

MY LAST CORONAGRAPH

by James Daley

Like so many amateur telescope makers, I got my start by making a Newtonian while in high school. With a mirror grinding kit from E&W Optics, I ground and polished a 6-inch plate glass primary mirror, built a tube, and began viewing the Moon and stars. I was smitten. My life's work in optics, both professionally and as an amateur, was cast.

I became interested in the solar coronagraph in 1963 after reading an article in the February 1963 issue of *Applied Optics*, titled "Reduction of Scattered Light in the Coronagraph," by Gordon Newkirk Jr. and David Bohlin. I knew then that I must build one. I ground and polished a 3.4-inch fused silica objective lens and soldered up some brass tubing with O-ring flanges to make what may have been the world's first evacuated coronagraph. Since then I've made three more coronagraphs, each one an improvement on the last. This story describes the culmination of my coronagraph efforts, along with some observing techniques.



The author's first coronagraph

HISTORY

In the late 1870s, solar astronomers pondered the possibility of observing the corona without an eclipse. Early attempts, starting in 1878, continued for 52 years without success. Despite the efforts of many notable astronomers, none succeeded in observing the corona in full daylight. Astronomers knew from eclipse observations that coronal light was polarized. Using a Savart polariscope, R. W. Wood made



The current coronagraph, in Jim Daley's Ludwig Schuppan Observatory, in New Ipswich, New Hampshire.

a failed attempt to detect this intrinsically strong polarization. Professor H. O. Barnard urged Bernard Lyot to continue Wood's quest based on Lyot's success measuring planetary polarization with a very sensitive polarimeter of his own design. Lyot realized that scattered light from the telescope optics would overwhelm the light of the corona even in the clearest skies of high-altitude mountain sites. He set out first to measure the sources of scattered light from a single-element crown glass objective lens of 80 mm aperture and then, based on his findings, designed an entirely new and elegant optical system that produces an artificial eclipse.

In the spring of 1930, Lyot, using lumber lying about the Pic du Midi Observatory, built the world's first coronagraph. He reduced the above-mentioned objective's aperture to 30 mm and, on July 25th of that year, observed prominences without a filter! He did find that a red glass filter substantially improved the contrast. Using his polarimeter he detected the inner corona. On July 30, Lyot used a simple spectroscope and observed the 5,303-angstrom iron line in the inner corona.

On June 12, 1931, a new and improved coronagraph of 130 mm aperture was installed and further spectroscopic work was done. Lyot's final coronagraph, built in 1935, was a 200 mm beauty. His images of the inner corona at many wavelengths remain among the

best photos extant. I was born a year later.

The Lyot coronagraph makes it possible to view and image the Sun's most beautiful features: the prominences. Standing on or sometimes well proud of the Sun's limb, these magnificent objects often reach heights of hundreds of thousands of kilometers. They occur in every imaginable structural form, some stable, some erupting, some collapsing, giving astronomers, particularly astrophysicists, a classification dilemma. Thankfully there exist varied but useful morphological classification schemes tailored to both the amateur and professional astronomer.

Prominences are observable almost every clear day and their antics delight the keen observer. During my amateur telescope making years I've had long experience building and using coronagraphs, yet every observation brings a feeling of wonder. These ethereal objects, to me, are simply amazing.

ATMOSPHERIC CONDITIONS

Observing prominences makes one very aware of the daytime sky quality. A sky suitable for imaging the corona itself is blue right up to the Sun's limb. These are the rare days, usually after a storm clears the atmosphere of particles, when it is possible to view or image the inner corona in the iron green line (Fe XIV) at 5,303 angstroms. The prominences are much brighter and perfect skies are not need-

ed to easily view them in the red emission line of hydrogen at 6,563 angstroms. This line, named H-alpha, is the first of the hydrogen Balmer series of lines which extend into the deep violet.

The Earth's atmospheric light scatter is caused by airborne particles with strong forward scattering properties, such as dust, smoke, pollen, and high-altitude ice crystals. The larger the particle, the more forward (propagated roughly in the direction it comes from the source) the scattering is directed, and the narrower the scattering angle. This is extremely harmful to solar observations of such a delicate nature.

SEEING CONDITIONS

To record prominence fine structure the seeing must be good indeed. At my site the best seeing occurs in the morning hours when the Sun is between 12 and 36 degrees elevation angle with a weak southwest air flow. Although atmospheric turbulence is minimized at these low angles, the path length is long, and I need to be sure that the jet stream is north of the line of sight. High altitude northerly winds destroy seeing at my location. This does not preclude noontime observations, as on rare occasions I observe very fine seeing with a stronger southerly or southwesterly breeze. Additionally, precise instrument focus can only be achieved in near perfect seeing. I often use the prominences' smallest bright "knots," as they are called, as point sources for focusing the instrument.



The objective lens cell and focus mechanism

- A Fused silica objective lens
- B Aluminum occulting cone with polished face
- C Copper cooling coils soldered to internally blackened copper drum
- D Copper heat conducting vanes aligned north-south
- E Field lens
- F Lyot stop
- G Limb scanning mirror (tip/tilt)
- H Achromatic relay lens
- I Infrared blocker
- J H-alpha interference filter
- K CMOS sensor array (focal plane)



Schematic diagram of the coronagraph, not to scale

SPECIAL FEATURES OF MY FINAL CORONAGRAPH

I made the 5-inch diameter 89-inch focal length (f/18) objective lens from a Corning #7980 fused silica blank. This material is by far the best for ground-based instruments, with extremely low internal scatter, and, when carefully polished, shows an incredibly smooth and scatter-free surface quality. The lens is ground to a coma-free shape. Light aspheric figuring corrected the lens for spherical aberration. The remaining lens aberration is astigmatism, but it is harmless out to the tops of even tall prominences.

The lens is mounted in a cantilevered cell attached to a focus slide. A long extension rod attached to the focuser's lead screw reaches a handy position.

After over 60 years building coronagraphs, I find this focusing arrangement offers the only practical method of keeping the Sun precisely focused on the occulting cone rim for any chosen spectral line. It also allows the occulting cone to be mounted solidly in a fixed location, minimizing optical problems in the relay section.

The next special feature is the water-cooled occulter and heatsink drum. The solar heat load for this instrument is about 12 watts. This level of heat, if left to accumulate, will corrupt the wavefront due to induced tube currents. Various schemes abound in the literature to remove this heat. My design addresses both the energy reflected off the occulting cone and the non-trivial heat absorbed by the cone itself. The photo, taken during construction, shows the polished aluminum occulting cone, heavy copper central support rod with its short heat conducting vanes, and gravity-fed water-cooling coils and drum. The internal surface of the drum was later painted flat black. The drum assembly is supported by

the straps shown, which are screwed to wood rails glued to the inner tube walls.

The effectiveness of this heat removal method is easy to demonstrate, especially under superb seeing when cooling counts the most, by shutting off the water flow and



The polished aluminum occulter in its water-cooled copper housing

watching the image slowly degrade.

The third special feature is the limb-scanning mirror and unique position of the relay lens. My elbow arrangement allows the Lyot stop, scanning mirror, and relay lens to be tightly packed. With this optical geometry (see diagram), the optical axis of the relay lens always coincides with the center of the CMOS chip. After placing the prominence image on the chip center by tilting the gimbal-mounted diagonal scanning mirror, the image is then on the axis of the relay. This feature is vitally important because relay lenses are the source of the greatest off-axis aberrations in most coronagraphs. One must strive to keep its working field small. My ray trace results, using OSLO, confirm this.

A fourth simple feature is a blue filter window mounted on the tube top surface just before the Lyot stop. It forms a viewing port

to check the centering of the entrance pupil image on the Lyot stop. Because most of the imaging is in the light of H-alpha, the blue filter effectively blocks the red in skylight as a source of diffuse scatter, and thus needs no cover.

The Lyot stop is vital to the success of a coronagraph. Its purpose is to block the bright diffracted light of the objective's edge. It must be sized (on theoretical grounds) such that only 85 percent of the objective's aperture is allowed through the stop. In my instrument, the field lens, which images the aperture on the stop, provides a 0.724-inch intermediate pupil diameter. I punched a 0.625-inch hole in thin aluminum for the stop aperture. The stop is painted with the best flat black obtainable.

THE H-ALPHA INTERFERENCE FILTER

I chose an inexpensive commercial grade 10-angstrom (full width at half maximum) interference filter of about 21 mm clear aperture made by Andover Corporation. The filter is located within 1 mm of the detector window where the beam cones are very tiny at f/21 (the final f number set by the Lyot stop), thus small errors in filter surface flatness are optically harmless. The coronagraph is so scatter-free that I can take advantage of the filter's thermal and tilt insensitivity and the full Doppler coverage it affords.

THE TUBE

The tube is made from 3/16-inch pine planks that I re-sawed from 1-inch-thick rough lumber, ensuring that the tube is both lightweight and very stiff. The cross section is 6 by 6 inches, reinforced with 1/2-inch square longe- rons and crosspieces glued in place. The rear section of the tube, from the occulter onward, is flanged to the main tube so that this section can be easily removed for bench work. Various removable panels are provided for easy hand access to specific components. The tube is left rough sawn inside to reduce light scatter when sprayed flat black, and the outside is sanded smooth and painted white.

My mount is a solid German equatorial with 3.5-inch diameter polar and declination shafts. It can be seen in the photo of the telescope. A 9-inch diameter bronze worm wheel provides the smoothness and stiffness required to keep the Sun's image hidden behind the occulting cone, even in a fair breeze. The mount is equipped with fine motion controls in right ascension and declination, either manual or motor driven. The mount is bolted to a heavy concrete pier within a small roll-off roof observatory. All this permanence of setup is an absolute requirement because a beautiful clear sky can appear and disappear in just an hour, so I must be ready to jump into action. I can begin imaging just 8 minutes after entering the observatory.

IMAGING

Images are collected by taking 6-second-duration videos using SharpCap 3. The videos are processed with AutoStakkert! and gently sharpened in RegiStax using wavelets. I find time-lapse movies to be exciting and informative; this is done by making a video* with each exposure typically 4-seconds apart. Playing the video at normal rates shows the dynamic behavior of almost all prominences. I usually make the movie cover 1 to 2 hours, which plays back in less than a minute. Measuring knot velocities is very interesting with apparent speeds of 35-110 kilometers per second rather common as they plunge into the photosphere.

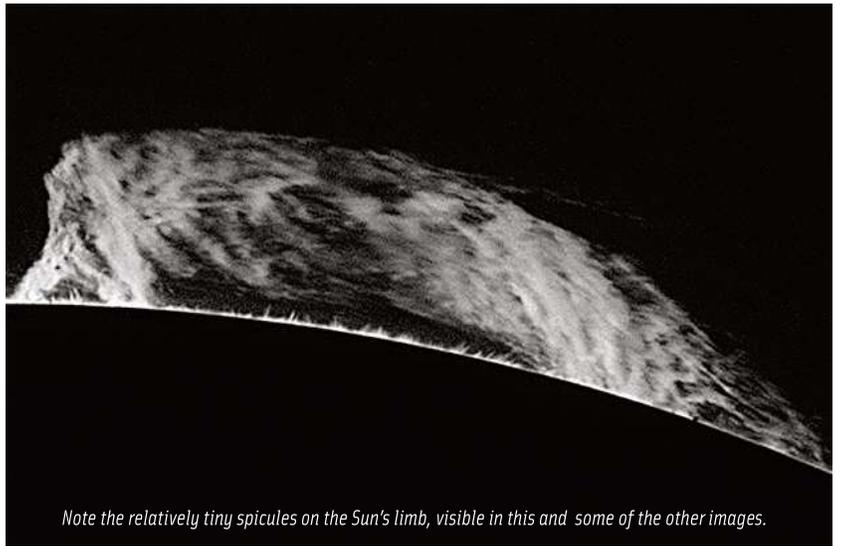
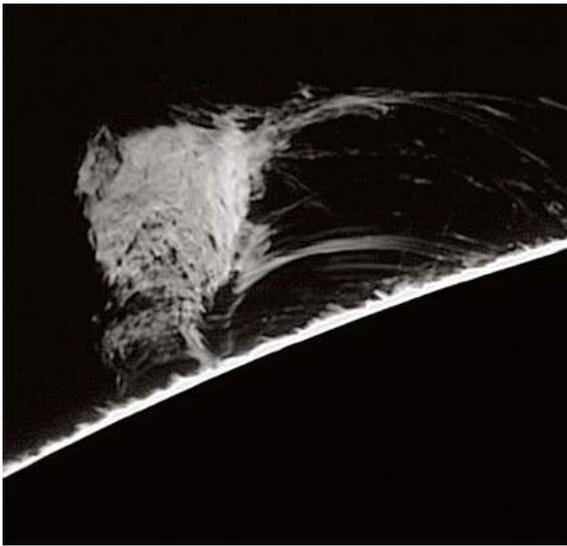
I hope this article will create some interest in observing the Sun with a Lyot coronagraph. For the advanced telescope maker and optical designer, the coronagraph represents an optical system of unsurpassed economy, intrinsic delight, beauty, and, of course, a joyous celebration of M. Bernard Lyot's genius. ✨

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

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**An example of these videos can be seen at youtu.be/fz0yMfQchgM*





Note the relatively tiny spicules on the Sun's limb, visible in this and some of the other images.

