# 1 Executive Summary

The STEREO mission gave us a tantalizing glimpse of the capabilities of multi-spacecraft imaging to resolve coronal structures and extract information vital to modeling and forecasting solar events. However, it also demonstrated the limitations posed by a limited number of spacecraft. While significant progress has been made over the past two decades in detecting, analyzing and understanding CMEs and associated energetic charged particles, another breakthrough is needed in our observing capability of solar transients and their heliospheric consequences to facilitate the next generation science needed to uncover the complex three-dimensional (3D) internal structure of CMEs. Advances in smallsat communications and miniaturization of coronagraphs make feasible multi-spacecraft missions to image solar transients from multiple viewpoints at reasonable cost. As the number of spacecraft increases from a half-dozen in 2030 to dozens in 2050, the 3D reconstruction of these structures will improve commensurately allowing a full self-consistent modeling of both the magnetic and plasma 3D structure of a CME and thus leading to robust quantification of the space weather effects of CMEs, for the first time. These advances can be used predictively to safeguard space assets and the journey to Mars.

# 2 Driving Science Questions

The study described herein is motivated by two overarching (O)bjectives and several (Q)uestions that must be answered to achieve these objectives.

- O: Determine the multiscale plasma and magnetic field properties of CMEs and shocks
  - Q: How does the global 3D morphology of CMEs/shocks evolve in the inner heliosphere?
  - Q: How do CME plasma structures observed at the Sun map into the properties of ICMEs?
  - Q: What is the initial CME magnetic field structure and how is it modified by propagation in the inhomogeneous solar wind?
  - Q: How close to the Sun and under what conditions do shocks form?
- O: Determine how the dynamic inner heliosphere controls the transit of transients to Earth and beyond
  - Q: How is the solar wind in the inner heliosphere determined by coronal and photospheric structure?
  - Q: How do interplanetary CMEs interact with the ambient solar wind?
  - Q: How do interplanetary CMEs interact with each other?
  - Q: How can the transient evolution be captured to improve operational space weather forecasting?

All of these questions have been studied in one form or another, but definitive answers that enable incorporation into operational models remain elusive due to the lack of simultaneous multi-scale, multi-viewpoint observations.

# 3 Current State

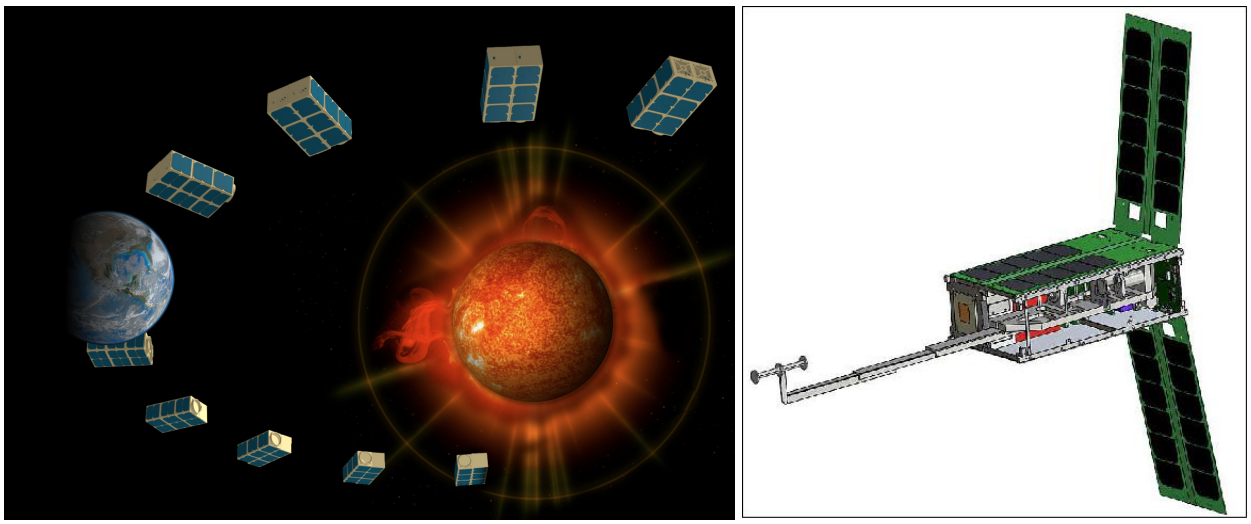
Our current understanding of CME propagation and evolution is insufficient for the reliable prediction of space weather based on remote observations. Even if our understanding of and ability to simulate the physics was perfect, our predictions would still be confounded by our limited ability to provide inputs that describe the 3-dimensional structure of these CMEs. In the recent past, the STEREO mission, combined with SOHO, provided as many as 3 viewpoints for observing CMEs.

However, while these missions brought about a transition in the capacity to derive three-dimensional (3D) kinematic characterization of transients via forward modeling and triangulation-type analyses, due to the very complex structure of most CMEs, three viewing angles does not

suffice for full 3D tomographic imaging. Resolving the internal structure of CMEs requires more viewpoints. Incorporating more detailed 3-D inputs to heliospheric models would help reveal why the models are in error and help improve both the models and our understanding of the underlying physics. Solar Tomography using Thompson scattering can provide the needed 3-dimensional input to a degree of accuracy only limited by the number of viewpoints and the resolution of the imagers.

Davila [1994] and references therein provide an excellent summary of the technique and, most importantly, the benefits of additional viewpoints spread over a broad range of angles. Figure 4 of that paper demonstrates the technique in a simple 3X3 array. Figure 6 of that paper demonstrates that a large range of angles is required for the reconstruction, and Figure 7 shows that the fidelity of the reconstruction increases dramatically with increasing numbers of observation points. More recently Vourlidas et al. [2020] details the added benefits of a solar polar viewpoint. However, the propulsion requirements of such a mission drive up cost. Figure 1a depicts such a concept using multiple white-light images to reconstruct CME electron densities from remote locations providing these data at least 12 hours in advance of any terrestrial effects even for the fastest CMEs.

With current technology, such a mission concept using cubesats would be infeasible primarily due to limitations on the communications system. However, recent advances in laser communications for cubesats that only level state-of-the-art pointing requirements on the bus [Mathason et al., 2019] will likely reach TRL 9 by 2025 and smallsat scale propulsion system for both delta-H control (e.g. the MarCO cold-gas thrusters system) and high delta-V propulsions systems (see the Busek portfolio for example) are reaching maturity. Additionally, the MiniCor concept [Korendyke et al., 2015] demonstrates the feasibility of a miniaturized white-light coronagraph capable of providing STEREO quality imagery in a cubesat form factor. Figure 1b shows the MiniCor cubesat



(a) (b)

Figure 1: Tomographic reconstruction from multiple viewpoints can provide detailed 3-dimensional electron density reconstructions as well as their evolution in time. These detailed inputs are necessary to move space weather modeling to an operational, predictive capability. They are enabled by near term advances in cubesat scale optical communications and white-light coronagraph miniaturization technologies.

design. These two advances combined enable a swarm of cubesats capable of returning white-light coronagraph data from deep space for the cost of a single SMEX mission. Alternatively, a more capable smallsat with additional instrumentation could add multi-point in-situ measurements and EUV imaging to further enhance science return with a cost within a MIDEX.

# 4 Roadmap to 2050

By 2030, the goal would be to utilize near term technologies in laser communications, coronagraph miniaturization, and small sat propulsion systems to have a MIDEX class mission dedicated to a formation of 6 in-ecliptic smallsats separated by 30 degrees in heliographic longitude doing tomographic imaging in both white-light and EUV along with in-situ measurements. With a complementary dedicated theory and modeling effort to incorporate these data into improved models, these measurements would be sufficient to answer or make significant progress on all of driving science objectives in Section 2 and allow formulation of the next key set of required measurements.

By 2040, the goal would be to have a dedicated campaign increasing the number of spacecraft as well as upgrading instrumentation to incorporate new technologies. With advances in electric propulsion for smallsats (e.g., Kolbeck et al. [2019]), a pair of out-of-ecliptic viewpoints would be added to further reduce reconstruction error. Instrumentation on these spacecraft would be informed by modeling needs that are realized by the initial 2030 swarm. The detailed 3-dimensional evolution of CMEs in the corona also enables theoretical insights that add new physics to the models. The modeling effort should now be looking to achieve predictive capability and testing against the in-situ data gathered by the formation.

By 2050, the goal would be to have a sufficient theoretical understanding of the evolution of CMEs and energetic particles in the heliosphere that the models are now fully predictive relying only on remote observations including the 3-D tomographic inputs. The fleet will continue to be replenished at minimal cost as the similarity of the spacecraft enables economies of scale to reduce costs. The fleet, at this point, might be turned over to an operational entity such as NOAA for maintenance and operational forecasting while NASA turns its focus to whatever new frontier is revealed by the discoveries of the last two decades.

# *References*

Joseph M. Davila. Solar Tomography. *ApJ*, 423:871, March 1994. doi: 10.1086/173864.

Jonathan Kolbeck, André Anders, Isak I. Beilis, and Michael Keidar. Micro-propulsion based on vacuum arcs. *Journal of Applied Physics*, 125(22):220902, 2019. doi: 10.1063/1.5081096. URL https://doi.org/10.1063/1.5081096.

C. Korendyke, D. Chua, R. Howard, S. Plunkett, D. Socker, A. Thernisien, P. Liewer, David Redding, J. Cutler, J. Forbes, and A. Vourlidas. Minicor: A miniature coronagraph for an interplanetary cubesat. 2015.

Brian Mathason, Michael M. Albert, Doruk Engin, He Cao, Keith G. Petrillo, Jacob Hwang, Khoa Le, Kent Puffenberger, Slava Litvinovitch, Mark Storm, and Richard Utano. CubeSat lasercom optical terminals for near-Earth to deep space communications. In Hamid Hemmati and Don M. Boroson, editors, *Free-Space Laser Communications XXXI*, volume 10910, pages 24 – 29. International Society for Optics and Photonics, SPIE, 2019. doi: 10.1117/12.2508047. URL https://doi.org/10.1117/12.2508047.

A. Vourlidas, S. Gibson, D. Hassler, T. Hoeksema, M. Linton, N. Lugaz, and J. Newmark. The science case for the $4\pi$ perspective: A polar/global view for studying the evolution & propagation of the solar wind and solar transients, 2020.