Helio2050: Ground-based Synoptic Studies of the Sun

V. Martinez Pillet (NSO), S. Gibson (HAO), A. Pevtsov (NSO), A.G. de Wijn (HAO), S. Gosain (NSO), J. Burkepile (HAO), C.J. Henney (AFRL), J. McAteer (NMSU), K. Muglach (GSFC), H.M. Bain (CIRES/NOAA), W. Manchester (UMich), H. Lin (UHawaii), M. Roth (KIS), K. Ichimoto (UKyoto), Y. Suematsu (NAOJ)

Ground-based synoptic solar observations provide critical contextual data used to model the large-scale state of the heliosphere, the only astrosphere we can concurrently measure in situ. The next decade will see the combination of telescopes and space missions, which will study our Sun's atmosphere microscopic processes with unprecedented detail. This white paper describes existing and future contextual synoptic observations needed to fully exploit this new knowledge of the underlying microphysics that leads to magnetic linkages between the Earth and the Sun. This combination of a better understanding of small-scale processes and the appropriate global context enables a physics-based approach to Space Weather comparable to Terrestrial Weather forecasting.

A multi-pronged approach to understanding a connected heliosphere

Stars and planets interact through a diverse suite of messengers: radiation in the form of photons, electromagnetic fields, and charged particles. NASA's Heliophysics System Observatory and the NSF's Daniel K. Inouye Solar Telescope use these multi-messenger signals to study the Sun-Earth interactions. These projects often target the **microphysics** that describes the magnetic connectivity between the Sun and the heliosphere. To fully exploit these detailed observations and to drive heliophysics discovery between now and 2050, the **large-scale context** provided by ground- and space-based synoptic observations is required.

Existing ground-based synoptic programs are aging rapidly and are used in ways that differ from their original intentions. Most prominently, GONG (Hill 2018) was designed for Helioseismology but is most demanded today as a provider of the magnetic boundary conditions for solar wind models. A wealth of theoretical knowledge about the connectivity between the Sun and the planets has emerged in recent years (see, e.g., Chen 2017). This knowledge did not contribute to the design of existing synoptic networks and, as a result, no synoptic data are available to predict key Space Weather drivers such as the magnetic field of coronal mass ejections (CMEs), in particular the Bz component, which determines the coupling with the Earth's magnetic field (Kilupa, 2017).

Magnetic boundary data that creates the heliosphere

Global 3D semi-empirical models simulating the heliosphere (such as WSA; Wang and Sheeley 1990; Arge et al. 2003) use synoptic magnetic field maps to model a time-dependent heliospheric solar wind. Much of the space weather activity can only be interpreted in light of such global 3D simulations (Bain 2016). Investigations are underway to use heliospheric solar wind models to drive simulations of the geomagnetic impacts of space weather at the Earth, thus coupling space weather phenomena across the entire Sun-Earth system.

The models are further utilized by injecting a solar wind disturbance (representing a CME) at the model's inner boundary and propagating it throughout the solar system. While the background solar wind is calculated from photospheric magnetic field synoptic maps, the CME modelling component uses a cone model (Odstrcil & Pizzo 1999) fed by parameters derived from coronagraph observations. These contain no direct measurement of the CME magnetic fields, resulting in a purely hydrodynamic propagation of the CME and so giving significant **but limited** estimates of the time of arrival, CME speeds, and densities.

CMEs are more prevalent at solar maximum. During the minimum of the cycle, the open magnetic flux at the Sun's poles establishes a quasi-dipolar magnetic configuration in the heliosphere. Then, the Earth spends most of the time magnetically connected to the polar coronal holes (Luhmann et al. 2009). Unfortunately, these polar coronal holes are the hardest to observe from the Earth. In them, the magnetic configuration is relatively simple with vertical field lines, but at the poles, this corresponds to *transverse* magnetic field orientations, as seen from the Earth. The Zeeman effect makes these transverse signals harder to observe compared to longitudinal ones. ***To obtain polar maps from the ground, increased magnetic sensitivity to transverse fields is mandatory and demands new instrumental approaches.***

Boundary data and the propagation of solar eruptive structures

Most of the widely used 3D global heliospheric models that propagate CMEs do not propagate magnetized CMEs, and cannot predict the value of Bz, the southward magnetic field component in the CME at the Earth. This inability is a critical aspect for establishing the connectivity between the Earth and the Sun, which current models miss. Capable models are becoming a reality (Jin et al. 2017; Torok et al. 2018), but ***quantifiable forecasting of Bz requires the propagation of magnetized CMEs from the solar source into the heliosphere and demands adequate boundary data.***

Chromospheric vector fields are a primary candidate for improving boundary data (Georgoulis et al., 2018). Mapping the field configuration at multiple heights will produce data for constraining the magnetic structure of solar filaments associated with the core of the CME and will generally serve as improved initial boundary conditions for CME modeling. During and after the eruption, we expect interactions with the background corona leading to CME deflections, etc., but, despite these complexities, persistent correlations demonstrate that CMEs maintain a non-negligible memory of their solar source region (Yurchyshyn et al., 2001; Marubashi et al., 2015). ***Such work indicates that data-driven propagation of magnetized CMEs is a possibility but needs proper boundary data***.

Coronal data to inform and constrain CME models.

The nature of the CME source region, for example, the presence of stored magnetic energy in the form of a magnetic flux rope, can have signatures in coronal observations such as prominences and their cavities (Gibson, 2018). Ground-based synoptic coronagraphic observations are key to analyzing evolution leading up to the eruption, with important information from the morphology, plasma properties, and polarimetry of CME source regions. During an eruption, such observations yield global evidence for effects described above which may alter the pre-eruption magnetic structure and so Bz at the Earth. ***Coronal observations provide ground truth validation and constraints on models of CMEs.***

Helioseismology as a window to the sources of solar magnetism

The origin of the solar magnetism lies in the interior below the visible photosphere. This location is where large-scale motions of the plasma generate the field via a dynamo mechanism. Helioseismology—analysis of properties of acoustic waves traveling in the solar interior—is the best probe of these motions and provides early indications of incoming solar cycles and their strengths**. However, much research is still needed to develop helioseimological signals as a reliable forecasting tool**.

Helioseismic holography is a technique used to infer active regions on the **far-side** surface of the Sun (Lindsey & Braun 2017). This approach exploits acoustic travel-time reductions in magnetized areas that result in a phase shift of the waves. These phase changes make large active regions readily apparent in reconstructed seismic travel-time images. Since the sensitivity in these maps depends on accurate and precise measurements of the phase shift between acoustic waves in the solar atmosphere, improved understanding of phase shift from multi-height observations is needed to reduce the noise in far-side maps, thus enhancing the detectability of weaker active regions and improving the modeling of the global heliosphere. ***Observations required to address this phase shifts include multi-wavelength, multi-height measurements of the velocity and vector magnetic field from the photosphere through the chromosphere.***

Solar synoptic observations between now and 2050

Key measurement capabilities for future ground-based solar synoptic facilities, involving the US and the broader international communities, include the following:

- Measure the **boundary data** as a function of height that propagates the magnetic connectivity into the heliosphere, with improved sensitivity to the **polar regions**;
- Map the **3-D magnetic topology** of solar erupting structures from the chromosphere to the corona, and better anticipate the severity of space-weather events;
- Monitor processes in the **solar interior** and the **far side** that impact heliospheric conditions; and
- Provide global **context** for high-resolution solar observations as well as for *in situ* measurements.

References

Arge, C. N.; Odstrcil, D.; Pizzo, V. J.; Mayer, L. R., 2003, AIP Conference Proc., 679, 190
Bain, H. et al., 2016, ApJ, 825, 1
Chen, J., 2017, Phys. Plasmas 24, 090501
Georgoulis, M. K.; Alexander N.; Hongqi Z., 2018, Phil. Trans. R. Soc. A. 377:20180094
Gibson, S. E., 2018, Liv. Rev. Sol. Phys., 15:7
Hill, F., 2018, Space Weather, 16, 1488
Jin, M. et al., 2017, ApJ, 834, 173
Kilpua, E.; Koskinen, H. E. J.; Pulkkinen, T. I., 2017, LRSP, 14, 5
Lindsey, C.; Braun, D., 2017, Space Weather 15, 761
Luhmann, J. G. et al., 2009, Solar Physics, 256, 285
Marubashi, K. et al., 2015, Solar Physics, 290, 1371
Odstrčil, D.; Pizzo, V. J., 1999, JGR, 104, 28225
Török, T. et al., 2018, ApJ, 856, 75
Wang, Y.-M.; Sheeley, N. R., Jr, 1990, ApJ, 355, 726
Yurchyshyn, V. B.; Wang, H.; Goode, P. R.; Deng, Y., 2001, ApJ, 563, 3