COSMO: The COronal Solar Magnetism Observatory

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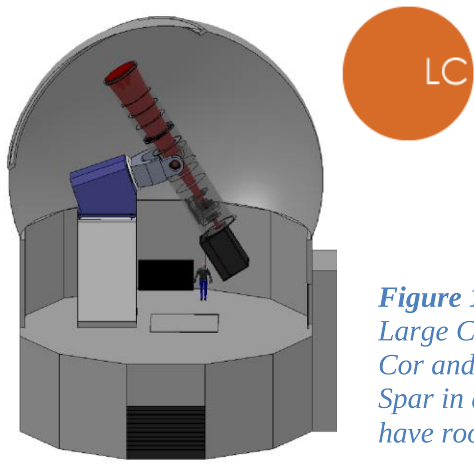
Synopsis

The COronal Solar Magnetism Observatory (COSMO) will make the first synoptic, simultaneous measurements of magnetic and plasma properties of the global solar atmosphere, filling crucial gaps in our understanding of the drivers of solar eruptions and the evolution of the coronal magnetic field on time scales from minutes to decades.

- **COSMO uniquely addresses critical Heliophysics science.** With an unparalleled combination of large field of view and high magnetic sensitivity, the 1.5m COSMO Large Coronagraph (LC) opens a new window on coronal magnetism on global scales. Along with K-Coronagraph (K-Cor) middle-corona observations and the Chromosphere and Prominence Magnetometer (ChroMag) observations of the photosphere and chromosphere, these capabilities enable researchers to finally answer crucial questions about solar eruptions, coronal heating/solar wind acceleration, and the solar dynamo.
- **COSMO is mature.** K-Cor has been operating at the Mauna Loa Solar Observatory (MLSO) since 2013 and ChroMag is soon to be deployed. Also at MLSO, the 20cm Upgraded Coronal Multichannel Polarimeter (UCoMP) is proving the power of global coronal spectropolarimetry and whetting the community's appetite for the unprecedented sensitivity of the LC.
- **COSMO is low risk.** A recent development: the NSF-funded COSMO Site and Design Advancement (COSADA) is a three-year effort currently underway that reduces risk through site selection and final design of the LC.
- **COSMO has broad community support.** The fact that COSMO fills a critical gap in our observational capabilities was recognized in the last Solar and Space Physics Decadal Survey. COSMO builds on the legacy and thriving user base of the MLSO, which has provided global synoptic solar observations to the community for over sixty years.
- **COSMO is complementary to other solar telescopes.** The breakthrough observations obtained by COSMO will not be provided by any other current or proposed observatory, and will enhance the value of other ground- and space-based Heliophysics assets.



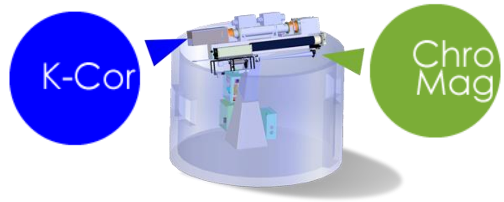


__Figure 1.__ The COSMO suite of instruments. The 1.5-m aperture Large Coronagraph (LC) is in a stand-alone dome, while the K-Cor and ChroMag are mounted to the solar pointed Community Spar in a separate dome (not to scale). The Community Spar will have room for instruments that are developed by the community.

Why COSMO?

Society has become increasingly reliant on technologies that are susceptible to damage by space weather events. Our understanding of the processes responsible for these events and our ability to predict them are impeded by the lack of synoptic observations of the magnetic field and plasma properties of the upper solar atmosphere where they originate. The **Coronal Solar Magnetism Observatory (COSMO)** will fill this critical information gap. The central instrument is a 1.5m-aperture **Large Coronagraph (LC)** that will obtain daily measurements of the temperature, density, and velocity of coronal plasma, and the strength and direction of magnetic fields over a large field-of-view at the spatial and temporal resolutions required to address the outstanding problems in solar physics. Supporting instruments focus on photospheric, chromospheric and prominence magnetometry (**ChroMag**), and observing the electron scattered K-corona (**K-Cor**) (***Figure 1***). This suite of comprehensive observations will not be provided by any current or proposed observatory and will enable breakthrough science and enhance the value of data collected by other observatories on the ground and in space. The National Center for Atmospheric Research's (NCAR's) High Altitude Observatory (HAO) leads the development of COSMO, with partners from the University of Michigan, the University of Hawaii, George Mason University, the National Solar Observatory, and the Harvard-Smithsonian Center for Astrophysics. The COSMO suite of instruments are in an advanced state of readiness. The K-Cor is operational, ChroMag is soon to be deployed, and the LC is currently advancing towards Final Design. A site survey is underway to determine the best location for the COSMO observatory.

COSMO uniquely addresses critical Heliophysics science

The **overarching goal** of the COSMO is to make the first synoptic, simultaneous measurements of magnetic and plasma properties of the global solar atmosphere, filling crucial gaps in our understanding of the drivers of solar eruptions and the evolution of the coronal magnetic field on time scales from minutes to decades. The COSMO science objectives are:

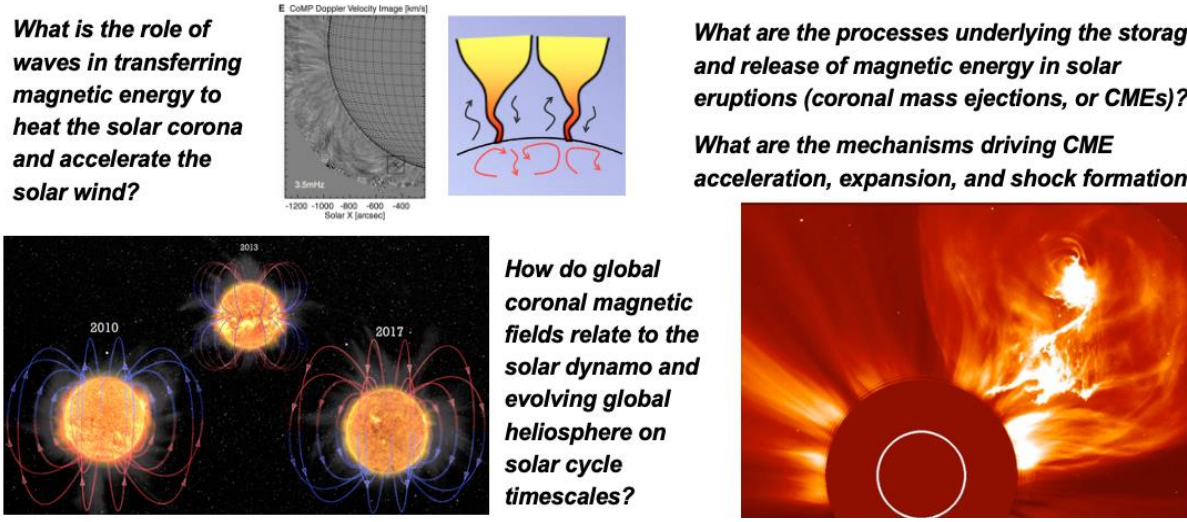


Figure 2. COSMO observations are central to critical questions in Heliophysics. Top left: *Solar image shows the Coronal Multichannel Polarimeter (CoMP) landmark measurements of ubiquitous Alfvénic waves in the corona (Tomczyk et al. 2007) that may transfer energy from the solar surface to heat the corona and accelerate the solar wind (cartoon from S. Cranmer).* ***Bottom left:*** *The global solar corona changes on solar cycle timescales, providing clues to the solar dynamo and evolving heliosphere (picture from L. de Almeida et al. 2017).* ***Right:*** *CMEs are driven by magnetic energy stored in the corona; driving mechanisms for their eruption and dynamic evolution are largely unknown (SOHO/LASCO).*

COSMO Science Objectives 1) ***Understand the storage and release of magnetic energy by characterizing the physical processes leading up to eruptions, and***

COSMO Science Objectives 2) ***Understand coronal mass ejection (CME) dynamics and consequences for shocks by characterizing local and global interactions***

Objectives 1 and 2 address solar activity which is driven by energy stored in the magnetic field and released in eruptive events like CMEs (***Figure 2, right***). The severity of solar storms at Earth depends on the direction of the magnetic field embedded in ejecta that originated in the solar corona, yet the magnetic field and plasma properties in the upper solar atmosphere *are not routinely observed*. The COSMO-LC will provide global synoptic observations of both linear and circular polarization, quantifying magnetic energy buildup prior to an eruption and choosing between models of CME drivers (*see white paper by Gibson et al. 2022*). Along with LC plasma observations (*see white paper by Landi et al. 2022*) and observations from K-Cor, these measurements will shed light on mechanisms driving CME acceleration, expansion, and formation of shocks (*see white paper by Burkepile et al. 2022*).

COSMO Science Objective 3) ***Determine the role of waves in solar atmospheric heating and solar wind acceleration by characterizing spatial and temporal wave properties***

CoMP observations demonstrate the ubiquity and diagnostic capability of coronal MHD waves (Tomczyk et al. 2007; 2009; Threlfall et al. 2013; de Moortel et al. 2014; Long et al. 2017; ***Figure 2, top left***) However, it is difficult to put limits on the contributions of waves to coronal heating due to the unknown degree of spatially-unresolved wave power (McIntosh & De Pontieu 2012) or to analyze their contribution to solar wind acceleration in faint open-field coronal hole regions (de Moortel and Nakariakov 2012). The LC will place bounds on unresolved wave power, quantifying the contribution of waves to coronal heating, and in combination with ChroMag, observe connectivity of waves from chromosphere to corona (*see white paper by Morton et al. 2022*).

COSMO Science Objective 4) *Understand how the coronal magnetic field relates to the solar dynamo and evolving global heliosphere by characterizing variations on solar cycle time scales* Historically, MLSO white-light coronal data spanning more than six decades show variation of open and closed field structures and CME activity (Fisher and Sime 1984; St. Cyr et al. 2015). With COSMO, we will extend our long-term observational record to include the magnetic properties of the solar corona. In particular, the LC circular polarization measurements uniquely measure the Sun's large-scale toroidal magnetic field (B_{los} at the limb), allowing analysis of the evolution of the global magnetic field on solar cycle time scales (***Figure 2, bottom left***). (*see white paper by Dikpati et al. 2022*).

COSMO is mature

The science questions and the instrument requirements they drive can be addressed by a suite of three synoptic ground-based telescopes working in unison to enable the study of the solar atmosphere as a coupled system (***Figure 1***).

Large Coronagraph (LC) The central instrument in the COSMO suite is a 1.5m-aperture Large Coronagraph (LC) that will obtain daily measurements of the strength and direction of coronal magnetic fields over a large field of view (FOV). 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° (± 2 R_{sun}) global FOV allows the study of typical large-scale coronal structures. The broad wavelength range (380 to 1450 nm) is crucial to observe many visible and near-IR emission lines over a range of formation temperatures between 0.01 to 5MK and to observe line pairs at several temperatures for line-ratio density diagnostics. The line-of-sight (LOS) coronal magnetic field strength can be measured directly through the Zeeman effect observed in circular polarization of coronal forbidden emission lines. The linear polarization of emission lines from resonant scattering is a measure of the plane-of-sky (POS) direction of the magnetic field. Finally, MHD waves seen in time series of Doppler images can be used to infer the POS coronal magnetic field strength through coronal seismology (*see white paper by Morton et al. 2022*).

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 (Lin et al. 2004) and the HAO/NCAR Coronal Multichannel Polarimeter (CoMP; Tomczyk et al. 2008) and Upgraded CoMP (UcoMP; Landi, Habbal and Tomczyk 2016). These efforts have been enabled by recent advances in detector technology that make possible the observation of near-IR emission lines that are highly sensitive to the Zeeman effect. However, these prototype instruments are severely limited by the modest apertures of the available coronagraphs.

K-Coronagraph (K-Cor) The K-Cor (de Wijn et al. 2012) is the one component of the COSMO suite that is fully operational at MLSO (***Figure 3***). Coronal broadband "white light" polarization observations provide a direct measurement of the column density of coronal electrons that is independent of thermodynamic factors, yielding 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 dual-beam optical system images the orthogonal linear polarization states simultaneously in order to cancel noise in the polarization measurement caused by seeing and intensity variations from aerosols passing through the FOV.

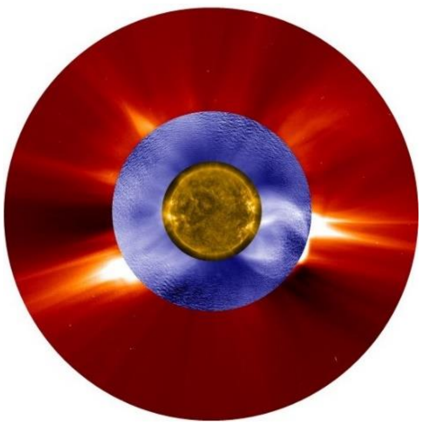


Figure 3. *The January 1, 2016 CME as seen in this composite image from SDO AIA (gold), COSMO K-Cor (blue), and LASCO C2 (red).*

The K-Cor FOV of ±3 R_{sun} (see ***Figure 3***) 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 high time cadence allows K-Cor to adequately sample the plane-of-sky velocity and acceleration profiles and expansion rates of CMEs. The inner FOV is ±1.05 R_{sun} providing measurements into the lowest coronal scale height where most CMEs originate and are accelerated. K-Cor observes the low and middle corona filling an observational gap in space-based coronagraph observations, as shown in ***Figure 3***. K-Cor observing cadence of 15 s, is rapid enough to detect and follow the dynamical processes of CME initiation, prominence eruption/rotation, magnetic reconnection, wave propagation, and shock formation. K-Cor has a fully automated data processing system operating at MLSO coupled with a CME detection algorithm developed by Thompson et al. 2017 that issues CME alerts to community members often before the CME has entered the LASCO FOV. This constitutes an important component of an early warning system for solar energetic particle events (St.Cyr et al. 2017; *also see white paper by Burkepile et al. 2022*).

ChroMag Chromospheric observations provide important information on plasma conditions in the solar atmosphere needed to bridge observations of the photosphere to those of the corona. ChroMag (de Wijn et al. 2014) has: 1) a 13.5-cm aperture telescope with tunable filter/polarimeter; 2) FOV of ±1.125 R_{sun} including full solar disk and above the limb; 3) spatial resolution of 2.25 arcseconds; 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. The ChroMag instrument is currently under construction with deployment set for 2023. (*see white paper by de Wijn et al. 2022*).

COSMO Community Spar The LC will be a stand-alone instrument and will reside in its own dome**,** while the ChroMag and K-Cor instruments will reside on a separate solar pointed platform (spar) in a nearby smaller dome. The spar has eight sides on which to place instruments (***Figure 4***). After COSMO is completed, the project will make space available on this pointing platform to the community to conduct instrumentation development and observing campaigns. We will especially encourage and support a diverse group of young researchers to develop instruments and deploy them to the community spar. Through the community spar, COSMO will provide infrastructural, logistical, and engineering support to drive a new generation of instrument builders and scientists across the academic community in the U.S.

Figure 4. *Rendering of the COSMO Community Spar.*

Modeling and Analysis Tool Development Concurrent with hardware developments over the past two decades has been steady progress in the development of modeling and analysis tools that will enable researchers to achieve the goals of COSMO.

Forward modeling based on the theoretical synthesis of the Stokes profiles of M1 forbidden emission lines (Casini and Judge, 1999) has been used by researchers (Bak-Steslicka et al., 2013; Rachmeler et al. 2014; Gibson, et al. 2017; and others) to gain insight on coronal magnetic topology from linear polarization measurements.

Solar coronal density and temperature distributions have been reconstructed using tomographic methods (Frazin et al. 2007). The more difficult problem of tomographically reconstructing the vector magnetic field from polarization measurements has recently been achieved for FeXIII forbidden lines (Kramar et al., 2016).

Observations of the ubiquitous waves in Doppler images of the solar corona have been used to map the wave phase speed using time-distance coronal seismology. This has yielded, for the first time, large-scale maps of the plane-of-sky component of the coronal magnetic field (Yang et al. 2020).

And recent advances in chromospheric and coronal polarized diagnostics (e.g. Dima & Schad, 2020; Schad & Dima, 2021; Paraschiv & Judge, 2022) using Stokes IQUV observations allow the inference of full vector magnetic fields, under various assumptions, and global inversion frameworks are under development (Dalmasse et al. 2019; *see white paper by Gibson et al. 2022*).

<u>COSMO is low risk</u>

In May 2019, a team comprised of NCAR/HAO and partner institution personnel was invited to submit a full proposal in response to the NSF Mid-scale Research Infrastructure-1 (MSRI-1) solicitation. This proposal, submitted under the category of Design Project, was reviewed highly, but not selected at that time. In assessing proposal reviewer comments and in subsequent discussions with NSF/AGS program officers, the COSMO project ascertained that **a significant reduction in schedule and cost risk could be achieved through proactive steps toward COSMO site selection and the completion of the design of the LC.**

In 2020, the NSF funded the three-year, $5.6M **COSMO Site and Design Advancement (COSADA)** effort to address these two risk areas. The COSMO site must have extraordinarily dark daytime skies, characterized by an extremely low level of aerosols, since the solar corona is observed superimposed on the sky background. Following an extensive data mining exercise, six sites were selected to test for the location of COSMO with sky brightness, seeing and meteorological instruments. Testing has started at one site, a second site was just recently approved for testing, and agreements for testing the remaining four sites are now being negotiated. **COSADA deliverable: a prioritized list of the top two sites.**

The second issue, the design of the Large Coronagraph, is challenging because 1) it will be the largest refracting telescope in the world at 1.5 m, 2) it will have a large FOV and 3) it must be maintained to very high cleanliness standards to minimize instrumental scattering. The engineering firm European Industrial Engineering (EIE) has been engaged by the project and is working with NCAR/HAO staff towards the Large Coronagraph final design. **COSADA deliverable: final design of the LC including all reviews and a high fidelity cost estimate for COSMO facility.**

COSMO has broad community support

COSMO was endorsed in the latest Solar & Space Physics Decadal Survey, 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, "*Exploring the Geospace Frontier: Quo Vadis*?" - a 2016 community meeting of NSF/GEO/AGS/Geoscience SHINE, CEDAR and GEM community representatives - undertook a discussion of the infrastructure required for discovery research in the 21st century, with consideration of both basic and applied research driven by cutting edge observations of the Earth-Sun system. The driving science of COSMO, i.e., 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 COSMO team, in collaboration with community members including members of the COSMO Steering Committee, are currently developing a Detailed Observing Plan to maximize the benefits of the COSMO suite of instruments. Starting from the Science Traceability Matrix developed for the 2019 MSRI-1 proposal, a set of Observing Programs utilizing all three COSMO instruments has been developed and will be run on a synoptic basis to ensure the necessary data are taken for scientific closure on the COSMO Science Objectives described above.

The COSMO user base builds on the legacy and thriving user base of the Mauna Loa Solar Observatory (MLSO), which has provided global synoptic solar observations to the community for over sixty years. MLSO data services host over 500 TB of solar data dating back to the 1960s. Since 2017, MLSO has served over 550 users from 79 academic and educational institutions, 61 research labs, and 15 private industry and other groups, providing access to over 80 unique observational solar data products.

COSMO is complementary to other solar telescopes

The comprehensive observations obtained by the COSMO suite of instruments will not be provided by any other current or proposed observatory. The COSMO facility will enable breakthrough science and enhance the value of data collected by current and proposed observatories on the ground (e.g. DKIST, FASR, NG-GONG) and in space (e.g. Hinode, STEREO, SDO, GOES, PSP, Solar Orbiter, PUNCH).

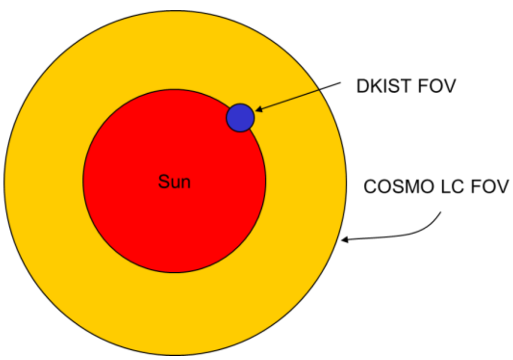


Figure 5. *The COSMO-LC field of view (yellow) is shown in comparison to that of the DKIST (blue).*

COSMO will work especially closely with the Daniel K. Inouye Solar Telescope (DKIST; Rimmele et al. 2020), a 4-m aperture solar telescope which has the ability to measure coronal magnetic fields above the limb using the same Zeeman and Hanle diagnostics as COSMO. Due to its large aperture, the DKIST is optimized for high spatial resolution observations over a maximum 5 arcminute field-of-view (***Figure 5***). DKIST will be used to pursue a range of user defined observations on the solar disk and above the limb, but with a FOV that is small compared to large scale coronal structures. 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).

In summary, COSMO will provide synoptic data over spatial and temporal scales not available from other observatories. Coupled with new model developments, these data will spur improved prediction of space weather phenomena and mitigate their damaging effects for the benefit of society. The technical readiness of COSMO has been demonstrated with prototype instruments, and the highest risk areas for COSMO are being addressed through the ongoing COSADA effort, conducting a site survey and advancing the Large Coronagraph to final design. COSMO is complementary to other next generation ground- and space-based solar facilities, and has a maturity reflected by its endorsement in the last Heliophysics Decadal Survey (Baker, Charo and Zurbuchen, 2013).

COSMO is unique, timely, technologically achievable, and relevant to society.

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