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The Heliospheric Meteorology Mission: A Mission to DRIVE our Understanding of Heliospheric Variability

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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 to . 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. We propose a mission 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.

Keywords: dynamo theory, magnetic fields, sunspots, solar activity, space weather, space weather forecasting

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1. INTRODUCTION

It is widely acknowledged that the discipline of space weather forecasting is five to six decades behind its terrestrial equivalent (e.g., Schrijver et al., 2015). Advances in the latter were precipitated by observational advances where data from beyond one local time frame (e.g., Holton, 1992) and, at the dawn of the satellite era, when global perspectives of tropospheric weather systems (e.g., Wexler, 1962) were brought to bear. One significant advance in the interpretation of meteorological data followed the identification of Rossby waves in the upper stratosphere (Rossby, 1939) and the recognition that local weather disturbances are intrinsically tied to these global-scale weather patterns (Gray, 1968). This determination led to significant advances in short-, mid-, and long-term forecasting skill (e.g., Thompson, 1983; Win-Nielsen, 1991) 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 (e.g., Lorenz, 1973). 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? What follows is just one possible approach to closing that "60 year" gap.

The Heliospheric Meteorology Mission (hereafter, HMM) directly addresses the primary goal of the 2013 Heliophysics Decadal Survey (NRC, 2013) "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." Fundamental knowledge of our heliospheric evolution developed through the hand-in-hand combination of observation and modeling with HMM will inform other community models and "Determine the interaction of the Sun with the solar system and the interstellar medium" and to look beyond for analogies with comparative heliospheres and their interactions with exoplanet atmospheres "Discover and characterize fundamental processes that occur both within the heliosphere and throughout the universe." 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 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. As such, HMM realizes the vision of the *DRIVE* initiative of the Decadal Survey (See section 4 of NRC, 2013).

2. SOLAR GLOBAL WEATHER

Since the 2006 launch of the twin Solar-Terrestrial RElations Observatory (STEREO; Howard et al., 2008) satellites and the Solar Dynamics Observatory (SDO; Lemen et al., 2012) in 2010, a picture of globally connected solar phenomenology has developed—the idea that emergence of magnetic flux in one location can trigger an event on the other side of the Sun. Furthermore, spatial and temporal relationships in the pattern of magnetic flux emergence have revealed that the Sun undergoes quasi-annual episodes of significantly enhanced activity of an amplitude equivalent to the more familiar solar magnetic cycle (McIntosh et al., 2014, 2015, 2017). These well-studied strongly-longitudnal flux emergence processes (e.g., Carrington, 1858; Castenmiller et al., 1986; Brouwer and Zwaan, 1990), appear to be driven by magneto-Rossby modes on the global scale (e.g., Zaqarashvili et al., 2015; Gurgenashvili et al., 2017; Dikpati et al., 2017, 2018; Löptien et al., 2018) which then force significant increases in the production of active regions (with the flares and Coronal Mass Ejections— CMEs— that result). Further, these flux emergence episodes also drive significant modulation in the short-wavelength radiative output and shape the magnetic skeleton of the heliosphere that also ducts the solar wind (e.g., McIntosh et al., 2015; Krista et al., 2018).

Comparing periods of enhanced solar activity with the occurrence of most destructive of solar storms (see e.g., **Figure 1**) we deduce that both are intrinsically tied to these active solar longitudes. Those active solar longitudes persist for many solar rotations (e.g., McIntosh et al., 2017) with periodic surges of the timescale of 11-ish months (e.g., McIntosh et al., 2015). Therefore, monitoring, understanding and forecasting the origin of these active longitudes is of vital importance in the context of short and long-term forecasting for the geospace and heliospheric environment, in addition to the protection of vital space and ground infrastructure. From our current, limited, vantage point we will not gain insight into these processes and, as a result, solar storms will remain high-frequency intrinsically unpredictable events, i.e., *exactly* where terrestrial meteorology was half a century ago with respect to the predictability of extreme weather events at the dawn of the space age and prior to global observations of our planet's atmosphere.

3. THE HMM CONCEPT

From the previous section, it would appear that in order to significantly advancing our knowledge of the Sun's atmosphere and its evolution on timescales of months, weeks, and years that we *must* invest in an observing strategy for the entire solar atmosphere. Such a "meteorological" observing strategy may rapidly close the many decades of lag in understanding— hence the "Heliospheric Meteorological Mission."

In a proverbial nutshell, the HMM objective would be to fly a stream of fixed-design deep space hardened/validated smallsat spacecraft in orbits off the Sun-Earth line to monitor the 360 degree environment of the solar atmosphere and the heliosphere extending from it. These smallsats would have internal guidance, propulsion, and communications assets. Each spacecraft would be equipped with a number of well characterized, compact instruments belonging to a range of "plug-n-play" instrumentation and/or relay/transmitter equipment. These instruments would be supplied by the institutions in the community according to their particular technological heritage (see below). The data from the HMM fleet of spacecraft will

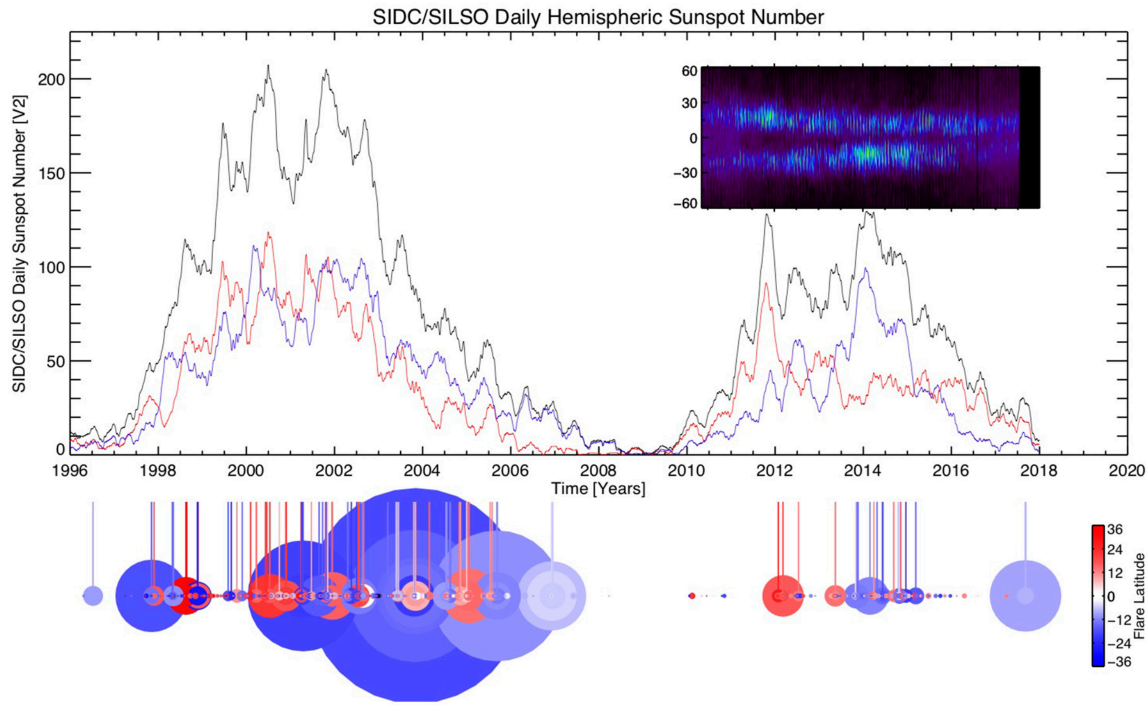

FIGURE 1 | A timeline representation of the major flare record of the past two solar cycles, with the daily hemispheric sunspot number. Without the effects of smoothing filters, the quasi-annual Rossby-mode-driven surges in solar magnetic activity are clear, as is the lack of hemispheric synchronization. (The largest surge *without* a large flare reported by GOES is that in mid 2012 in the southern hemisphere—which was responsible for the July 23 event). The inset shows the "Butterfly" (latitude vs. time) diagram of extreme-ultraviolet brightpoints (e.g., McIntosh et al., 2014) where several episodes of enhanced activity in each solar hemisphere are also clearly visible.

provide information on solar magnetism, the outer solar atmosphere, and *in situ* magnetic, thermodynamic, particulate and radiative environment. The community would decide on the optimal flight arrangement, including the arrangement of necessary relay platforms required to collect the data. The HMM fleet data will be an invaluable resource for the research community, model developers, and operational agencies where they can serve a dual purpose of being assimilated into current space weather forecast models while motivating advances required for next-generation forecast capability. HMM provides an observing strategy that is crucially missing from our current capability in a low-risk, high-heritage, and replaceable manner that engages and enables the entire national (and international) heliophysics community.

4. A NATIONAL STRATEGY

The HMM concept engages and enriches the operational, research, and technology communities in one effort to understand the meteorology of the Sun and Heliosphere. The observations acquired by the HMM fleet would be designed for direct assimilation into next-generation space weather forecast models—providing vital information about the global magnetic environment necessary for research efforts to understand the solar dynamo and other basic processes, drive surface (magnetic) flux transport models, and the current operational forecast models in addition to particular insight into flux distributions around the East limb that will become geo-effective in short order—in short, eliminating several scientifically strategic shortcomings. The broad distribution of the HMM *in situ* measurements can be used as validation points for those models of the magneto-thermal environment of the sub-1AU heliosphere. The technology enrichment comes from the distribution of construction efforts and the ability to adapt transforming technologies as they feedback from modeling and operational requirements.

4.1. Multi-Agency Strategy

The HMM concept would directly benefit multiple federal agencies—DoD, FAA, NASA, NOAA, and NSF—with space weather requirements. NASA and NSF would play a vital role in the fundamental understanding of the observational data and technology transfer in these compact, hardened, payloads. Furthermore, the data provided will be invaluable in assessing risk and providing ongoing evaluation of that risk for upcoming human missions away from our near-Earth space. The operational data and forecast model improvements that are driven by HMM will be of direct benefit to Space Weather Forecast operations in the commercial, military, and civilian domains.

4.2. An International Strategy

The HMM concept could, and maybe should, seek instrument contributions (like those below) from communities outside of the US where expertise exists. Again, the priority would go to high-heritage observations that are well-understood from the present perspective.

5. THE HMM TECHNOLOGY STRATEGY

HMM requires a smallsat platform, due to present restrictions on launch capability. Indeed, HMM can build off of the "Solar Weather Buoys" and "Telemachus" concept missions that were presented in the 2005 NASA Heliophysics Roadmap—slated for launch in 2022 (Hoeksema, 2005). The individual instrument engineering for HMM could, and maybe should, be distributed toward a common instrument interface on the spacecraft to significantly reduce cost. At time of writing several engineering and aerospace groups are exploring such spacecraft designs.

5.1. The HMM Proto-Payload Menu

As stated above HMM must leverage high-heritage, compact instrument packages. In this way the vantage point is the main, or only, element changed—the measurements are (relatively) well-understood. The Telemachus and Solar Weather Buoys missions built off of this concept, except for the application of compact imagers. Over the intervening 15 years since the development of that roadmap we've made tremendous strides in instrument miniaturization. So, in terms of a baseline payload, each HMM spacecraft would have one or more of the following:

- ⋆ A compact Doppler magnetograph, more compact that SOHO/MDI and or SDO/HMI. For example, Magneto-Optical Filter based designs have been considered for mission concepts like than on INSPIRE (Klesh, 2018).
- ⋆ A compact white light coronagraph and/or heliospheric imager suite like those implemented on the Parker Solar Probe, or Solar Orbiter missions.
- ⋆ An *in situ* space plasma suite, such as the EPSS package of the Messenger mission (e.g., Andrews et al., 2007), or the SWEAP experiments on the Parker Solar Probe (e.g., Kasper et al., 2016).
- ⋆ A compact magnetometer to characterize the variability in the interplanetary vector field (e.g., Anderson et al., 2007; Bale et al., 2016).
- ⋆ A compact EUV Imager like that implemented in the SWAP payload on the ESA PROBA mission (Berghmans et al., 2006).

In terms of the primary mission, characterizing the global magnetic environment of the Sun, the Doppler magnetograph would be the minimum payload requirement of the mission fleet, likely leveraging the experioences of the Solar Orbiter PHI team to deliver a spectrally stable Doppler magnetograph for such orbits (e.g., Dominguez-Tagle et al., 2014). Ideally, should a space-hardened spacecraft bus with sufficient mass/energy configuration be found then this "minimum requirement" can, and should, be expanded to include *in situ* experiments and a coronagraph before any EUV imager.

5.2. Data Relay Strategy

A vital aspect of HMM, and especially when deployed as part of any operational framework, is how the data from the network of satellites can be rapidly relayed to Earth. While power will be an issue, it seems like laser telecom will be the preferred method of high data throughput at low mass. In recent times, such technology is growing in readiness (Tardivel et al., 2018).

6. THE HMM RESEARCH STRATEGY

The observations and measurements acquired from HMM will enable a new generation of heliophysicists with a view to understanding the coupled solar system as a whole. There will be undoubted advances in understanding the processes of magnetic flux emergence and those deeper-rooted processes that drive the solar cycle (see e.g., Jiang et al., 2014; Upton and Hathaway, 2014; Virtanen et al., 2017; Whitbread et al., 2017, as contemporary examples). There will be progress in understanding the evolution of global-scale magnetic topology that results which will lead to breakthroughs in understanding the global distribution of solar wind energies and compositional characteristics. All-in-all HMM will explore the origins of the Sun's activity and predict the variations of the space environment like no mission ever before by engaging vast tranches of the US and worldwide community in the effort through the novelty of the data and distribution of the technology effort.

7. THE HMM FORECAST STRATEGY

In the HMM future, data assimilation-driven forecasts models using 360 degree information will be norm. The operational community at present requires knowledge that provides high skill predictions of space weather path, arrival time, and magnitude. At best these windows are broad, ranging from one to 3 days in scatter. In an environment of growing technological reliability it is too broad a window. Further, the critical failure of surface flux transport models to drive the current generation of forecast models mandates at least a mission to the"L5" Lagrange point to observe what may rotating onto the Sun-Earth line. As stated above, the data from HMM could be readily ingested into the current generation of models leading to significant improvement in skill just by providing a more comprehensive observational set. The research insight developed through the analysis of the global perspective provided by HMM will advance that further as we understand the evolution of the magnetically driven outer atmosphere. The data ingestion and assimilation effort that will be part of the mission will drive the creation of next-generation observationally-driven physics-based solar wind forecast models.

8. HMM BEYOND THE ECLIPTIC—TO THE POLES

The preliminary HMM configuration would be a "string of pearls" around the Sun in the ecliptic plane. However, it is becoming more and more obvious that our inability to observe the Sun's polar regions and characterize the evolution of plasma flows and magnetism at high solar latitudes is also limiting our understanding. Indeed, papers such as that cited above (e.g., McIntosh et al., 2014) point to 55° latitude as the potential origin of the Sun's dynamo and, hence, as the source of all space weather. To address this issue *continuous* observations of the high latitude solar atmosphere are required. Taking the HMM concept, and sequentially launching four or six of the *same* smallsats into highly inclined orbits or solar polar orbits would provide 4-π observations of the Sun.

Naturally, deploying advanced coronagraphs as part of an extended HMM, like those capable of measuring magnetic fields in the corona (e.g., Tomczyk et al., 2008) may provide unique perspectives on (and solutions to) the "B_z" challenge of measuring and forecasting the magnetic orientation of solar disturbances before they reach the Earth. The present paradigm is a very short warning (~20 min) from upstream monitors at the lagrange "L1" point. Clearly, a matter requiring an observational solution.

9. CONCLUSIONS

HMM is doable with present technology. This mission, or one like it 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. This short paper only scrapes the surface in terms of the numerous studies required to see something like HMM become reality.

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All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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