The Future of Heliophysics Research through Targeted use of Constellations

A White Paper to the Decadal Survey for Solar and Space Physics (Heliophysics) 2024-2033

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Synopsis:

Past advances in Solar and Space Physics have primarily leveraged single point observations or ad hoc combinations of spacecraft, while missions such as Cluster, MMS, and THEMIS have paved the way toward a "constellation era" in Heliophysics. This new era allows for unprecedented advancements into our understanding of the fundamental spatiotemporal nature of Solar and Space Physics, but presents its own set of unique challenges. This white paper seeks to outline the benefits and challenges of constellations, ranging from the Heliophysics System Observatory, to constellations consisting of a small number of spacecraft, to large-number constellations. In moving toward this constellation era, investments are required by our sponsors to best enable our continued scientific advancement in Solar and Space Physics.

History of Space Physics – Journey from Single-point to Multi-point:

The space age rapidly began with a number of first observations, enabled by the rapid access to space. Sputnik 1 launched in 1957 as the first artificial satellite and allowed for explorations of the density of the upper atmosphere, through investigations atmospheric drag [e.g., *1*], as well as insight into the ionosphere through study of the propagation of its radio signals. This was shortly followed by Explorer 1 in 1958, as the first American artificial satellite, which led to the hypothesis of the Van Allen Radiation belts [*2*]. The first spacecraft to explore interplanetary space, be it on accident, was Luna 1 in 1959. Three years later, Mariner 2 would become the first spacecraft to successfully conduct a planetary encounter with its flyby of Venus. From those early firsts, new exploratory missions would include, amongst others, Voyager 1 and 2 as the first spacecraft to visit the Gas Giants, with Voyager 2 also being the only in situ investigation of the Ice Giants to this day. Both Voyagers would later become the first, and so far, only, in situ observations of interstellar space. AMPTE in 1984 would pioneer international space collaboration with its fleet satellites and include active experiments upstream of Earth's magnetosphere. Ulysses, launched in 1990, would become the only spacecraft to have observed the high latitude solar wind. Most recently, Parker Solar Probe has become the first spacecraft to directly sample the sub-Alfvénic solar wind.

These advances have pushed the boundaries of what single point observations are able to newly explore and what discoveries can be elucidated from them. While technological advancements have enabled better, more accurate, observations at higher time resolutions and sensitivities, most of the Heliosphere -- spanning the sub-Alfvénic solar wind [e.g., *3*, *4*], polar solar wind through the solar cycle [e.g., 5, 6, 7], solar wind entry into planetary magnetospheres [e.g., 8, 9, 10, 11, 12, 13], the Van Allen radiation belts [e.g., 14, 15, 16, 17], the buildup and decay of the ring current's oxygen torus [e.g., 18, 19], nearly every layer of the ionosphere from the turbopause and higher [e.g., 20, 21, 22, 23, 24], the inner workings of magnetic reconnection at ion and electrons scales [e.g., 25, 26], planetary current systems and magnetospheric dynamics from Mercury to Saturn [e.g., 27, 28, 29, 30, 31], plasma interactions with moons and comets [e.g., 32, 33, 34, 35, 36], outer planetary radiation belts [e.g., 37, 38, 39], to the transition through the heliopause into the local interstellar medium [e.g., 40, 41] -- has now been sampled directly at least once.

This insight, from the vast history of single point observations, has now enabled us to better characterize the gaps in our understanding and envision new mission architectures that allow the spatiotemporal structuring and evolution of the Heliosphere to be revealed. With an even increasing urgency, future scientific investigations needs to use observations from multiple missions and/or rely on new targeted constellations. This will challenge the field and sponsors to find ways to support and expand upon these activities with a multi-faceted approach that allows for these different multi-point architectures.

The Role of the Heliophysics System Observatory:

With the combination of concurrent missions, including those in extended operations after the conclusion of their prime mission duration, NASA has established the Heliophysics System Observatory (HSO). While the HSO is largely comprised of missions in orbits driven by their prime mission, and without consideration of conjunctions with other observatories, it has provided the unique opportunity for researchers to investigate large-scale variations in the solar wind and Earth's magnetosphere through being able to construct a serendipitous constellation. This has been used in great success for investigations into large-scale longitudinal variations of CMEs [e.g., 42, 43, 44, 45], the radial evolution of CIRs in the solar wind [e.g., 46, 47, 48], EMIC wave generation in the global magnetosphere [e.g., 49], etc.

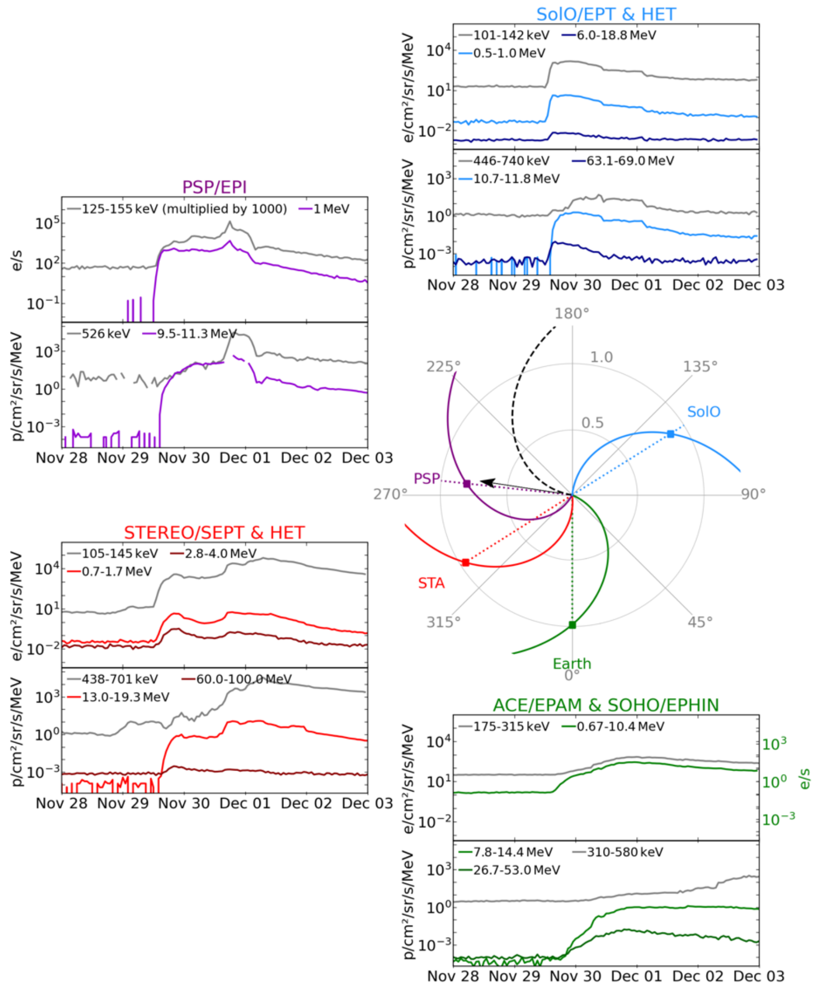

Figure 1: The HSO has been increasingly leveraged in investigations of large-scale variability within Solar and Space Physics. However, studies using the HSO must wait for fortuitous conjunctions and new mission formulation is discouraged from designing around a new missions' place in the broader HSO. From [42].

However, the reliance of the serendipitous timing of events and conjunctions within the HSO, along with it primarily being of use for studying large-scale variations rather than for mesoscale or microscale structuring, limits it from being able to address some of the most fundamental outstanding questions of Solar and Space Physics. As such, new dedicated constellations are required in the next decade to fill these targeted gaps. Additionally, new missions are typically not encouraged to consider how different launch dates may allow them to further leverage these pre-existing assets during proposal and development.

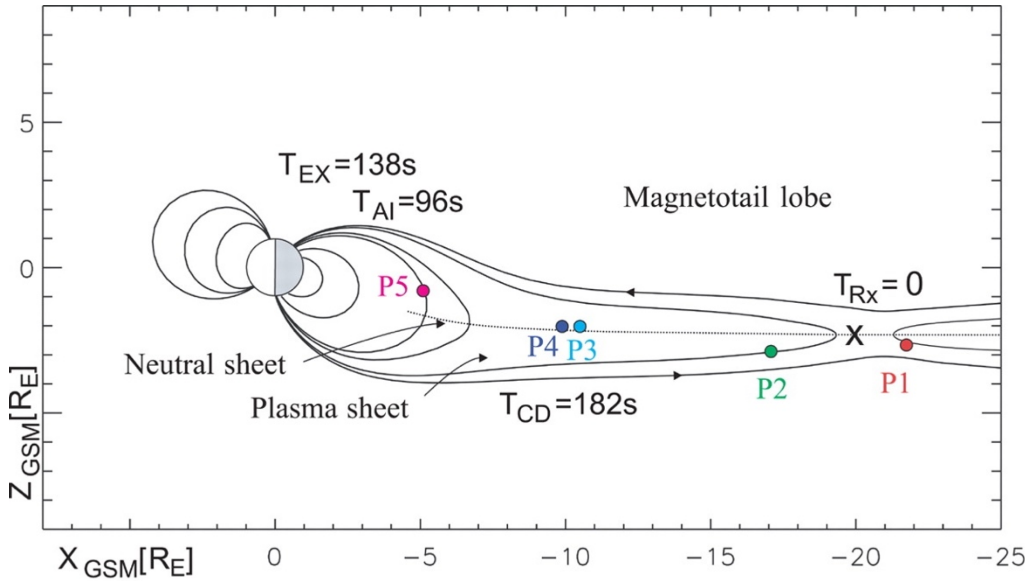

Figure 2. Constellations using a small number of spacecraft have successfully revealed spatiotemporal variations in Solar and Space Physics. Dedicated constellations allow spacecraft to be put into orbits that optimize inter-spacecraft separations and formations to address outstanding problems in Solar and Space Physics. From [50].

The Role of Small Constellations:

Constellations comprised of a limited number of spacecraft, such as two to five satellites, have demonstrated the great utility of such architectures for in situ sampling of the space plasma environment. The Cluster [51] and Magnetospheric Multiscale [MMS, 52] missions both used a tetrahedral formation that allowed the use of novel techniques to better explore the fundamental nature of space physics [e.g., 53, 54, 55, 56]. The THEMIS mission [57] originally consisted of five spacecraft with various apogees to allow in-depth exploration of substorm timing and bursty bulk flows within the magnetotail [e.g., 50, 58]. Two of the THEMIS spacecraft were re-purposed for lunar-plasma interactions as the ARTEMIS mission [e.g., 59], with the remaining THEMIS and ARTEMIS spacecraft continuing to provide multi-point observations throughout the outer magnetosphere to lunar distances [e.g., 60, 61].

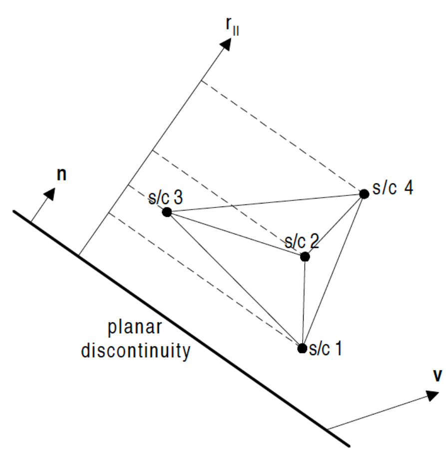

Figure 3. Constellations of four spacecraft can be flown in a tetrahedron configuration, allowing for detailed investigations of the gradients and transitionary boundaries that are fundamental to Solar and Space Physics. From [68].

New missions are being proposed and developed to utilize small number of spacecraft constellation architectures to explore Heliophysics, e.g. InterMeso [62, 63], MHM [64], MIO [65], MAKOS [66], GDC, and Daedalus [67]. The benefit of these architectures is the ability to use multipoint techniques on platforms with a diverse range of parameter observations, allowing for in-depth investigations across the constellation spacing. This unlocks the ability to determine higher order mesoscale variations in a system and probe the system using multi-point analysis techniques. Due to the limited number of spacecraft, however, these missions tend to be more targeted and tailored in their science objectives and are not as well-suited for reaching system-level insights. The targeted approach of these small-number constellations is optimized for significant science return and potentially paradigm shifting insight, but primarily for a few aspects of Solar and Space Physics.

The Role of Large Constellations:

Constellations of many spacecraft (i.e., greater than five spacecraft) enable global, distributed observations. A clear example of such an architecture is AMPERE/AMPERE-NEXT [69, 70, 71, 72], a unique public-private partnership funded by the NSF. This dataset, derived from the constellation of 66 Iridium Communications Network spacecraft, allows for the construction of global field-aligned current maps using avionics magnetometers on the spacecraft. While the constellation configuration limits spatial resolution of the AMPERE current distributions, the nature of this globally-distributed in situ measurement enables system-level insight of an important

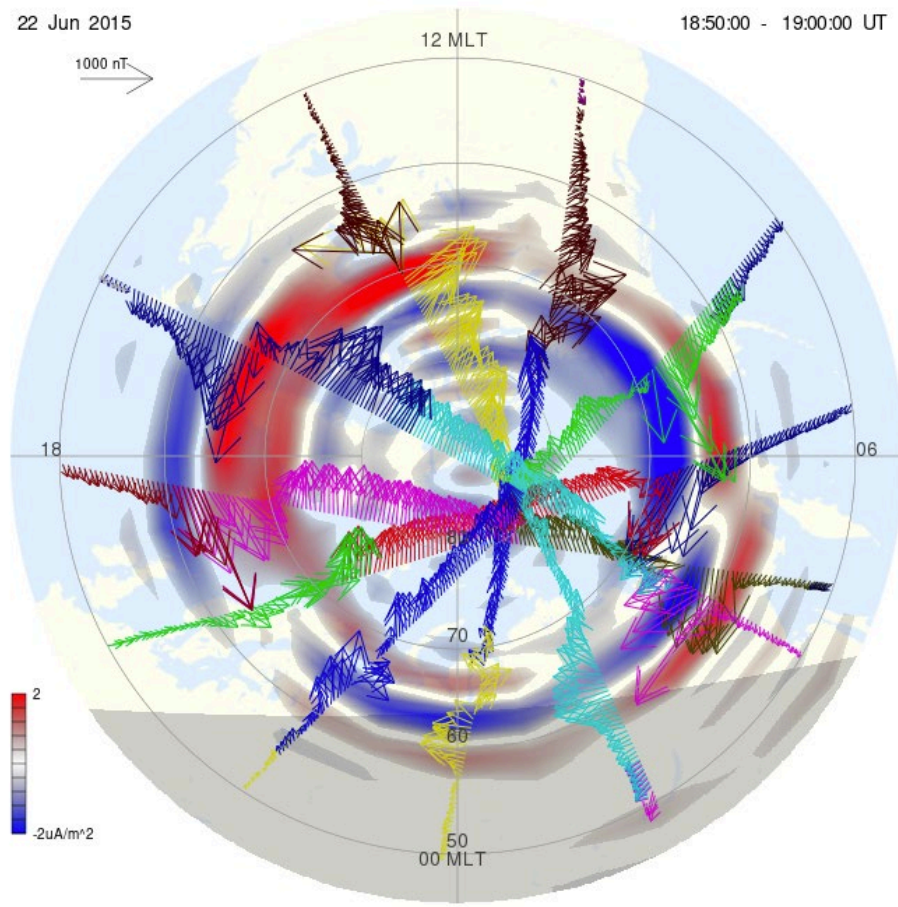

Figure 4. AMPERE utilizes magnetometers onboard 66 Iridium Communications spacecraft to construct maps of the global Field aligned current systems. This has required robust calibration and data cleaning efforts as well as novel visualization techniques, but also demonstrates the power of constellations of large numbers of spacecraft at addressing long outstanding issues in Solar and Space Physics.

aspect of magnetosphere-ionosphere coupling. A constellation architecture in this fashion has yet to be replicated in the Solar and Space Physics community as a stand-alone science mission, but is necessary for advancing understanding of full system dynamics and feedback.

The primary benefit of many-number constellations is the ability to reach global coverage across multiple scales, rather than the targeted investigations of small-number constellations. Additionally, these architectures can unlock observations across multiple domains, i.e., ability to span the solar wind, outer magnetosphere, inner magnetosphere, and ionosphere-thermosphere-mesosphere system. Large-number constellations can also leverage advanced tomography techniques, as well as higher order spatiotemporal reconstructions [e.g., 72, 73]. These added capabilities have led new large constellations to be formulated and developed for the next decade, e.g., HelioSwarm, MagneToRE [73], MagCon [74], and PILOT [75, 76].

Due to the number of spacecraft required, large-number constellations must have more tailored payloads, only being able to support up to a few select observations. The need for large numbers of sensors also motivates increased use of commercial-off-the-shelf (COTS) parts to reduce the total cost of the constellation. While COTS allows for potentially cheaper large constellation missions, they also come with their own considerations. COTS-based instrumentation typically has increased noise/background levels, coarser resolution, more limited dynamic range, and limited reliability in space applications (i.e., not rated to withstand radiation effects). Some science questions may be able to be answered with the targeted performance capabilities from COTS sensors [e.g., Luner Vertex], but not all.

Another consideration for large constellations is the challenge in data visualization. By achieving a constellation of many spacecraft distributed over a large range of spatial locations, visualization needs to move beyond time-series stack plots. This also allows a unique opportunity for the observations to be used in inversions to create maps of directly sampled and derived quantities, such as done for AMPERE [e.g., 72].

Cross-calibration between observatories also increases exponentially with additional spacecraft. In addition to re-tooling inter-calibration methods currently used by small-number constellations like MMS, large-number constellations will also require advancement in AI/ML techniques incorporated into ground processing that have so far not been demonstrated to be sufficiently robust.

A large increase to the number of spacecraft operating simultaneously will also require investments into the Deep Space Network (DSN) and Near Space Network (NSN) to facilitate the dramatic increase in contacts required. While some in the commercial industry (e.g., Amazon Web Services) have begun to expand private options for spacecraft contacts in Low Earth Orbit, constellations further from Earth require additional agency investment.

Figure 5. While COTS sensors are not viable solutions for all science questions, COTS sensors are beginning to be leveraged for low-cost instrument options for targeted missions where they are applicable. An array of Bartington Mag566 sensors are being used on the upcoming NASA Lunar Vertex mission.

Additionally, new technologies (e.g., laser communications) to increase bandwidth and decrease contact length should be a priority for advancement of communication infrastructure.

The Need for a Multitude of Constellations in the Next Decade:

While Solar and Space Physics is made up of a large number of sub-fields with a large diversity of science questions and topics, the field as a whole is moving toward constellation architectures for addressing the questions that have arisen over the last decade. In fact, three of the last four Explorer line missions to proceed to Phase B have been multi-point observatories (i.e., HelioSwarm, PUNCH, and TRACERS). While some investigations have been able to leverage the HSO, which is in and of itself invaluable, the community requires additional, targeted constellations going forward. Both small-number constellations and large-number constellations are needed in concert with the HSO to answer the diverse range of open questions, and the different sub-fields require their own targeted missions. As such, agencies serving the Heliophysics community need to prepare for these opportunities.

The main outstanding challenges and needs going forward are:
- Need to best leverage the HSO for future investigations, while understanding and balancing the need for new dedicated and targeted constellations.
- Need to coordinate new constellations with the pre-existing HSO, and the mechanism to do so during formulation, proposal, and development phases.
- Need for funding mechanisms to allow multiple constellation missions to be realized within the next decade across the sub-fields of Solar and Space Physics.
- Need for development of better AI/ML techniques to allow for ground cross-calibration of instruments on constellations with a large number of spacecraft.
- Need to develop improved visualization of observations from large spacecraft constellations.
- Need for investment into the DSN and NSN, as well as general communications technology, to better support many simultaneous multi-spacecraft constellations.

Ultimately, realizing a constellation-enabled future for Solar and Space Physics, while still embracing the diversity of sub-fields and science questions, *will require an increase in the NASA Heliophysics budget*, as well as investments into communication infrastructure. *Increased support from related NSF and NOAA departments* are also required for full realization of a multi-constellation era in Heliophysics. This will require the Solar and Space Physics Decadal to take a progressive, forward-looking stance on Heliophysics funding.

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