Imaging the innermost solar corona

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Apertures with nonuniform transmission properties can almost fully remove the usual diffraction rings and are therefore ideally suited to observe the Sun’s upper atmosphere.

The nonthermal heating processes that dominate the solar corona (featuring a temperature of \( \sim 1 \) million degrees Kelvin compared with 6000 \( ^\circ \)K at the visible surface below) are still not fully understood. Improved understanding of this regime is crucial for better insights into how solar activity (see Figure 1) affects Earth and its environment. Since the Sun’s upper atmosphere is about 1 million times fainter than the solar disk, the inner corona remains unobservable in the optical with today’s telescopes, except for brief moments during a total eclipse.

Diffraction by the solar disk at the focus of a conventional telescope produces a halo 100 times brighter than the corona. A Lyot coronagraph, invented in the 1930s, can remove this diffuse light using an elaborate experiment that combines two masks, one in the focal plane and the other applied to an image of the aperture. Unfortunately, this cannot be used for observations very close to the solar limb. A space occulter flying in formation with a spaceborne coronagraph can recreate the conditions of natural eclipses and may therefore be a better solution. But unless extremely large devices are developed, they barely approach the innermost corona.

Instead, we propose to use an aperture characterized by variable transmission to strongly reduce the diffraction ‘feet’ of the telescope response, thus yielding a negligible halo (see Figure 2). This is referred to as apodization, a classical optical technique already described in detail half a century ago\(^1\) and topical today in the context of exoplanet detection. Constraints for the Sun are quite different from those for exoplanets, however, because of the Sun’s enormous angular size. Beam shaping\(^2\) cannot be used here, and the prolate spheroidal functions of Aime\(^3\) are no longer the most suitable telescope-transmission equations.

The apodized solar coronagraph must be a refractor or an off-axis reflector. For the sake of image quality the first optical surface must perform the apodization. A prototype of such a window is being developed at the Observatoire de la Côte d’Azur in France. It is constructed by depositing reflective particles in a vacuum chamber. The apodizing window will keep the entire image, encompassing the solar disk and the corona, in the telescope’s focal plane, allowing observations of the transition zones between photosphere, chromosphere (a thin layer at higher altitudes), and corona.

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We initially suggested the use of prolate spheroidal functions as variable-transmission descriptors, mainly because these functions are the best apodizers in terms of energy concentration and because they are also used for exoplanet detection. Although this is the best solution for exoplanets, it is no longer appropriate for the Sun. We have not carried out an exhaustive analysis of all possible transmission equations but a simple Sonine function (see Figure 3) of the form \((1 - r^2)^\nu\) for the amplitude, where \(r\) is the distance from the center of the aperture and \(\nu = 1\) gives better results than more complex prolate spheroidal functions. Ideally, the transmission must decrease as smoothly as possible from unity at the aperture center to zero at the edge.

The apodized telescope would allow access to the entire chromospheric emission spectrum, which is as yet poorly understood. This will enable comprehensive studies of magnetic fields and wave propagation through the photosphere to the corona. The extremely low-altitude corona observed at visible or infrared wavelengths is the only part of this regime where magnetic fields can be measured precisely while simultaneously observing waves. Such measurements will provide clues for a better understanding of the physics and heating of the chromosphere and corona. They could also be very useful for studies of the recently discovered chromospheric jets, which are likely to play a role in heating those media and accelerating particles.

Observations of the solar corona down to its innermost regions will help us understand the heating of the Sun’s upper atmosphere. This will represent an important step toward forecasting space weather. Developing a suitable window of adequate transmission and free of diffusion will be a technological challenge. To demonstrate the potential of this technique, we are designing prototypes using metallic evaporation. We expect to test their quality in the near future.

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**References**