COSMO ChroMag: The Chromosphere and Prominence Magnetometer

A White Paper Submitted to the Decadal Survey for Solar and Space Physics

Alfred de Wijn[1*], Steven Tomczyk[1], Joan Burkepile[1], Roberto Casini[1], Giuliana de Toma[1]

[1]National Center for Atmospheric Research, High Altitude Observatory
[*]Corresponding author, dwijn@ucar.edu

Synopsis

We discuss the Chromosphere and Prominence Magnetometer (ChroMag) of the Coronal Solar Magnetism Observatory (COSMO). Regions of twisted or sheared magnetic fields and prominences are known to be the sources of eruptions that make up the bulk of space weather impacts (Schrijver 2009; Gibson 2018). However, our capability to diagnose magnetic field in the solar chromosphere and prominences, while critical to our ability to understand the physical processes associated with eruptions, is very limited. ChroMag will provide the community with synoptic observations of magnetic field in the chromosphere that are currently unavailable yet critical to these and many other outstanding questions about the processes that operate on both short and long timescales in the outer solar atmosphere. ChroMag is in an advanced state of construction and will be deployed to the Mauna Loa Solar Observatory in 2023. We discuss the three of four COSMO science objectives that are relevant to ChroMag, instrument characteristics, data interpretation, and complementarity to other observatories and broader impacts. We argue for continued development of spectropolarimetric data interpretation tools and techniques, and inclusion of ChroMag-like capabilities in future global networks of observatories.

Introduction

The Coronal Solar Magnetism Observatory (COSMO, described in a white paper by Tomczyk et al. 2022) will make the synoptic measurements of the properties of the magnetized plasma of the solar atmosphere from the photosphere through the chromosphere and into the corona. These measurements will fill crucial observational gaps that currently inhibit substantial progress 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 consists of three instruments: the Large Coronagraph (LC) that will obtain daily measurements of coronal temperature, density, velocity, and the strength and direction of magnetic fields over a large field-of-view; the K-Cor that observes the electron scattered K-corona; and the Chromosphere and Prominence Magnetometer (ChroMag) that is the subject of this white paper.

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 at NCAR's Mauna Loa Solar Observatory (MLSO), the LC is currently advancing towards Final Design, and a site survey is underway to determine a location for the COSMO observatory. ChroMag is soon to be deployed to MLSO.

Science Objectives

COSMO has four Science Objectives (SOs). Only SO 3 does not depend on ChroMag observations. We discuss the other three SOs here briefly.

COSMO Science Objective 1: Understand the storage and release of magnetic energy by characterizing the physical processes leading up to eruptions.

Coronal mass ejections (CMEs) are driven by magnetic energy and the cause of many space weather impacts. It is known that the sources of these eruption are regions of twisted or sheared magnetic fields, including active regions (sunspots; e.g., Schrijver 2009) and quiescent prominences (e.g., Gibson 2018). However, current diagnostic capabilities of magnetic field in the solar atmosphere are inadequate to make significant progress on understanding the associated physical processes. Magnetic field extrapolations from photospheric measurements of the underlying magnetic fields are ill-posed and furthermore rely on questionable assumptions (e.g., that the magnetic field is force-free in the photosphere). It is therefore critical to diagnose magnetic field in the chromosphere and corona directly to determine how a non-potential configuration of the field arises and how the energy is injected and stored prior to the onset of flares and CMEs (Georgoulis, Nindos, and Zhang 2019).

COSMO ChroMag fills an observational gap. It has the capability to diagnose plasma parameters in the photosphere and chromosphere, and, by virtue of being a synoptic instrument with a field-of-view that covers the full disk of the sun, will observe the evolution of many CME precursors leading up to eruption.

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

MHD waves are omnipresent in the solar atmosphere, as first demonstrated by CoMP observations by Tomczyk et al. (2007) and subsequently confirmed by Hinode (de Pontieu et al. 2007). Since then, much has been learned about roles of waves in the energy balance of the outer solar atmosphere, and it has become clear that the photosphere, chromosphere, transition region, and corona are more intimately connected than previously thought (see, e.g., Carlsson, de Pontieu, and Hansteen 2019 for a review). New instrumentation has mainly focused on high spatial and temporal resolution, but with limited or no capability to diagnose the magnetic field in the chromosphere. Consequently, lacking measurements, current 3D radiative MHD numerical simulations are poorly constrained, and their properties in the middle to upper chromosphere, TR, and corona often do not match the observations (e.g., Olluri et al. 2015). The likely source of the discrepancies is that the magnetic field properties are not properly captured in the simulations.

Again, COSMO ChroMag fills an observational gap. It is capable of observing at high cadence adequate to observe the signatures of many kinds of MHD waves. ChroMag will signficantly exceed its requirement to observe spectro-polarimetric signals with an SNR of 1,000 in one line in less than a minute. Its ability to diagnose magnetic field in the chromosphere is a key advance for these studies (see also a 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.

It is well-known that the heliosphere undergoes drastic changes during the magnetic solar activity cycle. Observed through proxy-magnetometry diagnostics (e.g., sunspot number, etc.) have been made for hundreds of years. The last few cycles have been observed also by photospheric magnetographs such as the Helioseismic and Magnetic Imager on the Solar Dynamics Observatory (SDO/HMI; Schou et al. 2012), but no long-term synoptic observational record exists of the chromospheric and coronal vector magnetic field. It is clear, however, that multi-height observations (i.e., of the magnetic field in the photosphere, chromosphere, and corona) are necessary to understand many fundamental phenomena such as the role of magnetic helicity in the solar cycle (Low 1998). There is also a use for such observations in space weather research and operations. (See a white paper by Bertello et al. 2022 for a discussion on this subject.)

COSMO ChroMag helps address this objective by providing a synoptic, long-duration observational record of the magnetic field in the photosphere and chromosphere, amongst other measures.

Instrument Characteristics and Status

The ChroMag design is driven by the requirements to have a 2.25 R_{sun} field-of-view that encompasses the entire disk of the sun plus prominences that extend above the limb, high cadence (less than 1 min per spectral line to reach a polarimetric sensitivity of 10^{-3}), and produce observables that allow the diagnosis of the parameters of the magnetized plasma in the photosphere and chromosphere. Physics implies a trade between field-of-view, spatial and spectral resolution, and observation cadence. The ChroMag instrument uses a small 13.5-cm telescope and reaches a reasonable spatial resolution of 2.25 arcsec and spectral sampling between 9 pm in the visible to 34 pm in the NIR. It has at its core a narrow-band tunable Lyot filter. Lyot filters are excellent choices for instruments with large fields of view because a clever arrangement of the optical components can render them much less sensitive to the effects of angle-of-incidence than other narrow-band filters such as Fabry-Pérot interferometers. The ChroMag Lyot filter uses liquid crystal devices for fast wavelength tuning with no moving parts to reach high cadence. ChroMag will observe five key spectral lines: He I 587.6 and 1083 nm for prominences, H I 656.3 nm and Ca II 854.2 nm for the chromosphere and Fe I 617.3 nm for the photosphere (the same line that

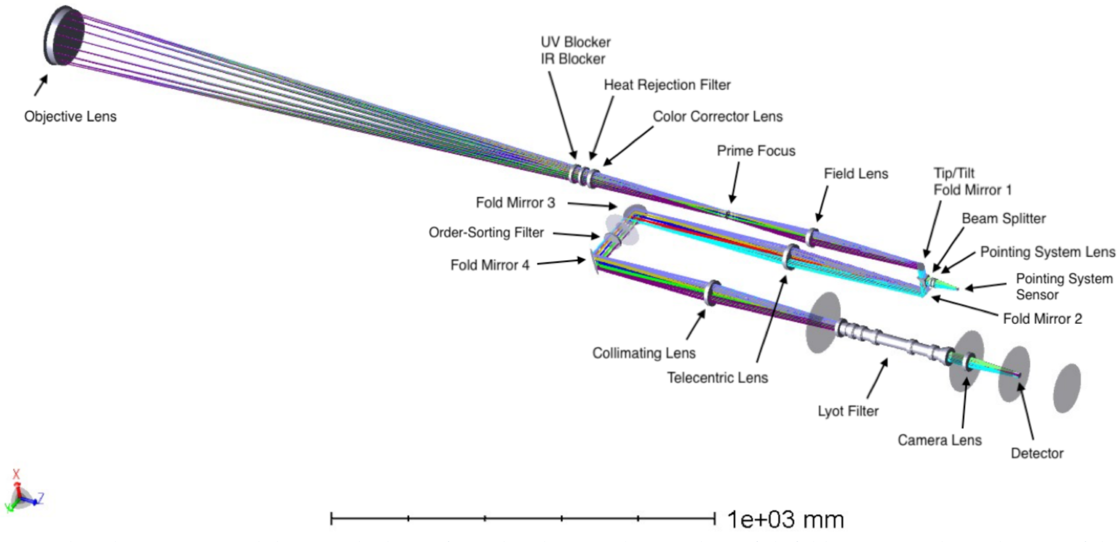

Figure 1. The ChroMag optical design. The beam from the objective lens to the tip/tilt fold mirror is above the rest of the instrument. The folded design allows a long optical path while maintaining an overall physical size that fits on the MLSO spar.

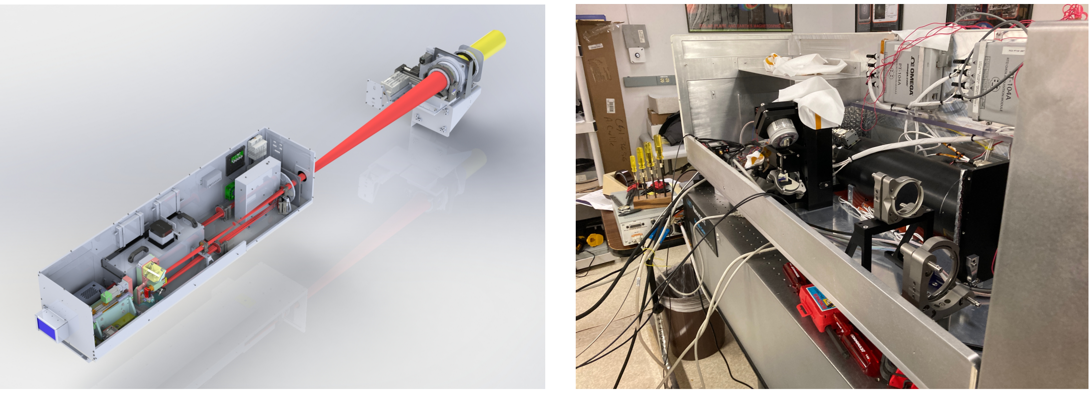

Figure 2. Left: a render of the ChroMag mechanical model. Right: a picture showing the back-end of the instrument in the Lab. The black cylinder in the back is the Lyot filter. The tip/tilt fold mirror 1 and fold mirror are on the left. The two lenses in the foreground are the field lens (top) and the telecentric lens (bottom).

SDO/HMI observes). ChroMag mounts to a solar-pointed platform but is otherwise a stand-alone instrument.

ChroMag is in an advanced stage of development. Tests with a prototype (de Wijn, Tomczyk, and Burkepile 2014) revealed shortcomings of its simplistic optical design and difficulty with thermal stabilization of the Lyot filter. Consequently, the optical design was changed to improve spectral purity of the observations, a tip/tilt image stabilization system was added to mitigate the effects of atmospheric seeing, and the Lyot filter was modified for both thermal stabilization and thermal compensation. These changes have been implemented in a new optical and mechanical design. Lab characterization of the instrument is underway. ChroMag will be deployed to the spar at the Mauna Loa Solar Observatory (MLSO) in early 2023.

Data Interpretation

Interpretation of magnetic field strength and orientation, and other plasma parameters, from spectro-polarimetric observations of lines that form in the photosphere has become routine with the advent of space-borne polarimeters, in particular SDO/HMI. These interpretations, commonly called “inversions,” rely on simple atmospheric models that are limited in their applicability to the photosphere. The assumptions made in these inversion codes are not valid in the chromosphere. More sophisticated inversion codes are required to interpret those data. However, because of the increased complexity, application of these codes on large scales is difficult due to increased computational cost and other issues such as instabilities in convergence to a solution as well as finding a good initial guess. Interpretation of spectro-polarimetric data of lines that form in the chromosphere has therefore only been done on small scales and has required experienced users to operate the inversion codes.

The full potential of ChroMag will only be realized if data can be interpreted in an automated pipeline that requires little supervision. Fortunately, significant progress is being made to address the above issues and diagnostic tools and techniques are maturing. ChroMag will benefit from the efforts of, e.g., the Community Spectro-Polarimetric Analysis Center at the High Altitude Observatory, as well as related efforts of the DKIST team to interpret chromospheric observations. In order to process the large quantities of data that ChroMag will produce, machine learning techniques and/or neural networks will be necessary to accelerate the inversion process (e.g., like the IRIS^2 system; Sainz Dalda et al. 2019). A more comprehensive discussion of the need for the development of spectro-polarimetric inversion tools and techniques for chromospheric and coronal diagnostics is presented in a white paper by (Reardon et al. 2022).

Complementarity and Broader Impacts

Instruments with capabilities like ChroMag are highly relevant to many open questions in heliophysics. Not only is ChroMag a key component of COSMO, but it is also highly complementary to other observatories, particularly those that observe at high spatial resolution but with much smaller fields-of-view such as the Goode Solar Telescope (Goode et al. 2010) and the Daniel K. Inouye Solar Telescope (DKIST; Rimmele et al. 2020). DKIST is the most advanced and largest high-resolution solar telescope today. ChroMag data will provide invaluable contextual information for DKIST. Since both instruments are located on the tops of Hawaiian islands, co-temporal observations are expected to be extremely common.

The success of GONG and SDO shows the immense value provided by synoptic instruments particularly if they provide nearly uninterrupted observations, i.e., “all the Sun, all the time.” It is therefore not surprising that both the proposed Solar Physics Research Integrated Network Group (SPRING) and the next-generation ground-based solar observing network (provisionally called ngGONG, see the white paper by Pevtsov et al. 2022) observatory networks include instruments with capabilities like ChroMag. One ChroMag at a single site will observe many filaments, prominences, ARs, flares, and CMEs. But it is not possible to track the evolution of these structures over periods of more than typically a few hours due to degradation of seeing conditions in the late morning to early afternoon, and consequently it will observe only a fraction of all eruptions (Hill and Newkirk 1985). A network of ChroMags such as proposed for SPRING and ngGONG would permit study of energy build-up over periods of days, and would hardly ever fail to observe a flare or CME. For a complete discussion of the science that would be enabled by a next-generation global observatory network, see the white paper by Pevtsov et al. (2022).

Summary

ChroMag is a key element of COSMO and critically important for its success. ChroMag is currently in the last stages of assembly and will be deployed to MLSO in 2023. It will provide the community with synoptic observations of magnetic field in the chromosphere that are currently unavailable yet critical to many outstanding questions about the processes that operate on both short and long timescales in the outer solar atmosphere. Interpretation of ChroMag data requires continued effort to improve spectropolarimetric tools and techniques so they can be applied with little to no supervision to the large volume of data that ChroMag will produce (see the white paper by Reardon et al. 2022). A network of ChroMag-like instruments that can observe the sun uninterrupted by night time or poor weather would produce an even richer data set and enable studies that would otherwise require spaceflight (see the white paper by Pevtsov et al. 2022).

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