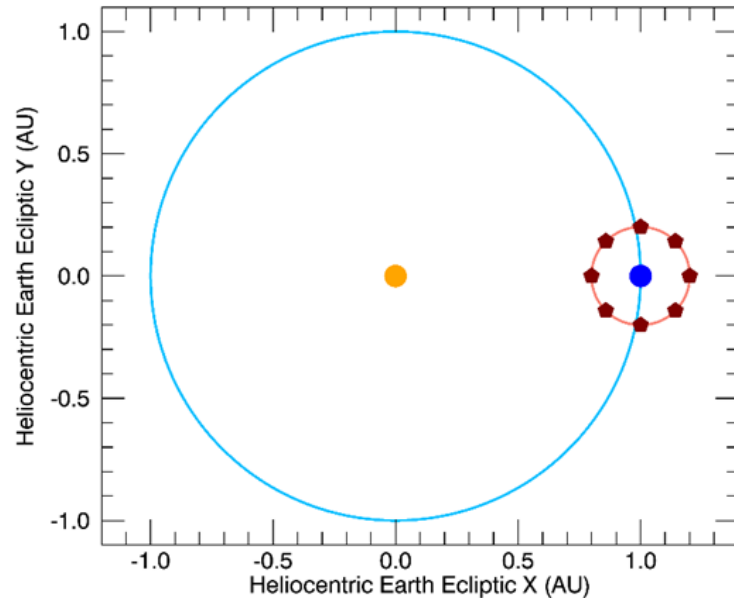


The NASA Heliophysics budget should be augmented to allow NASA to enter into milestone-based reimbursable space weather missions leading to DOC/DOD data purchase agreements

New Architectures: solar and heliosphere panel

Justin C. Kasper, April 13 2022

A platform with 10x the warning of L1 could be provided commercially today



- Launch, spacecraft, and operations as low cost commodities permit advanced heliospheric space weather observations at substantially lower cost
- Consider this concept for an 8 spacecraft ring of cheap spacecraft with simple plasma, magnetometer, and radiation sensors in a ring around Earth in 0.2 AU distant retrograde orbits
 - Minimum of 25 hour advance warning
 - 3D information on shock fronts, flux rope structure, and energetic particles



Problem

- A company could easily build and launch this platform for less than \$100M, and make a profit selling the data for less than \$20M/year, comparable to other data buys by the US government, but it is very challenging to invest this kind of capital without a guaranteed customer
- NOAA cannot commit to data buy without seeing the data first
- Pitching this to NASA as science mission increases the cost and the schedule and dilutes funding for science missions

Solution

- The NASA Heliophysics budget should be augmented to allow NASA to enter into milestone-based reimbursable space weather missions leading to DOC/DOD data purchase agreements
 - The milestones are spread from start through initial operations, limiting the exposure of the company
 - After early data are produced, NOAA may enter into a data purchase agreement for the operational data
 - NASA may also enter into an agreement for advanced science quality data products, or fund a science program through a guest investigator program

New Architectures: Solar & Heliosphere

Comments to the Space Weather Operations & Research Infrastructure Workshop
Phase II

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College of Engineering
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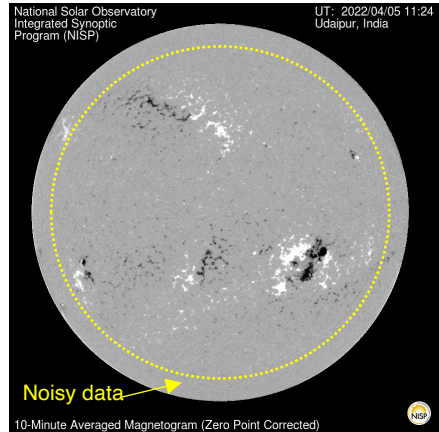
Grand Challenge

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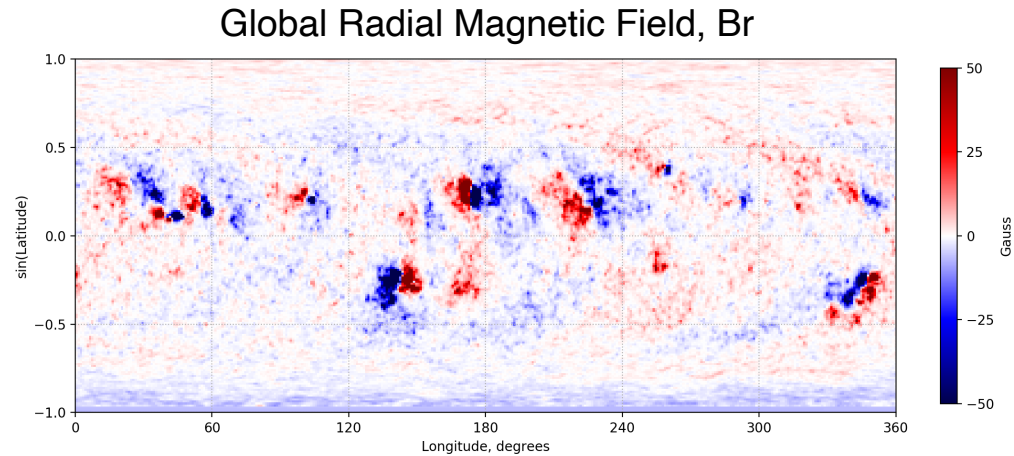
Boundary condition for *all* interplanetary space weather models

Example: WSA/*Enlil* solar wind & CME propagation model

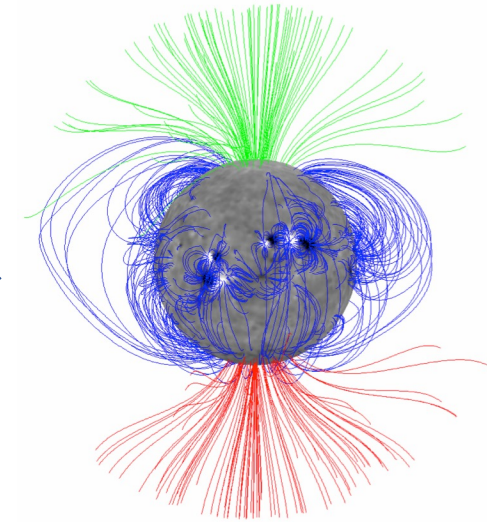


Full **disk** magnetogram:
only measured from Sun-
Earth line in the ecliptic

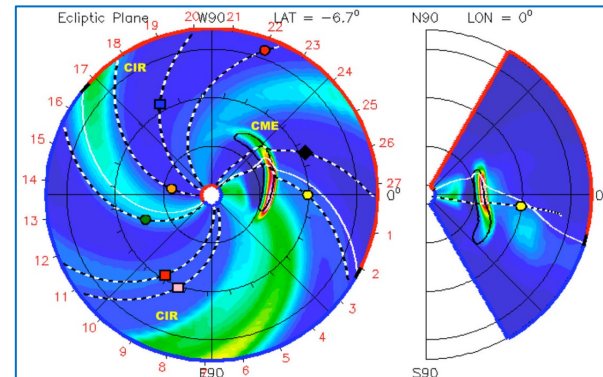
Current CME arrival time error ± 10 hours
(Riley *et al.*, 2018)



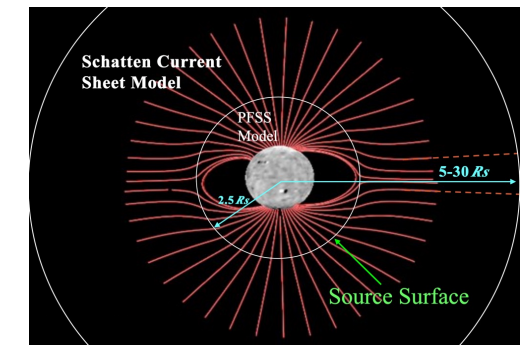
27-day rotational "Synoptic Map"



Coronal magnetic field
model



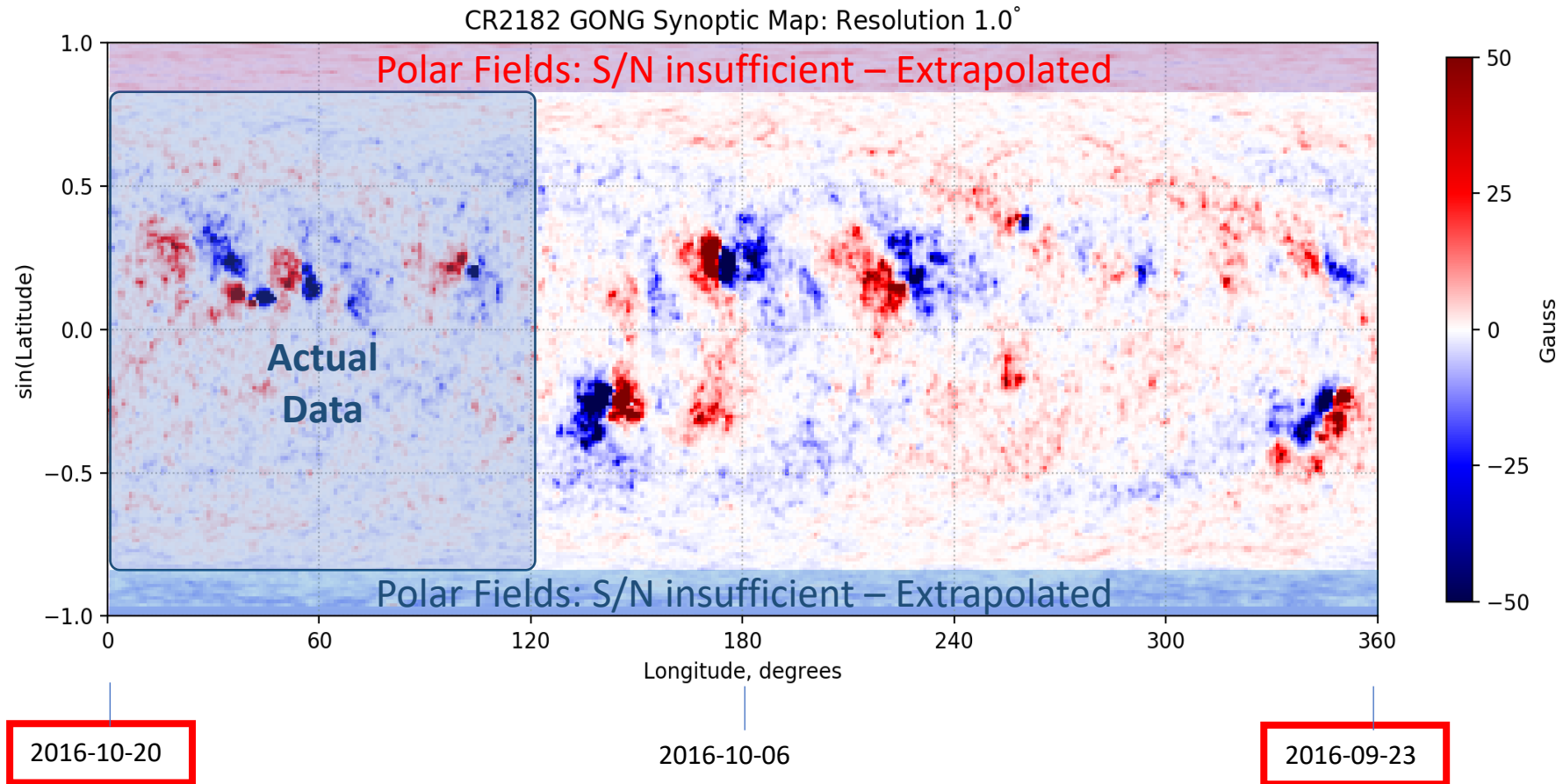
Solar Wind & CME propagation to 2AU
Enlil MHD model



Solar Wind to $\sim 20 R_{\text{sun}}$
WSA empirical model

An inconvenient truth: the Sun is spherical

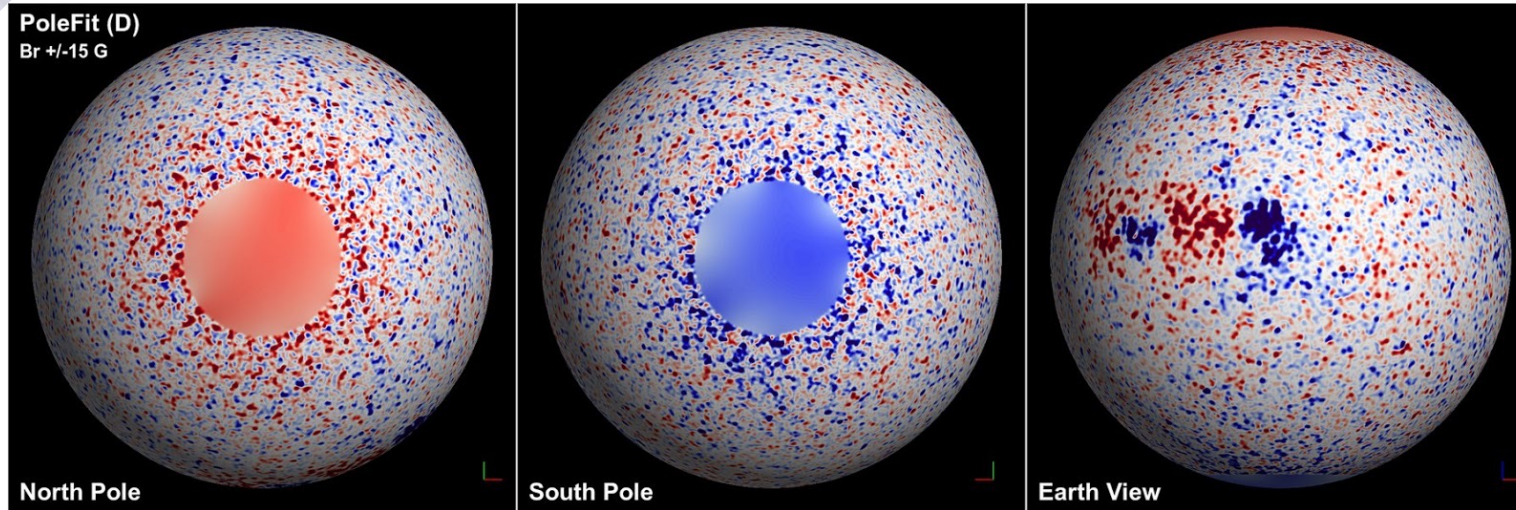
From a single vantage point in the ecliptic, only $\sim 1/3$ of the sphere is measurable at any one time, and the polar fields are never measured well.



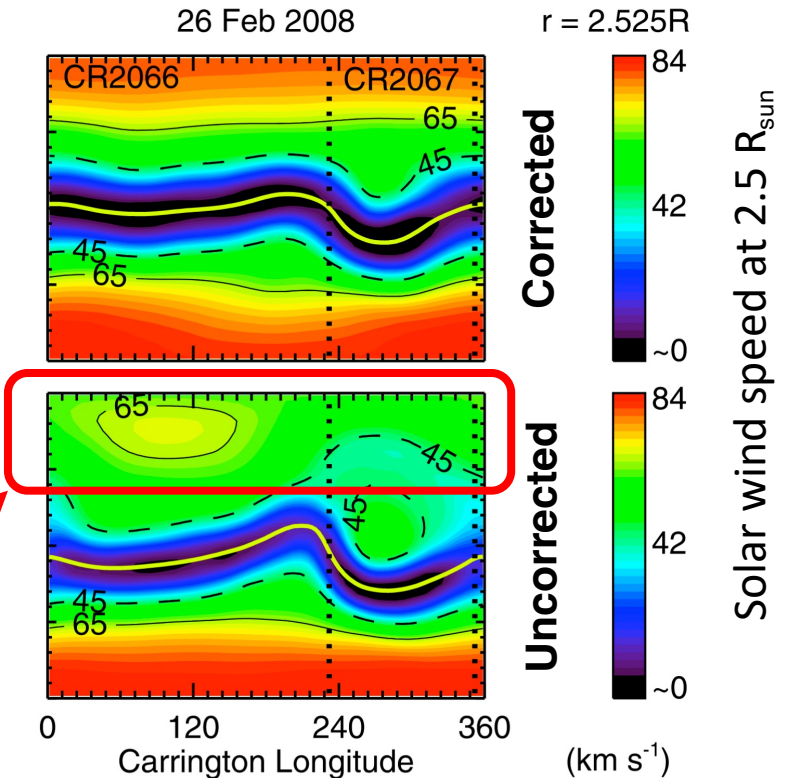
Solar wind modelers and forecasters routinely multiply synoptic map flux values by *ad hoc* factors of 2–4 to match measured conditions at L1.

27 days of data
The real sun never looked like this

Polar extrapolations are very approximate...



...and cause large errors in solar wind speed



North pole fast wind completely missed by uncorrected polar field extrapolation.

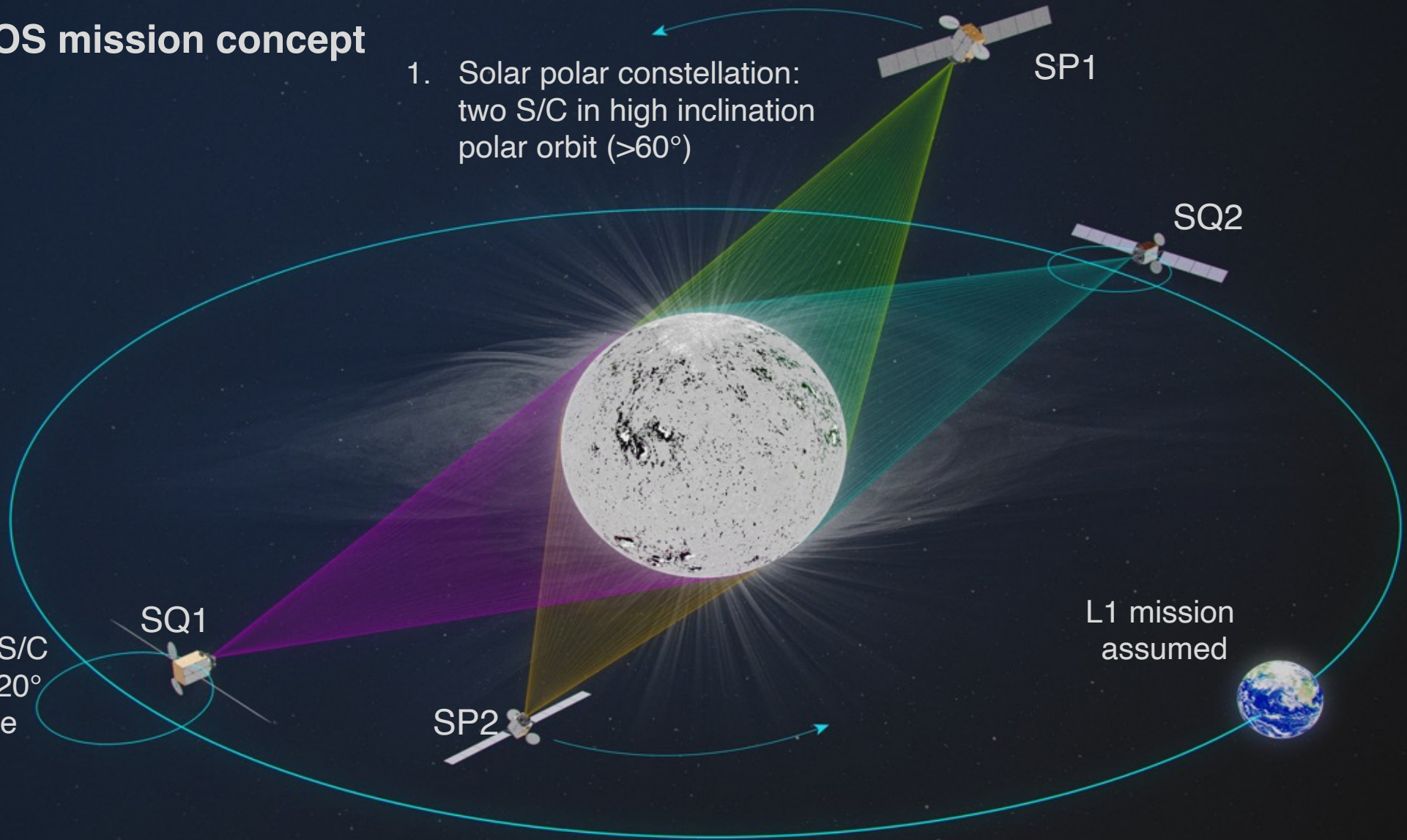
Sun et al. 2011

The most critical missing piece in space weather observing architectures: *Full-Sun Observations*

4π HeliOS mission concept

1. Solar polar constellation: two S/C in high inclination polar orbit ($>60^\circ$)

2. Solar quadrature constellation: two S/C in ecliptic at 90° - 120° from Sun-Earth line



“4 π HeliOS” mission concept will advance space weather research *and* operations

- All spacecraft are 3-axis stabilized imaging platforms.
- Full solar coverage: >80% over mission life.
 - Coverage is defined as being within 60° of center from each Sun-spacecraft line.
- Solar Polar orbital inclination: minimum 60°, desired > 80°.
 - Requires Jupiter gravity assist mission profile.
 - Will enable CME viewing “from above”, greatly improving geomagnetic storm predictions
- Solar Quadrature elements: $\pm 90^\circ$ to $\pm 120^\circ$ longitude from the Earth. L5 or L4 gravity wells not required.
- Perihelia for all elements: ~1 AU

4 π HeliOS Instrument Suite

Common instrument suite on all spacecraft affords redundancy and enables intercalibration

Remote Sensing Instruments

- Doppler Vector Magnetograph
Full disk FOV
- Solar Spectral Irradiance monitor
170–340 Å
- Extreme Ultraviolet Imager
 $\pm 3 R_{\text{sun}}$
304 Å & 171 Å
- White-light Coronagraph
2.5–20 R_{sun}

In situ Sampling Instruments

- Magnetometers
0–1000 nT ; Boom: 3 m
- Solar wind Faraday Cup
<1000 km/s
- Solar Wind & CME Composition
200–2000 km/sec
- Energetic Particle Suite
Electrons: 10 keV – 10 MeV
Ions: 10 keV/nuc – 300 MeV/nuc

Augmentation

- White-light Heliospheric Imager
4°–24° (~16-96 R_{sun})

High Risk / High Reward

- Golf-NG
g-modes

4π HeliOS mission technology challenges

Multiple high resolution & high cadence S/C implies very high data rate (TB/day).

- Ka RF may be sufficient but requires large gimbaling antenna.
- Optical communications would be enabling.
 - Requires development of **deep space optical data infrastructure**.

Solar Polar requires Jupiter Gravity Assist for inclination $> 60^\circ$ on a reasonable schedule

- C3 requirements imply compact, lightweight, payload to afford single launch of 2 S/C.
- Large, lightweight, solar panels for power at Jupiter orbital distances.
- Innovative propulsion to reduce SMA and eccentricity of orbit:
 - **Ion engines** – Pros: existing technology. Cons: heavy fuel load.
 - **Nuclear thermal** – Pros: compact, high thrust. Cons: new technology.

Autonomous spacecraft, instrument, and data systems operations

- Helioseismology requires 100 msec timing accuracy across constellation
- **AI required** for this level of mission complexity

New Architectures: Solar and Heliosphere

Perspectives from the Heliosphere: ICMs, SEPs, Suprathermal particles, and the nature and structure of the solar wind

Susan Lepri, Professor, The University of Michigan
Director, Space Physics Research Laboratory



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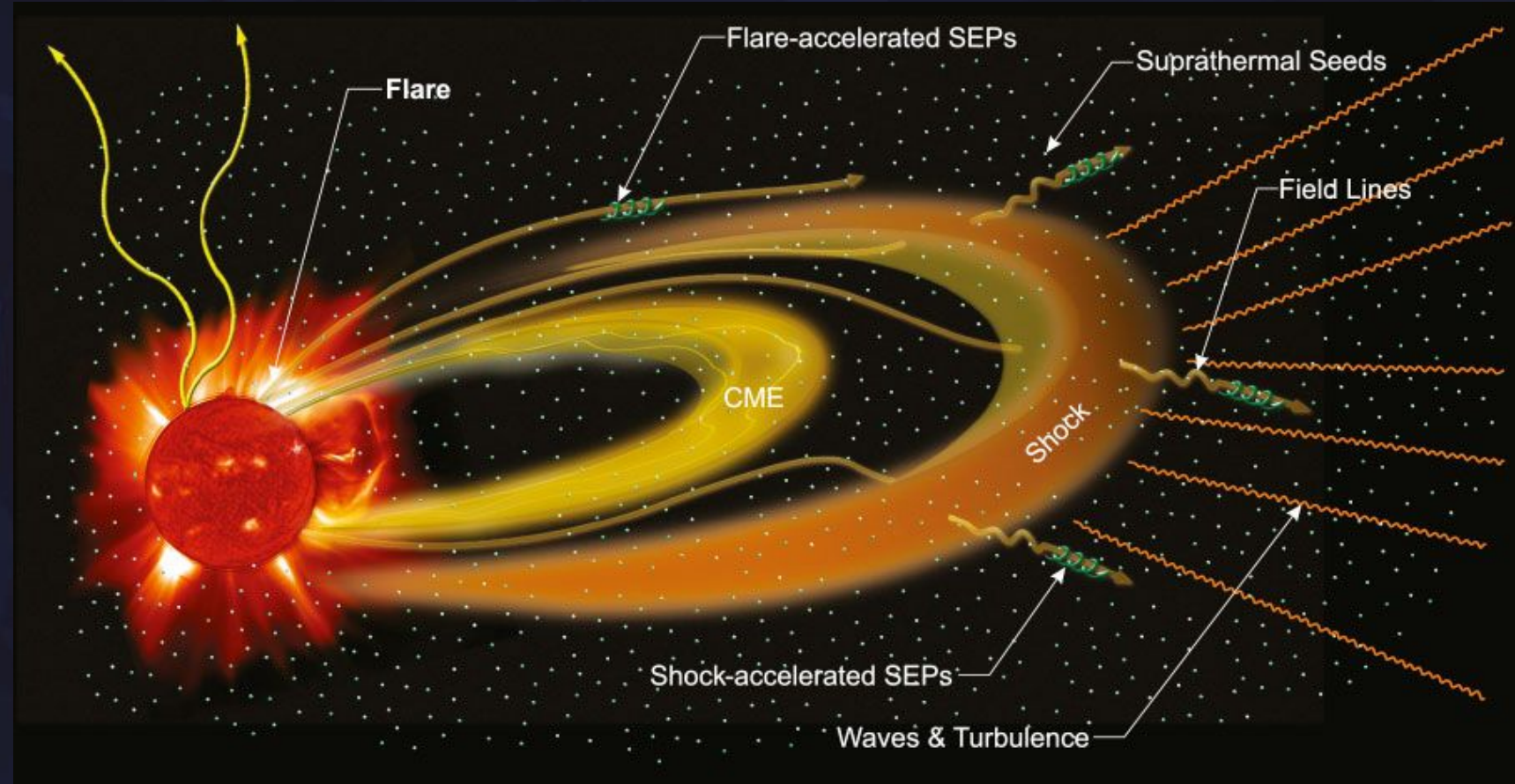
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Finding the gaps: ICMEs/Shocks

Desired information

- Time of Arrival, Duration, Geoeffectiveness: Nowcasting vs. Forecasting
- ICME/Shock structure, extent, and magnetic topology at Earth or other planetary bodies and spacecraft



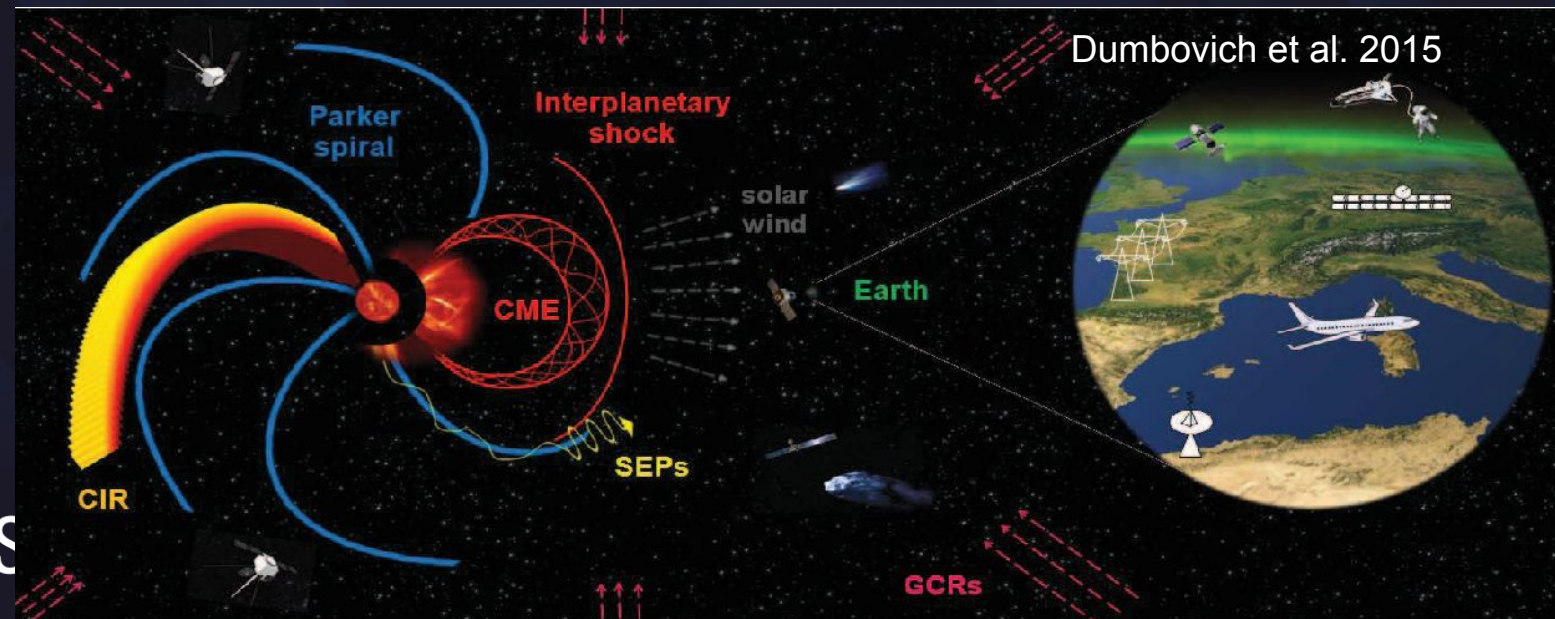
Desai and Bergess 2008



Finding the gaps: Solar Wind

Desired Information

- Time of arrival and boundaries/duration of HSS, SIR/CIR
- Plasma and magnetic properties of HSS, SIR/CIR
- Preconditioning
- Solar cycle evolution, effects
- Identification of HSS/SIR/CIR/ICME
- 3D heliosphere



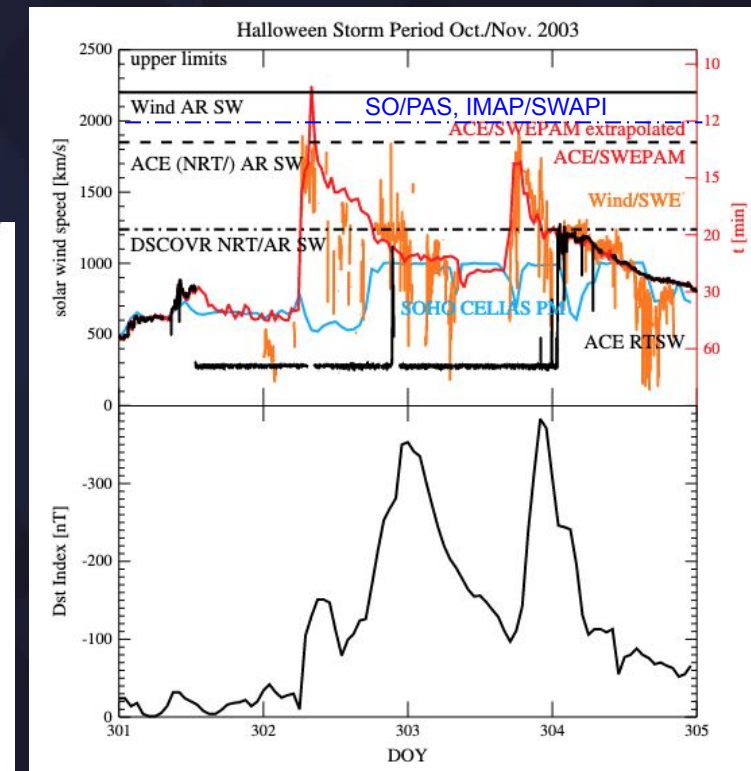
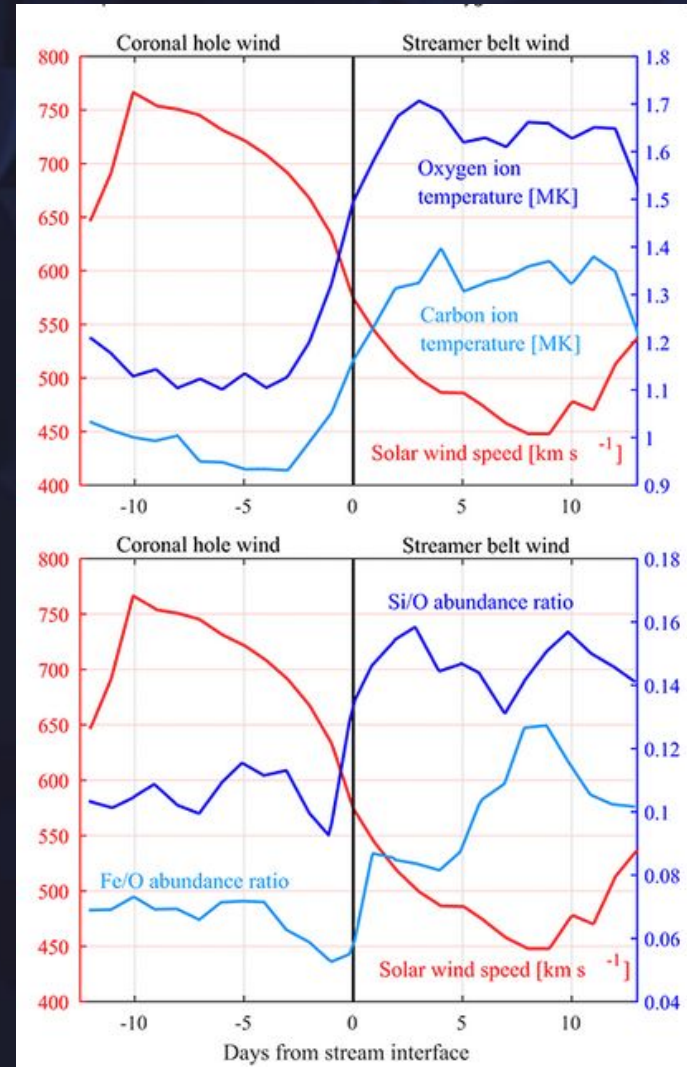
Gaps in in-situ plasma measurements

- Recent instrument capabilities do not extend to high enough wind speeds or proton fluxes to capture largest events.
- No real-time monitoring of solar wind heavy ion composition
- Latest SWx missions do not prioritize heavy ion composition
- Connection/tracking between remote observations at the Sun and in-situ is challenging

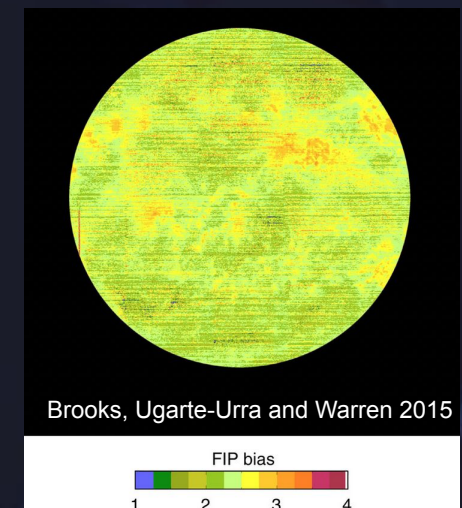
Necessary measurements/tools

- Bulk plasma
- Heavy ion composition
- Suprathermal particles
- Solar energetic particles
- Fields
- Model boundary conditions and constraints

Von Steiger et al. 2000

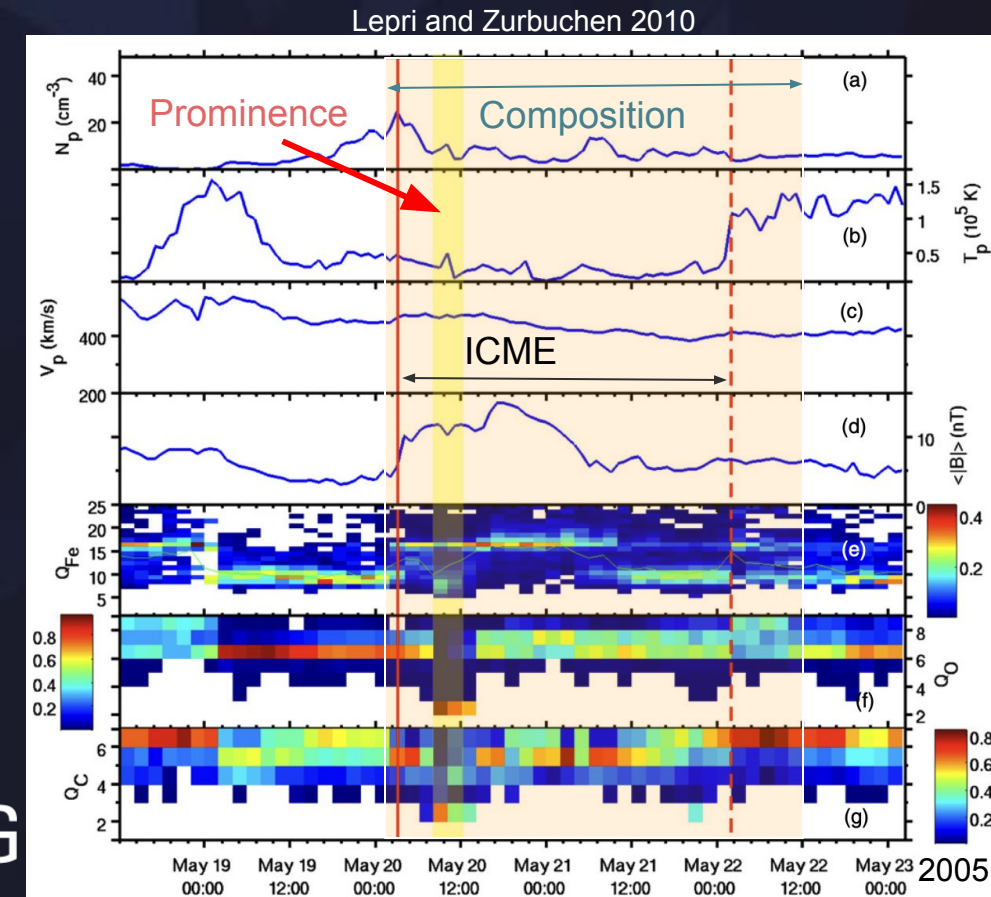
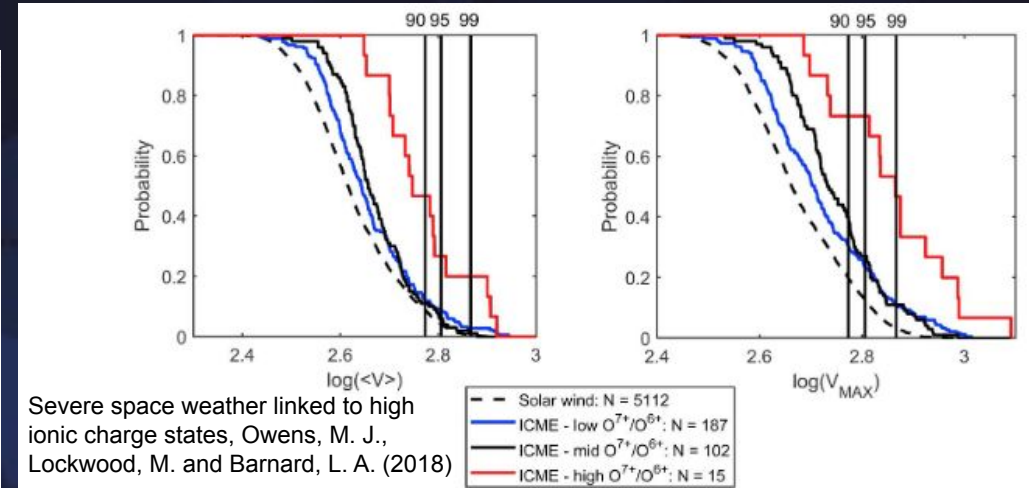
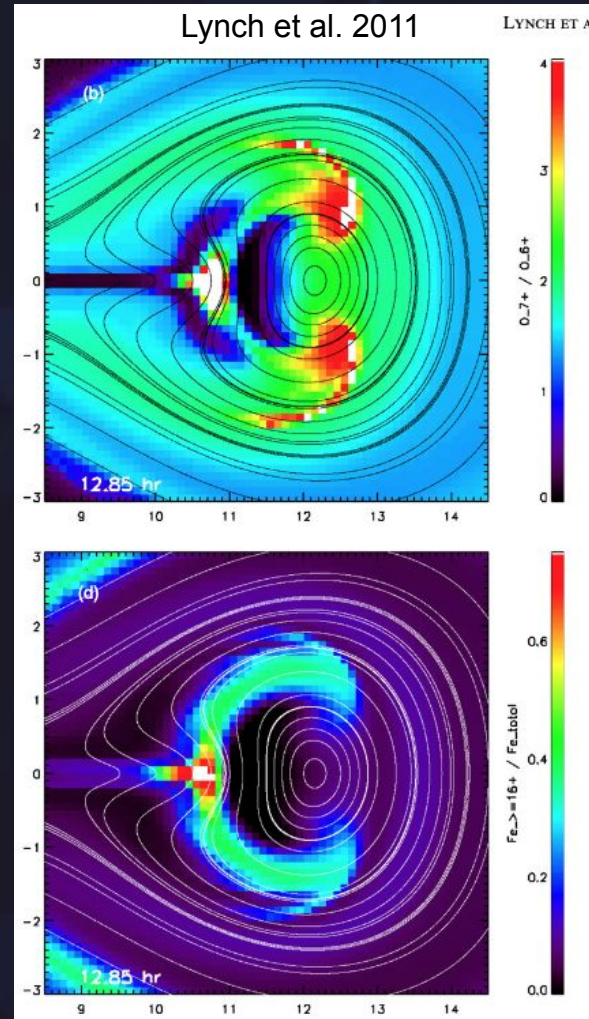


Posner, Hesse, St. Cyr, 2014



Gaps in in-situ plasma meas.

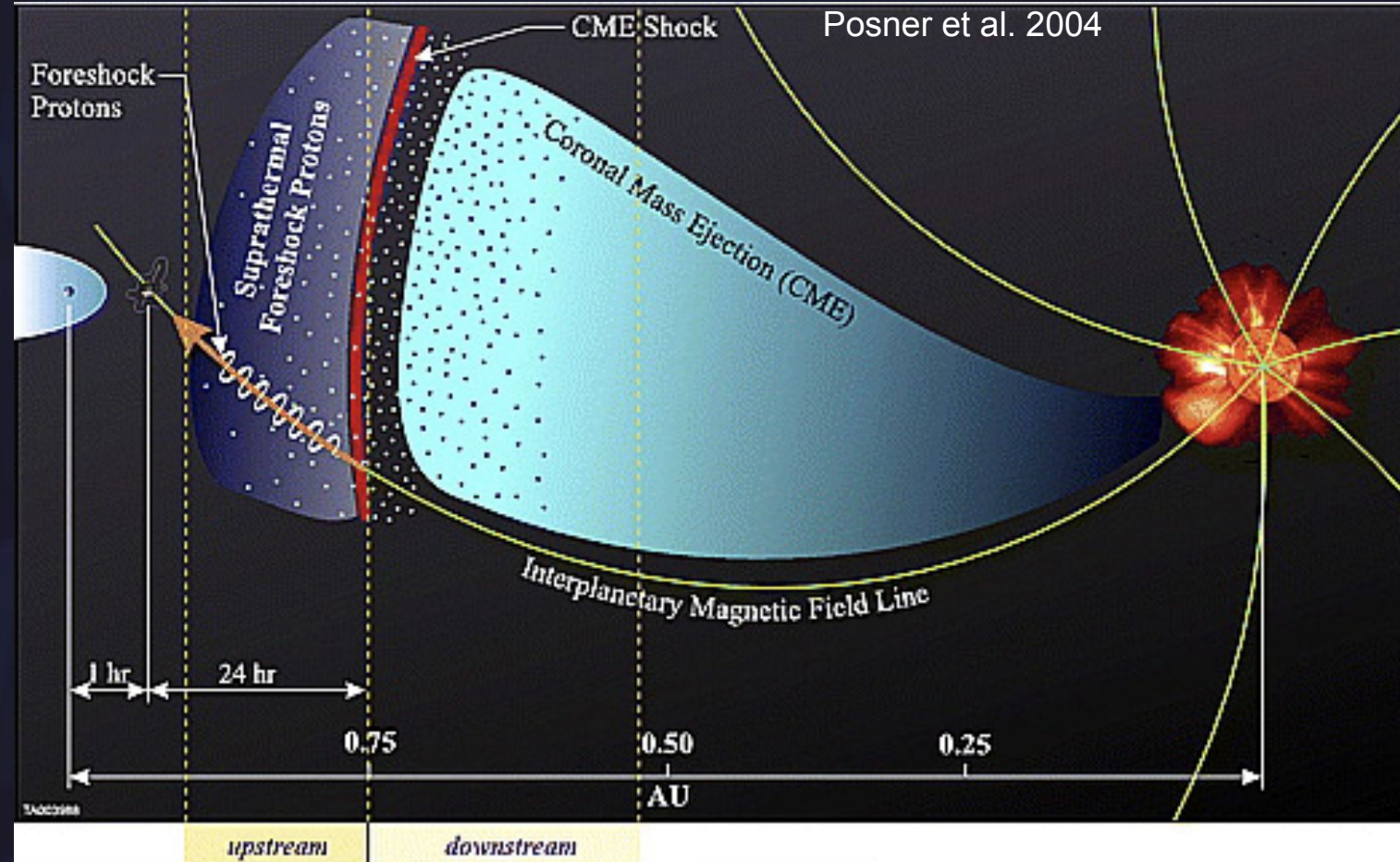
- Heavy ion composition plays a major role in
 - Differentiating HSS from ICMEs
 - Characterizing ICME internal structure
 - Linking in-situ measurements to solar sources, physical processes
 - Constraining models of CME initiation, energization, heating, release and propagation.
 - Facilitating nowcasting
 - Quantifying total mass and pressure
- Solar Wind models are developing routine ways to incorporate composition, but data is scarce for validation.
- Composition can be a key distinguishing marker or training set for Machine Learning



Gaps in suprathermal particle and SEP measurements

Suprathermal particles

- Seed particle population of SEPs.
- Leading indicator of shocks, 5-72 hrs warning depending on strength of shock.
- Current capabilities lack sensitivity to measure the many orders of magnitude required to observe suprathermal particle fluxes
- Long accumulation times required to collect sufficient counts, limiting ability to resolve smaller scale composition, structures, variability, adequate timing info.



Mission and Measurement concepts

 Priority
 Easy to do

- Multipoint in situ plasma (*including heavy ion composition and suprathermal particles*  ), and magnetic field measurements
 - >0.1 AU upstream 
 - ~0.3 AU from Earth
 - distributed in the range 0.7–1 AU to track outward flow, spatial variation 
 - Off Sun-Earth line, out of ecliptic
- Distributed space weather observatory network related to lunar, planetary manned and robotic missions 
- Complementary measurement quantities across platforms (continuity) and between remote and in-situ platforms (e.g. similar species measured via remote spectroscopy and in-situ composition). 
- Long baseline measurements with uniformity of measurements (same and improved parameters, timescales)  
- Solar cycle predictive capability, background solar wind, solar climate
- Nowcasting of wind type
- Both spinning and 3 axis stabilized orientations



Mission and Measurement concepts

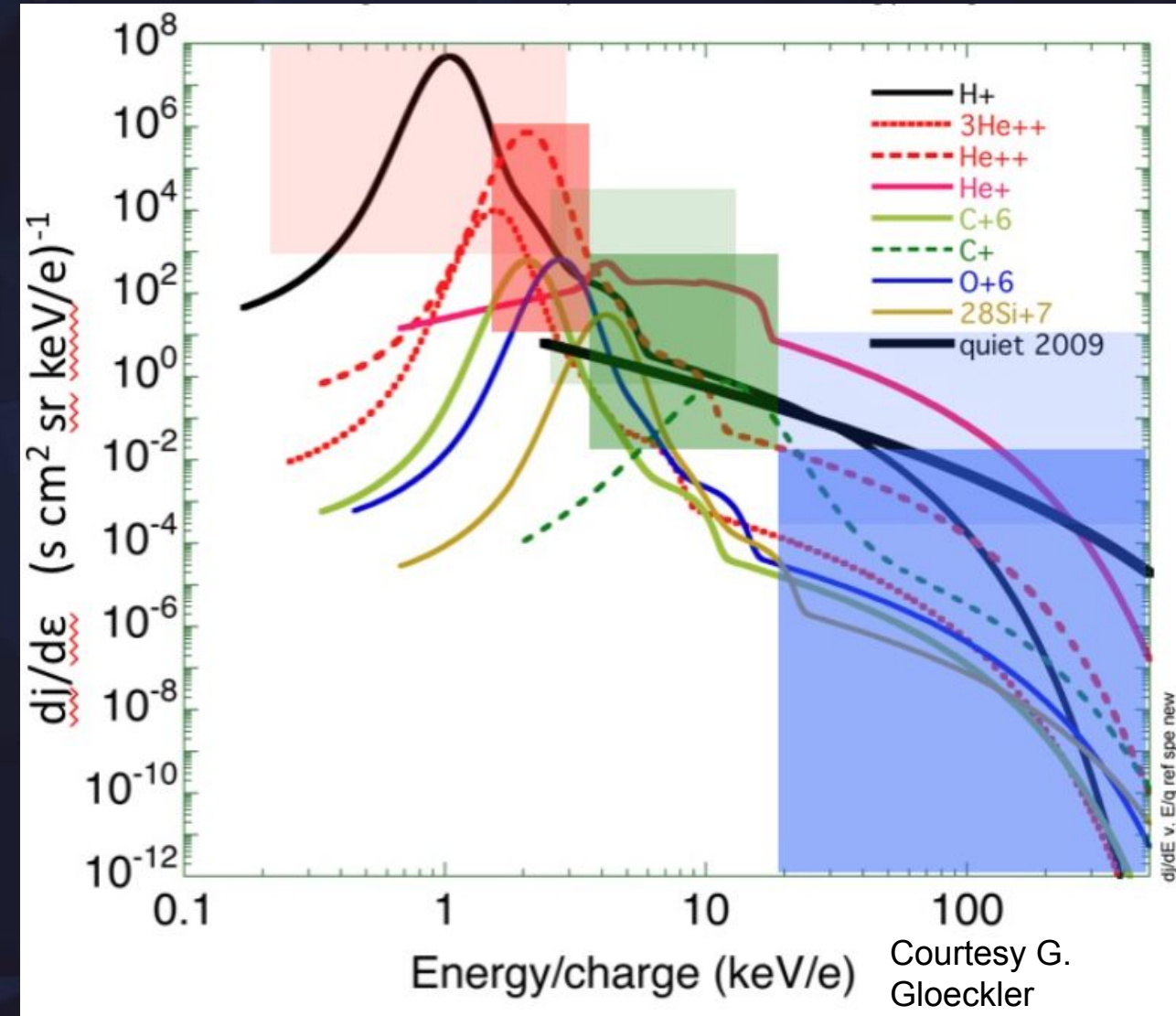


Priority



Easy to do

- High cadence measurements to determine the impacts of smaller scale structures
- Required in-situ instruments:
 - High resolution proton (up to 3000 km/s?) and electron measurements
 - Measurements of heavy ion composition (He-Fe, 0.5-100 keV/e)  
 - Measurements of suprathermal particles (6-200 keV/e), including composition  
 - SEPs
 - Magnetic field measurements (B_z , $|B|$, rotation)
- Increased telemetry downlink or new compression schemes, algorithms
- Real-time data for bulk plasma, magnetic fields, AND composition, suprathermals, SEPs.  
- Novel image, data processing, machine learning algorithms, and software onboard or on the ground 
- Models: inputs, data assimilation, improve sparse data sets, links from engineering to target. 



Challenges?

- High time resolution requires large FOVs or geometric factors
- Higher mass, charge, and/or energy measurements typically require larger, more massive instruments
- Large FOVs can be obtained by spinning, which prevents imaging of Sun
- 3-axis stabilized require large native physical or electrically controlled FOVs
- Miniaturization is difficult when instruments require high voltages for ion and electron steering/selection
- Telemetry required could be high for information on many species or rich datasets
- Measurements of protons, heavy ions, and suprathermals require many orders of magnitude in detection sensitivity
- Trade off simplified instrumentation or data collection to get key parameters vs all desired parameters



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Enabling Solar & Heliospheric Novel Architectures

Nicole Duncan

Space Sciences Portfolio Manager

Mission Development, Ball Aerospace



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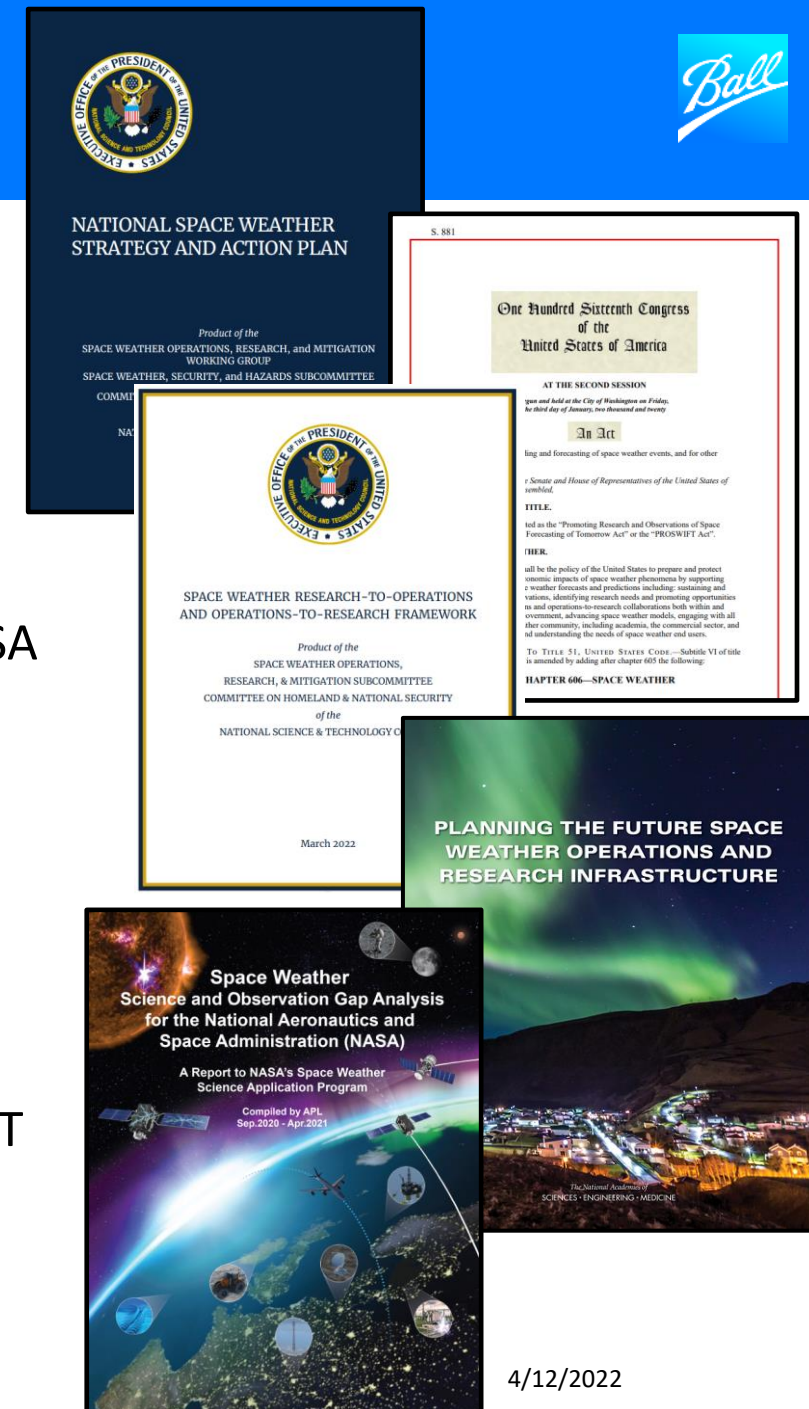
Guiding Questions

- What are the novel observational/model architectures/technologies that we are not utilizing as yet?
- What is needed to build a fluently operating architecture from the multi-source / multi-organization observational base we presently have?
- What are the government/private resources (data/platforms) that we could utilize but are not employing right now?

ARCHITECTURE FORMULATION

Moving to a Systems Paradigm

- Cross-agency space weather roadmap
 - Single long-term plan with budget targets
 - Outlining how to integrate inputs from SWAG, SWx roundtable, NASA SWx Gap Analysis, SWORM, NASEM workshops & 2024 Decadal
 - If Decadal provides roadmap, need plan to refresh < 10 years
- Consider the role of competed missions (e.g. Explorers)
 - Community concern about prioritization of SWx science goals
 - Congress should provide additional funding to implement PROSWIFT



How can planning for R2O2R effect Mission Formulation?

- Opportunities in Mission Formulation
 - Consider STM/STDT traceability to operations
 - How do observations support model development?
- Varying success operationalizing science data
 - Standardize interfaces and data products
 - Improve data access for all users
- Plan to transition
 - Consider if/how/when to transition management
 - Latency - Consider use of NOAA MOPS throughout mission

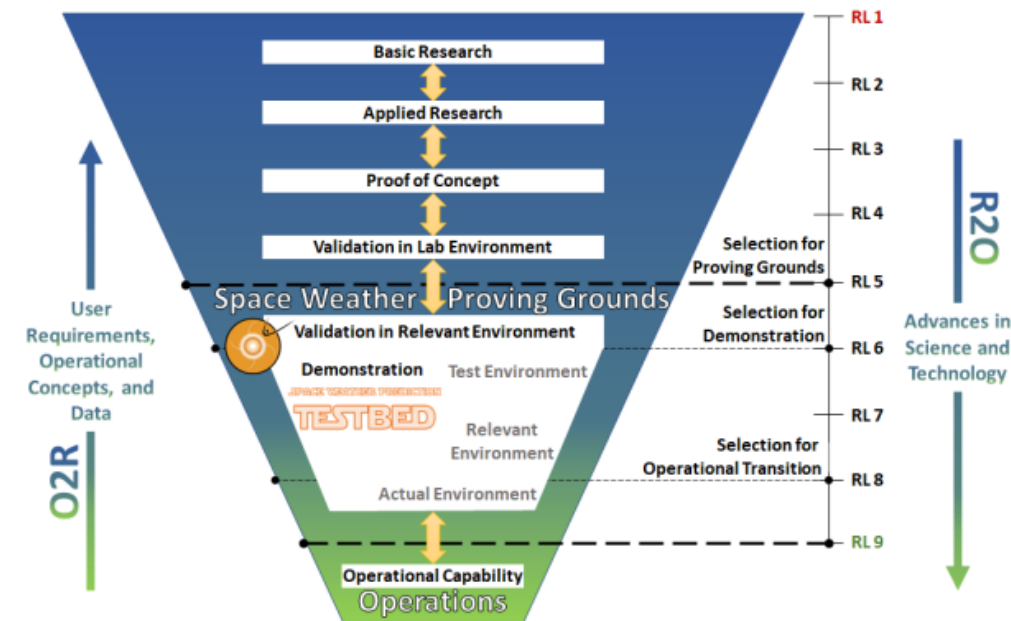
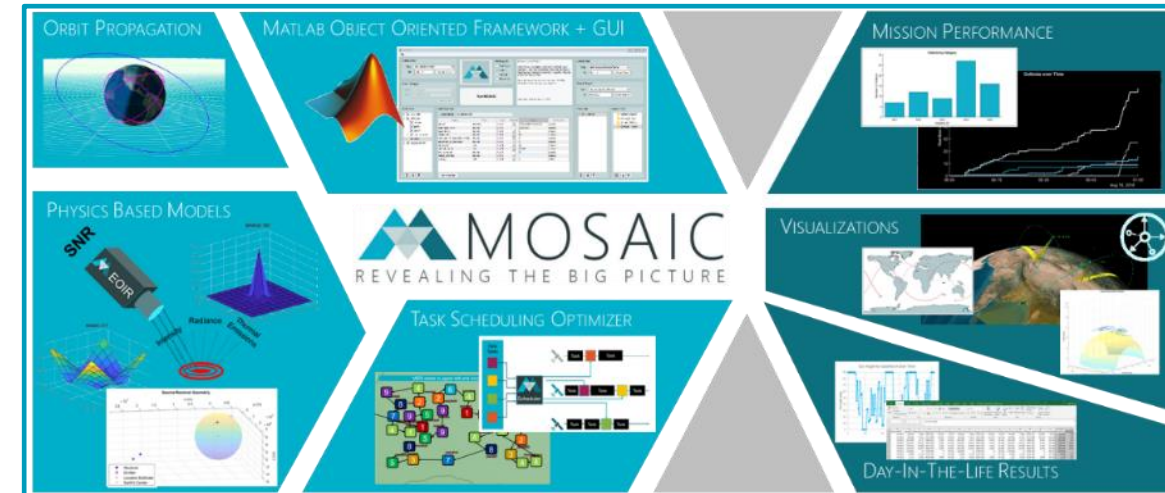


Figure 1: Research to Operations to Research Process (NOAA Example)

SWx R2O2R Framework March 2022

Consider models and practices from across the space sector

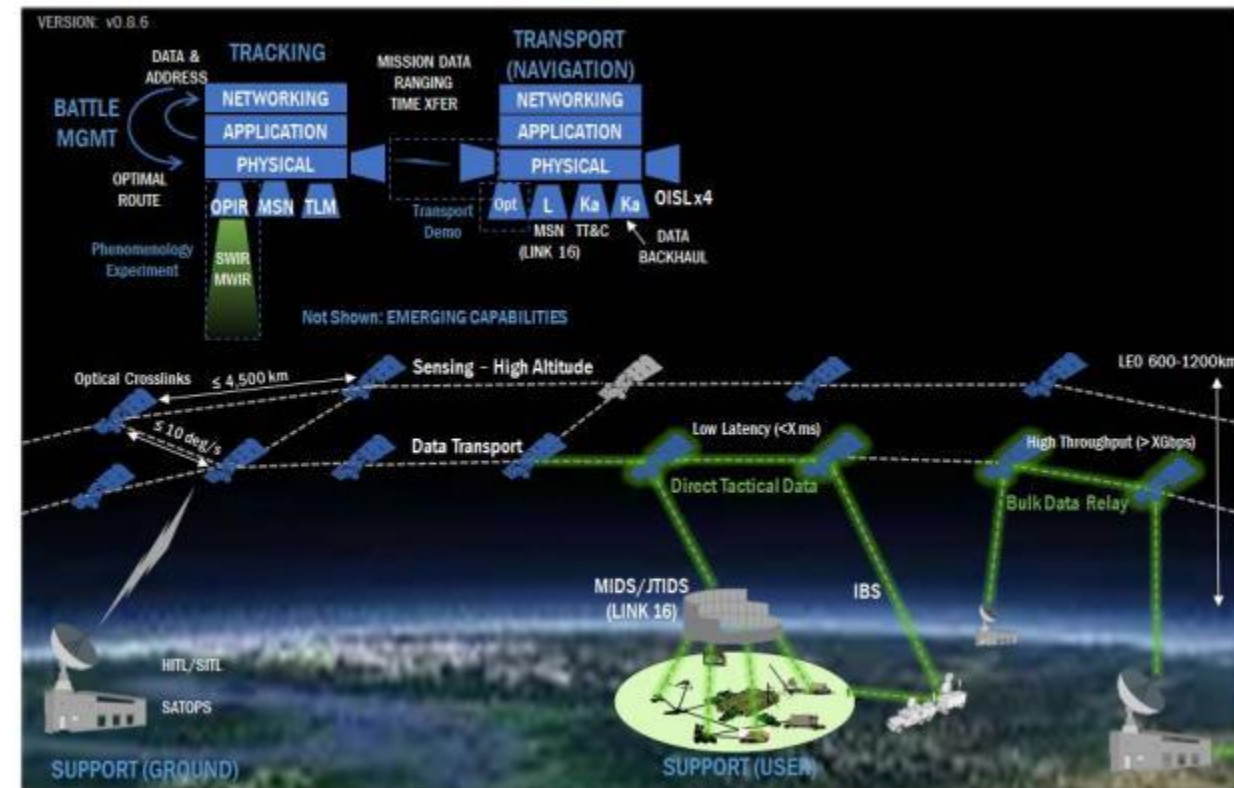
- Industry prime model – for best value
 - Public/private partnership
 - Agency defines mission/observation goals
 - Industry designs & develops mission
 - Industry teams compete for architecture studies
- Commercial practices – for lowest cost
 - Minimal oversight/insight
 - Few deliverables
 - Industry-defined Mission Assurance
 - Acceptance of existing capabilities and interfaces



Ball's MOSAIC mission analysis suite optimizes & streamlines mission design from top-level mission goals

Consider data networks for increased downlink capability

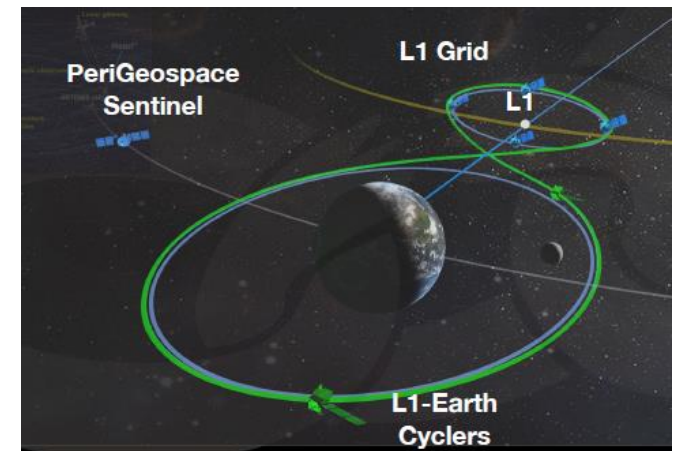
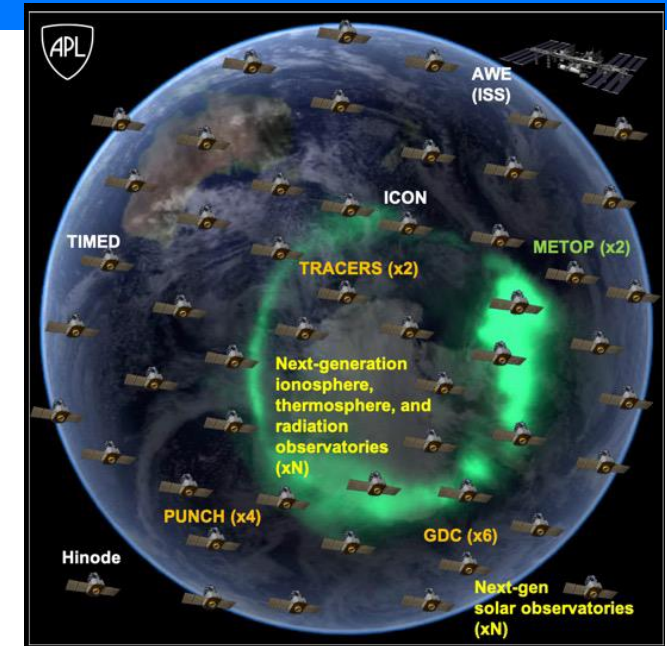
- Leverage near-Earth commercial & DoD comm networks
 - Can Civil agencies purchase services?
- Develop deep space comm network
 - Opportunity to trade telecom resources for increased capabilities (propulsion, instruments, rideshare, mass & cost savings)
 - Commercial network, or agency-developed
 - Partnerships with Planetary & Exploration?



Example: SDA transport layer provides communications to other layers for tracking, controlling and targeting

Constellations will change Mission Development

- Developers need guidance
 - Assurance expectations at constellation and element levels
 - Testing/workmanship requirements for 1 & n+1 units
 - Sparing approach
 - On-board AI/ML TRL maturation & qualification
- The agencies should consider
 - Refreshed contracting mechanisms and funding profiles
 - Constellation-specific technology development to support on-board and on-the-ground autonomy
 - How does autonomous flying impact Space Traffic Mgmt?



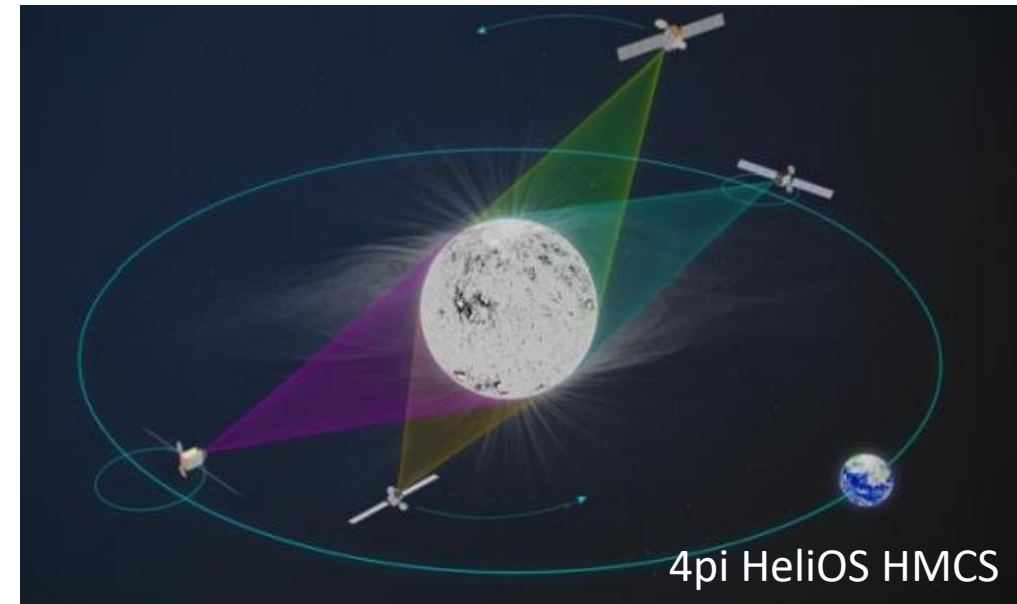
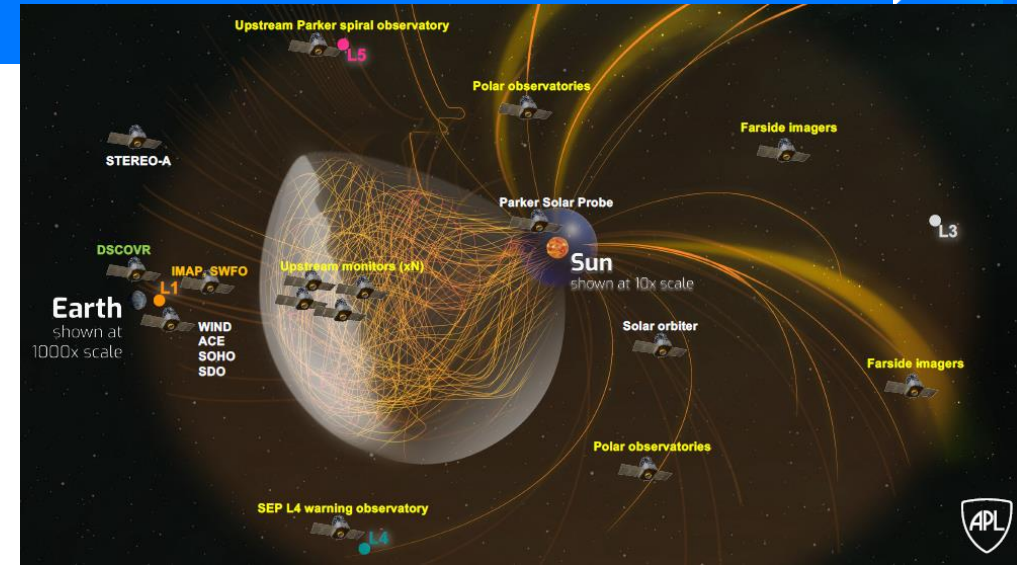
Images courtesy of JHU/APL

CONSTELLATIONS



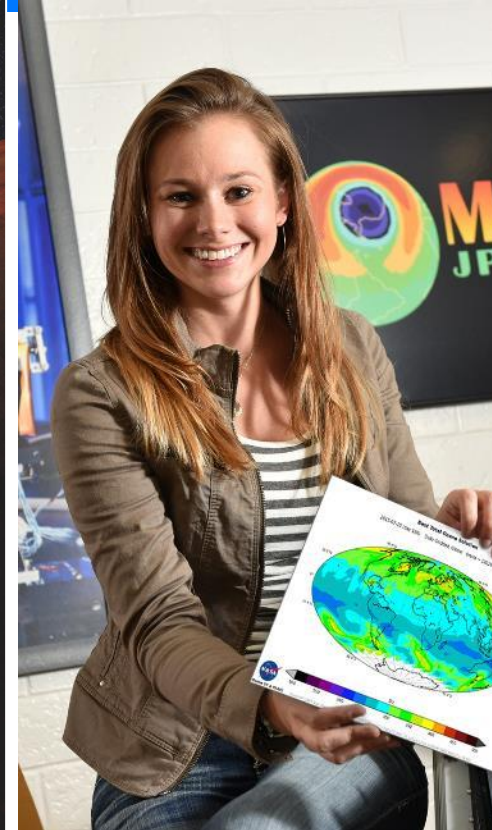
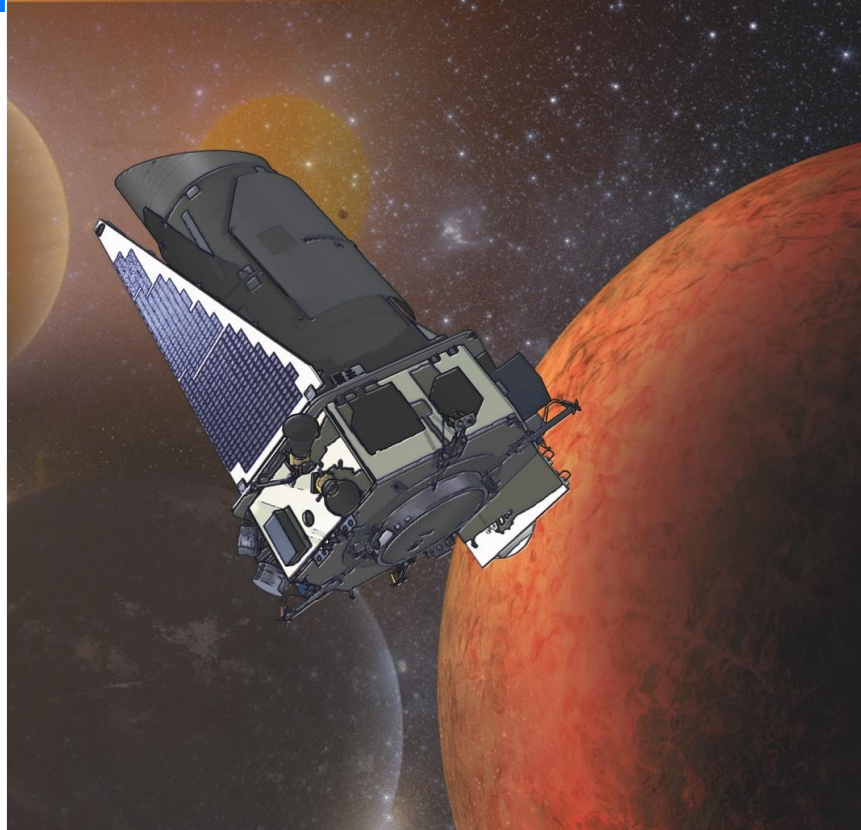
Consider deploying constellations over time

- Programmatic advantages
 - Long-term science goals without long-life parts
 - Opportunity to evolve instruments & provide resiliency
 - Could increase rideshare utilization
- For cost effectiveness
 - Issue competitions/contracts for multiple units
 - Fund all procurements with first unit build for bulk buys
 - Workmanship or reduced testing for n+1 units
 - Maintain workforce by minimizing time between builds
 - Standardize interfaces & resources



Images courtesy of JHU/APL

4/12/2022



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