The Solar Eclipse of April 8, 2024
Demonstrating Issues in Analyzing SpectroBurst™ Spectra
Alexander Scheeline

On April 8, 2024, the second total solar eclipse to cross Illinois since the invention of SpectroBurst™ spectrometry passed over the southern part of the state. Your intrepid author was in Olney, commonly known for its albino squirrels, to observe the event. After faring poorly in photographing the eclipse of 2017 (in Goreville, farther south than Olney), I rethought what I was trying to do and how to do it. I knew my tripod was a bit shaky. During setup, one leg failed to lock when extended. Fortunately, my wife had brought a roll of tape, and we kluged a brace that allowed successful photography. What follows is an explanation of some problems in interpreting SpectroBursts, how the solar eclipse provided an unparalleled opportunity to illustrate the issues, and examples of processed images that clarify where we are and what developments are still needed to provide a fully functioning spectrometer.

SpectroBurst Spectrometry

A stack of double-axis gratings are interposed in a system imaging a pinhole source onto a rectangular detector. As explained in Alexander Scheeline and Bùi Anh Thụ, "Stacked, Mutually-rotated Diffraction Gratings as Enablers of Portable Visible Spectrometry," *Appl. Spectrosc.* **70(5)**, 766-777 (2016). DOI: 10.1177/00037028166382246, such a grating stack results in thousands of spectra dispersed in a cylindrically symmetrical pattern. The two double axis gratings (numbered 0 and 1) with grating spacing along their $x$ and $y$ axes of $d$ (they could have different spacings, which would make the math messier, but in practice having a single value for $d$ seems to be adequate) produce spectra described by:

$$n_{eff} = \left(n_{x1}^2 + n_{y1}^2 + n_{x0}^2 + n_{y0}^2 + 2\left(\left(n_{x1}n_{x0} + n_{y0}n_{y1}\right)\cos\theta_g + \left(n_{y0}n_{x1} - n_{x0}n_{y1}\right)\sin\theta_g\right)\right)^{1/2}$$

$$\theta_{n_{eff}} = \arctan\frac{n_{y1}\cos\theta_g + n_{x1}\sin\theta_g + n_{y0}}{n_{x1}\cos\theta_g - n_{y1}\sin\theta_g + n_{x0}} \qquad n_{eff}\lambda = d\sin\beta \qquad r = f\tan\beta$$

where

| | |
|---|---|
| $\lambda$ | Observed wavelength |
| $\beta$ | Diffraction angle |
| $\theta_g$ | Rotation of the $x$ axis of grating 1 compared to grating 0 |
| $f$ | Camera focal length |
| $r$ | Distance at which the wavelength appears in order $n_{eff}$ vs. the center of the SpectroBurst |
| $\theta_{n_{eff}}$ | Orientation of the order vs. grating 0's $x$ axis |

In summary,

$$\begin{pmatrix} r \\ \theta \end{pmatrix} = \begin{pmatrix} f\tan\left(\sin^{-1}\left(\dfrac{n_{eff}\lambda}{d}\right)\right) \\ \arctan\dfrac{n_{y1}\cos\theta_g + n_{x1}\sin\theta_g + n_{y0}}{n_{x1}\cos\theta_g - n_{y1}\sin\theta_g + n_{x0}} \end{pmatrix} = \begin{pmatrix} f\dfrac{n_{eff}\lambda}{\sqrt{d^2 - \left(n_{eff}\lambda\right)^2}} \\ \arctan\dfrac{n_{y1}\cos\theta_g + n_{x1}\sin\theta_g + n_{y0}}{n_{x1}\cos\theta_g - n_{y1}\sin\theta_g + n_{x0}} \end{pmatrix}$$

Once $r$ and $\theta$ are known, $x$ and $y$ can be computed. As is commonly known for Cartesian coordinate systems, $x = r \cos \theta$, $y = r \sin \theta$. If a digital camera is used, $x$ and $y$ can be converted to pixels. Thus, grating behavior and pictures taken of spectra can, to a first approximation, be compared to each other.

For the case of a single grating, $n_{x1} = n_{y1} = 0$. This simplifies some of the expressions.

$$n_{eff} = \left(n_{x0}^2 + n_{y0}^2\right)^{1/2} \qquad \theta_{n_{eff}} = \arctan\frac{n_{y0}}{n_{x0}}$$

Concepts to Be Illustrated

If only it were as simple as just applying the equations above!

All dispersive spectrometers are imaging systems into which one or more dispersing elements (gratings or prisms) are inserted. Thus, the observed spectrum is a superposition of the imaging properties of the spectrometer/camera, the dispersive properties of the grating/prism, the response of the detector, noise in any of the system components, and the behavior of the light source being observed. It is rare that a natural phenomenon can demonstrate this superposition. Images from the eclipse do exactly that. We will show:

1) Noise, saturation, and scattered light.
2) Reduction in wavelength resolution due to the spatial extent of the source.
3) Differences in resolution when dispersion is not aligned with the smallest source dimension.
4) How to improve spectral resolution if known distortion by the optical system can be removed from the raw data.

Limitations in Data Collection and Consequent Interpretation Constraints

The camera used for collecting data was whatever is built into a Samsung S20 5G cellular telephone. Rather than using the default camera app, an app specifically for eclipse photography, *Solar Snap* ([https://play.google.com/store/apps/details?id=com.riseupgames.solarsnap&pli=1](https://play.google.com/store/apps/details?id=com.riseupgames.solarsnap&pli=1)) was employed. While focus was optimized as closely as feasible, some blur was inevitable because
1) a solar blocking filter was required during partial eclipse to avoid destroying the camera sensor,
2) because of the brevity of totality, refocusing after the solar filter was removed seemed inadvisable,
3) between the solar filter and the camera input (or, during totality, without the solar filter in the line of sight) was the double-axis diffraction grating. Since neither the filter nor the grating film were optically flat, focus could not be optimized across the entire field of view.
4) The eclipse was viewed through high cirrus clouds, which scattered light.
5) Since the grating and filter were held in place by Velcro and kept aligned with the axis of the phone/camera with masking tape, stray light could

enter the camera through the gaps between filters and around the Velcro mounting.
6) We nearly suffered a tripod collapse! Fortunately, we had enough left-over tape to brace the offending leg. While this problem didn't hinder data collection, I mention it to indicate how little issues that would be no problem under some circumstances may prove crucial during an eclipse. Incidentally, I learned during the 2017 eclipse that my tripod was too short for comfortable shooting. I supplemented the height of the tripod with some concrete blocks and that solved the problem. The picture above, taken by my wife, shows me and the setup.

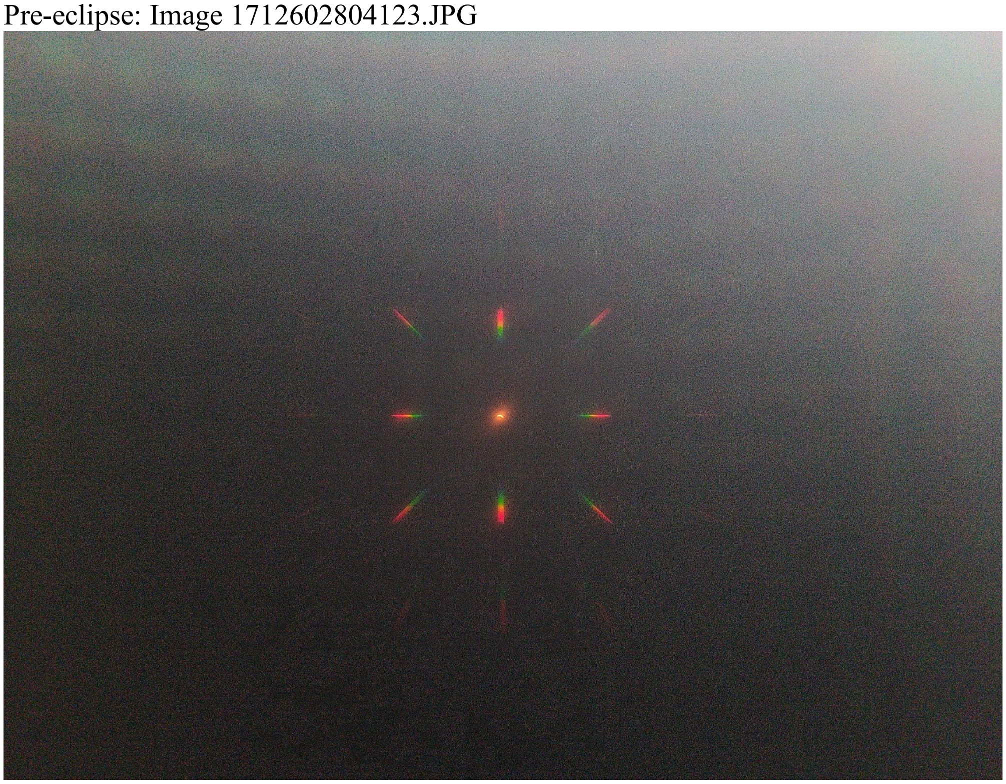
## The Data

Hats off to Stellarnet, a long-time vendor of array detector spectrometers. They posted data from one of their broad-band instruments showing the solar spectrum during the eclipse. Resolution far outshines anything SpectroClick can do. They only show partial eclipse data (since they were in Florida, far from totality). See the video about half-way down the page at https://www.stellarnet.us/the-2024-solar-eclipse-with-stellarnet/. See the dip in the spectrum at 760 nm? That's oxygen absorbing light.

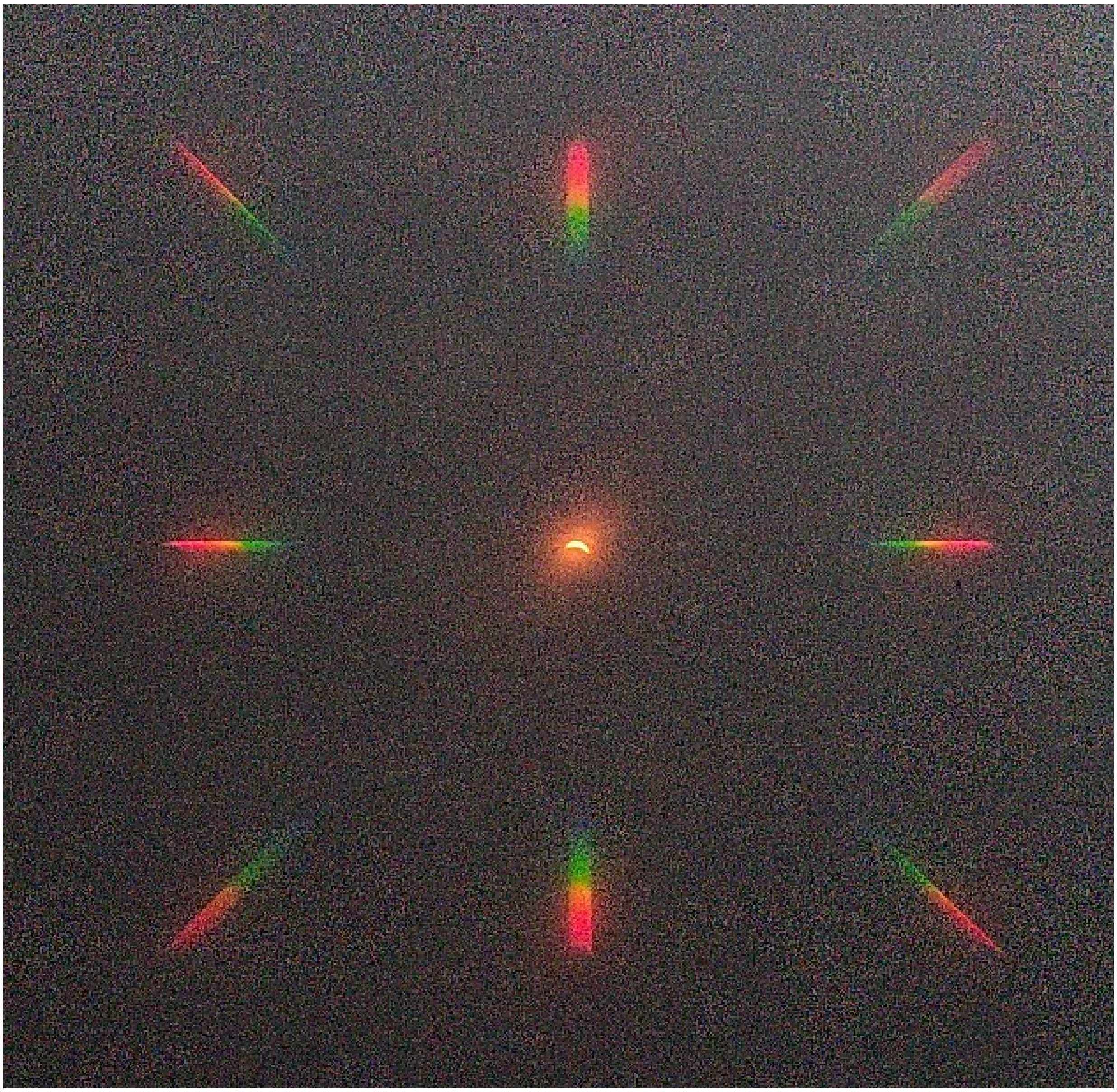
The solar corona shows some continuum (emission at all wavelengths), but is dominated by line spectra of hydrogen, helium, and a handful of other elements in the visible region of the spectrum. See http://solar.physics.montana.edu/takeda/REU_ecl/images/solar_flash_spectrums.jpg for a beautiful example. You might bookmark this image for comparison to the data below.

I took 89 frames totaling almost 1 GB. Of these, three frames, one from two minutes before totality and two from during totality illustrate the points I'm trying to make. These are not chosen as the best images for scientific analysis – they are overexposed, but the main points are vivid. During the discussion, I will show extracted spectra from similar frames, taken only seconds before or after those included here, that are not saturated (or are only saturated in part). My image identifiers are given only so that I can go back to the images if anyone asks questions.

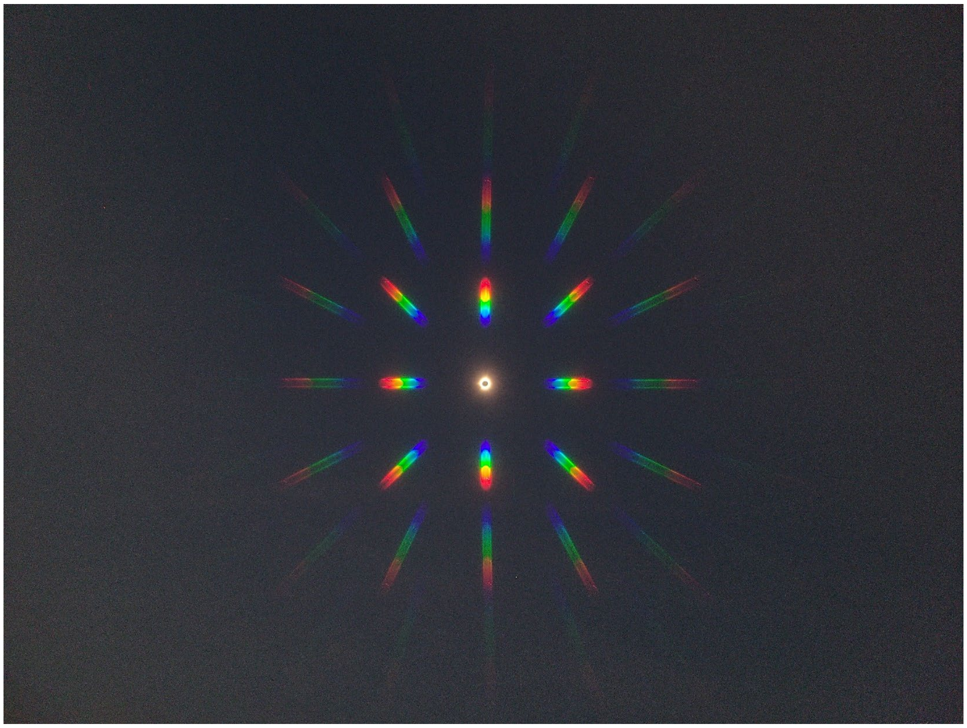
Pre-eclipse: Image 1712602804123.JPG

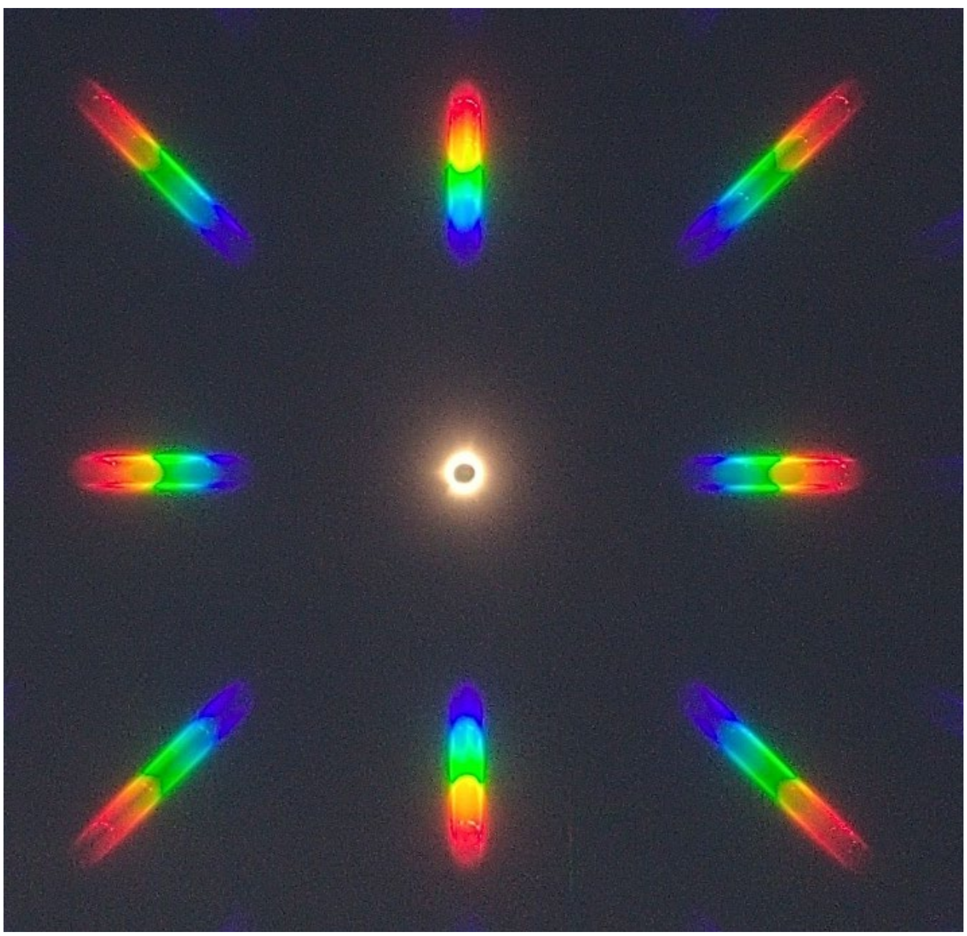


Next, the same image, zoomed in to show only orders (0,0), (1,0), (1,1), (0,1), (-1,1), (-1,0), (-1,-1), (0,-1) and (1,-1) (in each case $n_x$ and $n_y$).

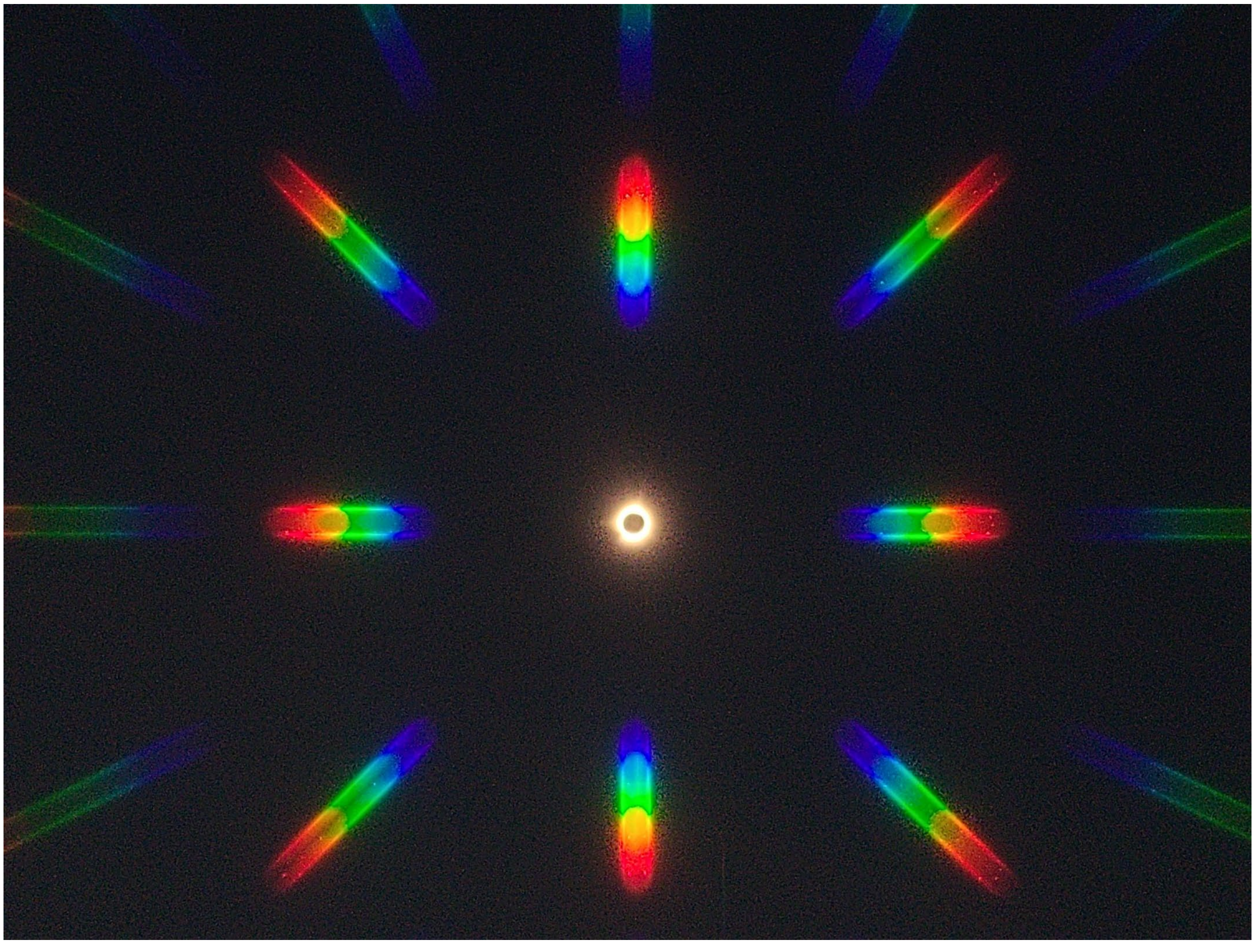


Now we show a frame from during totality, frame 171602949269.JPG, followed by a zoom-in as above:





I can't resist one more where optical zoom on the camera was used to only capture a few orders and thus to enlarge the solar image as well, frame 1712603036204.JPG



What the Data Teach

The first thing is to simply admire the beauty of a solar eclipse, the moon shadowing the sun, and the color separation provided by a grating. Now let's look at the details.

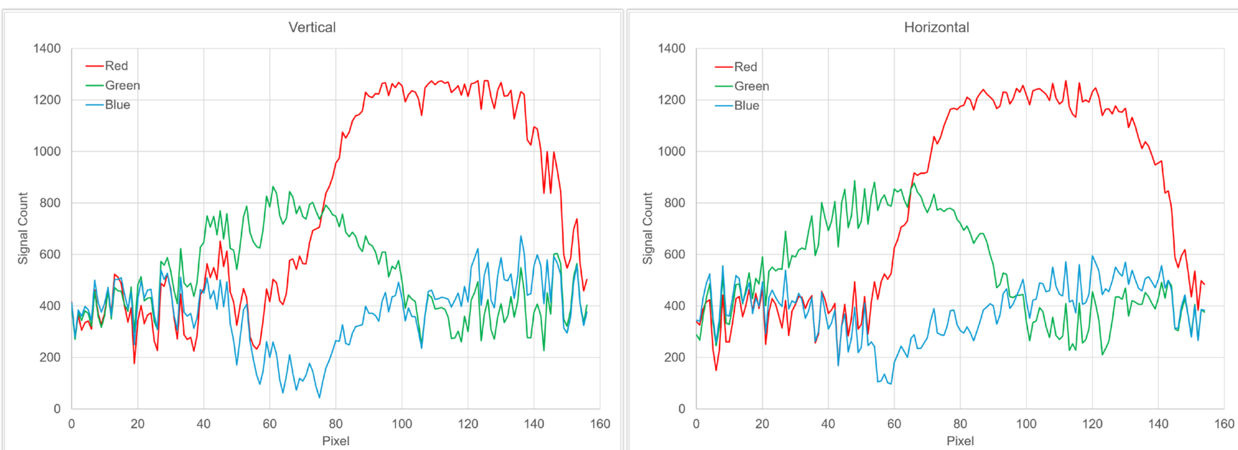
The first message comes from the Stellarnet spectra. The solar spectrum is not a pure blackbody spectrum; it is modulated by absorbance by various atmospheric gases. That means that any drift in wavelength calibration or change in spectrometer resolution will change the measured intensity of light in any spectrometer. What if the light source isn't the sun – say, an LED? Those same gases absorb and have non-unity refractive index. *Wavelength drift and resolution drift due to temperature changes, vibration, or mechanical flexing are noise sources in all spectrophotometry.* In the rest of this blog post, resolution is poor so we can't demonstrate the problem, but the Stellarnet spectra highlight the issue.

Look at the first image from frame 1712602804123 on P. 3. See how the background isn't black? It's grey, and the grey is brightest in the upper right of the image. This is stray light, light that entered the camera by scattering or reflecting off the cardboard frames holding the solar filter and diffraction grating and sneaking through the gaps between the frames and the camera lens. The mean grey level can be filtered out of the image using image processing software (ImageJ and GIMP are free resources. Photoshop and its competitors are also available). The discussion here will not undertake to remove the stray light before data extraction, and examples will use data that isn't significantly influenced by the light background.

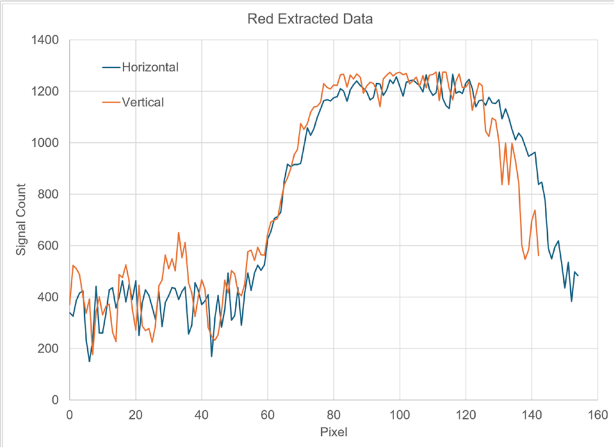
The zoomed-in version of image 1712602804123 on P. 4 shows an image of the partially eclipsed crescent sun and 8 diffracted orders along the $x$ and $y$ axes and along the image diagonals. Notice that each of the spectra differ geometrically. The grating spreads light along orders, starting at the center of the image. For orders distributed horizontally, each point of the crescent sun is dispersed, leading to a vertically narrow spectrum but with wavelength blur along the spectrum. For orders vertically dispersed, the spectra are curved in the same direction as the crescent sun. Look at the upper order ($n_x = 0$, $n_y = 1$). Yellow curves upward toward the red part of the spectrum. Now look at the lower order ($n_x = 0$, $n_y = -1$). Yellow still curves upward, but this time towards the green part of the spectrum! The lower spectrum will primarily blur yellow with green, while the upper spectrum will primarily blur yellow with red. If, however, we take a tiny slice of the spectrum (say near $x = 0$, ignoring the width of the solar crescent), the blurring won't reduce resolution but the position of the spectrum in $y$ will be offset from what it would be if we looked at dispersion from the tips of the crescent. *Source shape and position influence wavelength calibration*. *Lateral averaging across the width of the source reduces wavelength resolution, independent of the grating*. This is true of all spectrometers, but it's rarely as visually striking as in this image.

Around the solar crescent is a yellow glow. I can't be sure, but I think this is due to high cirrus clouds blurring the image. Notice how grainy the image is. It is not clear if this is due to the JPG image compression and decompression algorithms used to rapidly save the images while avoiding using too much memory. In any event, the graininess is an example of noise. The spatial resolution of the image is poorer than the 64 megapixel camera specification would suggest.

Despite the graininess, we can learn a few things by extracting spectra. Compare the $x$ (horizontal) spectrum to the $y$ (vertical) spectrum in 1712602804123




The two cross-section plots look similar. Let's overlay the red portion, but shift the horizontal axis so that the sharp rise where the yellow band is (green falling, red rising) is aligned. We see:

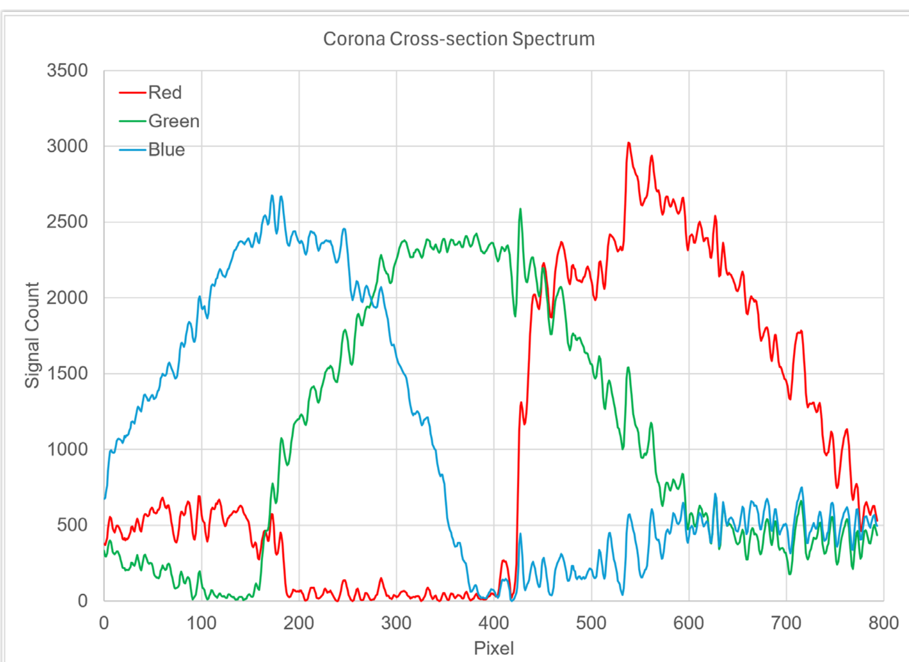



Sure enough, the vertical spectrum cuts off more sharply; It falls in 7 fewer pixels than the horizontal spectrum. It isn't blurred by the width of the solar arc; it's only blurred by the slight thickness of the nearly-eclipsed disk. We can't tell from this noisy data how degraded a real-world spectrum would be, but we can see that for identical dispersion, differences in spatial extent change what the dispersed spectrum looks like. In real-world spectrometers, slight differences in lateral magnification due to the optical aberration known as coma produces effects similar to what we see here.

One final point about spectra in 1712602804123. The spectra that point to the corners of the image have a length that is $\sqrt{2}$ longer than either the horizontal or vertical spectra. That means, all else equal, that the signal on each pixel is reduced by this amount and the dispersion is increased by that amount. The overall effect, however, is complicated by seeing the arc of the eclipsed sun at a different projection angle than either the horizontal or vertical spectra. To relate all the spectra requires taking all the geometric effects into account.

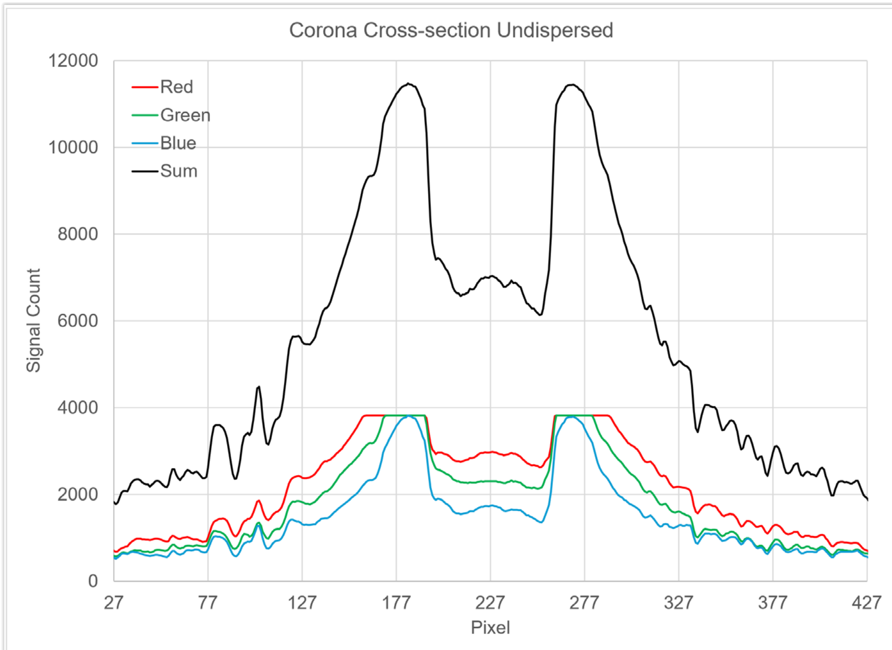
Moving on to the image of the totally eclipsed sun, images 171602949269 and 1712603036204, we see spectra of the corona. Now we have a nearly circular light source with a hole in the middle. Each point on that circle is dispersed by the grating. Thus, any emission line will appear as a circle in the dispersed spectrum. The circles are particularly evident in image 1712603036204. Could we extract a clean spectrum from such messy data?

In principle, the answer is yes. Let's extract the (1,-1) data in the lower right of 1712603036204. Extracting across a width of 15 pixels, we get:




Other than seeing the red, green, and blue pixels responding differently to different wavelengths and seeing the fall-off in response at the blue and red ends of the spectrum, there's almost no structure visible in this extraction! Human eyes are great at seeing patterns – far better than simple automatons.

Could we simulate a spectrum and compare our simulation to the image? Sure! The easy model for the coronal spectrum is to assume it's spatially just a donut – a bright ring with a hole in the middle, and each point exhibiting the same atomic emission spectrum. What does the image show? A 15 pixel high cross-section of zero order is plotted next.




The first thing to notice is that the red pixels saturate in the brightest part of the corona. From about pixel 160 to pixel 191 (to the left of the donut hole) and from pixel 263 to pixel 288 (to the right) the red data flat-line at the highest value that can be represented in the image. The blue data are likely more reliable for devising a model, but even here, the hole in the donut isn't completely empty (due to some combination of scattered light and signal bleeding between adjacent, saturated pixels – and possibly earthshine reflecting off the lunar surface).

Let's list the lines we'll model (a subset of those in the corona), based on Montana/Takeda image. Intensities are guesses based on the image (human eye estimates of intensities are always suspect, and when they're based on processed images for which camera and optical characteristics are unknown, they're doubly suspect. But I have to start somewhere.).

| Line | Hα | He I | Hβ | FeXIV | ?? | ?? | He I | C I | Hγ | Hδ |
|---|---|---|---|---|---|---|---|---|---|---|
| Wavelength (nm) | 656.3 | 584.3 | 486.1 | 530.3 | 518.5 | 517.5 | 501.6 | 447.8 | 434.0 | 410.2 |
| Relative Intensity | 1000 | 500 | 400 | 50 | 50 | 50 | 50 | 50 | 300 | 200 |

Now we need to choose a dispersion. Ignoring the slight nonlinearity in dispersion with angle (at small angles), the center of the solar disk is at pixels (2035,1679) while the center of what is likely the Hα image is at pixels (3225,2837) in order (1,-1) in image 1712603036204. That means dispersion is 656.3 nm across 1660 pixels or 0.395 nm/pixel. As a check, the center of the circle due to the He I line is at (3052,2670) giving a dispersion of 0.411 nm/pixel. Use 0.4 nm/pixel in modeling.

The solar shadow has a radius of 34 pixels. The peak corona intensity is at an additional radius of 7 pixels. To a reasonable approximation, intensity (for all three colors and for their sum) then falls off as an exponential, following roughly $I = I_0 e^{-0.025p}$ where $p$ is how many pixels a point is outside the main emission ring. To model the spectrum:

1. Set the center of the emission line at the appropriate radius from the origin.
2. Over a circle of radius ~ 200 pixels, compute the intensity for each pixel for that line

3. Set a cutoff intensity for each pixel of 255 counts (that's the actual cutoff for JPGs and BMPs)
4. Add all the lines together at the appropriate radius
5. See what it looks like and tweak the model

I pulled up my trusty Embarcadero *Delphi* compiler and got to work. Here's the image as it first came out.

Compare this to the actual photograph. There's no light between the circular patterns due to line emission. We need to add continuum. A little added coding and tweaking of relative line intensity gives:

Perfection? No. Not bad? Yes. What is missing?

1) The intensity in the middle of the donut hole in the corona isn't zero – there's earthshine reflected by the moon. Looking back at the "Corona Cross-section Undispersed" plot, data practically screamed this, but I missed it until I saw the simulation above!
2) There's no noise and no scattering from the clouds. Since the simulation is a BMP, there's no information loss that inevitably occurs in JPG encoding.
3) The relative response at different wavelengths was only approximate, and there was no attempt to match the blackbody curve for the continuum. There's too much blue (relatively) in the simulation with continuum.

I could of course refine all the parts of the model, but successive improvement of models as differences between observation and model are noticed is a lot of what science is about.