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Image Processing of Narrow Band Solar Eclipse Data Using Python and MaxIm DL

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Image Processing of Narrow Band Solar Eclipse Data Using Python and MaxIm DL

Rydia Hayes-Huer

Submitted in Partial Completion of the Requirements for Departmental Honors in Physics

Bridgewater State University

May 11, 2020

Dr. Martina B. Arndt, Thesis Advisor
Dr. Thomas P. Kling, Committee Member
Image Processing of Narrow Band Solar Eclipse Data Using Python and MaxIm DL

Rydia Hayes-Huer

Mentor: Dr. Martina Arndt

May 2020

Abstract

On July 2, 2019, a total solar eclipse (TSE) was observable from Chile and Argentina. In Chile, I worked alongside the Solar Wind Sherpas, an international group led by Dr. Shadia Habbal from the University of Hawai‘i Institute for Astronomy, to make observations of the solar corona and gather information about its elemental composition. Narrow band data were collected for Fe XI, Fe XIV, and Ar X. Data collected during TSE observations can be used to help solve two puzzles in solar physics: the coronal heating problem and the mechanisms responsible for the fast and slow solar winds. Narrow band images were processed and analyzed with MaxIm DL and the process was replicated by code I wrote in Python. The goal for this project was to write image processing code in Python to recreate what the image processing package MaxIm DL does.
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Acknowledgments

I would like to thank my mentor, Dr. Martina Arndt, for all her guidance and support throughout this project.

I would also like to thank Dr. Shadia Habbal for making it possible to be a part of the July 2, 2019, total solar eclipse expedition and for all the hard work she put into it to ensure its success. And thank you to the Solar Wind Sherpas who worked with me and who also made this expedition successful and a special thanks to Mr. Judd Johnson for teaching us how to use the equipment, Dr. Miloslav Druckmüller for creating beautifully processed eclipse images, and Mr. Sage Constantinou and Mr. Bryan Yamashiro for helping with Python code.

Thank you to the Mamalluca Team: Mr. Rob Havasy, Miss Hayley Arndt, Mr. Ben Boe, Ms. Tülin Bedel, Mr. Benedikt Justen, Mr. Danilo LoBarenchea, Ms. Sarah Auriemma.

Thank you to fellow Bridgewater State University Physics students Ms. Auriemma and Mr. Daniel Smith for all their contributions to pre-eclipse solar monitoring and for being a fantastic team.

Thank you to the Adrian Tinsley Program (ATP), the National Science Foundation (NSF), and the Massachusetts Space Grant consortium for providing funding for this project.

And lastly, thanks to the MaxIm DL team for providing a license to use from home during the 2020 pandemic.
1. Introduction

1.1 The Sun

At only 150 million km away, the Sun is the closest star to Earth. It is a yellow dwarf main sequence star composed of mainly hydrogen. It has a radius of $7 \times 10^5$ km and is made up of highly ionized gas called plasma (“Our Sun In Depth”). Plasma swirls within the Sun, creating electric currents and producing a magnetic field that extends far beyond our solar system.

1.1.1 Composition and Structure

The Sun is composed of $\sim 73\%$ hydrogen, $25\%$ helium, $1\%$ oxygen, and the remaining $1\%$ is made up of heavier elements, such as carbon and iron (Table 1.1) (Chown 27).

<table>
<thead>
<tr>
<th>Element</th>
<th>Atmospheric Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>H</td>
</tr>
<tr>
<td>Helium</td>
<td>He</td>
</tr>
<tr>
<td>Oxygen</td>
<td>O</td>
</tr>
<tr>
<td>Carbon</td>
<td>C</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>N</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
</tr>
<tr>
<td>Neon</td>
<td>Ne</td>
</tr>
<tr>
<td>Sulfur</td>
<td>S</td>
</tr>
<tr>
<td>Argon</td>
<td>Ar</td>
</tr>
</tbody>
</table>

Table 1.1: Elemental Composition of the Sun

There are three inner layers and three outer layers of the Sun (Fig. 1.1). The inner layers include the core, radiative zone, and convection zone. The core is $\sim 1.5 \times 10^7$K (27 million °F). Within the core, hydrogen is consumed through thermonuclear reactions forming helium, generating and releasing energy in the form of light. Just outside the core is the radiative zone, where temperatures drop from $\sim 7 \times 10^6$K to $2 \times 10^6$K (13 million to 3.6 million °F). The energy released from the core is carried
through this region by photons, which are absorbed and re-emitted so many times that a photon can take as many as one million years to escape this layer in what is referred to as the “random walk” (Carroll and Ostlie 276-277). Outside the radiative zone is the convection zone, where energy continues to make its way to the surface of the Sun through convection currents of heated and cooled gas.

![Figure 1.1: Layers of the Sun](image)

The outer layers include the photosphere, chromosphere, and corona. The photosphere is the visible surface of the Sun and extends to $\sim 100$ km. It is the brightest and coolest layer ($\sim 5 \times 10^3 K$, or 8,500°F). Temperatures rise through the chromosphere, which extends another 2 thousand km, to $2 \times 10^4 K$ (35,540°F). Separating the chromosphere from the corona is the transition region, where temperatures rapidly rise to $\sim 1 \times 10^6 K$ (1.8 million °F). Coronal temperatures can reach over $2 \times 10^6 K$ (3.6 million °F), three orders of magnitude hotter than the photosphere. At such high temperatures, hydrogen and helium are stripped of their electrons. Only the heavier elements, such as iron and calcium, are able to retain some of their electrons.

### 1.1.2 Solar Cycle

The Sun is like a giant magnet with the poles aligned with the spin axes. Every 11 years, the poles switch. This cycle affects solar activity, including the frequency of Sunspots. The start of the 11-year solar cycle is solar minimum, when the Sun is least active and has the fewest spots. Halfway through the cycle, the Sun reaches its solar maximum when Sunspot activity is dramatically higher (Fig. 1.2). The more solar activity there is, the more solar magnetic fields are affected—which in turn impacts the solar corona.
A closer look at the most recent cycle shows that solar maximum occurred near 2014 (a period of heightened solar activity) and minimum took place near 2019 (lessened solar activity) (Fig. 1.3).

Figure 1.3: Sunspot numbers from 2008 to 2020 from spaceweatherlive.com including white light images of the 3/20/2015 and 7/2/2019 TSEs taken by M. Druckmüller. Notice that coronal magnetic fields are concentrated near the equator near solar minimum.
1.2 Total Solar Eclipses

1.2.1 Geometry

A Total solar eclipse (TSE) occurs about every 18 months. While the moon passes between the Earth and Sun every 29 days, the moon’s orbit is inclined by $\sim 5$ degrees (Fig. 1.4). As a result, the Sun, moon, and Earth are perfectly aligned every 6 months. However, the moon is not always the same distance away from the Earth—for a TSE to be visible, the moon must be at its closest point, or perigee. These conditions are met about every 18 months.

![Diagram of solar eclipse phases and alignment](image)

**Figure 1.4:** Conditions for a solar eclipse are dependent on the inclination of the moon’s orbit, from www.virtualtelescope.eu

The moon casts a shadow that is $\sim 1.6 \times 10^5$ m in diameter ($\sim 100$ miles) that moves across Earth at $\sim 450$ m/s ($\sim 1000$ mph). The path traced by this shadow is called the path of totality (Fig. 1.5).
Within the penumbra of this shadow, an observer on Earth will see a partial solar eclipse. The path of totality is cast by the umbra of the moon’s shadow (Fig. 1.6).

TSEs are broken into five stages (Fig. 1.7). Totality begins on second contact (C2) and ends on third contact (C3), and usually only lasts a couple of minutes.
1.2.2 Solar Wind Sherpas

The Solar Wind Sherpas are an international group of scientists led by Dr. Shadia Habbal of the University of Hawaii Institute for Astronomy, that travel the world to observe and collect data on TSEs. As of 2019, they have been on 15 eclipse expeditions, including the 2 July 2019 TSE. They specialize in using coronal forbidden emission lines, such as Fe XI and Fe XIV, to measure electron temperatures, ionic properties, and the properties of the magnetic field out to several solar radii. To do this work, they use state of the art instruments that they routinely improve upon.

1.3 Solar Physics Puzzles

1.3.1 Coronal Heating

The corona is the hottest, yet dimmest of the Sun’s outer layers (∼1 million times fainter than the solar surface), and can only be observed from Earth during a TSE (Fig. 1.8). The fact that the corona is so much hotter than the photosphere even though it is farther away from the Sun’s surface is known as the coronal heating problem.
This coronal heating problem, first discovered in the 1940s, has baffled astronomers for more than half a century. Current understanding is that the corona is most likely heated by more than one mechanism. Some of the mechanisms proposed are energy deposits from rising and crashing plasma waves, and nanoflares—continuous explosions caused by twisting magnetic fields in the corona (Zell 2015).

1.3.2 Solar Winds

Solar winds are pushed out through gaping holes in the corona, known as coronal holes, carrying an imprint of the magnetic field. The speeds of these solar winds fall into two categories: slow ($\sim 3.5 \times 10^5$ m/s or $7.8 \times 10^5$ mph) and fast ($\sim 9 \times 10^5$ m/s $2 \times 10^6$ mph). The mechanisms responsible for these two wind speeds is another unsolved solar physics puzzle.
Solar winds are slow at the equator and fast at the poles; NASA’s Parker Solar Probe spacecraft is currently gathering data along the Sun’s equator. The “closed corona” refers to large loops of magnetic field lines over magnetically active regions. “Open corona” regions do not form loops and stretch out into space, where solar material can escape and cooler coronal holes are created. These cooler areas are at the source of the faster winds at the Sun’s poles. Theories on the mechanisms responsible for the solar wind speeds include the expansion factor theory, which claims both fast and slow solar winds originate on open field lines, and the theory that open and closed field lines switch through a process called magnetic reconnection (Garner 2018).

1.4 Data to Inform Solutions

In order to test coronal heating and solar wind speed models, theorists need data from the photosphere far out to several solar radii. Plasma temperature, composition, speeds, and density are all important model parameters that can be determined by
observing coronal lines, spectra, and white light.

### 1.4.1 Coronal Lines

Coronal lines can be used as a diagnostic tool to infer electron temperatures, ion densities, abundances and charge states, and the properties of the Sun’s magnetic field (Habbal et al. 2011) (Zanna and DeLuca 2017) (Fig. 1.10).

![Figure 1.10: Ionization equilibrium curves for coronal lines commonly used for eclipse observations (Habbal et al. 2011)](image)

Coronal structures, such as loops and hooks (Fig. 1.11) have been shown to be dominated by two electron temperatures which correspond to the peak ionization temperatures of Fe XI ($1 \times 10^6K$) and Fe XIV ($2 \times 10^6K$) (Habbal et al. 2010).
Emissions from Ar X and Ar XI, which are formed at similar temperatures to Fe XI and Fe XIV respectively, have also been found to be an excellent diagnostic tool (Zanna and DeLuca 2017). The Fe/Ar ratio in both the Fe XI and Fe XIV temperature regions can help identify candidate regions for the origin of slow solar wind throughout the corona (“Observing the Corona”).

1.4.2 Spectroscopy and White Light Imaging

Spectroscopy is the study of the interactions of matter and electromagnetic waves using the absorption and emission of light. Spectroscopic measurements of the corona can be used to determine coronal composition and plasma speeds.

White light images (the light our eyes can see) are important to determine coronal densities and magnetic field morphology—they provide a context in which researchers can interpret results.
2. Total Solar Eclipse of 2 July 2019

2.1 Eclipse Details

The path of totality for the 2 July 2019 eclipse traversed the South Pacific Ocean and passed through Chile and Argentina (Fig. 2.1). The Solar Wind Sherpas created three teams to travel to separate sites along the path of totality to maximize potential data collection: Rodeo and Mascasín in Argentina and Cerro Tololo Inter-American Observatory (CTIO) in Chile. I was assigned to the Mascasín, Argentina group, along with Dr. Arndt and fellow student Ms. Sarah Auriemma.

![Figure 2.1](xjubier.free.fr)  
**Figure 2.1:** Path of totality for the 2 July 2019 TSE from xjubier.free.fr

All teams rendezvoused in Santiago, Chile before breaking off to their respective sites. Our team was later relocated to Mamalluca Observatory in Chile (Fig. 2.2) due to poor weather making travel across the Andes into Argentina impossible.

![Figure 2.2](www.eclipse-chasers.com)  
**Figure 2.2:** Mamalluca Observatory site within path of totality from www.eclipse-chasers.com
Totality at Mamalluca Observatory began at 4:38:35 PM local time and lasted 2.5 minutes (Fig. 2.3). The altitude of the Sun was 13°37’17.5”.

![29°00’24’S 70°42’06”W](image)

Total solar eclipse visible (100.00% coverage of Sun)  
Magnitude: 1.014  
Duration: 2 hours, 23 minutes, 14 seconds  
Duration of totality: 2 minutes, 30 seconds  
Partial begins: Jun 23, 2019 at 3:23:31 pm  
Full begins: Jun 23, 2019 at 4:38:35 pm  
Maximum: Jun 23, 2019 at 4:39:50 pm  
Full ends: Jun 23, 2019 at 4:41:05 pm  
Partial ends: Jun 23, 2019 at 5:46:45 pm  
Times shown in local time (CLT)

**Figure 2.3:** Solar eclipse time and duration at Mamalluca Observatory from www.timeanddate.com

### 2.2 Pre-eclipse Solar Monitoring

Solar activity monitoring began on 6/1/19 before traveling to South America. Monitoring solar activity during the Sun’s rotation prior to a total solar eclipse aids in the prediction and analysis of the shape of the corona during the eclipse. I created a program in Python using the SunPy package to download and organize FITS (Flexible Image Transport System) images from The Solar Dynamics Observatory (SDO)’s Atmospheric Imaging Assembly (AIA) for the wavelengths 171 Å and 193 Å. SDO is a space-based telescope launched by NASA in 2010 that orbits the Sun, taking around 480 solar images in multiple wavelengths a day. I collected an average of 960 images a day from June 1st to July 2nd. Mr. Dan Smith, a fellow student assigned to the Cerro Tololo, Chile team, converted the FITS images to TIFF (Tagged Image File Format). He then applied a log transformation to each image using MaxIm DL to enhance the contrast, bringing out more detail so that solar activity could be more easily identified. The enhanced images were stitched together in Python to create daily movies of the rotating Sun. Ms. Auriemma wrote a Python script to generate seamless animations of the rotating Sun for the entire monitoring period in 171 Å, 193 Å, and 6173 Å (both intensity and magnetogram) from SDO.

I gathered Active region data from NOAA (National Oceanic and Atmospheric Administration) and coronal hole data from CHIMERA (Coronal Hole Identification via Multi thermal Emission Recognition Algorithm) (Fig. 2.4). These data are freely available from SolarMonitor.org.
Figure 2.4: CHIMERA image from SolarMonitor.org. Coronal holes are labeled CH1-CH4.

I used Stellarium, an open-source planetarium software, to get a visual sense of the Sun’s altitude during totality (Fig. 2.5). The lower the Sun is in the sky, the more atmosphere sunlight has to go through. This has to be taken into account during data analysis. On eclipse day, totality for the TSE began at 4:38 PM and lasted until 4:41 PM. Sunset was at 5:46 PM.

Figure 2.5: Predicted altitude of the Sun during maximum eclipse as seen from Mamalluca Observatory using Stellarium.
All pre-eclipse data products were compiled onto portable hard drives and distributed to eclipse teams, along with a calendar summarizing solar activity (Fig. 2.5). Levels of solar activity were determined by looking at the number of sunspots, location and size of coronal holes, and any significant magnetic field activity. There were no sunspots, which was not unusual for solar minimum.

<table>
<thead>
<tr>
<th>Sunday</th>
<th>Monday</th>
<th>Tuesday</th>
<th>Wednesday</th>
<th>Thursday</th>
<th>Friday</th>
<th>Saturday</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO DATA</td>
<td>NO DATA</td>
<td>CH data available</td>
<td>CH data available</td>
<td>CH data available</td>
<td>CH data available</td>
<td>CH data available</td>
</tr>
<tr>
<td>2 Day - 30</td>
<td>3 Day - 29</td>
<td>4 Day - 28</td>
<td>5 Day - 27</td>
<td>6 Day - 26</td>
<td>7 Day - 25</td>
<td>8 Day - 24</td>
</tr>
</tbody>
</table>

- Activity on equator on E limb
- CH data available
- Low lying activity on NE limb
- Two pairs of large magnetic regions straddling W limb
- CH data available
- Activity on equator on W limb
- Activity on equator on W limb
- CH data available
- CH data available

Figure 2.6: Calendar summarizing daily solar activity
3. Methods

3.1 Equipment

Each observing site was outfitted with a white light imaging assembly, spectrometer, and narrow band imaging assembly. The equipment for Mamalluca Observatory was housed in a tent set up at an ideal observing location for the eclipse. Power was fed to the tent from an outlet in a nearby building. All equipment was also supplied with backup batteries. Special care was taken to keep all equipment within the tent clean and dust-free.

3.1.1 White Light Imaging Assembly

White light, also referred to as continuum, is the full spectrum of light emitted by the photosphere reflected by Thompson-scattered emission from electrons, and is the same light that our eyes are able to see. Each observing site was equipped with white light imagers (Fig. 3.1) to capture high resolution white light images. Each setup included a mount, multiple digital SLR cameras, and telescopic lenses. White light provides information about coronal structures as well as context for narrow band images and spectra taken by the other instruments. Solar Wind Sherpa Ms. Tülin Bedel operated the white light imagers at the Mamalluca Observatory.

Figure 3.1: White light imaging assembly at Mamalluca
3.1.2 Spectrometer

Spectra from the Sun’s corona during a TSE can yield information about the corona’s ion composition and speed. The spectrometers at each site were designed by Dr. Adalbert Ding and provide high resolution spectra. Each spectrometer used three cameras to record spectra in the red, green, and blue channels via a series of diffraction gratings (Fig. 3.2).

Ms. Auriemma assisted Mr. Benjamin Boe, a PhD candidate from the IfA, with the delicate alignment of the optical equipment within the spectrometer, as well as with its calibration and installation at the eclipse site. Mr. Boe operated the spectrometer during the eclipse.

3.1.3 Narrow Band Imaging Assembly

The narrow band imaging assemblies were designed and built at the Institute for Astronomy at the University of Hawai‘i. Each assembly comes equipped with six Atik 314L cameras with fans to keep them at 0°C and filters which tune to specific wavelengths emitted from plasma at temperatures ranging between 0.5 and 2.5 million K and allow for the exploration of the whole corona during each eclipse observation (Zanna et al. 2014). Heaters are needed for each filter. The narrow band imaging assembly at the Mamalluca site was equipped with filters for Fe (iron) XI and XIV, and Ar (argon) X. Fe XI and Ar X detect plasma at ∼1 million Kelvin, and Fe XIV detect plasma at ∼2 million Kelvin. Table 3.1 lists the wavelengths and temperature
for each filter. On band refers to each ion’s spectral line. Off-band wavelengths are slightly tilted to isolate and remove continuum from on band images (Habbal 2010).

Table 3.1: Spectral lines collected from the Narrow Band imagers

<table>
<thead>
<tr>
<th>Spectral Line</th>
<th>Fe XI (nm)</th>
<th>Fe XIV (nm)</th>
<th>Ar X (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization State</td>
<td>Fe$^{10+}$</td>
<td>Fe$^{13+}$</td>
<td>Ar$^{9+}$</td>
</tr>
<tr>
<td>on band $\lambda$</td>
<td>789.2</td>
<td>530.3</td>
<td>553.4</td>
</tr>
<tr>
<td>off band $\lambda$</td>
<td>788.0</td>
<td>529.0</td>
<td>552.3</td>
</tr>
<tr>
<td>$T_{max}$ (10$^6$K)</td>
<td>1.16</td>
<td>1.8</td>
<td>$\sim$1</td>
</tr>
</tbody>
</table>

I assisted with the time-consuming task of assembly and alignment of the narrow band imagers at the Mamalluca site (Fig. 3.3). Proper alignment of the six cameras took several days and the help of multiple people to achieve. Each camera was aligned to a distant reference point—we chose a prominent mountain peak in the general direction of the upcoming eclipse as our reference. The cameras were covered by Mylar solar shields to protect the optics from the Sun. The solar shields sustained damage from repeated re-use and were repaired with electrical tape and a Sharpie.

Figure 3.3: Aligning the narrow band imagers at the Mamalluca site. Image by Dr. Martina Arndt.

Each on/off band camera pair was controlled by their own laptop (Fig. 3.4). The mount was operated via a controller. I set up each computer and handled the operation of the narrow band cameras and mount during this expedition as well as file and data management.
3.2 Data Collection

3.2.1 Calibration Images

To reduce noise caused by the cameras’ sensors (such as defective pixels), dark frames were taken by covering each lens completely with a black plastic bag and several jackets (Fig. 3.5) immediately after the eclipse. For each iron band, 100 dark frames were taken at 0.1s and 100 at 6.4s, 80 were taken at 0.2, 0.4, 0.8, 1.6, and 3.2s for a total of 400 dark frames, and 20 were taken at 12.8s. For each argon band, 40 dark frames were taken each for exposure times of 0.1s and 12.8s, 100 for 0.2s exposures, 80 for 0.4, 0.8, 1.6, and 3.2s exposures, and 60 for 6.4s exposures.
To account for dust and other defects, 300 sky flat field images were taken for each filter, with 300 corresponding dark flats on the morning of the eclipse starting at 9 AM. Cameras were pointed at an even section of the sky away from the Sun to collect sky flats and then covered (similarly as Fig. 3.5) for dark flat collection. Figure 3.6 shows an example of sky flat and dark frame calibration images.

**Figure 3.5**: The narrow band imagers were covered with a black plastic bag and several jackets while collecting dark frames.

**Figure 3.6**: Calibration flat field (left) and dark flat frame (right) for Fe XIV

### 3.2.2 Narrow Band Data

An observing plan for the eclipse was provided by Solar Wind Sherpa Petr Štárha which included exposure times (Table 3.2) and the order in which they needed to be taken, as well as a short buffer to allow for the removal of the solar shields. The
program used to operate the cameras was updated with this information so that data collection would be automated during totality.

Table 3.2: Narrow band exposure times

| Spectral Line: Fe XI, Fe XIV, and Ar X | Exp. Times (s): 0.1, 0.2, 0.4, 0.8, 1.6, 3.2, 6.4, and 12.8 |

Because the window of totality is so short, we performed several practice runs the day before and the day of the eclipse. The laptops were restarted a few hours before the eclipse to avoid program freezing. Tracking and alignment were checked periodically leading up to totality. In order to begin data collection simultaneously on all three laptops, Ms. Auriemma helped initiate the scripts at the start of totality. No problems were encountered during the implementation of the observing plan and I was able to witness my first total solar eclipse during data collection.
4. Image Processing

All three observing sites had excellent weather and were able to gather data. The next step is to prepare these data for analysis and I focused my efforts on the data from Mamalluca.

4.1 Calibration

The calibration process was first performed with MaxIm DL and then I wrote code in Python to replicate—and understand—the process. I chose a 0.8s Fe XIV eclipse image to process in MaxIm DL and in Python. To prepare an image for data analysis, a raw image has to be corrected for hot pixels and other defects. We do this by “subtracting out” master flat and dark field calibration images. To create master calibration images, the following steps were taken:

- the following sets were combined and averaged: 80 0.8s dark frames, 300 1.11s sky flat field images, and 300 1.11s dark flats
- the averaged dark flat was subtracted from the averaged flat field image
- the averaged flat was then divided by its median to create a master flat

\[
\text{master flat} = \frac{[(\text{sky flat})_{\text{ave}} - (\text{dark flat})_{\text{ave}}]_{\text{median}}}{(\text{sky flat})_{\text{ave}} - (\text{dark flat})_{\text{ave}}} \quad (4.1)
\]

The averaged dark frame was then subtracted from the eclipse image and the eclipse image was divided by the master flat. This flat “subtraction” process was repeated for the corresponding off band images.

The next step is to align the calibrated on and off band images and subtract the off band to remove continuum:

\[
\text{Calibrated} = \left(\frac{\text{image} - \text{dark flat}_{\text{ave}}}{\text{master flat}}\right)_{\text{on band}} - \left(\frac{\text{image} - \text{dark flat}_{\text{ave}}}{\text{master flat}}\right)_{\text{off band}} \quad (4.2)
\]

To test whether images processed with Python were the same as those processed with MaxIm DL, images were first compared by manually looking at pixel counts in
SAO DS9. As a next test, the images were then loaded into an array in Python and the ratio of each pair of calibration images was taken to determine whether or not the images were the same—if each pixel value is 1, the images are the same.

### 4.2 MaxIm DL Image Processing

Image processing in MaxIm DL can be done through creating calibration sets (Fig. 4.1). To create a set, the calibration type (in this case, DARK or FLAT) was selected and the appropriate TIFF files were loaded into the set. For dark sets, Dark Frame Scaling and Bad Pixel Map were set to “none”. For flat sets, Flat Norm. was set to “Monochrome”. Combine Type was set to “Average” for all sets.

![Image processing in MaxIm DL](image)

**Figure 4.1:** Calibration setup in MaxIm DL

MaxIm DL also includes a “stack” feature, with different options for combining images (i.e. average, sum, etc.). The stack feature was used to combine and average each set of calibration images. The combined images were then exported as FITS for comparison with images combined and averaged in Python. After completing comparisons, the eclipse images were processed according to the steps previously outlined using calibration sets. The calibration sets enable image processing without the need to manually stack and average calibration images.
4.3 Python Image Processing

To process images in Python, I took advantage of several packages: AstroPy for FITS handling, Skimage for circle detection, SunPy for analyzing solar data, NumPy for creating arrays, MatPlotLib for creating plots, os for file handling, and PIL for TIFF handling.

To combine and average images, the os package was used to locate the directory containing calibration images. The first image in the directory was opened with PIL and stored into a NumPy array with float64 data type to avoid loss in pixel counts. The remaining images were added to the array via a for-loop and the final array was divided by the number of images within the directory. AstroPy was used to write the resulting image to a FITS file.

Once all calibration images were combined and averaged, AstroPy was used to create variables for each image so that mathematical operation could be performed between them to complete the processing steps for the on and off band eclipse images and to also compare the images processed with Python to those processed in MaxIm DL.

Skimage was used to locate the Sun’s center in both the processed on and off band eclipse images so that they could be properly aligned and the off band image could be subtracted off.
5. Results/Discussion

5.1 Results

When comparing calibration images created with Python to those created in MaxIm DL using SAO DS9, no deviations were found between their pixel counts (Fig. 5.1). Comparisons of calibration images performed with Python showed a negligible difference between pixel counts (Fig. 5.2).

Figure 5.1: Comparison in SAO DS9 between master flats prepared in MaxIm DL (left) and Python (right). Physical x and y coordinates represent a specific location in the image. The pixel count at that location is outputted in the “Value” field. Multiple coordinates were compared and no deviations were found.
Figure 5.2: Comparisons done with Python. Python calibrated images were divided by MaxIm DL calibrated images and the resulting arrays were checked for deviations from 1. The complete code can be found in the appendix.

The ratio of fully calibrated eclipse images (Fig. 5.3) deviated from 1 by up to 12%.
Attempts to align and subtract the off band image from the on band image were unsuccessful (Fig. 5.4). The alignment is close enough that you can get a sense of what subtracting the continuum off will look like. However, the alignment needs to be as close to perfect as possible before subtracting the off band image in order to extract meaningful data from the eclipse image.
Figure 5.4: Off-band subtracted eclipse image. Hough circle from the Skimage package was used to align the on and off band images. The alignment was unsuccessful as evidenced by the bright crescent along the left limb

5.2 Discussion and Future Work

Before the eclipse image was divided by the calibrated master flat, image processing in Python yielded nearly identical results to image processing in MaxIm DL. A closer look at MaxIm DL’s flat calibration process may be necessary to root out the cause for the variations in pixel counts—some calibration processes are handled automatically in MaxIm DL, such as applying pedestals to keep pixel counts from becoming negative and renormalization to adjust the range of minimum and maximum pixel counts.

Additionally, to properly subtract off the continuum from the eclipse image, I will continue to work on methods to align the on and off band eclipse images. There are a number of packages for Python designed to aid in circle detection and image alignment. Hough circle showed promising results, but will need very fine tuning to manually adjust the center and rotation of the images. However, it would be preferable to create a program that allows a user to easily reproduce this image processing step without the need to adjust so many parameters if possible.
References


Appendix

Python program to take the average of a set of images

```
import the necessary packages:
In [1]:
import os
from PIL import Image
import numpy as np
from astropy.io import fits
import matplotlib.pyplot as plt

Locate files and create an array to store image data:
In [2]:
files = os.listdir('Jerk FLATS/')
image = Image.open('Jerk FLATS/' + files[0])
im = np.array(image, dtype=np.float64)
# Define the first image in the directory
# Store image data in a numpy array

Run a for-loop to stack each image's data into the array:
In [3]:
for i in range(1, len(files)):
    currentimage = Image.open('Jerk FLATS/' + files[i])
    im = np.array(currentimage, dtype=np.float64)
    # Open the next image in directory
    # Store image data into the array

Take the average and save in fits format:
In [4]:
im = im/len(files)
# Average by dividing by the number of images added to the array
In [5]:
fits.writeto('MasterDkFlat.fits', np.array(im))
# Write the array to a fits file
```

Calibration

```
import necessary packages:
In [1]:
from astropy.io import fits

Get FITS data:
In [2]:
MasterDkFlat = fits.getdata('MasterDkFlat python.fits')
MasterFlat = fits.getdata('MasterFlat python.fits')
MasterDark = fits.getdata('MasterDark python.fits')

Subtract master darkflat from master flat to create calibrated master flat:
In [3]:
CalMasterFlat = MasterFlat - MasterDkFlat

Save new calibrated master flat:
In [4]:
fits.writeto('CalMasterFlat.fits', CalMasterFlat)

Subtract master dark from eclipse image and save:
In [5]:
im = fits.getdata('FEXIvon python.fits')
In [6]:
im = im - MasterDark
In [7]:
fits.writeto('FEXIvon DarkSub python.fits', im)
```
Python and MaxIm DL Comparisons

```python
# from astropy.io import fits
import matplotlib.pyplot as plt
import numpy as np

Create arrays for each FITS file to be compared:

```python
# Master Flats
FP = fits.getdata('Master F.P.fits')  # Python
FM = fits.getdata('Master F.M.fits')  # MaxIm DL

# Master Darks
DP = fits.getdata('Master D.P.fits')
DM = fits.getdata('Master D.M.fits')

# Master Darkflats
DFP = fits.getdata('Master DF.P.fits')
DFM = fits.getdata('Master DF.M.fits')

# Eclipse Image
P = fits.getdata('ON P.fits')
M = fits.getdata('ON M.fits')

# Dark-Subtracted Eclipse Image
DSP = fits.getdata('D-SUB P.fits')
DSM = fits.getdata('D-SUB M.fits')

# Dark-Subtracted Flat
DSFP = fits.getdata('D-SUB F.P.fits')
DSFM = fits.getdata('D-SUB F.M.fits')

Check the ratio between FITS images created with Python and MaxIm. If they are the same, the elements in the new array should equal 1:

```python
F = FP / FM
D = DP / DM
DSP = DSFP / DSM

print(F)

```
```
[[1.00000004 0.99999996 1.00000004 ... 1.00000002 1.00000004 1.00000006]
 [0.99999997 1.00000001 ... 1.00000005 1.00000006 1.00000005]
 [1.00000004 0.99999994 ... 1.00000005 0.99999995 1.00000004]
 ...
 [1.00000005 1.00000001 1.00000005 ... 0.99999995 0.99999999 1.00000001]
 [0.99999999 0.99999999 1.00000006 ... 0.99999999 0.99999995 1.00000003]
 [0.99999996 0.99999998 1.00000004 ... 1.00000005 0.99999999 1.00000004]]
```

Each element does not equal 1. This function will check if any element deviates from 1 by more than 0.0001%:

```python
def compare(array):
    stop = False
    for i in range(len(array)):
        if stop:
            break
        for j in range(len(array[i])):
            if abs(1-array[i][j]) > 0.000001:
                print("flagged element: ",array[i][j])
                stop = True
                break
        if not stop:
            print("Comparison complete - no significant deviations found")
```
If an element is found in the array that deviates from 1 by more than 0.0001%, the function will print the flagged element and stop searching.

```
print("Compare Flats:")
compare(F)
print("\nCompare Darks:")
compare(D)
print("\nCompare Darkflats:")
compare(DP)
print("\nCompare Eclipse Images:")
compare(ON)
print("\nCompare Dark-Subtracted Eclipse Images:")
compare(OS)
print("\nCompare Dark-Subtracted Flats:")
compare(DSF)
```

Compare Flats:
Comparison complete - no significant deviations found

Compare Darks:
Comparison complete - no significant deviations found

Compare Darkflats:
Comparison complete - no significant deviations found

Compare Eclipse Images:
Comparison complete - no significant deviations found

Compare Dark-Subtracted Eclipse Images:
Comparison complete - no significant deviations found

Compare Dark-Subtracted Flats:
Comparison complete - no significant deviations found

Now check calibrated eclipse images. Calibrate the Python eclipse image by multiplying the dark-subtracted eclipse image by the median of the dark-subtracted flat divided by the dark subtracted flat:

```
CALP = DSP**(np.median(DSFP)/DSFP)
```

Create an array for the Maxim DL calibrated eclipse image and compare:

```
CALM = fits.getdata("CAL M.fit")
print("\nCompare Dark-Subtracted Flats:")
compare(CALM/CALP)
```

Compare Dark-Subtracted Flats:
flagged element: 0.0
If any element is equal to 0, this method will not work. Print the arrays to see what we’re working with:

```
print("Python:")
print(CALP)
print("\n\nMaxim DL:")
print(CALM)
```

Python:
```
[[26717.94011325 217.30229919 185.80324859 ... 170.58712979
  213.21088736 181.87925244]
 [23887.45134969 206.96658877 182.6859167 ... 211.34426434
  212.36295147 182.043917677]
 [30341.46497616 193.15838337 199.57730368 ... 186.77149573
  158.19860085 176.62228294]
 [25903.38311989 231.72122943 180.3629821 ... 183.27593972
  202.94495791 212.57424484]
 [202945.45840411 185.64518184 183.7142409 ... 179.18130527
  203.59997055 187.44895253]
 [30079.59990793 187.27691957 162.69519913 ... 148.49146819
  190.39256195 195.26261825]]
```

Maxim DL:
```
[[ 0.  218.88367 178.28442 ... 170.5742 213.04367
  181.39848]
 [ 0.  211.63455 184.36287 ... 218.31424 211.81859
  181.12777]
 [15808.511 195.30585 200.30295 ... 185.68859 157.94012
  175.91824]
 [ 0.  235.21863 183.41208 ... 185.11542 284.26736
  214.16678]
 [19931.246 188.9746 186.63771 ... 180.99197 285.46616
  188.90335]
 [17889.285 190.08168 165.80177 ... 158.48117 192.56099
  197.80101]]
```

Things look pretty close except for the first column. Trim the first column and try again:

```
CALM = np.delete(CALM,0,1)
```

This is closer, but not as close as the other comparisons. Adjust the function accordingly to check for any serious outliers:

```
def compare(array):
    stop = False
    for i in range(len(array)):
        if stop:
            break
    for j in range(len(array)):
        if abs(array[i][j] > 0.12):
            print("flagged element!",array[i][j])
        if not stop:
            stop = True
            break
    if not stop:
        print("Comparison complete - no significant deviations found")
```

```
print("\nCompare Dark-Subtracted Flats:")
compare(CALM)
```

Compare Dark-Subtracted Flats:
Comparison complete - no significant deviations found

There's up to a 12% deviation from 1.