The importance of ground-based observations of the solar corona

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Summary

The solar corona is a unique physical system that expands to fill interplanetary space providing a direct connection between the Sun and the space environment at Earth. The continual eruption of magnetic flux into the solar atmosphere creates stresses which give rise to various forms of solar activity and result in the global restructuring of the corona and heliosphere over the solar cycle. The highly conducting corona continually evolves as it processes solar magnetic fields into metastable states and eventually ejects them into the heliosphere as Coronal Mass Ejections (CMEs), which are the primary driver of major interplanetary disturbances at Earth. Understanding the processes responsible for the Sun’s continuous release of plasma and energy and their impact at Earth and throughout the heliosphere are primary goals of programs including the NSF National Space Weather Program and the NASA Living With a Star. To address these goals, The National Center for Atmospheric Research (NCAR) operates the Mauna Loa Solar Observatory (MLSO) containing a suite of instruments designed to provide the community with observations for studying both short- (minutes-hours) and long-term (years) changes on the Sun from the photosphere, through the chromosphere and into the corona. Among these instruments is the MK4 white light K-coronameter, which records images of the low corona (1.12 to 2.9 solar radii), as illustrated in Figure 1. The MK4 instituted improvements over the earlier MK3 K-coronameter which operated from 1980 to 1999, while utilizing the same telescope, and optical path of the MK3. A new state-of-the-art ground-based COSMO K-coronagraph has recently been designed that will significantly improve the ability to detect and measure coronal structures, such as CMEs, from the ground at a small fraction of the cost of its space-based counterparts. The new instrument will provide extremely high time cadence (15 seconds) and will provide new white light views into the very low corona (down to 1.05 solar radii) where most CMEs form. These observations will provide exciting and novel information of CME formation and propagation and enhance the value of existing and new observatories on the ground (e.g. SOLIS, ATST, COSMO, FASR) and in space (e.g. SDO, Hinode, STEREO, SOHO, Rhessi, and ACE).

The importance of low coronal observations

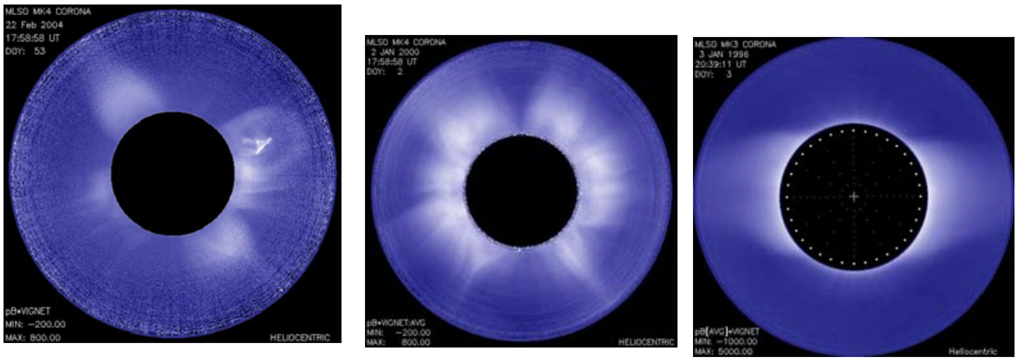

Figure 1. The corona recorded by the Mauna Loa K-coronameter. **Left:** An image of a CME taken on February 22, 2004 showing the classic 3-part structure (loop-caivity-prominence) of CMEs. **Center and Right:** These images show the evolution of the global corona over the 11-year solar cycle. The center image was taken during solar maximum on January 2, 2000 by the MK4 K-coronameter, the right image was acquired during solar minimum on January 3, 1996 by the MK3 K-coronameter.

Coronal activity is driven by the free energy contained in the twisted magnetic fields (the electric current systems) generated as the highly conducting plasma responds to the emergence of magnetic field and plasma from beneath the solar surface and to rotational and convective sub-photospheric motions. Strong flares are frequently associated with large, sudden releases of coronal plasma and magnetic field into the heliosphere, known as CMEs. CMEs are the primary drivers of major geomagnetic storms and may be an essential component of the solar dynamo by removing magnetic flux and helicity from the corona, thus aiding in the polarity reversal of the solar magnetic field every ~11 years (Low 1996). CMEs and other space weather events are driven by changes in the coronal magnetic field. White light observations do not provide direct detection of the magnetic field. Observations of the magnetic field are a critical component to understanding solar activity and are discussed in other papers (COSMO, ATST, FASR). However, heat conduction constrains the million degree coronal plasma to follow magnetic field lines so that the plasma acts as a tracer of the coronal magnetic field morphology. White light coronal observations record the plasma (density) structure and by inference, the magnetic topology of the corona (e.g. Ko et al. 2008) . CMEs can be unambiguously detected and tracked in white light. In fact, most of the basic properties of CMEs (e.g. location, width, speed, mass) have been determined from white light observations. Since the 1970s, space-based coronagraph observations from OSO-7, Skylab, SMM, SolWind, SOHO, and STEREO, have provided numerous discoveries about CMEs and the global structure of the corona. The Mauna Loa K-coronameters have provided valuable and complimentary imagery of the low corona in support of these and other space-based missions since 1980. Mauna Loa observations of the very low corona have contributed important information on CMEs including: 1) detection of intensity dimings (and thus density loss) in the corona due to the passage of a CME (Hansen et al. 1974); 2) determining that the largest CME acceleration occurs below 3 solar radii; 3) provide measurements of the initial CME acceleration that result in more accurate CME start times (MacQueen et al. 1985), 4) have shown that most CMEs form in the first coronal scale height (Harrison et al. 1990); 5) identified that bright new helmet streamers are the newly closed magnetic fields which were opened during a CME (Hiei et al. 1993). These observations have revealed that the forces responsible for CME production and propagation occur very low in the solar atmosphere. Our understanding of CME formation, their relation to other forms of solar activity and the manner in which they drive geomagnetic responses has dramatically improved. Many discoveries have been achieved through combined observations, of the inner and outer corona, chromosphere and photosphere. These discoveries have reinforced the need for white light observations, particularly in the region of the very low corona.

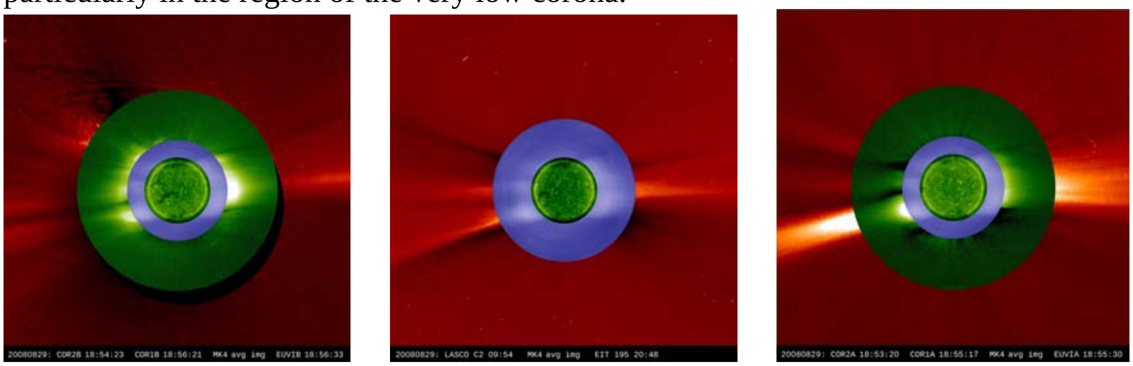

Figure 2. Composite images for the corona: Left: STEREO-B EUV (disk), MK4 (blue), COR1B (green) and COR2B (red). Center: EIT (disk), MK4 (blue) and LASCO C2 (red). Right: STEREO-A EUV(disk), MK4 (blue) COR1A (green) and COR2-A (red). MK4 provides unique observations of the very low corona that compliment space-based coronagraph fields-of-view.

The benefits of the new ground-based COSMO K-coronagraph

The Mauna Loa MK4 K-coronameter observes lower in the corona (1.12 solar radii) than any existing coronagraph. It furnishes unique observations of the density structure of the low corona used for studying features such as coronal mass ejections (CMEs), coronal cavities, helmet streamers, transient dimmings and polar plumes. Since 1980, MK3 and MK4 have observed over 1000 CMEs (examples are shown in Figs. 3 and 4) and have recorded density changes in the corona for over 3 solar cycles. This long-term record is unique and compliments the wider fields-of-view of space-based coronagraphs. MK3/4 observations have been combined with STEREO, Hinode, SOHO, SMM, SolWind, TRACE, and other space- and ground-based data to provide a more complete view of the corona and CME dynamics.

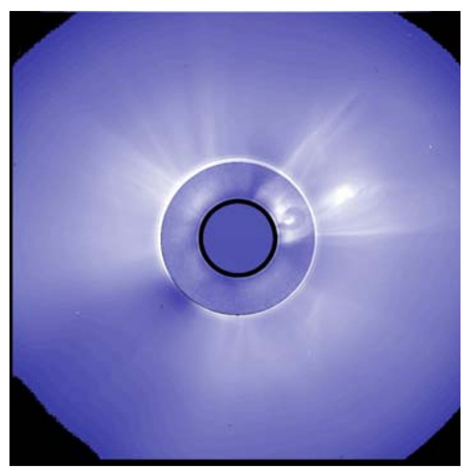

Figure 3. A CME observed on Aug 2, 2001 as seen in the low corona by MK4 and the outer corona by LASCO

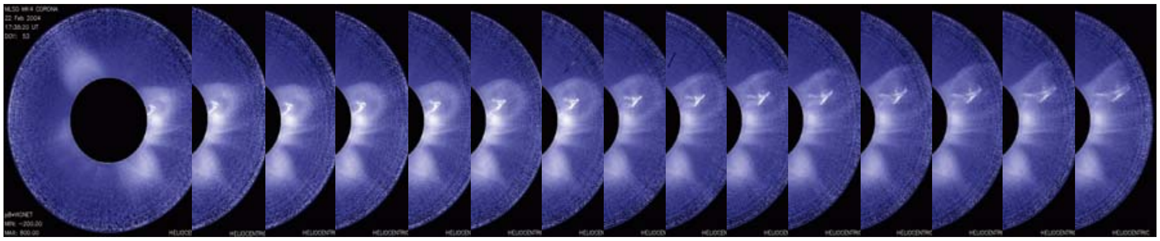

Figure 4. A sequence of MK4 images, taken every 3 minutes, on February 18, 2003 recording a CME, showing the propagation of the CME through the low corona.

The MK4 is an internally occulted coronagraph. Externally occulted coronagraphs are ideal for viewing farther out into the corona and provide lower scattered light than internally occulted instruments. However, externally occulted instruments are not able to view very low in the corona unless the occulter lies at extremely large distances from the image plane. Space-based missions, such as the European Space Agency Proba-3, are invoking formation flying with one spacecraft acting as the occulter and a second spacecraft acting as the detector to view low in the corona. Such missions should provide high quality low coronal images but at great expense and for limited mission lifetimes. The primary source of unwanted scattered light for an internally occulted coronagraph comes from solar light falling directly on the objective lens. At pristine ground-based coronal sites such as Mauna Loa, the scattered light from the objective is much greater than the background sky light levels. Under these conditions, the scattered light from a ground-based coronagraph is the same as the scattered light for an internally occculted space-based coronagraph. ***There is no scattered light advantage in viewing the low corona from a space-based internally occulted corongraph.*** State-of-the-art ground-based coronagraphs, such as the COSMO K-coronagraph, will provide as high a quality signal-to-noise images as a space-based instrument given the same detector.

The Mauna Loa MK4 includes a 1-D detector with 4.86” pixels and the MK3 scanning device which rotates 360 degrees in 3 minutes building up an image of the low corona in polarization brightness (pB). It was installed at MLSO in 1998 replacing the MK3 detector and some optical components still utilizing the MK3 telescope, scanning apparatus and optical path. Its performance was an improvement over the MK3 but is constrained by the Mk3 scanning and optical system technologies designed in the 1970s. Improved detector technology and methods for removing systematic noise allow for the development of an entirely new telescope that will provide significant improvements in instrument performance. The COSMO K-coronagraph will take full advantage of these improvements providing exciting opportunities for discovery. Full funding for design and fabrication has been provided by NCAR and will include a 2-D high speed detector and a substantially better objective lens and hepa filter system for keeping the objective lens clean, which is the key to minimizing unwanted scattered light. The COSMO K-coronagraph will acquire images every 15 seconds over a field-of-view from 1.05 to 3 solar radii. It will provide the high-time cadence measurements needed to determine the rate of change of CME acceleration and lead to a better understanding of the forces driving CMEs that are needed to differentiate between the many competing models of

CME formation. A 15 second time cadence makes it possible to detect fast mode MHD coronal waves (as observed with EIT and STEREO EUVI) above the solar limb. It also provides better detection of precursor changes of CMEs that can lead to better prediction of CME onsets. The improved signal-to-noise (factor of 10 over MK4) can also provide observations of many halo CMEs from the ground. Currently MK4 is only able to detect the denser regions of the brighter halo events. Better signal will also provide significantly better density measurements in coronal holes, which is important for the study of solar wind acceleration and coronal heating and in identifying changes in the density structure preceeding the formation of a CME. The lower FOV will provide the first routine white light measurements into the 1st scale height of the corona for viewing CMEs as they form. The COSMO K-Coronagraph has other advantages over the MK4 including: many fewer moving parts, making it more robust and easier to maintain, improved calibration hardware and uniform spatial resolution. The new coronagraph is approximately the same size as the current MK4 and can fit on the existing spar at Mauna Loa, so additional costs for infrastructure are minimal.

Ground-based is cost effective

The COSMO K-Coronagraph has been fully funded by NCAR for $2.2 million, a small fraction of the cost of similar space-based telescopes. Some of the many advantages of ground-based observing include:

1) Instrumentation can be upgraded for very modest investments

2) Operating and maintaining ground-based operations are significantly lower than space-based platforms.

3) Facilities can be maintained for decades, providing a continual record of observations needed to understand changes occurring over solar cycle time periods

4) Telemetry costs are significantly cheaper than space-based, providing high time cadence data at a fraction of the cost of space-platforms.

One of the obvious advantages of space-based platforms are high duty cycles. However, ground-based networks, such as GONG, are able to deliver high duty cycles. An international network of low cost K-coronagraphs could provide nearly continuous observations of the low corona for space weather studies and forecasting, enhancing observations from space-based coronagraphs and other instrumentation.

Additional information about the COSMO K-coronagraph can be found at: http://mlso.hao.ucar.edu/mlso_newcoronagraph.html

Agency support for ground based observations

Agencies can enhance the benefits of ground-based observations through support of ground-based networks and new instrumentation, encouraging new instrument scientists, and support for research that includes ground-based observations.

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