



# Images and Spectra of the 2017 Total Solar Eclipse Corona From Our Oregon Site

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We report on early results from a suite of instruments for imaging and spectra we deployed to Salem, Oregon, for 2 min of totality at the August 21, 2017, total solar eclipse. Our instruments included refracting telescopes and telephoto lenses for use with CCD detectors and DSLR cameras, narrow-band filters at the wavelengths of coronal emission lines ([Fe XIV] 530.3 nm and [Fe X] 637.4 nm), and spectrographs. We also monitored the effect of the eclipse penumbra and umbra on the terrestrial atmosphere. The total solar eclipse of August 21, 2017, was the first whose totality crossed only United States territory since the origin of the country, and the first to cross the Continental United States from coast to coast in 99 years. As a result, major campaigns of scientific research and of outreach were carried out.

**Keywords:** corona, eclipse, sun, spectra, sunspot cycle, saros

## INTRODUCTION

The total solar eclipse of August 21, 2017, was the first whose totality crossed only United States territory since the origin of the country, and the first to cross the Continental United States from coast to coast in 99 years. As a result, major campaigns of scientific research and of outreach were carried out.

Our own expedition team included six scientists, 8 undergraduate students, 3 graduate students, and several collaborators at our main scientific site on the campus of Willamette University, Salem, Oregon. We took advantage of the unusual-for-us ground access by shipping a variety of telescopes, spectrographs, Lyot-type filters, cameras and telescope-mounts across the country by truck in addition to air shipping of international and other equipment. We coordinated with colleagues 65 min farther along the path of totality, in southern Illinois, in order to be able to calculate velocities of changing coronal features.

We were particularly interested in the shape of the corona as part of a synoptic observation set that began early in the previous solar-activity cycle, and linking to older radial-filter observations by Newkirk and others (described with a full set of images in Golub and Pasachoff, 2010, 2014). The ellipticity is greater at solar minimum, and the flattening index in this 2017 eclipse, as well as those measured for the 2019 and 2020 eclipses, should give indications on the strength of the forthcoming cycle, which follows the declining peak of the recently past cycle and its two predecessors.

Our observations follow earlier high-resolution imaging in streamers (Pasachoff et al., 2007, 2009) and in polar plumes (Pasachoff et al., 2008). We discussed dynamics in Pasachoff et al. (2011) and Pasachoff et al. (2015). We use photographic techniques upgraded from earlier drawings and paintings (Pasachoff and Olson, 2014, 2015).

Pasachoff discussed the range of science carried out at eclipses (Pasachoff, 2009a,b, 2017a,b, 2018a). Pasachoff and Fraknoi (2017) provided a Resource Letter about observing solar eclipses following Pasachoff's Resource Letter about solar science and outreach (Pasachoff, 2010).

## OBSERVATIONS AND METHODS

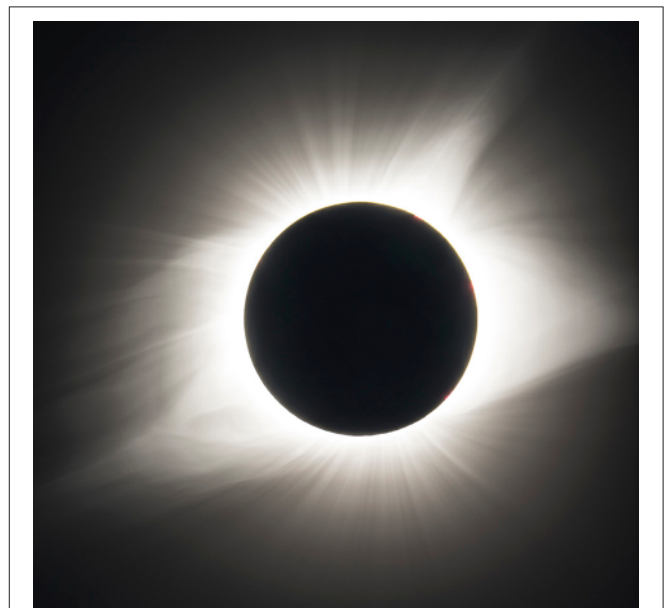
As is well known, the white light corona—the scattered light of the photosphere on free electrons (Thomson scattering)—is a very good indicator of magnetic fields on the Sun, and, these magnetic field lines generate different structures of the solar corona, e.g., helmet streamers, loops, coronal holes, polar plumes, etc., of a different size and brightness. The relationship of the individual white-light coronal structures to the distribution of magnetic fields observed on the surface of the Sun is sometimes quite problematic, particularly, as observed from the coronagraphs on the *Solar and Heliospheric Observatory* (SOHO) and the Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI; Howard et al., 2008) suite of instruments on NASA's *Solar TERrestrial RELations Observatory* (STEREO). (The instrument suite was named after Fr. Angelo Secchi, director of the Vatican Observatory in the 19th century, whose 200th birth anniversary was celebrated with a symposium in Rome; Pasachoff, 2018b.) One of the ways to do this is to observe the white-light corona during total solar eclipses at high spatial resolution with subsequent computer data processing, e.g., Koutchmy et al. (1988), Druckmüller et al. (2006). High-quality pictures of the white-light corona during the eclipse and their processing with a computer allows us to distinguish small-scale coronal structures, for example, around 5 arc seconds or less, whose contrast between them is very low, and which are lost with standard exposures. The most recent occasion of this kind was the total solar eclipse observed on August 21, 2017, in a narrow totality path throughout the US, from northwest coast to southeast coast.

We used 20 Nikons, mainly D810s, which lack the moiré-reducing filter that has been introduced into many camera models but that slightly degrade the resolution. Our lenses included Nikkor 800 mm and 400 mm non-mirror lenses as well as 500 mm mirror lenses and a Tele Vue refractor. **Figure 1** shows a composite made from 11 originals with the 800 mm lens. Our in-house techniques can now match the quality and contrast accessible in the past for our expedition's and other expeditions' by the high-contrast data reduction made most famous by Druckmüller though now available from several people.

We see the paucity of coronal streamers at high latitudes, revealing the coronal plumes that we studied at the 2006, 2008, and 2009 eclipses (Pasachoff et al., 2007, 2008, 2009, 2011).



**FIGURE 1** | High-contrast imaging showing the paucity of equatorial coronal streamers at this solar-minimum phase of the sunspot cycle, incorporating 11 individual images taken with a Nikon D-810 DSLR camera and a 800-mm Nikkor lens and processed by Christian Lockwood.



**FIGURE 2** | A stack of 3 1/40-s images that is closer to the perception of the eclipse to the unaided eye than the high-contrast composites (Ron Dantowitz).

**Figure 2** shows the overall structure of the corona. A composite of our images has been used to successfully compare with the predictions (Mikic et al., 2018) made pre-eclipse on the basis of the prior month of magnetograms of the solar disk from the HMI instrument on NASA's Solar Dynamics Observatory. Nandy et al. (2018) used a solar-surface flux-transport model for predicting the coronal configuration.

We also obtained a series of flash chromospheric and coronal spectra using high-resolution (HiRes) and low-resolution

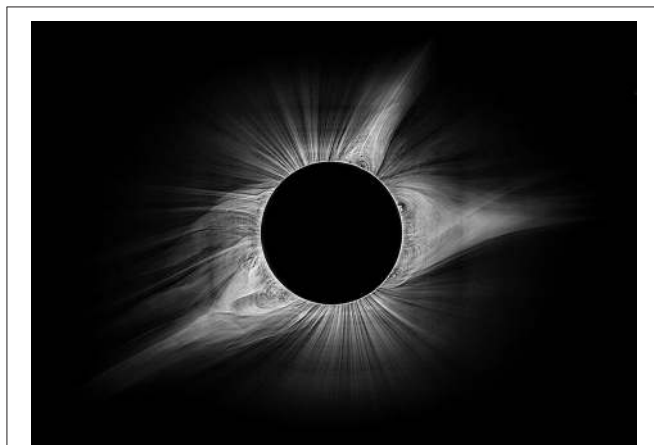
(LoRes) spectrographs. Two slitless spectrographs were used in different dispersion/resolution. These two spectrographs were adapted on an equatorial mount. The LoRes spectrograph was used for the recording of the visual spectrum from 420 nm up to 680 nm. The second spectrograph (HiRes) was used for the capturing a spectral band from the forbidden [Fe XIV] 530.3 nm emission line up to the forbidden [Fe X] 637.4 nm emission line. Our spectrographs correlated with two narrow band Lyot filters tuned to 530 nm (FWHM 0.38 nm) and 637.4 nm (FWHM 0.5 nm) on a 10 cm Tele Vue refractor with a 220 mm coelostat.

We brought a meteorological station to measure air temperature, atmospheric pressure, solar radiation, relative humidity and wind (speed plus direction) at our site, to monitor the effect of first the penumbra and then the umbra, continuing the work described in (Peñaloza-Murillo and Pasachoff, 2015). In addition, an array of photo-sensors was used to measure the sky brightness.

## RESULTS

**Figure 3** shows a stacked image of the white-light corona as processed by Roman Vanúr from the 800 mm telephoto lens, using 85 individual pictures of different exposures from 2 to 1/500 s. To show higher contrast that reveals the structure of the underlying magnetic field, we used an especially-high-frequency filter. Tian et al. (2017) and Chen et al. (2018) have described the coronal configuration and a coronal cavity over a prominence region, which also shows on our images. Hanaoka et al. (2018) have described changes over an expanse of umbral motion across the United States.

**Figure 4** shows a sample slitless spectrum, taken several seconds before 3rd contact, showing the forbidden [Fe X] coronal red line at 637.4 nm and the forbidden [Fe XIV] coronal green line at 530.3 nm as well as chromospheric lines at low heights above the limb. We have been monitoring the ratio of these



**FIGURE 3** | A stack of images taken with an 800-mm f/5.6 lens and displayed at exceedingly high contrast (Jay Pasachoff, Vojtech Rušin, Roman Vanúr, and the Williams College Eclipse Expedition team).

spectral lines over the last solar-activity cycle, showing that the lower-ionization line, typical of a coronal temperature of 1 MK or less, is stronger than the higher-ionization line, typical of a coronal temperature of  $\sim 1.5$  MK at solar minimum, as we found here. In comparison, at solar maximum, we have found the ratio to have been reversed, with the [Fe XIV] line stronger than the [Fe X] line. Our previous observations include Voulgaris et al. (2010) from the 2006 and 2008 eclipses and Voulgaris et al. (2012) from the 2010 eclipse.

## DISCUSSION

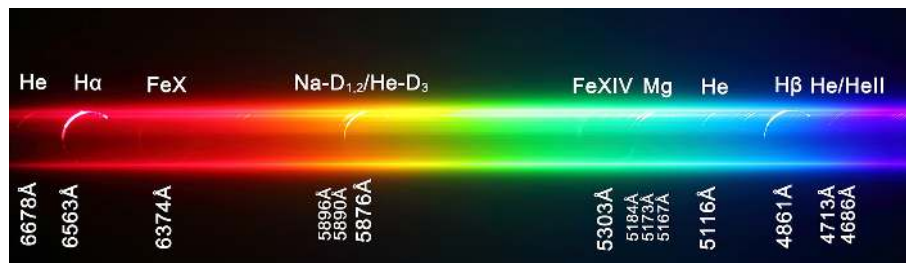
**Figure 5** shows the prominent prominence, the innermost corona, and 3rd-contact chromosphere. Our series of observations allowed timing of 1 m 54 s of totality at our site (17:17:21–17:19:15 UTC), which we are comparing with the predictions that depend on the exact value for the solar diameter (Pasachoff et al., 2017d), given the 3-D mapping of the moon in recent years from the Japanese Kaguya spacecraft and the NASA Lunar Reconnaissance Orbiter.

Besides the helmet streamer and threadlike rays, the corona shape was dominated by coronal holes with well-developed polar plumes. The northern coronal hole was located in position angles (PA)  $35\text{--}338^\circ$ . There was an interesting intensity break at PA  $298\text{--}305^\circ$  at the solar surface, even though some faint rays were observed in the middle; they expand with height above the limb. This intensity break separated two helmet streamers. The southern coronal hole was located in PA  $158\text{--}208^\circ$ .

Preliminary comparison of our coronal observations from Oregon with those 65 min later along the path from Carbondale, Illinois, show a strong, narrow edge of a streamer flipping its orientation, giving a speed of hundreds of  $\text{km s}^{-1}$ , as well as a newly brightened polar plume (Pasachoff, 2017c; Pasachoff et al., 2017e, 2018a,b).

After calibrating our spectra, we detected the red coronal line emitting uninterruptedly around the solar limb, even also above the solar magnetic poles. By contrast, the strongest intensity of the green coronal line was detected in two areas, in the east (no sunspots were present) and northeast limbs, caused by the existing—close to the limb—active sunspots 2672. We have been monitoring the ratio of these spectral lines over the last solar-activity cycle. We detected that the ratio of the intensity of these two lines varies by the area of interest. There are many areas around the solar limb in which the red coronal line is much stronger than green line. The lack of homogeneity in the ratio of two lines means that the coronal temperature strongly varies according from place to place, following the heterogeneity of the two emission lines. The absence of the green emission line signifies a coronal temperature of 1 MK or less. The presence of the green line, the higher-ionization line, is typical of a coronal temperature of  $\sim 1.9$  MK at solar minimum, as we found over some active areas. In our results, we did not detect the forbidden yellow coronal line of Ca XV at 569.4 nm ( $\sim 3\text{--}5$  MK), even above from the rising sunspots on northeast limb.

We continued our observations of the terrestrial atmosphere and its response to eclipses (Peñaloza-Murillo and Pasachoff, 2015; Pasachoff et al., 2016). The air-temperature measurements



**FIGURE 4** | A sample spectrum showing chromospheric lines at 3rd contact as well as forbidden coronal spectral lines, especially the standard [Fe X] at 637.4 nm and [Fe XIV] at 530.3 nm (Aris Voulgaris).

from our Oregon site on the top of a building on the campus of Willamette University show a drop of  $3.1^{\circ}\text{C} = 5.5^{\circ}\text{F}$ , with a delay of 4.8 min after central totality, at 0.5 m above the station base. Other results show that at 1 m and 2 m above the station base the drops were  $2.5^{\circ}\text{C} = 4.5^{\circ}\text{F}$  with a delay of 4.8 min, and  $1.6^{\circ}\text{C} = 2.9^{\circ}\text{F}$  with a delay of 6 min, respectively. These results were typical for both variables according to those published by Burt (2018) for this eclipse in sites like Whitman (Nebraska), Crossville (Tennessee), and McClellanville (South Carolina). We also detected a slight increase in atmospheric pressure at totality and a pronounced drop in wind speed along with a reduction (symmetric) in variability during the eclipse in accordance with Aplin and Harrison (2003) for the eclipse of August 11, 1999, in the UK. This drop of wind speed is associated with a stabilization in wind direction between  $264^{\circ}$  and  $312^{\circ}$  clockwise from north.

**Figure 6** shows a comparison in which one of our processed eclipse images fills the gap between the on-disk image from the Solar Ultraviolet Imager (SUVI; Seaton and Darnel, 2018) on NOAA's Geostationary Operational Environmental Satellite-16 (GOES-16) spacecraft and a coronagraph image from the Large Angle Spectrometric Coronagraph (LASCO; Brueckner et al., 1995) on board SOHO. The combination of these images enables features to be traced from the disk through our image of the lower and middle corona to the lower-resolution C2 LASCO image.

The basis for our analysis of the large-scale white light coronal structure is this combined image of the eclipse white-light corona, the SOHO/LASCO C2 corona and the GOES-16/SUVI Sun of 30.4 nm. Looking at the SOHO white-light corona, we see three significant and bright helmet streamers, two of which are localized above the western limb of the Sun and one above the southeastern limb of the Sun. Streamers/rays that are less pronounced are located above the eastern limb (three examples) and above the western edge (one example). Similar polar rays also show, though they had been hidden for much of the past decade by high-latitude streamers typical of solar maximum. Pasachoff et al. (2008) had reported on motions and brightness changes in polar plumes during the 2006 total eclipse.

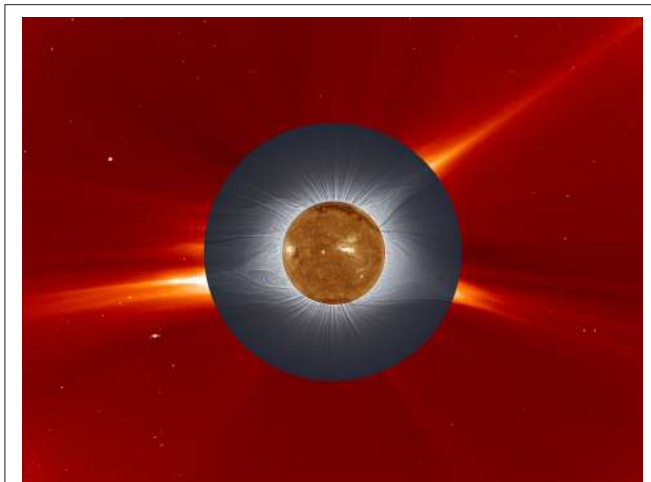
In sum, the white-light corona on August 21, 2017, was observed on the descending branch of cycle 24, whose magnitude according to many features of solar activity—e.g., sunspot numbers, the 2,800 MHz radio flux, the green-line corona intensities, etc.—was the lowest in the last four solar cycles.



**FIGURE 5** | The chromosphere, the innermost corona, and prominences at 3rd contact. Coronal cavities are nicely seen above prominences on the west solar limb (Ron Dantowitz).

Although the solar activity was relatively low through the first part of the year 2017, it increased in August and September. Then the activity again diminished. On the day of the eclipse, the large active area was located in the middle of the solar disk, so it could not be responsible for coronal structures that are observed above the solar limb. However, there was a small sunspot group near the limb on the far side, and became visible the next day as it rotated onto the near side of the disk. Based on our analysis, we come to the following conclusions:

- The shape of the white light corona was a transient type with three or four distinctive helmet streamers and well-developed coronal holes above the two poles of the Sun, where polar plumes were observed.



**FIGURE 6** | A combination of one of our composite eclipse images between an EUV image from GOES-16/SUVI at 19.5 nm (corresponding to Fe XI/XII emission at about 1.5 MK) and an image from the LASCO C2 coronagraph, occulting up to 2.5 solar radii revealing the connection between structures in the extended corona and the source regions on the solar disk. It is improved from our Astronomy Picture of the Day image from September 27, 2017 (<https://apod.nasa.gov/apod/ap170927.html>), with a more detailed eclipse composite and a GOES-16 image instead of the earlier Solar Dynamics Observatory image (eclipse: Jay Pasachoff, Vojtech Rušin, Roman Vanúr, and the Williams College Eclipse Expedition team).

- At the preliminary phase 0.8 of Cycle 24, the Ludendorff flattening index reached 0.24 and replicates the cyclical variability as obtained from many observations since 1851. In other words, the shape of the white-light corona matched that of similar phase in the previous cycles, in spite of the fact that the peak of this cycle was much lower. (See, for example, <http://sidc.oma.be/silso>.)

- Just over 1 h following our observations in Oregon, structural changes occurred in the base of the SE helmet streamer, as well as a change in the brightness of some polar plumes, perhaps showing a change in the flow of particles into the solar wind.

- Above the southeast limb of the Sun, at a height of about 0.85 radius, a dark arc was observed (there are bright arches as well, but the darker is better visible), whose feet at the solar surface are  $104^\circ$  apart, which is an extraordinary value. Loops or arcs are generally seen in helmet-streamer boundaries, which was also the case with all the helmet streamers.

- Thin coronal rays or loops began to appear in the tops of some of the prominences.

STEREO observations show that the streamers are composed of still-finer-resolution features (DeForest et al., 2018), and our highest quality data reduction matches that idea. High-quality observations of the white-light solar corona, with its processing, allow us to separate different coronal structures (in the sense of their brightness, size, shape, along the line of sight, etc.). Thus, the corona becomes highly structural in every direction, composed of many structures of small dimensions. The white-light corona is also highly dynamic. The coronal structures and their dynamics are linked to the magnetic field, both local and global.

Given the descent into the delayed solar-activity minimum and the desirability of predicting and eventually determining the height and activity of the next solar maximum, we look forward to carrying out similar observations at the total solar eclipses of 2 July 2019 from Chile and of 14 December 2020 from the Atlantic Coast of Argentina. See <http://eclipses.info> for links and <http://totalsolareclipse.org> for additional images and references from not only the 2017 total solar eclipse but also from the three partial solar eclipses of 2018.

## DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this manuscript will be made available by the authors, without undue reservation, to any qualified researcher.

## AUTHOR CONTRIBUTIONS

JP organized the effort and supplied scientific and logistic backing. CL operated cameras and composited images. EM operated and organized cameras and worked with data. RY organized and operated the meteorological station. CP programmed cameras, operated them, and worked with spectral data. MP-M consulted on the meteorological station and analyzed the data. DS provided the liaisons to space EUV observations. AV built and operated imaging and spectral instruments. RD built and operated imaging and spectral instruments. VR participated in the observing and provided analysis of the images. TE provided the observations from along the totality path.

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