The Solar Wind at Mesoscales – Revealing the Missing Link

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

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Synopsis:

Mesoscale dynamics are fundamental in space physics, but fall within an observational gap of current and planned missions. Particularly in the solar wind, measurements at the mesoscales (100's R_E to a few degrees heliographic longitude at 1 au) are crucial for understanding the connection between the corona and an observer anywhere within the heliosphere. Mesoscale dynamics may also be key to revealing the currently unresolved physics regulating particle acceleration and transport, magnetic field topology, and the causes of variability in the composition and acceleration of solar wind plasma. Studies using single-point observations do not allow for investigations into mesoscale solar wind dynamics and plasma variability, nor do they allow for the exploration of the sub-structuring of large-scale solar wind structures like coronal mass ejections (CMEs), co-rotating/stream interaction regions (CIR/SIRs), and the heliospheric plasma sheet.

To address this fundamental gap in our knowledge of the heliosphere at these scales, new dedicated mesoscale missions are required in the next decade. This white paper outlines the current gaps in our understanding resulting from limited measurements at this critical scale and the need for an asserted effort in addressing these gaps.

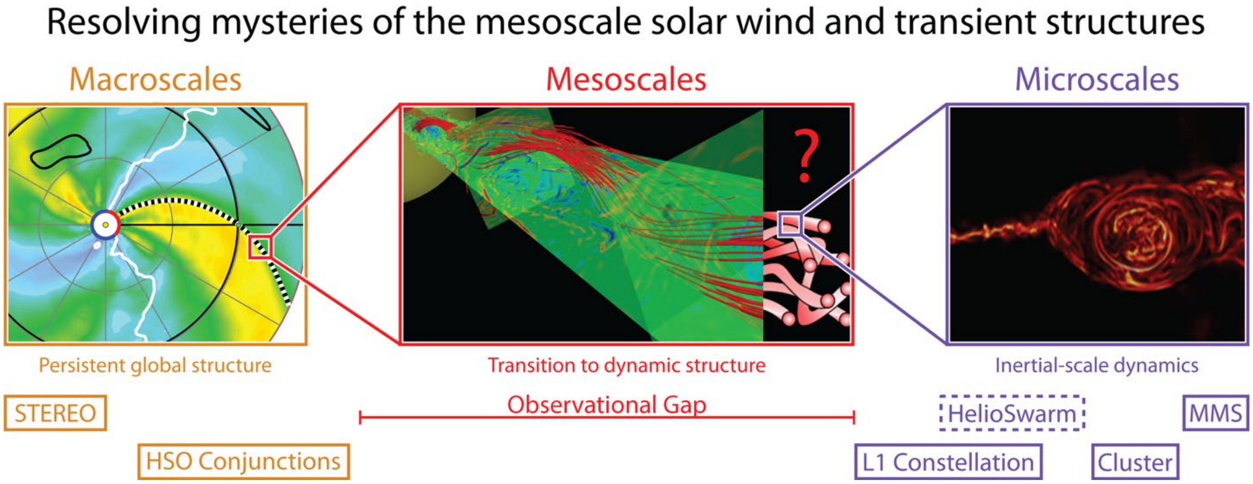

Figure 1: Mesoscale dynamics are fundamental to solar wind dynamics, enabling interaction between macro and micro scale dynamics, but currently fall within an observational gap. Left panel from *Allen et al.* (2020), middle panel adapted from *Maruca et al.* (2021), and right panel from *Lazarian et al.* (2020). *Fundamental knowledge gaps in solar wind dynamics and structure exist at these critical mesoscale lengths due to an observational gap.*

Current Knowledge of the Multi-scale Solar Wind and Transients:

The solar wind is a multi-scale and highly dynamic system with interplay between the micro-, meso-, and macro-scales. Decades of single-point observations have led to great insight into the large-scale variability in the solar wind and its transient phenomena, such as coronal mass ejections (CMEs), stream and co-rotating interaction regions (SIR/CIRs), and solar energetic particle (SEP) events associated with flares and/or CMEs. These observations have revealed differences between high-speed streams originating from coronal holes, typical slow solar wind, and Alfvénic slow solar wind (e.g., *D'Amicis et al.*, 2019) and established the current paradigm under which the solar wind is interpreted today.

Previous studies from the Solar Terrestrial Relations Observatory (STEREO) mission and other serendipitous multi-point observations have allowed investigations of spatial variations of the solar wind and transients over large distances. For instance, the radial evolution of the expanding solar wind has been studied statistically using observations from Helios (*Perrone et al.*, 2019), while the radial evolution of CIRs has been studied within the orbit of Earth (e.g., *Richter & Luttrell*, 1986; *Schwenn*, 1990; *Jian et al.*, 2008; *Allen et al.*, 2021a, b) and between Earth and Mars (e.g., *Geyer et al.*, 2021). Multi-point observations of CIRs, and their associated energetic particles, over large longitudinal separations have also revealed significant temporal evolution of the structures as they corotate over 10's of degrees longitude (*Mason et al.*, 2009; *Jian et al.*, 2019; *Allen et al.*, 2021a). Additionally, radial (e.g., *Burlaga et al.*, 1981; *Liewer et al.*, 2020) and longitudinal (e.g., *Kilpua et al.*, 2009; *Farrugia et al.*, 2011; *Kollhoff et al.*, 2021) studies of CME structures have found significant variations over these large separations.

On smaller, ion kinetic scales (<1000 km), the solar wind and transients have been found to be highly turbulent and structured, with clear signs of coupling processes over a large range of spatiotemporal scales (e.g., *Bandyopadhyay et al.*, 2018; *Roberts et al.*, 2020). While the Magnetospheric Multiscale (MMS) and Cluster missions, designed to target kinetic scales, have demonstrated the importance and richness of small-scale and highly dynamic plasma processes, these scales are "on the receiving end" of the turbulent cascade that is driven by the large-scale solar wind structures (*Verscharen et al.*, 2019). As such, the intermediate scale, between the small, kinetic scale dynamics explored by MMS and Cluster and the larger-scale structuring and variations observed by STEREO and multi-mission comparisons, represents the critical scale needed to understand cross-scale processes in the solar wind. This intermediate scale – the mesoscale – is crucial for understanding the connection of the corona to an observer anywhere within the heliosphere, as well as for revealing the currently unresolved physics regulating particle transport, magnetic field topology, and the variability in composition and acceleration of solar wind plasma.

The mesoscale solar wind currently falls within a gap both observationally and in spatiotemporal scales of current simulations, and as such is a critical missing link in our fundamental understanding of the heliosphere. A new mission targeting this critical gap of mesoscale dynamics in the next decade would enable investigations into how solar sources imprint themselves into the solar wind at 1 au and beyond via mesoscale structuring, how mesoscale variability evolves as it propagates from the Sun, and how the intrinsic structure of the solar wind impacts the structure of transients and particle acceleration and transport. The mesoscale regime of the solar wind may likely be the missing piece to long sought questions of sources of solar wind, particle acceleration, and particle transport. Gaining the ability to probe the mesoscale solar wind will allow for leaps in our understanding of these outstanding questions.

The Need to Explore and Identify the Origin of the Mesoscale Variability of the Background Solar Wind and Transient Solar Wind Structures:

The solar surface exhibits structure on granule and supergranule scales (shown in model results in Figure 2a). As solar magnetic structures convect out with the solar wind, they can undergo meandering due to footpoint motion, reconnection, stochastic motion, and evolution (e.g., *Borovsky*, 2008; *Ashraf & Li*, 2019; *Bian & Li*, 2021). As such, once flux tubes reach 1 au, they can be tangled into a complex meso-structure (illustrated in Figure 2b) (*Borovsky*, 2008). These

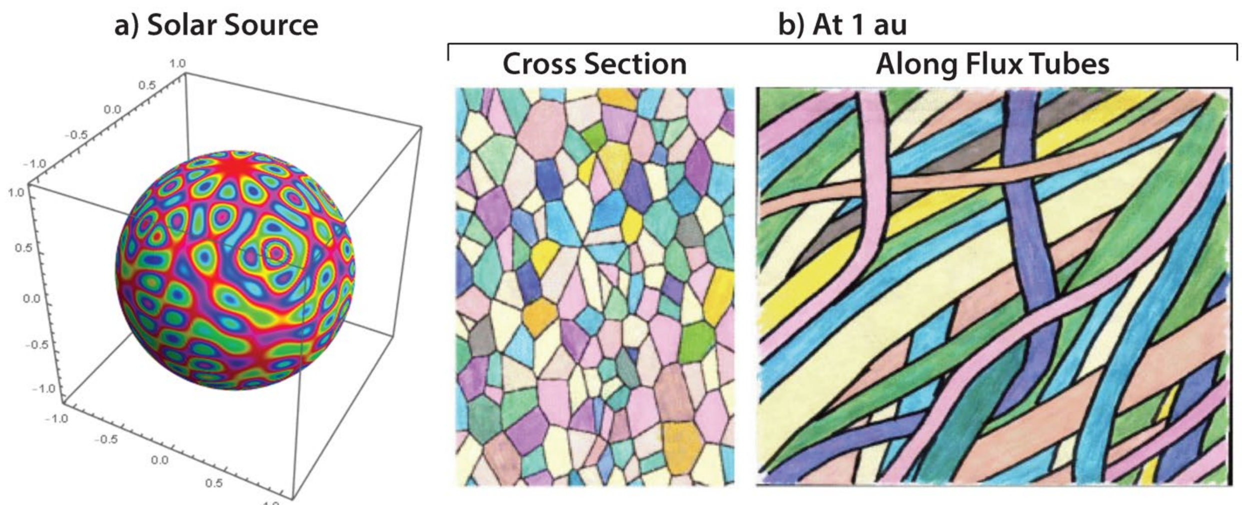

Figure 2: (a) Modeled representation of typical topology of magnetic structures on the solar surface (adapted from *Bian & Li*, 2021). (b) As these structures convect outward to 1 au, they can undergo processes such as expansion and stochastic meandering, but may preserve their characteristics as granule to supergranule relics on the Sun (adapted from *Borovsky*, 2008). *The nature of flux tube structure at 1 au remains a fundamental open question.*

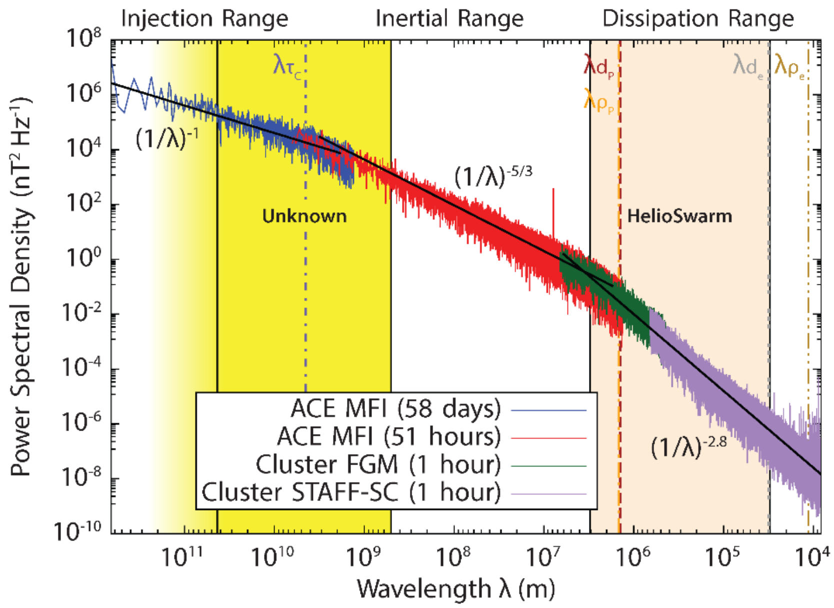

Figure 3: The power spectral density of magnetic field fluctuations for intervals of solar wind plasma beta ~1 shows two spectral breaks (adapted from *Verscharen et al.* 2019). While the upcoming HelioSwarm mission will explore the transition between the inertial and dissipation ranges, *the spatiotemporal dynamics between the injection and inertial range are still unexplored.*

processes and structuring can lead to various effects, such as "dropout" phenomena in energetic particles (*Mazur et al.*, 2000). However, the fundamental structuring and coherence of flux tubes in interplanetary space remain largely unknown.

Moving from the large-scale structures to mesoscale and smaller ranges, the nature of injection range fluctuations in the solar wind is not well understood, nor is the transition at the break point between the injection range and the inertial range (see *Verscharen et al.*, 2019). Persistent, large-scale structures may transition to dynamic structures at scales near 10^9 – 10^{10} m (Figure 3). However, this critical transitionary scale between injection range and inertial ranges has been elusive from a single-spacecraft vantage point, as these observations are limited in the ability to distinguish between temporal variations and those resulting from convection of spatially-variable solar wind over an observer. While the currently planned HelioSwarm mission will, for the first time, robustly explore the spatiotemporal transition between the inertial range and dissipation range, the injection-to-inertial range transition will remain unexplored. *Only through multi-point observations with separations on the order of this critical scale can we robustly explore fundamental transitions in the solar wind.*

In addition to the currently unconstrained, fundamental mesoscale structuring of the solar wind, sub-structuring of transient events is also not well understood. The small number of studies that have utilized fortuitous, but sporadic, multi-mission conjunctions to investigate the mesoscale structuring of CME shocks have shown that CME-associated shocks and magnetic ejecta have smaller-scale structuring, although the degree of such structuring is largely not understood (e.g., *Bale et al.*, 1999; *Knock et al.*, 2003; *Pulupa & Bale*, 2008; *Koval & Szabo*, 2010; *Lugaz et al.*, 2018). The various scale lengths of the solar wind, CME sheath, and CME ejecta are expected to be different from one another (e.g., *Ala-Lahti et al.*, 2020). Additionally, comparisons of shocks between the Advanced Composition Explorer (ACE) and Wind missions have found that energetic particle time-intensity profiles often change over mesoscales, indicating important effects of mesoscale structuring on particle acceleration and transport (e.g., *Neugebauer et al.*, 2006). *Observations such as these indicate that the "large-scale-only" view of the solar wind is an incomplete picture of the fundamental structure of the solar wind and the important processes that define its evolution.* Dedicated multi-point observations are needed to reveal these fundamental physical processes.

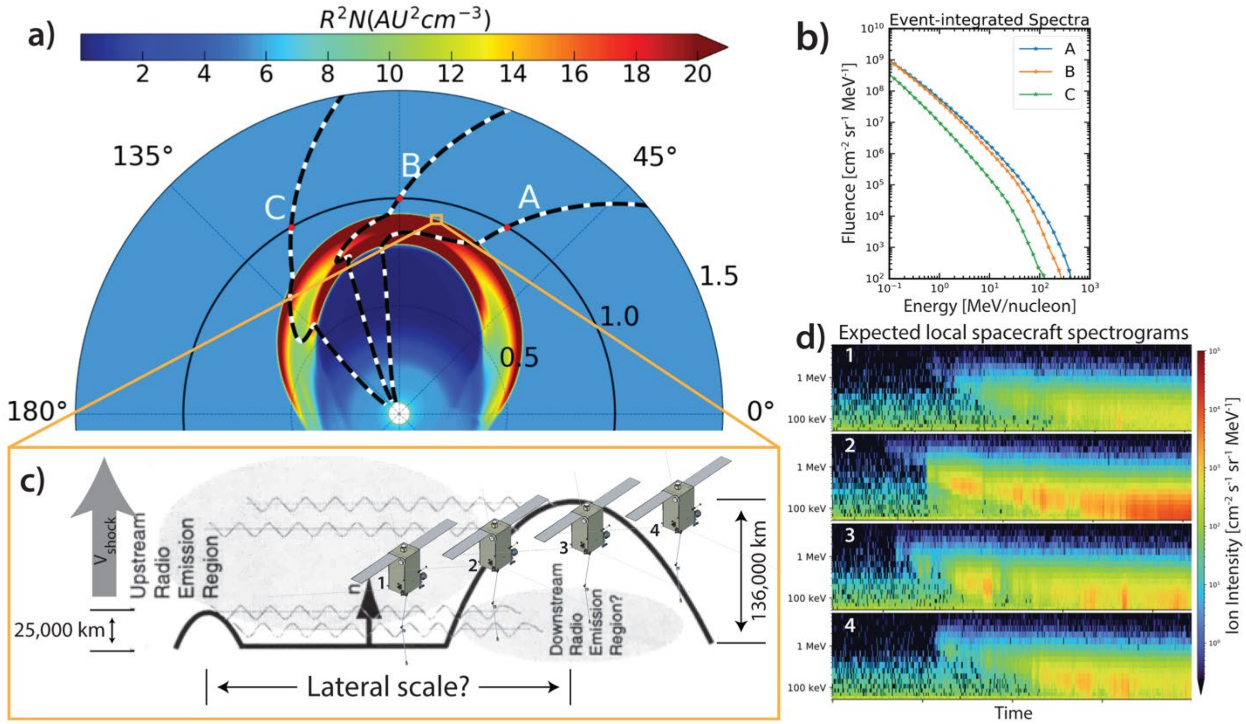

Figure 4: (a) Simulation of large-scale CME structure near 1 au yielding (b) longitudinal variations in event-integrated particle spectra. (c) Mesoscale structuring of a CME shock inferred from radio wave observations (adapted from *Bale et al.*, 1999) with (d) potential observations from four spacecraft highlighting variations and impacts on particle dynamics. *Mesoscale structuring of CMEs and effects on particle acceleration are poorly understood and cannot be fully addressed by previous, current, or planned missions.*

The Need to Understand and Characterize the Impact of These Mesoscale Variations on Particle Acceleration and Transport:

Particle acceleration is fundamentally dependent upon local conditions in the acceleration regions and, as such, mesoscale variations in the solar wind and along/within transients will affect acceleration processes. For example, a CME expanding into solar wind streams with spatial pressure variations may lead to deformation of the CME structure (e.g., *Owens et al.*, 2017), resulting in spatially varying shock structure in the mesoscale range. Such mesoscale variations along a shock surface lead to localized differences in shock parameters affecting particle acceleration, and so could potentially explain the variations observed in Figure 4b-c. *Detailed observations at multiple points along such structures are required to determine mesoscale effects on CME-associated particle acceleration.*

Radio wave observations have demonstrated the presence of mesoscale variations in shock structures (e.g., *Bale et al.*, 1999; Figure 4c); however, it remains unknown to what degree the mesoscale structuring affects particle acceleration. While current models can reproduce large-scale variation in event-integrated particle spectra along an interplanetary shock (Figure 4a-b), which have been observed by conjunctions of spacecraft at large separations (e.g., *Hu et al.*, 2018), these approaches are unable to capture the effects of mesoscale structuring or short time cadence evolution (Figure 4d). For example, an event-integrated spectra includes particles accelerated from various locations along the shock structure, but the seed populations and freshly accelerated ions

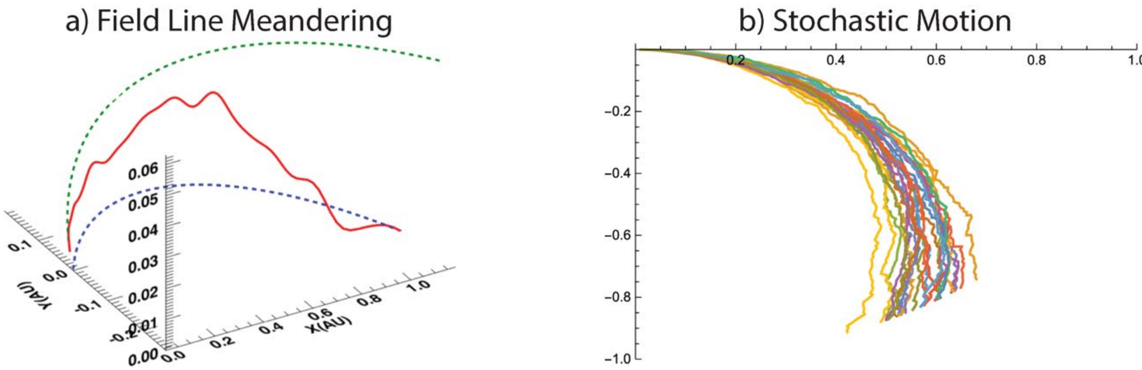

Figure 5: (a) Field line meandering (from *Ashraf & Li*, 2019) and (b) stochastic motion (from *Bian & Li*, 2021) are important mechanisms that cause the location of energetic electrons reaching 1 au to dramatically deviate from the nominal Parker Spiral. *The relative contributions of these processes on particle transport are unknown, but critical to understanding particle dynamics.*

will be more localized to the mesoscale variations of the structure. Better understanding the role that mesoscale structure plays in controlling the variability of particle acceleration along an interplanetary shock is critical for investigating the causes of observed variation between events and potential seed populations.

Additionally, our understanding of flare acceleration of energetic electrons will be greatly advanced through a robust exploration of mesoscale particle variations. For instance, *Li et al.* (2020) found that the injection timing of energetic electrons compared to hard X-ray observations suggests the presence of two distinct electron populations in an impulsive solar energetic electron event. The presence or absence of these electron populations can differentiate between different types of magnetic reconnection at the flare site (e.g., interchange reconnection versus reconnection between two closed field lines). However, the determination of the path length that the energetic electrons traversed from the flare to the observer is the primary source of ambiguity in these observations, which may be a result of mesoscale variations impacting particle transport. For example, field line meandering and/or stochastic motion can lead to uncertainties of where a source region maps to of up to 10° in longitude at 1 au (*Bian & Li*, 2021, Figure 5). Observing energetic electrons at multiple spacecraft with a close separation (<10° total span) will allow for the determination of acceleration time scales of electrons at solar flares, through fractional dispersion analysis (FVDA, *Zhao et al.*, 2019), and so for differentiating among proposed reconnection mechanisms.

The complexities of transport between the corona and 1 au are apparent in impulsive SEP events. For example, when the two STEREO spacecraft were within 34° heliographic longitude of one another in 2014 (Figure 6a), a flare event occurred at an active region near the footpoints of both spacecraft (Figure 6b). During this event, as shown in Figure 6c, STEREO-A, despite the footpoint being slightly further from the active region, observed a higher peak in 55-65 keV electron intensity with an onset time about an hour earlier, and with higher anisotropy, than STEREO-B (*Klassen et al.*, 2016). Because transport of flare-accelerated energetic electrons depends on background solar wind structure, particle acceleration at flare sites, and the mechanisms driving cross-field diffusion, this event presents a clear example of the importance of mesoscale variations on the transport of energetic electrons from the flare site in the corona to 1 au. *As such, a robust* *multi-point investigation at mesoscale separations is required to disentangle the complexities of particle transport in the inner heliosphere.*

For particle transport from local acceleration sites associated with transients, mesoscale variations may also play an important role. As energetic particles propagate along a field line away from an acceleration site, such as from reverse shocks at CIRs, various processes (e.g., adiabatic cooling and particle scattering) leading to hardening of the lower-energy spectra are thought to occur (e.g., *Fisk & Lee*, 1980). However, this spectral hardening has not been observed as often, or as significantly, as expected (e.g., *Mason & Sanderson*, 1999; *Desai et al.*, 2020; *Allen et al.*, 2021a; *Joyce et al.*, 2021). To explain this discrepancy, several theories have been developed, such as compressive, non-shock related acceleration (e.g., *Giacalone et al.*, 2002; *Fisk & Gloeckler*, 2006; *Ebert et al.*, 2012; *Chen et al.*, 2015) and/or modifications to the magnetic topology, such as sub-Parker spirals (e.g., *Murphy et al.*, 2002; *Schwadron*, 2002; *Schwadron et al.*, 2020).

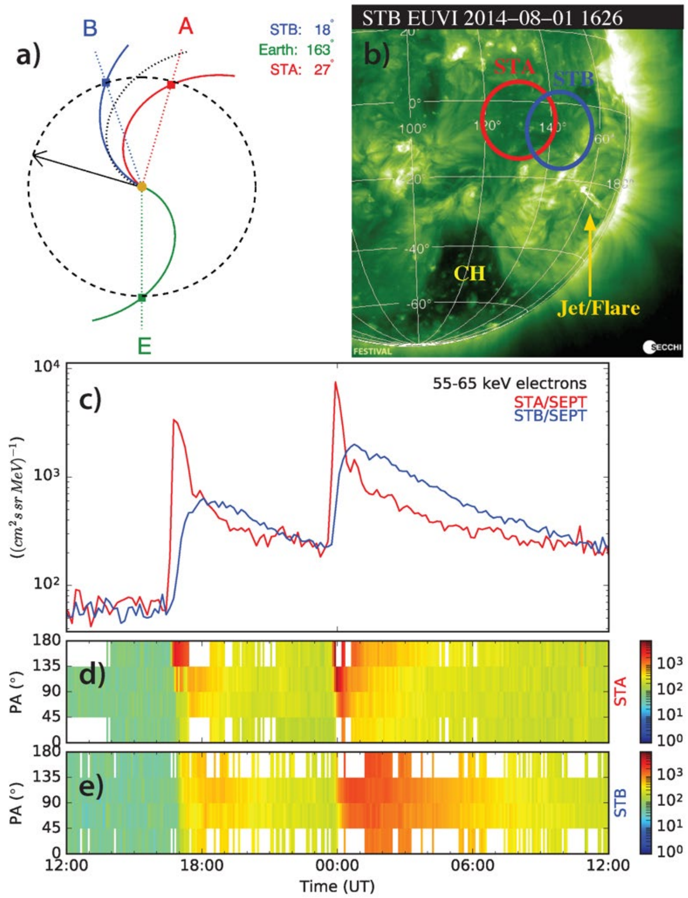

Figure 6: (a) The location of the STEREO spacecraft during a flare event, (b) the approximate footpoints of both spacecraft relative to the flare site, and (c-e) energetic electron observations at both spacecraft showing clear differences at 1 au over 10's degrees of longitude (adapted from *Klassen et al.*, 2016). *Transport of energetic electrons from flare sites to 1 au is complex, and requires multi-point measurements at mesoscale separations to constrain.*

While these other processes may explain the observed weak modulation of the particle spectra, a CIR observation utilizing a fortuitous multi-spacecraft vantage point seems to suggest strong path length-dependent modulation (*Zhao et al.*, 2016, Figure 7a-b). In this event, a CIR shock was observed at STEREO-B when it was ~23° from Earth, however the shock was not observed at ACE, and the CIR evolved too significantly relative to STEREO-A for comparison. STEREO-B and ACE measurements indicate strong path-dependent modulation of the observed particle spectra. However, the required assumption of negligible temporal evolution of the CIR between observations does not fully capture the possible variations of the shock and dynamics regulating particle acceleration and transport, adding ambiguity to the findings. Constraining the true path length to the reverse shock and spatiotemporal variations of shock-related acceleration is difficult with single point observations. *Only simultaneous, multi-point observations from different points within a CIR and its rarefaction region allows for differentiation between path-length dependent modulation and competing transport and acceleration processes.*

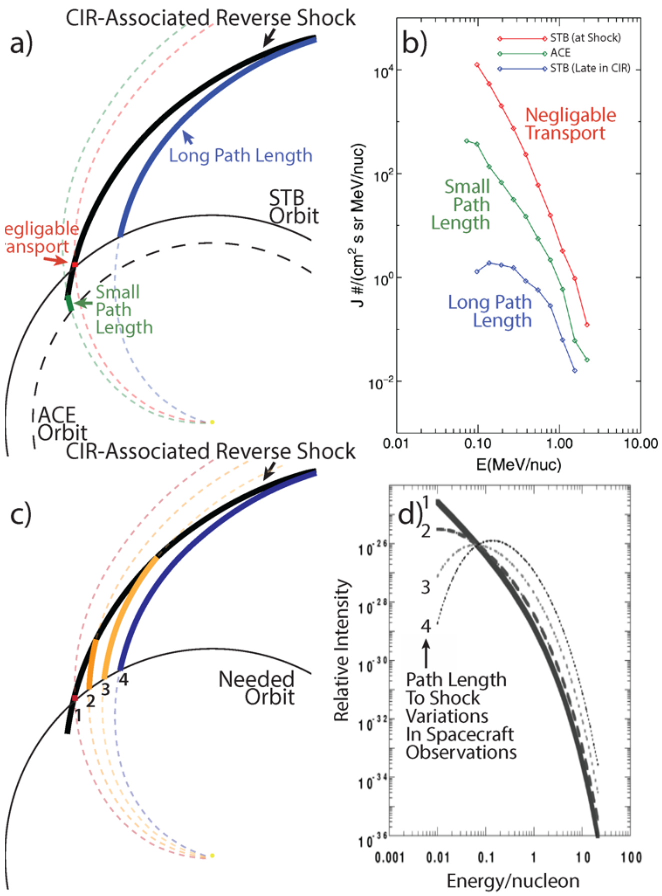

Figure 7: (a) Illustration of observation locations relative to a CIR-associated reverse shock inferred from (b) energetic particle spectra (adapted from *Zhao et al.*, 2016). *(c) Distributed observations at mesoscale separations are needed to (d) constrain the transport effect on particle spectra without ambiguities from temporal evolution* (adapted from *Mason et al.*, 1999).

The Need to Address the mesoscale Solar Wind this Decade:

Fundamentally understanding the mesoscale structure of the solar wind and transients and its subsequent effects on particle acceleration and transport will be paradigm shifting in our insight into the heliosphere, as mesoscale dynamics are vital for resolving long-standing questions of the community. As such, a new mission with an enabling, multi-point architecture is essential to address these objectives. A dedicated mesoscale solar wind mission (e.g., InterMeso, *Allen et al.*, 2022a, b) would fill a critical observational gap in the current Heliophysics System Observatory (HSO) as mesoscale solar wind structure and dynamics falls between the global scales studied by the in situ instrumentation on STEREO and occasional opportune conjunctions within the HSO, and the kinetic scales unlocked by MMS, Cluster, and the upcoming HelioSwarm mission (illustrated in Figure 1).

Resolving the critical physics and consequences of the mesoscale solar wind and transients, is also particularly timely for the next decade. With the continued operation of ground-based solar observatories (e.g., Daniel K. Inouye Solar Telescope, DKIST) and solar/heliographic imaging satellite missions, in situ based mesoscale missions would have complementary remote sensing observations of the solar footpoints of the spacecraft. The upcoming discoveries from HelioSwarm and the Polarimeter to Unify the Corona and Heliosphere (PUNCH) mission, enabling a better understanding of the initial mesoscale structuring of the coronal young solar wind, will feed directly into the interpretations of mesoscale variability at 1 au, allowing insight into the evolution of this mesoscale variability between the solar source and Earth at 1 au. Additionally, the European Space Agency (ESA) Vigil mission to L5, in partnership with the National Oceanic and Atmospheric Administration (NOAA), is planned to launch in 2027 and will include a heliospheric imager that can provide broader context for the in situ observations of the mesoscale solar wind. The potential synergies between a new, mesoscale solar wind focused, mission and upcoming missions (e.g., HelioSwarm, PUNCH, and Vigil) motivate such a mission within the next decade.

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