Mesoscale dynamics – the key to unlocking the universal physics of multiscale feedback

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The universal physics of multiscale feedback results from dynamical plasma physics occurring over temporal and spatial scales that span many orders of magnitude. We can broadly categorize these regimes into three scales: microscale, mesoscale, and synoptic. Though each regime encompasses vastly different temporal and spatial scales, summarized in Table 1, the *bidirectional feedback* across the scales is crucial to physical understanding and, ultimately, prediction. This is true of all of the physical systems that comprise the sub-disciplines of Heliophysics: Solar, Heliospheric, Magnetospheric, and Mesosphere, Ionosphere and Thermosphere (MIT).

At the smallest scale, kinetic physics deals with the motions and effects of individual particles. Dynamics in this regime include thin current sheets and magnetic reconnection, wave-particle interactions, kinetic plasma instabilities, and particle acceleration. The temporal and spatial scales are dictated by particle gyromotion. At the opposite end of the spectrum, synoptic scales are defined as significant fractional sizes of the system under consideration, and the timescales associated with synoptic spatial scales are determined generally by the timescale it takes to significantly alter the synoptic structure. Examples include:

Earth's magnetosphere - all regions including boundary layers; substorms and geomagnetic storms;

MIT - planetary waves, atmospheric tides, ionospheric convection patterns, and neutral wind fields;

Heliosphere - the HCS (ballerina skirt), corotating interaction regions, and CMEs;

Solar - the solar dynamo, the layers of the solar atmosphere (photosphere, chromosphere, transition region and corona), coronal holes, active regions, streamers, and the transition to solar wind state from each of these.

All physical systems within heliophysics are observationally under-sampled. The current technological and computational capabilities severely limit the community's ability to model and observe the orders-of-magnitude temporal and spatial chasms between kinetic and synoptic scales. Instead of a comprehensive modeling and observing program, we are forced to focus on restricted regions of parameter space. Furthermore, modeling must reduce the complexity of the phenomena it mimics, e.g. by restricting the spatial scales and timescales, approximating the physical interactions, simplifying boundary conditions, and reducing the dimensionality. Kinetic physics are often modeled with Particle-In-Cell (PIC) simulations, while large systems employ MHD modeling. Kinetic observations require rapid, in situ measurements (like PSP,

		Regime		
Characteristics		**Kinetic**	**Mesoscale**	**Synoptic**
Temporal Scale	Solar	<0.1 s	Hours to days	Days to decades
	Solar wind	seconds	10s of seconds to hours	Days to weeks
	M'sphere	<seconds	10s of seconds to minutes	10s of minutes to days
	MIT	seconds	Few minutes to hours	Hours to days
Spatial Scale	Solar	<1 km	1 Mm – 100 Mm	Solar radius (700 Mm)
	Solar wind	<1 Mm	10 Mm-thousands of Mm	1 AU (150,000 Mm)
	Magneto-sphere	<hundreds of km	Up to few RE	>few RE
	MIT	<meters	<100s km	<1000s km
Simulation		PIC	MHD, hybrid, mixed models, plug-ins	MHD, hybrid, mixed
Example		Wave particle interactions, ohmic heating, magnetic reconnection, plasma instabilities, small-scale gravity waves	Bursty bulk flows, FTEs, streamer blobs, solar bright points, ionosphere polar cap patches, gravity waves	Solar dynamo, streamer belt, CMEs, CIRs, substorms, planetary waves, atmospheric tides
Measurement approach		In situ fast instrumentation; spectroscopy	Constellations, coordinated system science measurements; spectral imaging	Widely separated, moderate temporal resolution; imaging

MMS, and FAST), or spectroscopy (DKIST, IRIS) while synoptic studies require widely separated spacecraft working together – such as STEREO in situ + L1 in situ, THEMIS radial conjunctions, solar and heliospheric imagers such as STEREO/SECCHI, SDO/AIA, and SOHO, and magnetospheric EUV and ENA imagers. More broadly, synoptic scales are studied with the ad-hoc Heliophysics System Observatory (HSO) that acts like a "system science" observatory. Note that the ballpark scales in Table 1 are simple guidelines, and don't even account for additional scale changes that occur, e.g. with solar cycle, or within sub-regions.

A Path Forward Using Mesoscales as a key for unlocking multi-scale feedback

The systems we study in heliophysics – the extended solar atmosphere, the solar-wind, the magnetosphere, and the MIT system – are all highly complex, multi-scale systems. To date, we have studied these systems piecemeal, generally confined to either the kinetic (micro) or synoptic scales, constrained by computing power and sparse and/or wavelength-specific measurements to uncover pieces of the puzzle. In the chasm between synoptic and kinetic scales lies the mesoscale. Itself comprising several orders of magnitude, the mesoscale is the fundamental link for the multi-scale, bidirectional feedback between micro and macro because it serves as a conduit for mass and energy flow. Turbulence is an example of synoptic energy transferring through mesoscales to kinetic. Avalanches are an example where the feedback and flow of energy is transferred in the other direction. The mesoscale-synoptic and mesoscale-kinetic connections are two-way interactions, that can both modulate and modify the transfer of energy across scales. Mesoscales transfer energy and mass across boundaries: from the sun to the solar wind, from solar wind to the magnetosphere, from the magnetosphere to (and back from) MIT. Although often treated separately, each of these systems are driven by the same fundamental physical processes, and in each instance, the orders of magnitude mesoscale regime is undersampled and undersimulated. Making progress in these systems over the coming decades requires a new approach, enabled by advancements in measurement technology and computational power.

Understanding the multi-scale feedback inherent to plasma dynamics throughout the heliosphere requires bridging the gap between kinetic and MHD and covering several orders of magnitude of time and space. ***The undersampled mesoscale regime is crucial to study and we believe could be a unifying focus of heliospheric research in the coming decades***. The primary suggested actions and the obstacles they overcome are described below.

1) 4π, continuous, high temporal and spatial resolution coverage of each system through constellations of spacecraft with imaging and in situ capabilities

Questions of cross-scale coupling and mesoscale dynamics cannot be answered by scattered single point measurements, or even by local constellations of satellite, such as Cluster or MMS. They require large constellations of spacecraft. The cases for magnetospheric and ITM constellations have been made for decades and are well known, and technical advancements in spaceflight have brought these within reach. A key framing for those missions (e.g. GDC and MagCon) is the study of mesoscale structures and dynamics, and how they modulate, regulate, and transfer energy and mass between the micro and synoptic scales. Solar and heliospheric physics require simultaneous 4π, multi-wavelength and multiscale remote observations[1], as well as networks of widely separated in situ spacecraft in the solar wind, including over the poles, to capture the unexplored mesoscale regime in the solar wind[2].

At the sun, mass and energy exchange occurs between the convection zone, the photosphere, the chromosphere and the corona, with mesoscale flux tubes as conduits. Observations of flux tubes are typically made with vastly different instrumentation, ranging from X-ray to UV to infrared, because of the huge range in temperatures. Additional complications are that the measurements range from optically thin to optically thick. Making the connection between such disparate measurements has been difficult. IRIS provides a glimpse of this connection, but in a very narrow window. DKIST is effectively a microscope. There

[1] See submitted WPs on 4π science by Gibson+, Vourlidas+, Newmark+, Hassler+

[2] See submitted WP 'Exploring the Critical Coronal Transition Region' by Vourlidas+

is currently no off-limb spectroscopic diagnostics[2]. To pull it all together we need to see the global picture and monitor the evolution simultaneously, but with commensurate capabilities.

The turbulence cascade in the heliosphere is some combination of structure and flows injected from Sun that interact via flow shears and in situ instabilities, and devolve into turbulence. Switchbacks observed with PSP are likely evidence of some of this feedback, but we need constellations of in situ combined with remote imagers to see this. PUNCH is a small step in this direction but will not get anywhere near to the kinetic scales.

2) Ability to fully model the 3D dynamics

Mesoscales can feedback on global scales and lead to "emergent" dynamics. Models of global dynamics only capture this effect when mesoscales are resolved, which has been difficult. The mesoscale can also serve to integrate small-scale kinetic effects to produce synoptic change, whose integral effect is comparable to a single, large event. A simple example is the integral effect of multiple flow bursts on building up the ring current. Yet mesoscale systems are extremely difficult to simulate as they often involve both kinetic and MHD physics. This requires expansive investment in modeling efforts in order to combine expertise from different regimes and develop new models that simultaneously extend from the global down through mesoscale to the kinetic, spatially and temporally. By 2050, global hybrid or spectral kinetic simulations may be available, allowing us to tackle the following types of problems:

- 4π studies of the solar atmosphere, with more focus of the high latitudes or the longitudinal science created by the massive rotational energy reservoir that will bridge between the apparently disparate "solar cycle" and "space weather" epochs.
- Solar 4π, time dependent connectivity of the solar wind and transients throughout the heliosphere. Turbulence models with expansion and that accurately capture feeding from the true mesoscales injected into the solar wind.
- Active regions, with ~100,000 current sheets present, are out of reach for numerical simulations that currently cannot simultaneously capture the kinetic physics of the current sheets, with the thermodynamics of the chromosphere-corona coupling, and include realistic photospheric footpoint motions. It is currently impossible to model the integral or cross-scale effects – i.e., kinetic to mesoscale to global in a single active region, let alone the entire solar atmosphere. Required is a 3D, time dependent model of the magnetic field, velocity, temperature, density, and optically thick and thin emission from the convection zone through the photosphere, chromosphere, transition region, and corona, out into the solar wind up to the Alfven Zone[3].
- Global magnetospheric models that include kinetic effects and their propagation throughout the system down to the ionosphere, including a fully coupled, self-consistent ring current and resolved boundary layers[4].

3) Broadly funded programs to pull together all of the needed expertise under a coherent umbrella

Expertise is often contained in 'silos', in which highly skilled individual researchers are confined to their respective discipline or niche. "Breaking down silos" is a common refrain, but we don't want to break down these silos of expertise. Instead, we need to organize the silos under coherent and cohesive long duration, well-funded work efforts. In the same way cross-scale simulations require models to match and ingest data from the different regimes, we need to build bridges between silos of expertise, not break them down. This includes training a new generation of scientists who do not necessarily belong to a silo, and can easily perform cross-over work, while providing career paths that involve cross-over work. We need to also attack different physical regimes with the same tools, to leverage cross-divisional expertise. Solar in particular has been hampered by different wavelengths and the types of analysis tools that are accessible to that wavelength range, rather than by physics. ***Mesoscale dynamics inherently forces us to cross silos, because that is the only way to understand the physics***. The DRIVE center program is a small step in the right direction, but its remit must be expanded.

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[3] See submitted WP, 'Heating of the magnetically closed corona', by Klimchuk+

[4] See submitted WP 'Active Geospace – 2050 Vision for First-Principles Modeling' by Merkin+