Heliospheric Meteorology: HMM, The $200 Mission

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What? To make transformational scientific progress with the space weather enterprise the Sun, Earth, and heliosphere must be studied as a coupled system, comprehensively. Rapid advances were made in the study, and forecasting, of terrestrial meteorology half a century ago that accompanied the dawn of earth observing satellites. Those assets provided a global perspective on the Earth's weather systems and the ability to look ahead of the observer's local time and move to a global perspective. From a heliospheric, or space, weather perspective we have the same fundamental limitation as the terrestrial meteorologists had—by far the majority of our observing assets are tied to the Sun-Earth line—our planet's "local time" with respect to the Sun. This perspective intrinsically limits our ability to "see what is coming around the solar limb" far less to gain any insight into the global patterns of solar weather and how they guide weather throughout the heliosphere. *An L5 mission alone is only incremental.*

How? We propose a concept—the Heliospheric Meteorology Mission (HMM)—to sample the complete magnetic and thermodynamic state of the heliosphere inside 1AU using a distributed network of deep space hardened *smallsats* that encompass the Sun. The observations and in situ plasma measurements made by the fleet of HMM smallsats would be collected and assimilated into current operational space weather models. Further, the HMM measurements would also being used in an nationally coordinated research effort—at the frontier of understanding the coupled heliospheric system—as a means to develop the next generation models required to provide seamless prediction for the geospace environment to protect vital infrastructure and human/ robotic explorers throughout the solar system. The HMM mission concept naturally allows for research-motivated technology development that can improve forecast skill.

Background Science: It is widely acknowledged that the discipline of space weather forecasting is five to six decades behind its terrestrial equivalent (Schrijver et al., 2015). Advances in the latter were precipitated by observational advances where data from beyond one local time frame and, at the dawn of the satellite era, when global perspectives of tropospheric weather systems were brought to bear (Rossby, 1939). One significant advance in the interpretation of meteorological data followed the identification of Rossby waves in the upper stratosphere and the recognition that local weather disturbances are intrinsically tied to these global-scale weather patterns. This determination led to significant advances in short-, mid-, and long-term forecasting skill and a perception that terrestrial storms, once considered to be intrinsically unpredictable, conceptually transitioned to an intermittent part of a global system that was predictable to an acceptable degree. The challenge to the solar physics and space weather community is simple—can the methodology and heritage of terrestrial meteorology be utilized to advance forecasting of the solar end of the sun-earth system through complete observations of the Sun's magnetized atmosphere? This whitepaper highlights just one possible approach to closing that "60 year" gap.

DRIVE: HMM directly addresses the primary goal of the 2013 Heliophysics Decadal Survey "Determine the origins of the Sun's activity and predict the variations of the space environment" while also offering considerable insight into how the geospace system responds through the second "Determine the dynamics and coupling of Earth's magnetosphere, ionosphere, and atmosphere and their response to solar and terrestrial inputs." HMM implicitly *diversifies* observing capability and extends the current Sun-Earth line based ground and space-based assets. The integration of operations, data analysis, and advanced numerical modeling will *realize* the scientific potential of the mission. The *integrated* observations provided by HMM, the flow of technology, and provision of operationally vital data will strengthen ties between agencies and agency disciplines. Research and operational insights will direct instrument and technology developments built into new payloads that permit the enterprise to *venture* forward

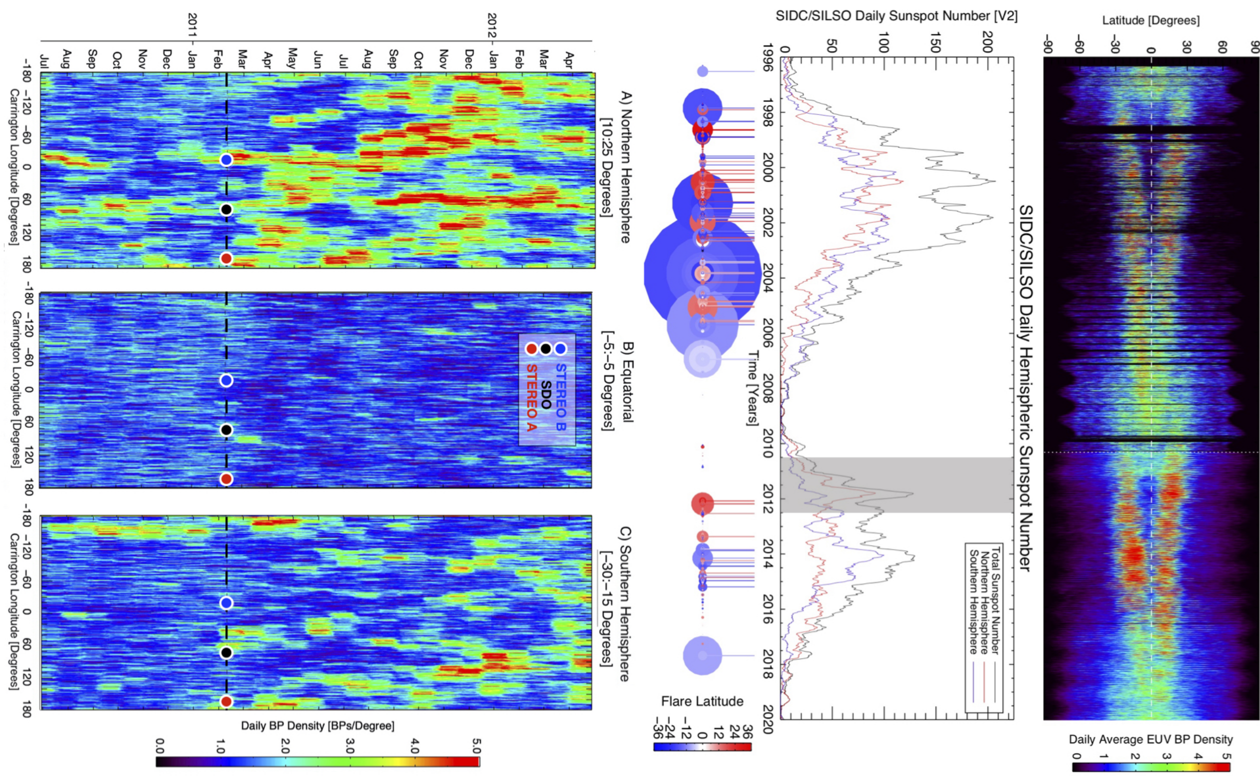

Figure 1. Rossby Waves & *Solar* weather—Intrinsically Linked: (TOP) the "Butterfly" (latitude vs. time) diagram of extreme-ultraviolet brightpoints where several episodes of enhanced activity in each solar hemisphere are clear. (MIDDLE) A timeline representation of the major flare record of the past two solar cycles, with the daily hemispheric sunspot number. Without the effects of smoothing filters, the quasi-annual Rossby-mode-driven surges in solar magnetic activity are also clear, as is the lack of hemispheric synchronization. The largest surge without a large flare reported by GOES is that in mid-2012 in the southern hemisphere—which caused the July 23 event. (BOTTOM) "Hovmöller diagrams" of solar magnetic activity during the time when the STEREO & SDO triplet were operational. These longitude vs. time (at fixed latitude) plots reveal new longitudinal physics of the Sun (*e.g.*, McIntosh et al., 2017, 2019; Dikpati & McIntosh 2020) that is critical to developing space weather predicability days, weeks and months advance, and critical at the strategic level (Dikpati & McIntosh, 2020). The magnetic Rossby waves revealed by these plots outline outbursts of magnetic activity that drive Space Weather.

and remain vital in the operational and research domains. Finally, the continuous streams of data analysis and assimilation, advanced system modeling and hardware developments will foster and environment of *education* and inspiration for the next generation of engineers and scientists, with a view to understanding the coupled solar system as a whole. As such, HMM realizes the vision of the DRIVE initiative of the Decadal Survey.

Getting Ahead of SWx: Surges of enhanced magnetic activity correlate with the occurrence of 95+% of destructive solar storms (Figure, top). Those surges are intrinsically tied to these active solar longitudes and Rossby waves (Figure, bottom). "Active longitudes" persist for many solar rotations with periodic surges lasting ∼11 months. Monitoring, understanding and forecasting the active longitudes and surges of flux emergence is vital to get away from the present paradigm. From our single vantage point we have no insight into the physics of these processes.

Without a concept like HMM, SWx events will remain intrinsically unpredictable, *i.e.*, exactly where terrestrial meteorology was *half a century ago* with respect to the predictability of extreme weather events, prior to global observations of our planet's atmosphere.

HMM Concept The preliminary HMM configuration would be a "string of pearls" around the Sun in the ecliptic plane. An inner heliosphere constellation is not a new concept; *Solar Sentinels*, with 4 inner heliosphere spacecraft with only in situ and SEP charged particle sensors, together with nearside and farside SOHO-like solar/ coronal imagers got as far as an STDT report in August 2006 but no further. We can leverage the technological developments of the last solar cycle or so, with miniaturized, low-power instruments with optimized SWx operational modes, to have a smallsat constellation with advanced (laser) communications. Like *Sentinels*, the payload could be fractionated, with 2 or 3 different types of smallsat—an in situ plasma, magnetographs, and coronal imagers varietals, for example. The community would decide on the optimal flight arrangement, including the arrangement of necessary relay platforms required to collect the data.

Repeated launches, with GOES-like redundancy and the economies of scale that come with multiple similar satellites could cover the ecliptic at relatively low cost and today's technology. Even so, one would need more than operations to justify the expense of multiple launches. *HMM would provide this over a 'simple' L5 mission with the (meteorological) science of solar activity, flare prediction and internal processes.* Further removal of limits to our understanding could be gained from adding out-of-ecliptic observations: Vourlidas et al. (2016) suggested a HMM-like concept having full 4π coverage, including polar observations, with 4 satellites in similar $\sim$0.5AU, 75° inclination orbits, separated 90° in longitude. Such inclinations would require solar sails or ion engines.

HMM Proto-Payload

- A compact Doppler magnetograph, more compact than that of SOHO/ MDI or SDO/ HMI.
- A compact WL coronagraph and/or HI like those implemented on PSP or Solar Orbiter.
- A compact (6U) version of HAO's CoMP spectropolarimetric imaging coronagraph – PELE – as was selected with the "Solar Cruiser" Phase A study.
- An in situ space plasma suite, such as SWEAP on PSP or EPSS on MESSENGER.
- A compact magnetometer to characterize the variability in the interplanetary vector field.
- A compact EUV Imager like that implemented in the SWAP payload on the ESA PROBA mission, or SolO.

Summary: HMM is doable with present technology. Such a mission—in whatever guise or formulation, not necessarily ours presented here—to observe the entire Sun all of the time, is *critical* in terms of scientific understanding of our star and for the operational need to protect our technologically advancing society.

A Heliospheric Monitoring Mission really is the $200 mission for Heliophysics in (by) 2050. As in, "Go to HMM. Go directly, do not pass 'Go', do not collect $200."

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