Heliophysics Decadal Survey Mission Concept Study

Pre-Study Report

Coronal Microscale Observatory (CMO)

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1 Science

1.1 Targeted Knowledge Gaps

Why the Sun has a tenuous upper atmosphere some 1000 times hotter than the photosphere is a fundamental open problem in space plasma physics despite decades of study. Observations by soft x-ray and extreme ultraviolet (EUV) imagers, which remotely sense spectral lines emitted from highly ionized coronal elements, have provided important clues regarding the nature of the heating. However, current instrumentation cannot resolve the structure of the heated regions, and the heating mechanisms remain unknown. The primary hypothesis is that, in most of the corona, heating is confined to narrow current sheets in which energy is dissipated despite the low resistivity of the coronal plasma. The characteristic width of these current sheets is estimated to be on the order of 100 km (Peter et al. 2013, Klimchuk 2015). We shall call time-variable energy releases on these scales *primary heating events*, which include both reconnection events and wave heating. Observing the heating substructure will prove to be key in testing reconnection and wave heating theories as they are refined in response to new data. Thus, **the first knowledge gap to be filled is direct observational knowledge of primary heating events on spatial scales significantly smaller than 100 km**.

The consensus view on the solar wind is that there are many types of solar wind that exhibit different plasma characteristics—e.g., plasma density, elemental composition, velocity, temperature, variability, and mesoscale structures—that encode how those types of solar wind were likely formed. Different types of solar wind result from the time-history of solar wind formation (Viall and Borovsky 2020), how it was heated in the low corona, how it was released into the heliosphere, and how it continues to be accelerated and heated through the middle and high corona. Thus, **the second targeted knowledge gap is the formation of the solar wind and the resulting mesoscale solar wind structures**.

The third, more narrowly targeted knowledge gap is the relationship of primary heating events, singly or collectively, to the formation of solar wind in specific environments, particularly active regions, quiet Sun, and coronal hole boundaries. The answers to the objectives addressed by CMO involve the fundamental physics of turbulence, waves, and magnetic reconnection, and how they occur in the unique solar environment. This has implications for stellar environments, Sun-Earth interactions, and how the Sun forms the heliosphere.

It has been fifty years since Parker (1972) proposed the inevitability of current sheets in the corona and their centrality to coronal heating in active regions. Since then, theory, simulations, and space-based observations have advanced dramatically; but theory has still not directly confronted observation—we have not seen “inside the machine.” We must break that barrier to move the field of coronal heating definitively forward (Rabin et al. 2021). At the same time, as emphasized in Heliophysics 2050 white papers by Klimchuk et al. (2021), Viall et al. (2021), and others, major advances in understanding the Sun-heliosphere system depend on linking fine-scale observations and modeling to mesoscale and large-scale counterparts. Thus, the Coronal

Microscale Observatory includes a coronagraphic instrument that, in combination with other space-based assets, will forge that connection for the solar corona.

1.2 Science Goals and Objectives

The following goals and objectives are condensed from the CMO Science Traceability Matrix.

1.2.1 Goals

Goal 1. What are the basic properties of primary heating events in the solar corona?
Goal 2. What is the role of primary heating events in the formation of the solar wind?

1.2.2 Objectives

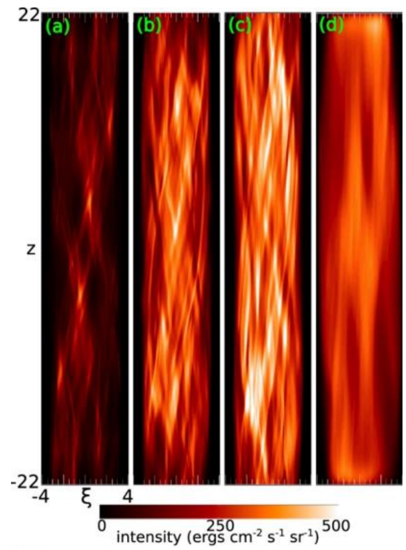

Fig. 1 Simulation of Fe XII emission from reconnection in braided magnetic loops (Pontin et al. 2017). (a)-(d) are times 44, 61, 78 and 309 s.

Goal 1

- Directly measure the spatial and temporal properties of coronal heating.
  - Determine the magnitudes, durations, and frequencies of nanoflares. Under what circumstances is coronal heating quasi-uniform and quasi-steady versus patchy and impulsive?
  - Distinguish drifting heating (resonant absorption of waves) from spreading heating (reconnection, as illustrated in Fig. 1).
  - Determine the basic nature of reconnection in different magnetic environments (plasmoids vs. turbulence).
- Directly measure the sizes, shapes, and evolution of the elementary magnetic structures that make up the corona.
  - Understand how these structures interact to produce nanoflares and how the structures are in turn modified and rearranged by the nanoflare reconnection.
  - Measure the conditions that result in clustering of nanoflares that produce bright coronal loops.
- Directly observe the substructures that make up flares.
  - Determine the prevalence and size distribution of reconnection plasmoids.
  - Determine similarities and differences among events spanning many orders of magnitude, from flares to nanoflares.
  - Determine the dependencies on magnetic geometry (reconnection in eruptive flares vs. confined flares).

Goal 2

- Determine how much solar wind originates from different source regions on the Sun, particularly from active regions, quiet Sun, and coronal hole boundaries.
  - Track flow streams from their source in the low corona through the middle corona (~1.05–3 Rs).
- Determine the relationship between the microphysics of coronal heating and the mesoscale physics of solar wind formation.
  - Measure the kinetic and thermal energy of individual streams of solar wind and relate them to the collective behavior of coronal heating in the source location.

2 Mission Concept

2.1 Mission Architecture

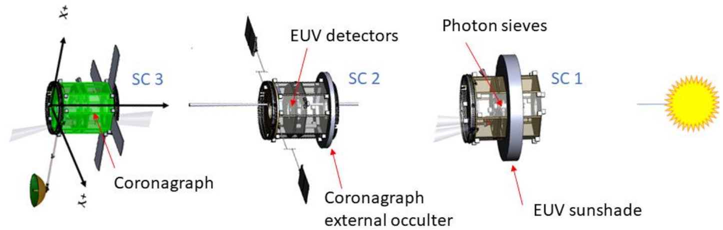

Fig. 2. Schematic illustration of the Coronal Microscale Observatory.

As illustrated in Fig. 2, CMO comprises three spacecraft (SC) flying in precise formation. SC1 and SC3 are separated by about 200 m, with SC2 about midway between them. SC1 and SC2 form a distributed multiband EUV telescope of focal length 100 m. SC2 and SC3 form an externally and internally occulted multiband, full-disk coronagraph. SC1 carries 6 photon sieves (Kipp et al. 2001), each 17 cm in diameter, which produce diffraction-limited EUV images on 6 photon-resolving CMOS array sensors on SC2. A single photon sieve EUV imager is expected to fly on the NSF VISORS mission in 2024. A sunshade on SC1 excludes disk and coronal light outside the field of view from the EUV telescope apertures. SC2 carries a precision disk occulter for the coronagraph optics. The two-spacecraft coronagraph is conceptually similar to the ESA PROBA-3 ASPIICS coronagraph (LRD 2023, Etienne et al. 2015) but has higher angular resolution and greater diagnostic power.

The three spacecraft maintain a precise formation to keep the EUV field of view stable and the coronagraph external occulter centered on the Sun. The challenging but attainable requirements on knowledge of inter-spacecraft separation (±15 mm) and transverse alignment ((±0.5 mm) are met with a precision 3D laser ranger and astrometric alignment system; however, the requirements on attitude control of the individual spacecraft are not unusual ((±5 arcsec). Liquid ionic thrusters provide fine control of the formation.

CMO will be located in a large-amplitude quasi-halo orbit around the Sun-Earth L1 point. The L1 location enables provides an uninterrupted view of the Sun and a low gravity-gradient environment that enables CMO to maintain formation for at least 5 years. CMO can be launched by several existing vehicles (including Falcon 9) and is compatible with the ESPA ring payload adapter.

2.2 Mission Measurements

The notional payload has been briefly described above.

2.2.1 EUV Imaging Requirements

- Spatial resolution of 40 km (0.06 arcsec) or better
- Temperature coverage from 0.2 MK to 10 MK
- Cadence 5 s or faster (0.1 s in flare mode)
- Field of view (FOV) at least 20000 km (30 arcsec) across
- Ability to center the FOV anywhere on the EUV Sun (to 1.2 Rs).

Ion	Wavelength (Å)	Temperature (MK)	Diffraction Limit (mas)
Fe XIX	108.4	8 – 10	16
Fe XVIII	93.93	4 – 11	14
Fe XV	284.2	1.6 – 4	42
Fe IX	171.1	0.4 – 1.4	25
Ne VII	465.2	0.3 – 0.8	69
He II	303.8	0.05 – 2	45

Table 1. CMO carries 6 EUV imagers with broad temperature coverage. 1 mas = 0.001 arcsec.

The proposed 6-band instrument meets or exceeds these requirements (Table 1). The field of view is expected to be at least 42 arcsec across.

2.2.2 Coronagraph Requirements

- Measure electron density, temperature, and radial flow speed
- Radial coverage 1.05–3 Rs
- Cadence 10 s
- Uninterrupted cadence for 16 hr or longer
- Angular resolution 3 arcsec

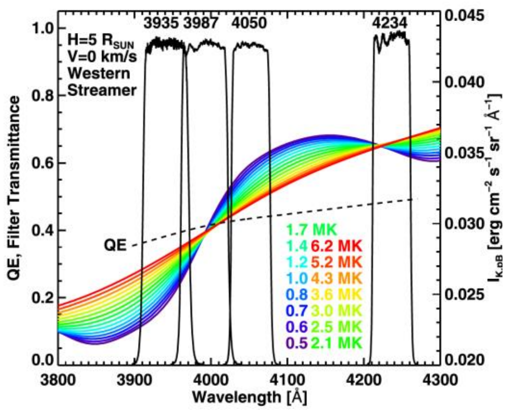

Fig. 3. The four-band coronagraph uses flux ratios between four carefully chosen filter passbands to measure temperature and radial flow speed as well as electron density (Cram 1976; Gopalswamy et al. 2021).

The proposed 4-band instrument meets or exceeds these requirements. It builds on the PROBA-3 coronagraph by increasing the angular resolution (important for elucidating coronal mesoscale structure) and incorporating the additional diagnostic capabilities of the balloon-borne BITSE coronagraph (Gopalswamy 2021).

3 Mission Cost

A preliminary cost analysis has been carried out by the NASA/GSFC Cost Estimation, Modeling and Analysis (CEMA) Office and the Mission Design Lab (MDL) team. The inputs to the estimate include instrument space, weight, and power requirements, a master equipment list developed during a one-week MDL study of the three CMO spacecraft, and mission operation requirements. Additional costs were estimated for field programmable gate array development, flight software and software test bed, flight spares and engineering test units, ground support equipment, and environmental testing. CEMA estimates the total NASA Phase A-E cost, including 30% reserves but excluding launch services, at $1.3B (70% confidence level) in FY27$.

4 References

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