

Investigating Coronal Magnetism with COSMO: Science on the Critical Path To Understanding The “Weather” of Stars and Starspheres

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Magnetism plays an important role in a diverse range of astrophysical phenomena such as star formation, accretion disks and jets, black holes, pulsars, quasars and active galactic nuclei. Magnetic fields influence the universe on spatial scales ranging from microscopic to the size of galaxy clusters. Yet despite the ubiquity of magnetic influences, *our detailed understanding of the role of magnetism in many astrophysical contexts is rudimentary*. This is particularly true in the case of the solar atmosphere. Magnetism plays the principal role in structuring and heating the million-degree coronal plasma and the continual eruption of magnetic flux into the solar atmosphere drives all solar activity including high-energy radiation, energetic particles, flares and coronal mass ejections. These phenomena are responsible for “Space Weather” and have important consequences for human assets in space and on the ground. To understand the role of magnetism in the solar atmosphere, it is necessary to measure the large-scale magnetic field of the solar corona and determine its relation to coronal plasma structures and their properties. Despite the dominant role of magnetism in the solar corona, *routine measurements of the strength and direction of coronal magnetic fields are currently not available*. The information learned from the solar corona and its magnetic field will advance the study of “stellar weather” and the impact that weather has on exoplanet habitability. In this whitepaper we will focus on the corona of the Sun - where resolved observations can lead the way, permitting the development of theoretical and numerical models that will be employed in other starspheres.

The **Coronal Solar Magnetism Observatory (COSMO)** is a unique ground-based facility designed to address the shortfall in our capability to measure magnetic fields in the solar corona. COSMO will have a fixed suite of instruments that will be operated in two modes. A synoptic mode will address the long term goals of COSMO with a set of standard data products that will be obtained daily. At the heart of COSMO is the 1.5-m aperture Large Coronagraph (LC) that will observe the radiation emitted by the corona in a number of visible and IR emission lines corresponding to plasma in the 0.01-5 MK temperature range. Post-focus instrumentation will analyze the polarization of the emitted radiation and infer the direction and strength of coronal magnetic fields, as well as the physical properties of the coronal plasma including temperature, density and dynamical status. The LC employs an innovative refractive design to obtain measurements over a 1 degree field-of-view at a spatial resolution of 2 arcseconds with high spectral resolution. It will be the largest refracting telescope in the world.

What is CoSMO?

COSMO comprises three telescopes, demonstrated with prototypes, which together span the solar atmosphere. The central instrument in the COSMO suite is a 1.5m-aperture coronagraph that will obtain daily measurements of the strength and direction of coronal magnetic fields over a 1° (± 2 R_{sun}) field of view (FOV). The line-of-sight strength of coronal magnetic fields can be measured directly through the Zeeman effect observed in the circular polarization of coronal forbidden emission lines. The linear polarization from resonant scattering of photospheric radiation is used to measure the plane-of-sky direction of the magnetic field (azimuth). The aperture of the LC is driven by the need to collect sufficient photons to achieve the magnetic field sensitivity for the Zeeman measurements. The 1° FOV allows the study of typical large-scale coronal structures. The broad wavelength range is critical to observe many visible and near-IR emission lines that provide information on the plasma thermal structure, density and dynamical status using standard diagnostic techniques. The COSMO LC derives its heritage from prototype instruments that have successfully demonstrated the feasibility of the proposed measurement techniques: the University of Hawaii Optical Fiberbundle Imaging Spectropolarimeter and the NCAR High Altitude Observatory (HAO) Coronal Multichannel Polarimeter [CoMP]. These instruments have demonstrated key capabilities and provided valuable information on fundamental coronal properties.

Coronal broadband “white light” polarization observations yield a direct measurement of the column density of coronal electrons that is independent of thermodynamic factors. These data provide important information on the basic properties of CMEs such as size, mass, speed, and acceleration. The 20-cm aperture K-Cor observes the linearly polarized component of continuum light in a 30 nm wide passband centered at 735 nm. The K-Cor full FOV of ± 3 R_{sun} is needed for observing the density structure of the global corona and for measuring the properties of dynamic events such as CMEs. The large FOV and 15 s cadence allows K-Cor to adequately sample the plane-of-sky velocity and acceleration profiles and expansion rates of CMEs. The lower limit of the FOV is 1.05 R_{sun} providing measurements of the lowest coronal scale height where most CMEs originate and are accelerated. The observing cadence of K-Cor is rapid enough to detect and follow the dynamical processes of CME initiation, prominence eruption/rotation, wave propagation, and shock formation. The K-Cor is the one component of the COSMO suite that is already operational. K-Cor went into service in September 2013, continuing a legacy of coronal whitelight observations spanning five decades.

Chromospheric observations provide important information on plasma conditions in the low- and mid-atmosphere that are needed to bridge observations of the photosphere to those of the corona. ChroMag has the following characteristics: 1) 13.5-cm aperture telescope with tunable filter/polarimeter; 2) FOV of 2.25 R_{sun} including full solar disk and above the limb; 3) Spatial resolution of 2.25 arcsec; 4) Spectral coverage including HeI (587.6 and 1083 nm) for prominences, HI (656.3 nm) and CaII (854.2 nm) for the chromosphere and FeI (617.3 nm) for the photosphere; 5) Filter bandwidth ranging from 0.009 nm in the visible region to 0.034 nm in

the IR; 6) Measurement of magnetic field, Doppler and line-width; 7) Polarimetric sensitivity of 10⁻³ in less than 1 minute per line; 8) Temporal cadence of less than 10 s per line for intensity and Doppler observations of MHD Waves. A ChroMag prototype has been completed and is operational at the solar-pointed spar at the Mesa Lab facility in Boulder, CO. The instrument is currently under construction, with deployment to Mauna Loa expected in 2019.

CoSMO: A Community Partnership

The National Center for Atmospheric Research (NCAR) along with partner institutions (the University of Michigan, the University of Hawaii, George Mason University, the Smithsonian Astrophysical Observatory, and the University of Colorado) will engage with industry partners to develop COSMO.

The Science of COSMO

Magnetism defines the complex and dynamic solar corona. Twists and tangles in coronal magnetic fields build up energy and ultimately erupt, hurling plasma into interplanetary space. These CMEs are transient riders on the ever-outflowing solar wind, which itself possesses a three-dimensional morphology shaped by the global coronal magnetic field. The severity of solar storms at Earth depends, in large part, on the strength and direction of the magnetic field embedded in ejecta originating in the solar corona. Space-weather forecast capability is held back by our current lack of basic scientific understanding of CME magnetic evolution, and the coronal magnetism that structures and drives it. Comprehensive observations of the global magnetothermal environment of the solar atmosphere are needed for progress, and yet current capabilities fall far short. *COSMO will provide unique new observations that are required for solving fundamental problems in solar and space physics.*

When it is fully implemented, COSMO will provide the community with comprehensive and simultaneous measurements of the magnetic and thermal properties of the solar atmosphere:

- Quantify coronal magnetism, which is the “missing link” for multiple critical questions for solar physics, and an essential element for improving space-weather forecasts.
- Provide a systems view that will drive the next generation of coronal and heliospheric models - those models will form the basis for stellar weather models.

Specific COSMO Science Goals

- Understand the storage and release of magnetic energy by characterizing the physical processes leading up to eruptions:
 - How does free magnetic energy accumulate in the corona prior to eruption? How does non-potentiality (the presence of currents) evolve prior to eruption?

- What is the role of reconnection in the CME onset? What are the polarimetric and morphological signatures of tether cutting (e.g., the formation/rise of a magnetic X line below the CME source region), and/or of a magnetic breakout topology (e.g., a magnetic null or X-line above the CME source region)?
- What is the role of ideal instabilities in the CME onset? Does the falloff of overlying magnetic fields or the degree of magnetic twist within source regions indicate that the CME is triggered by an ideal MHD instability? Is the observed twist of CME source regions sufficient to trigger the kink instability?
- Understand CME dynamics and consequences for shocks by characterizing local and global interactions:
 - What are the mechanisms driving CME acceleration and expansion? How does the magnetic field distribution (pre-eruption and post-eruption) correlate with CME velocity and acceleration? How does the topology of the source region and surrounding corona (e.g., degree of local magnetic expansion, X-line below or above source) influence acceleration and trajectory?
 - Where and when do shocks form in association with CMEs? How does CME acceleration and expansion correlate with shock signatures? How does the magnetic-field direction evolve within the CME?
- Determine the role of waves in solar atmospheric heating and solar wind acceleration by characterizing spatial and temporal wave properties:
 - To what extent do ubiquitous coronal MHD waves play a role in coronal heating? How much of this wave power is available to heat the corona? How is power distributed over spatial scales?
 - How does coronal wave dissipation differ in open vs closed field? What is the dependence on magnetic flux tube expansion? What are the implications for solar wind acceleration?
 - What are the origins of the waves observed in the chromosphere and corona? How do coronal and chromospheric wave power spectra correlate with photospheric power spectra?
- Understand how the coronal magnetic field relates to the solar dynamo and evolving global heliosphere by characterizing variation on a solar cycle time scale:
 - How does toroidal coronal magnetic field evolve over the solar cycle? Is there a band of toroidal field that is translated poleward, and if so, how is it removed as the poles reverse? What is the correlation to CME activity? What are the implications for the solar dynamo?
 - How does the global coronal magnetic topology evolve over the solar cycle? How do the spatial distribution of magnetic nulls and magnetic flux-tube expansion vary over the extended solar cycle? How does the global poloidal magnetic field reversal manifest in the corona? What are the implications for the global heliospheric magnetic field and solar wind?

- Constrain and improve space-weather forecast models through the incorporation of coronal and chromospheric magneto-thermal observations:
 - To what degree does non-potentiality in the global corona spatially and temporally correlate with the likelihood of eruption?
 - To what degree do measurements of the chromospheric and coronal magnetic field of the CME and its source region determine Bz in a magnetic cloud observed in situ?
 - To what degree do chromospheric and coronal energetics observed during the early onset of eruption determine CME arrival times?
 - To what extent does constraining solar wind models with global coronal and chromospheric magneto-thermal data improve solar wind forecasts?

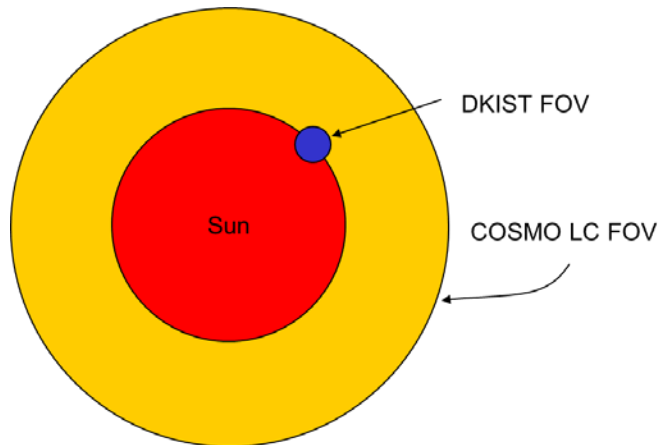
Community Advocacy for COSMO

COSMO was endorsed in the latest Solar & Space Physics Decadal Survey and described as one of the projects “exemplifying the kind of creative approaches that are necessary to fill gaps in observational capabilities and to move the survey’s integrated science strategy forward.” Further, a 2016 community meeting of the NSF/GEO/AGS/Geoscience SHINE, CEDAR and GEM community representatives “Exploring the Geospace Frontier: Quo Vadis?” focused on the infrastructure required for discovery research in the 21st century, with consideration for both basic and applied research driven by cutting edge observations of the Earth-Sun system. The driving science of COSMO, characterizing the magneto-thermal environment of the inner solar system, was featured as a high-priority stand-alone facility and also as the cornerstone of an advanced ground-based network. These documents illustrate how COSMO has been identified as a critical scientific need by the community. The measurements made by COSMO will be an observational driver for future space-weather models and present “Research to Operations” pathways that will strengthen HAO’s collaborations with NOAA’s Space Weather Prediction Center, the U.S. Air Force and the NSF’s National Solar Observatory (NSO). The unique observations provided by COSMO will complement and leverage other space- and ground-based investments like NASA’s Parker Solar Probe and NSO’s Daniel K. Inouye Solar Telescope.

Complementarity to the Daniel K. Inouye Solar Telescope (DKIST)

The product of the FOV and the area of the entrance pupil defines the light gathering power, or *étendue*, of a telescope. To avoid light losses, the *étendue* must be conserved through the post-focus optical system. While the DKIST telescope has a factor of 7 greater collecting area than the COSMO LC, the LC has a light gathering power that exceeds that of the DKIST by a factor of 20 owing to its larger FOV (see Fig. 1). The complementary nature of these telescopes is further illustrated if one considers that the filtergraph instrument behind the LC is capable of accepting the full *étendue* of the LC telescope, while all of the DKIST first light instruments have an instantaneous FOV that is less than the FOV of the DKIST telescope. For example, the

DKIST instrument best suited to observe the corona due to its long wavelength capability is the Cryo-NIRSP instrument. It has an entrance slit of 240×0.5 arcsec (120 arcsec^2 FOV) compared to the instantaneous FOV of the LC/filtergraph of $1 \times 10^7 \text{ arcsec}^2$. Noise calculations show that the LC/filtergraph will require 21 times longer than the DKIST/Cryo-NIRSP to scan in wavelength and achieve the same signal to noise ratio. But this is for only 1 position of the Cryo-NIRSP slit compared to the full 1° FOV of the LC. The LC/filtergraph can meet its measurement



requirement in 15 minutes; it would take 8.3×10^4 steps of the Cryo-NIRSP entrance slit and 995 hours for the DKIST/Cryo-NIRSP to achieve the same precision over a 1° FOV. In this sense, the COSMO LC is more analogous to the Large Synoptic Survey Telescope; its design reflects its primary mission as a synoptic monitor of the properties of the large-scale solar corona. As stated in the 2013 Solar & Space Physics Decadal Survey, “The large

field of view and continuous observations of COSMO will complement high-resolution, but small field-of-view, coronal magnetic field observations that may be taken by the ATST.” (ATST was the former acronym for DKIST). The different designs of the DKIST and the COSMO LC telescopes reflect their vastly different and complementary capabilities and missions.

COSMO Construction and Operations and Maintenance Plans

A risk assessment and cost analysis of the COSMO project was recently conducted by the Aerospace Corporation and resulted in rough order of magnitude (ROM) costs of \$75.2M for the design and construction of the full COSMO facility and an operations and maintenance (O&M) cost of \$4.3M per year over a 10-year period. These estimates include contingency at a level of 20% for the construction cost and 10% for the O&M costs. Since COSMO will replace HAO’s Mauna Loa Solar Observatory (MLSO), the \$1.4M per year operating costs of MLSO will be applied to COSMO operations and result in a required increment of \$2.9M per year for the operation and maintenance of COSMO.