Observing Coronal Microscales

Douglas Rabin, Adrian Daw, Kevin Denis, James Klimchuk (NASA Goddard Space Flight Center); Farzad Kamalabadi (University of Illinois Urbana-Champaign); Donald Schmit (Laboratory for Atmospheric and Space Physics, University of Colorado Boulder)

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This white paper calls attention to a new approach to observing, for the first time, individual energy-release sites in the solar corona to test theories of coronal heating. Because it addresses novel technology, this paper complements current white papers that discuss coronal heating in a broader theoretical and modeling context, such as “Heating of the Magnetically Closed Corona” by Klimchuk et al. (2020), and earlier white papers such as “RAM: The Reconnection and Microscale Mission” by Golub et al. (2013). We adhere to the spirit of Heliophysics 2050 in that we do not advocate particular missions. Rather, the focus is on a progression of science-driven technology advancements leading to the capability to study in detail small-scale structure that figures in almost all contemporary theories of coronal heating.

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, but the structure of the heated regions remains cloaked, 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 large-scale resistivity of the coronal plasma. The characteristic scale of these current sheets is estimated to be on the order of 100 km (Peter et al. 2013, Klimchuk 2015). If the history of solar observations is any guide, further substructure will prove to be key in testing theories as they are refined in response to new data.

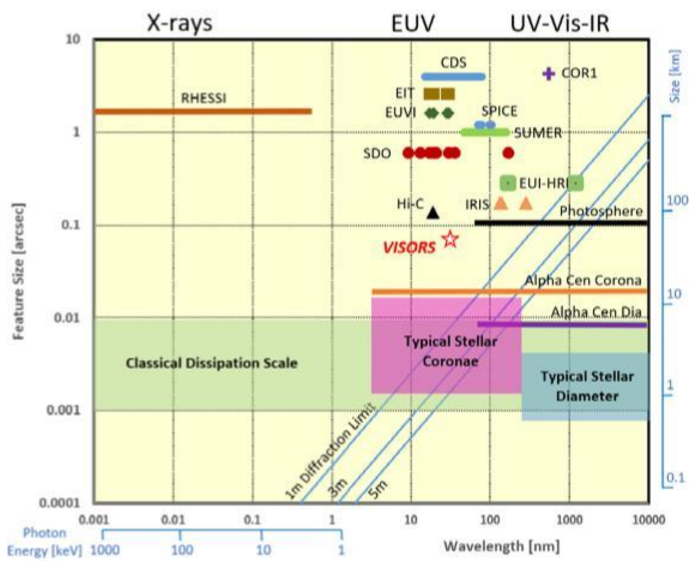

Fig. 1. Angular resolution versus wavelength with the diffraction limit indicated for representative apertures. Pixel sizes for many existing solar space instruments are shown. A more complete diagram would show ground-based capabilities at visible-infrared wavelengths using adaptive optics.

Figure 1 places the angular resolution challenge in broader perspective. Extreme ultraviolet (EUV) observations are heavily represented for two reasons: the rich EUV spectrum of high-temperature lines (5-10 MK) reveals impulsive heating events; and the diffraction limit varies as $1/\lambda$.

Conventional EUV telescopes based on mirror optics fail by an order of magnitude to reach the diffraction limit because their mirrors cannot be figured to the requisite accuracy (~λ/12). Even as figuring technology improves, EUV reflective optics are not naturally scalable; they become increasingly challenging as the aperture grows. Diffraction-limited EUV telescope mirrors are expected to remain infeasible or prohibitively expensive for the foreseeable future.

Diffractive optics (DO), including Fresnel zone plates and photon sieves (Attwood and Sakdinawat 2017; Kipp et al. 2001), are a scalable and relatively low-cost approach to ultrahigh angular resolution EUV and x-ray imaging. The primary advantages of DO are that they are thin, light, flat and obtain nearly diffraction-limited EUV images with greatly relaxed surface accuracy, ~1 μm as opposed to 1–10 nm for mirror optics. The primary disadvantage of DO is that they have a long focal length (varying as 1/λ) which is characteristically in the range 50–500 m for solar applications. This requires a distributed formation-flying telescope comprising an optics spacecraft and a detector spacecraft; but these can be CubeSats or smallsats. Another potential disadvantage of DO is that they are intrinsically monochromatic. With careful design, however, this characteristic can be used to advantage in combination with focus scans to measure Doppler motions or deconvolve closely spaced spectral lines (Oktem, Kamalabadi, and Davila 2014).

The long-term scientific objective of a diffractive optics development path is the ability to resolve coronal structures ≲10 km across and thereby study in detail structures 30–100 km in size. Also, although this paper focuses on observational tests of ubiquitous (nanoflare or wave) coronal heating, diffractive imaging is equally capable of revealing the small-scale structure of larger impulsive events classified as flares.

Diffractive optics can be used to achieve other astrophysical objectives (Skinner et al. 2004). The VTXO (Virtual Telescope for X-ray Observations) CubeSat mission concept completed a NASA Astrophysics feasibility study in 2019 (Krizmanic 2020).

Table 1 presents a potential development path for coronal microscale imaging and spectroscopy via diffractive optics. Phase 1 is underway as the NSF-funded VISORS (Virtual Super-resolution Optics with Reconfigurable Swarms) CubeSat mission expected to launch in 2023 or 2024. All subsequent "mission" characteristics are merely notional characteristics that are consistent with

Table 1. Development Path of Coronal Microscale Imaging via Diffractive Optics

Phase	Milestones	Resolution (mas)	DO Efficiency	Notional Mission Characteristics	Year
1	• Science proof of concept	150	10%	6U CubeSats; binary amplitude DO; LEO	2024
2	• High (>5 MK) and low (~1 MK) temperature sensitivity	50	25	12U CubeSats; binary phase DO; LEO or high-apogee orbit	2030
3	• Reach coronal resolution objective • Multi-temperature sensitivity • Doppler shifts	10	45	Smallsats; step-phase DO; high-apogee orbit or L1	2040
4	• Part of observatory-class payload • Multi-line imaging spectroscopy • Solar and non-solar targets	1	80	Midsats; continuous-phase DO; L1	2050

Notes: 1. Phase 1 is underway as the NSF-funded VISORS mission.
2. When more than one spectral line is imaged, listed resolution is the highest among them.
3. 1 mas = 0.001 arcsec; DO = diffractive optic

the listed milestones. The milestones are driven by a series of increasingly ambitious, science-driven objectives:

- Discern coronal features as small as ~150 km with high confidence.
- Detect transient high-temperature (5–10 MK) plasma on scales as small as 75 km.
- Reach the long-term coronal science objective of resolving and studying 30–100 km structures with multi-temperature sensitivity and the ability to measure Doppler motions, enabling detailed tests of competing theories.
- By 2050, offer milliarcsecond imaging spectroscopy as an established tool for observatory-class missions to study solar and stellar coronae and other astrophysical objects.

The technological challenges associated with the scientific development path in Table 1 fall naturally into two groups, diffractive optics and formation flying. The DO requirements for Phase 2 are expected to be satisfied in 2022 at TRL 5 using a photon sieve 170 mm in diameter. This "binary phase" device will achieve an efficiency >25% by introducing a $\lambda/2$ phase shift into alternate Fresnel zones instead of blocking them as in a classical Fresnel zone plate (a well-established technique for x-ray zone plates). Kinoform phase shifting will lift the DO efficiency to 45–50% by Phase 3.

The formation flying requirements associated with the DO imaging development path are well studied and feasible but not flight-validated. For that reason, the launches of the ESA Proba-3 mission (currently projected for mid-2022) and the VISORS mission by 2024 will be important for placing distributed telescopes (visible-light coronagraphs as well as EUV/x-ray imagers) on a firm technological footing.

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