Imaging Coronal Fine Structure Without an Eclipse

By Jim Daley

INTRODUCTION

Viewing the solar corona during a total eclipse is one of the most wondrous of human experiences. Recently two amateurs (Hripcsak 2023) have demonstrated that certain features of the inner corona can be observed under reasonably clear skies without an eclipse, even at sea level.

The familiar solar prominences are only about 100 times fainter than the Sun's limb over a 10 angstrom bandwidth and can be observed fairly well in small commercial solar telescopes. These instruments employ ultra-narrow (sub-angstrom) hydrogen-alpha filters and show the prominences somewhat more faintly than the Sun's surface features.

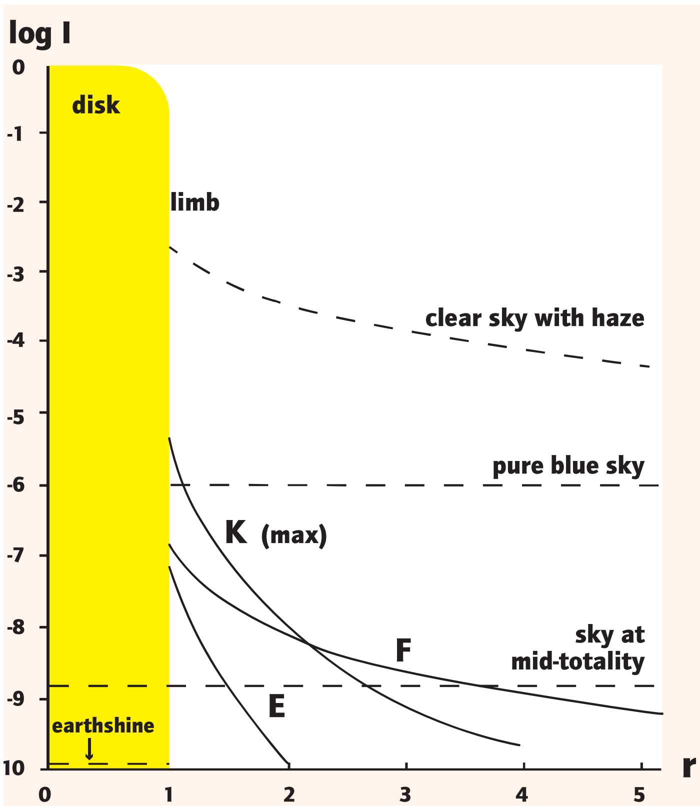

Fig. 1: relative intensities of the components of coronal light, K=continuous light due to electron scattering, F=inner zodiacal light, and E=combined light of emission lines. Graph redrawn by Reflector staff after H. C. van de Hulst in the book The Sun*, edited by Kuiper, 1953.*

Although prominences strongly interact with the corona they are not thought of as coronal structures, as their temperature is far too low. Fig. 1 (Kuiper 1953) shows the huge range of brightness, relative to the Sun, that one must work over to detect the K (continuum), F (Fraunhofer), and E (emission) corona. Despite appearing faintest on the chart, the E corona is the only one accessible to the amateur astronomer without an eclipse. This is because it is plotted there as the combined light of its widely spaced emission lines, with the total flux spread evenly over the entire visible region. However, when seen in isolation, the brightest lines often reach an intensity as high as 2×10^{-4} on the plot. At that intensity level, about 160 times fainter than the Hα prominences, they can be observed under a sky midway between hazy and a pure blue, in my experience.

All we need to isolate one of the brightest lines is a narrow band interference filter, a Lyot type coronagraphic telescope (see Daley 2023) and a nice blue sky. It sounds easy but in reality it represents perhaps the greatest challenge any amateur astronomer/telescope maker will ever encounter.

THE E CORONA SPECTRAL LINES

Called "coronium" before W. Grotrian discovered its true nature (Swings 1945), the E corona is made up of hundreds of mostly identified emission-lines, yet there are only about 15 lines in the visual light spectral region. Among these lines just the green 5303Å (Fe XIV) and the red 6374Å (Fe X) lines have sufficient brightness to be considered for imaging without an eclipse. These iron lines show noticeably different coronal forms, the 5303 line appearing somewhat "bushy" with soft loops and the 6374 line showing a well defined "loopy" and streamer/spray structure, especially when seen over big sunspots. 5303 is generally twice as bright as the 6374 line. Currently my coronal observations are limited to the 6374 red line. The atmospheric scatter at the red line is about half that of the green line, which goes a long way toward washing out their brightness difference. My backyard observatory, housing a homemade 5-inch coronagraph, is located at an elevation of only 1,300 feet, so atmospheric light scatter is potentially very troublesome.

SKY CONDITIONS

Sky quality sets the conditions for a modest success or utter failure in our quest to image the E corona in the light of either of the above spectral lines. This is because the sky's light near the Sun is strongly scattered by atmospheric particles (aerosols) such as ice crystals, dust, pollen, forest fire smoke, and airborne seeds such as dandelion, cat o'nine-tails and milkweed. In various proportions these countless airborne particles cause an aureole of brilliant light around the Sun. The phenomenon giving rise to this halo is called narrow angle forward scatter (Minnaert 1954). This scatter is most intense at the Sun's limb, just where we want to observe, and can raise the field glow in the focal plane well above the coronal light itself. Tiny ice crystals are by far the worst offenders, with a scatter angle so narrow that it concentrates the glow in a region just a few arcminutes wide against the limb! The few remaining professional coronagraphs are located on high mountaintops to get above most of the atmospheric particles.

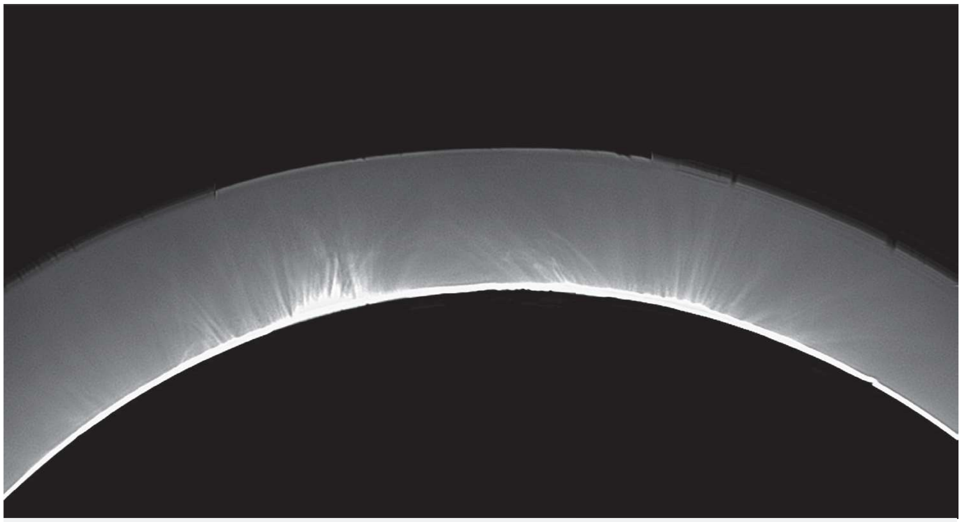

Fig. 2: fine coronal structure, captured April 25, 2024.

OPTICAL SETUP FOR IMAGING THE Fe X CORONA

After a year-long period of imaging solar prominences in Hα light with my homemade 5-inch Lyot coronagraph, (Daley 2023 — here you can find details on the instrument's construction), fellow club member Dave Groski suggested that I should should try to image the corona. After much thought about our local sky conditions, I decided an attempt at imaging the inner corona in Fe X light would be an interesting technical challenge and a chance to resolve the fine structure of coronal loop foot-points and other features. I thought an interference filter of 3Å bandwidth (full width at half maximum) would be about right, considering this (temperature broadened) coronal line is just under 1Å wide. A narrower filter would significantly raise the price, greatly lower transmission, and also introduce thermal stability issues, requiring a high priced temperature controller. As it is, a simple homemade flowing-water-jacketed "oven" keeps the filter close to its factory measured operating temperature of 24ºC. Given the filter's thermal coefficient of 0.18Å per degree C, a comfortable ±2ºC water temperature match seemed fine, and this has turned out to be the case. The filter, supplied by Rapid Spectral Solutions of Brattleboro, Vermont, has good optical quality in terms of wavefront error, allowing its placement near the pupil (just after the Lyot stop). It was supplied mounted in a standard 1.250-inch threaded eyepiece filter ring with a clear aperture of almost 1 inch, more than large enough to pass the 0.625-inch diameter pupil beam. The filter's transmission is a really good 57%, important for imaging success.

My first Fe X image of the corona (I am given to understand this is an amateur first for that spectral line) was obtained September 7, 2023. It was seen in the running video display as a small bump on the Sun's East limb, the limb itself just hidden behind the occulter. To test for its reality I simply moved the coronagraph in declination and observed the bump move with respect to the occulter. I quickly captured and processed a video. With many instrumental improvements, better and better coronal images were obtained. A comparison of PROBA2/SWAP 174Å Fe X extreme ultraviolet (EUV) images with my red Fe X images showed good position and structural correspondence (Habbal et al. 2011).

One big improvement to the instrument was the elimination of interference fringes created by my ZWO 1600MM CMOS camera, by tilting it 6º.

Another improvement was made by removing the detector window, avoiding shadows its imperfections cast on the sensor surface. This also allowed cleaning the chip's glued-on protective glass plate to get rid of most of the tiny dust specks and other particles. I also made a much longer camera barrel (1.25 inch) with an infrared blocker at the far end, which not only seals the detector against dust but also serves as the last window of the filter oven.

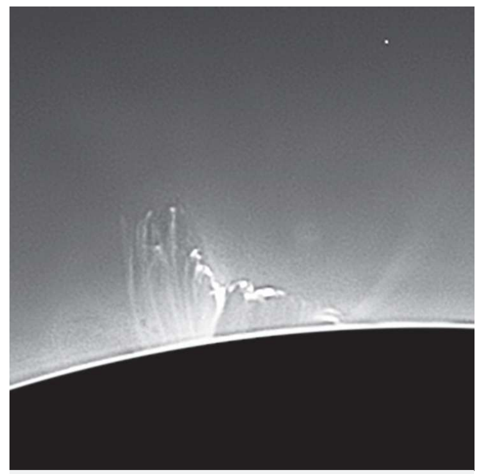

Fig. 4: This image, captured May 13, 2024, shows very fine structural detail over AR 6334, which is the region that gave us the great aurora of May 11.

It is vital that no optical element be near or imaged on the detector surface. Even the field lens showed very unpleasant defocused dust and smudges, as it is only 3/4 inch behind the in-focus occulter. To wash out these artifacts in the stacked image I adopted Lyot's method of continuously rotating the field lens on its optical axis during a (nowadays) video capture. The lens rotation speed is about 6 RPM.

An additional improvement in reduc-

Fig. 3: fine coronal structure, captured April 26, 2024. There are a few abrupt bends seen in the otherwise smoothly flowing streamers.

ing instrumental stray light was made by abandoning the traditional reflecting cone occulter. Instead I used a water cooled flat copper disk occulter painted with Black 4.0 *(culturehustle.com)* on the skyward face. This, combined with the comparatively steep curves of my coma-corrected fused silica f/18 objective, gives optically weakening (diverging) reflections of the occulter. This brightens the objective slightly but harmlessly. Adding a Lyot spot would block two of three reflections – one ghost of the occulter at 1/5th focal length and one double bounce image of the Sun called the 1/6th ghost – but the calculated focal plane irradiance resulting from this form of occulter without a Lyot spot is already well below that of the Fe X corona itself over the system's spectral bandwidth.

LUCKY IMAGING DILEMMA

For my setup, video single frame exposures run about 166 times longer than the typical 1 ms I use for prominence imaging. This makes the frame rate way too low and the exposures hopelessly long for freezing atmospheric turbulence, which is needed to use lucky imaging techniques. By binning 4× the exposure is reasonable (about 50 ms) but the resolution is only fairly good, just 2 pixels per Airy disk diameter. Typically, 300 frames can be captured with a 10-second-duration video. Ongoing experiments in optimizing the detector gain are promising, and perhaps may lead to 2× binning.

RECENT RESULTS

The two west limb images, Fig. 2, April 25, and Fig. 3, April 26, taken 23:32 hours apart, show interesting coronal changes and good fine structure detail including a few abrupt bends in the otherwise smooth flowing lines of the streamers in fig. 3. The exposures are 44.9 ms and 40.8 ms, respectively, with video durations of 10 seconds each. ✷

James Daley is the author of The Schupmann Telescope *(Willman Bell, 2007) and is a member of the Springfield Telescope Makers.*

The coronal images in this article were further processed by Reflector *staff, and some dust spot artifacts were retouched out. They are © 2024, James Daley.*

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