An Airborne IR Spectrometer for Solar Eclipse Observations

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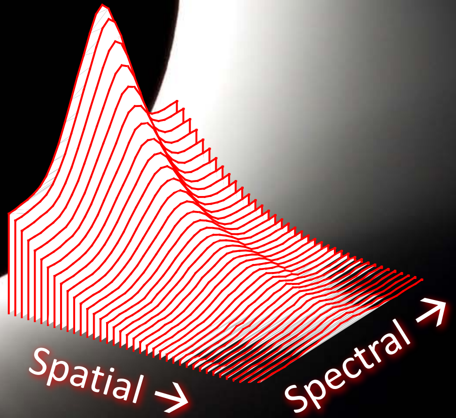


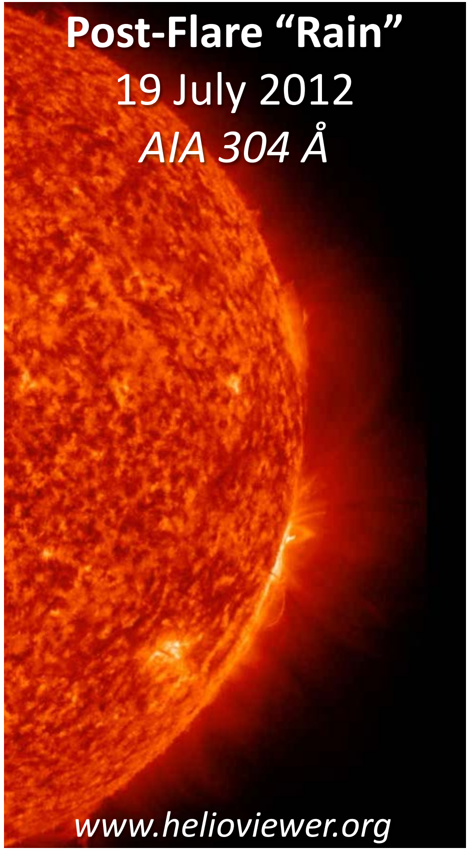
Photo Credit: NASA/Aubrey Gemignani

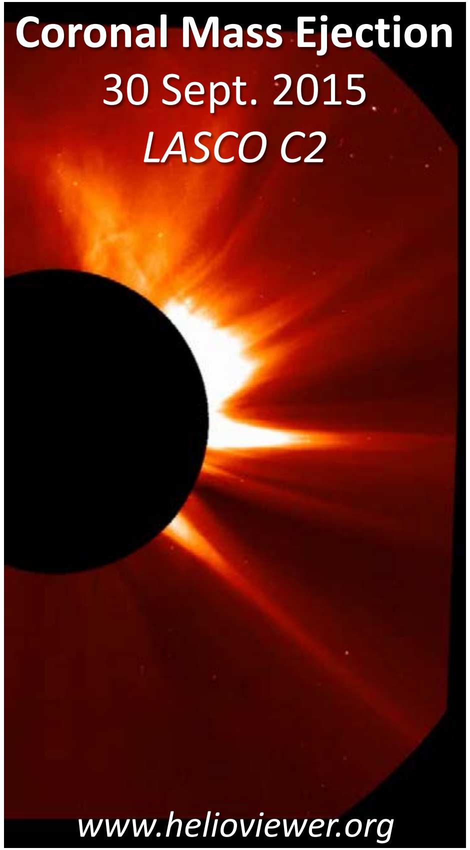
AIR-Spec Experiment

AIR-Spec measured **5 magnetically sensitive coronal emission lines** during the **2017 total solar eclipse** from the **NSF/NCAR Gulfstream V** research aircraft.

- New IR window in the solar corona
  - First time for high resolution coronal imaging spectroscopy, 1.4 – 4 µm
  - Pathfinder for observations of coronal magnetic fields
- New platform for high-resolution stabilized imaging on the GV
  - Enables new science in solar and atmospheric physics

Activity in the Solar Corona

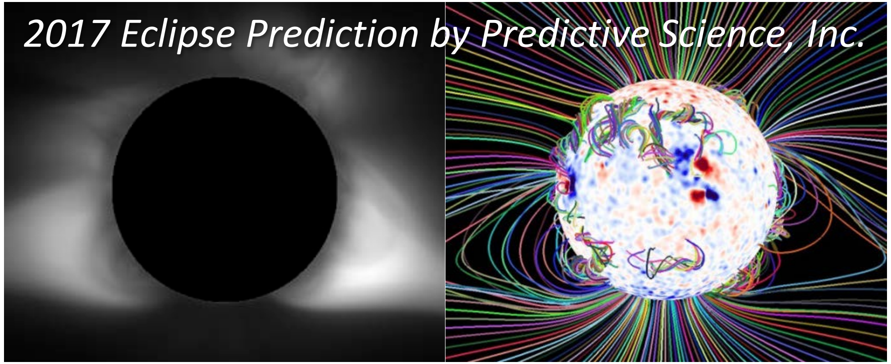




Coronal Magnetism

Coronal Magnetic Fields

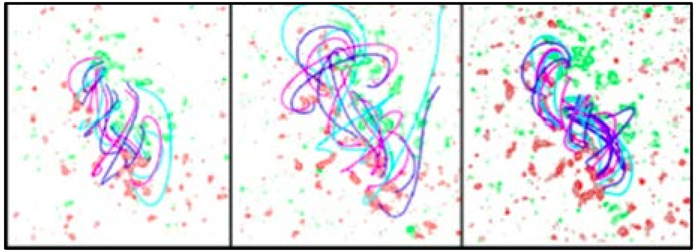
- Source of coronal heating
- Store energy for flares and CMEs
- Define coronal structure and dynamics
- But not routinely measured
  - Weak (3 – 13 G) → difficult to measure



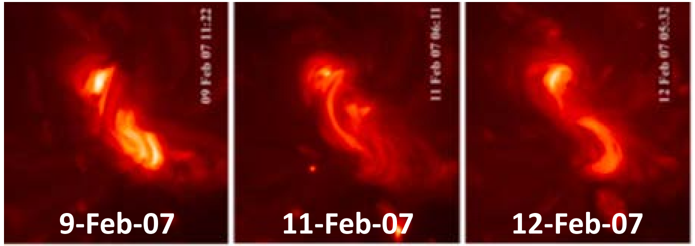
2017 Eclipse Prediction by Predictive Science, Inc.

http://www.predsci.com/corona/aug2017eclipse/solar_north.php

A. S. Savcheva et al. 2012, ApJ, 759, 105



Modeled B Field



Hinode X-Ray Telescope

Magnetic Field Modeling

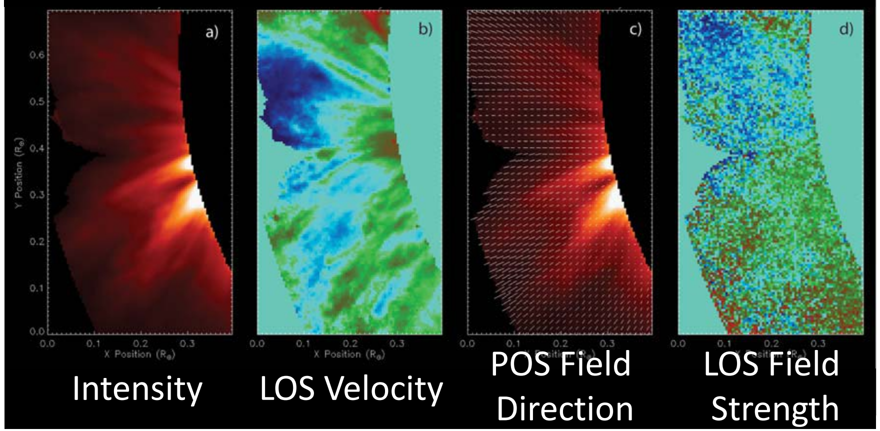
- Constraints: photospheric magnetic field, observations of coronal plasma
- Need routine measurements as ground truth for simulations

Coronal B Field Measurements

Method: Measure emission line polarization (e.g. Fe XIII, 1.0747 μm)

- **Circular** → LOS field strength (Zeeman effect, 10^{-4} × intensity)
- **Linear** → POS field direction (Hanle effect, 0.01 – 0.1 × intensity)

Coronal Multi-channel Polarimeter *Tomczyk et al. 2008*



- **Future direction**: expand to longer wavelength emission lines?
  - Higher signal: wavelength splitting $\Delta\lambda/\lambda \propto \lambda B$
  - Less impact from scattering and seeing
  - Recent improvements in IR detectors
- BUT mid-IR coronal emission lines are not well characterized. Need pathfinder mission to
  - Measure emission line properties
  - Develop technology for mid-IR coronal spectroscopy

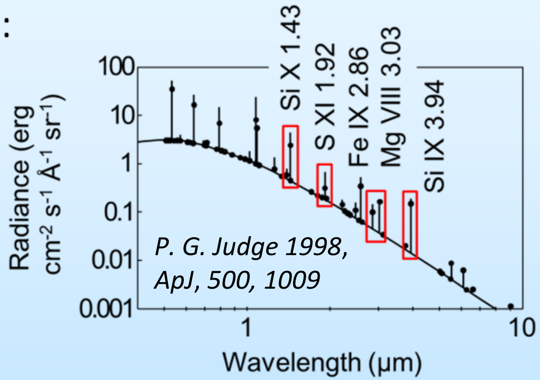
→ *Build a spectrometer (AIR-Spec) to observe the 2017 total eclipse*

Science Goals

Success Criteria

Identify one of the following magnetically sensitive coronal emission lines:

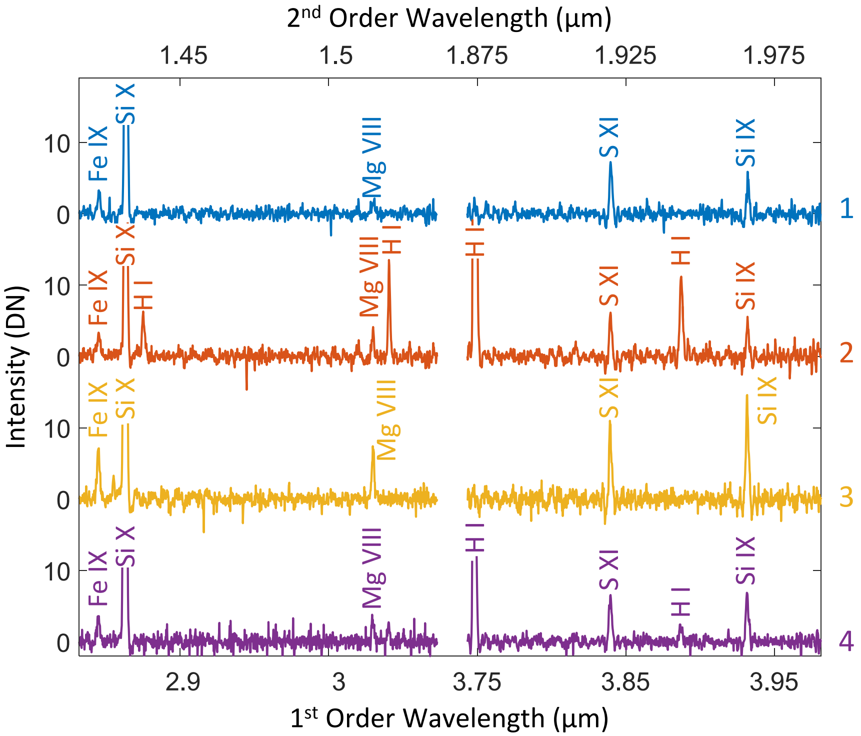
- **Si X**: 1.43 µm
- **S XI**: 1.92 µm
- **Fe IX**: 2.86 µm
- **Mg VIII**: 3.03 µm
- **Si IX**: 3.94 µm



Science Goals

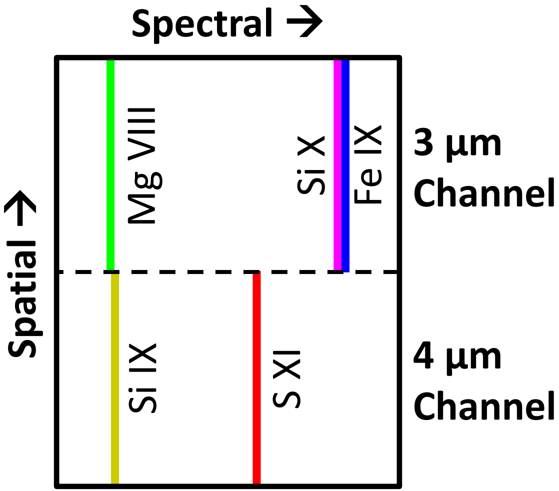
1. Identify line strengths as a function of position in the solar corona
2. Search for high frequency waves in the lines
3. Identify large scale flows in the corona
4. Complement ground-based eclipse observations

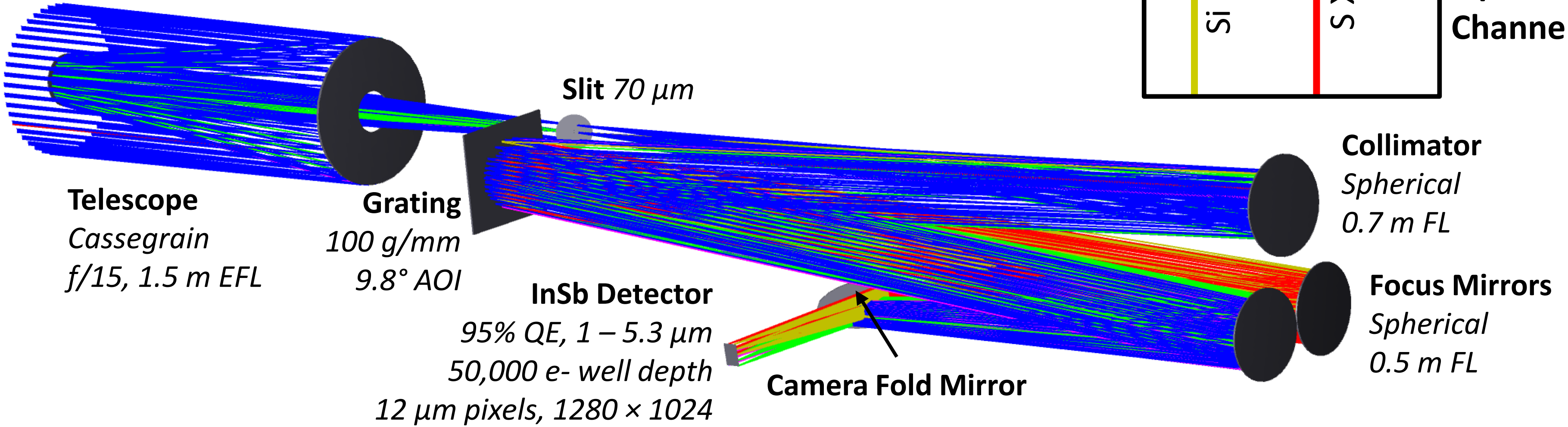
AIR-Spec Measurement



Optical Design

Channel/Order	3 μm/1st	4 μm/1st	3 μm/2nd	4 μm/2nd
Emission Lines	Fe IX, Mg VIII	Si IX	Si X	S XI
Spectral Range (μm)	2.82 – 3.07	3.74 – 3.98	1.41 – 1.54	1.87 – 1.99
Spectral Dispersion (Å/pix)	2.4		1.2	
Slit Length (R_{sun})	1.5			
Pixel Size (arcsec)	2.3			

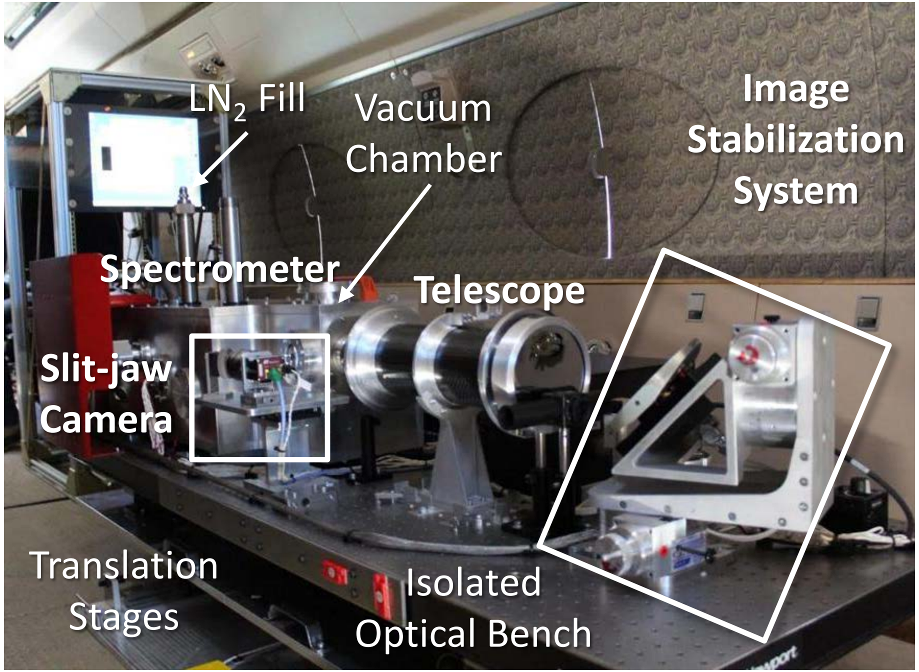




Instrument Implementation

*NSF/NCAR **G**ulfstream-**V** **H**igh-performance*
***I**nstrumented **A**irborne **P**latform for*
***E**nvironmental **R**esearch (**GV HIAPER**)*

***A**irborne **I**nfra**R**ed **Spec**trometer (**AIR-Spec**)*



*Biggest challenges: **image stabilization** and **thermal background reduction***

Image Stabilization System

Requirements

- Jitter below 2 pixels (4.6 arcsec) RMS over the exposure time of the IR camera
- Eclipse remains in the field of view for the length of totality (4 minutes)
- Algorithm can be fully tested before the eclipse (image-independent)

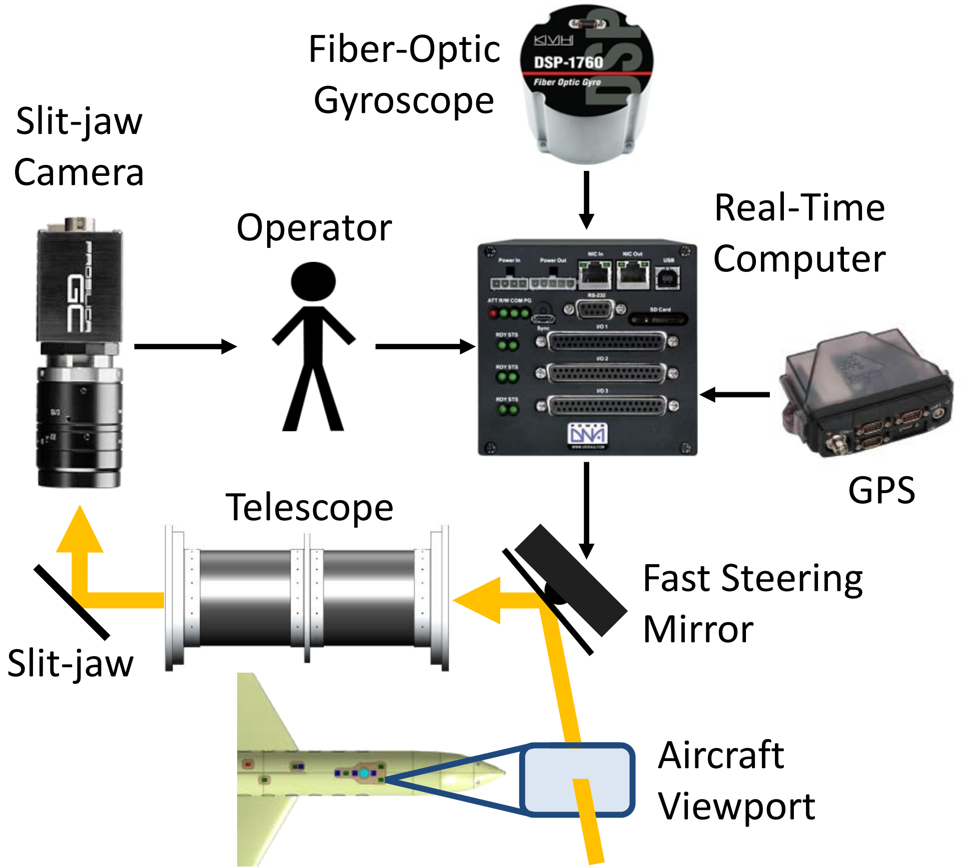
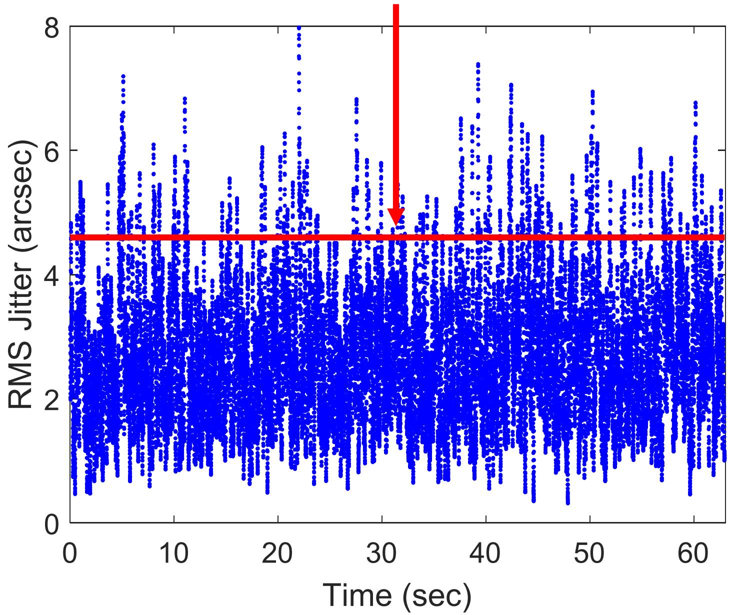


Image Stabilization Performance

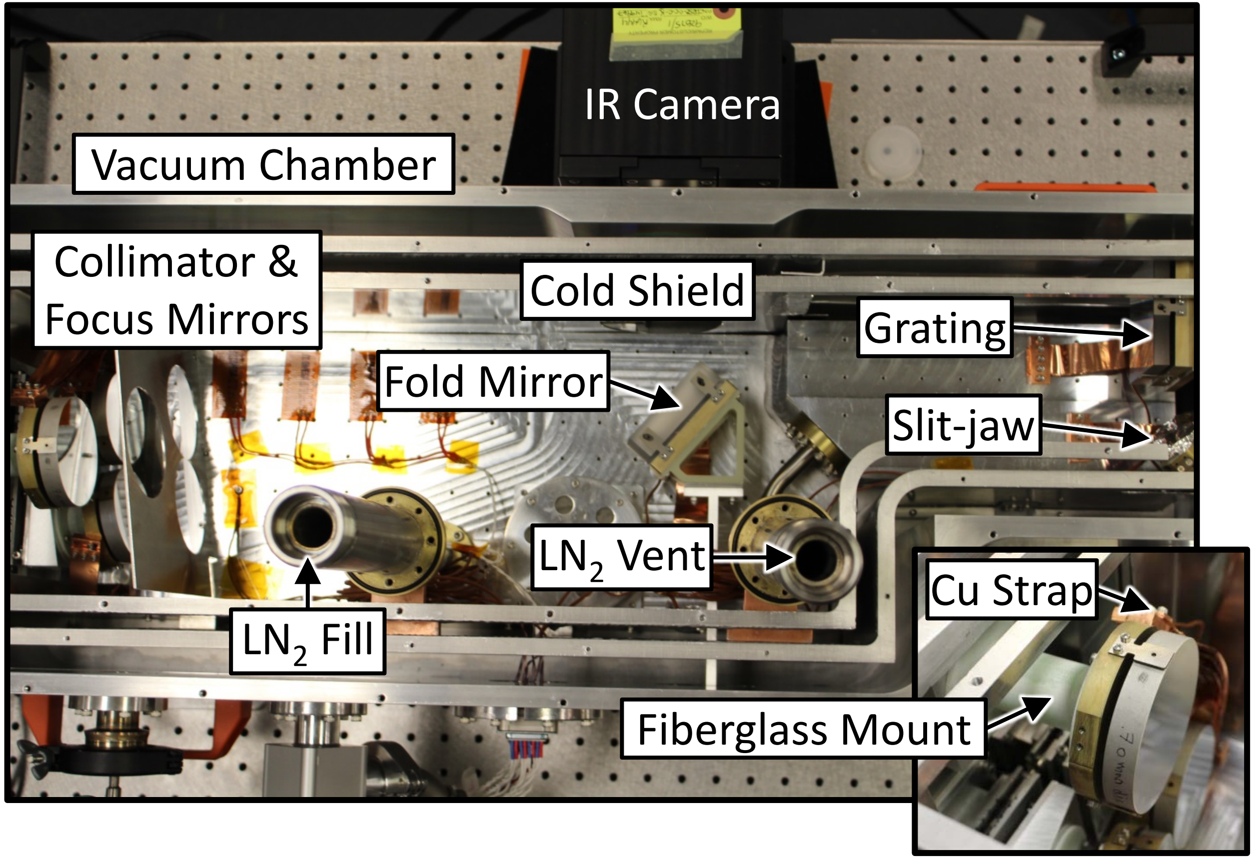
Full Moon, 14 Dec. 2016

94% of **60 ms** exposures have jitter below the **2 pixel** Nyquist limit



Total Eclipse, 21 Aug. 2017

Thermal Background Reduction



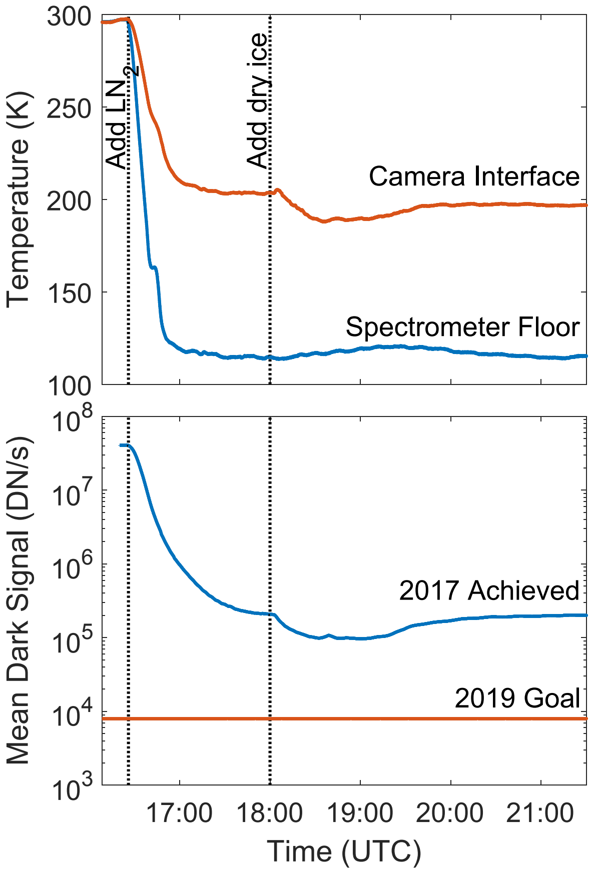
Spectrometer

- Optics and cold shield cooled to <150 K with LN_2
- Cold shield blackened to reduce reflectivity
- Vacuum chamber pressure below 10^{-3} Torr

IR Camera

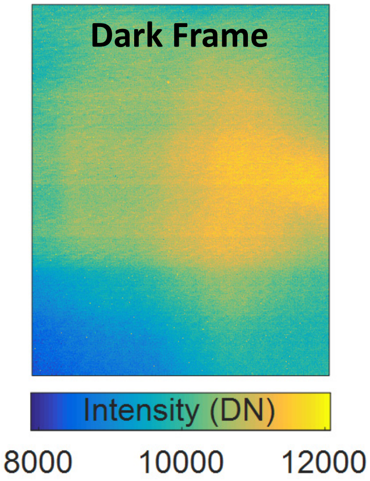
- Dry ice on camera interface
- Focal plane at 59 K
- Cold aperture to limit FOV
- Bandpass filter cuts 3.1 – 3.7 and > 4 µm

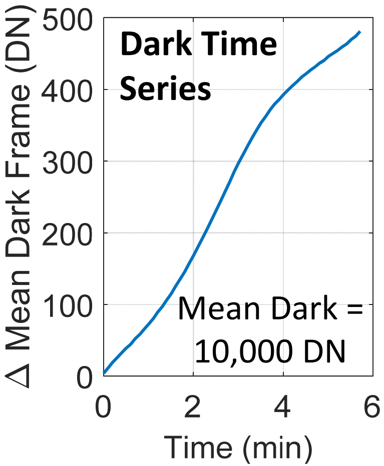
Thermal Background

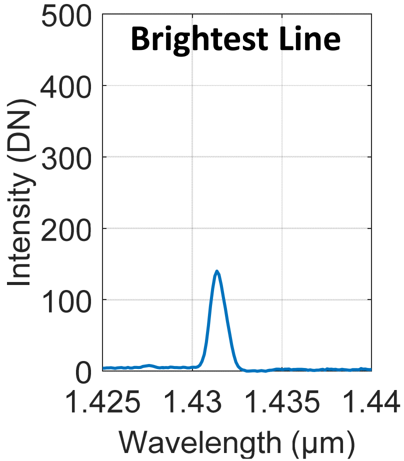


Even after reducing the background more than 200x:

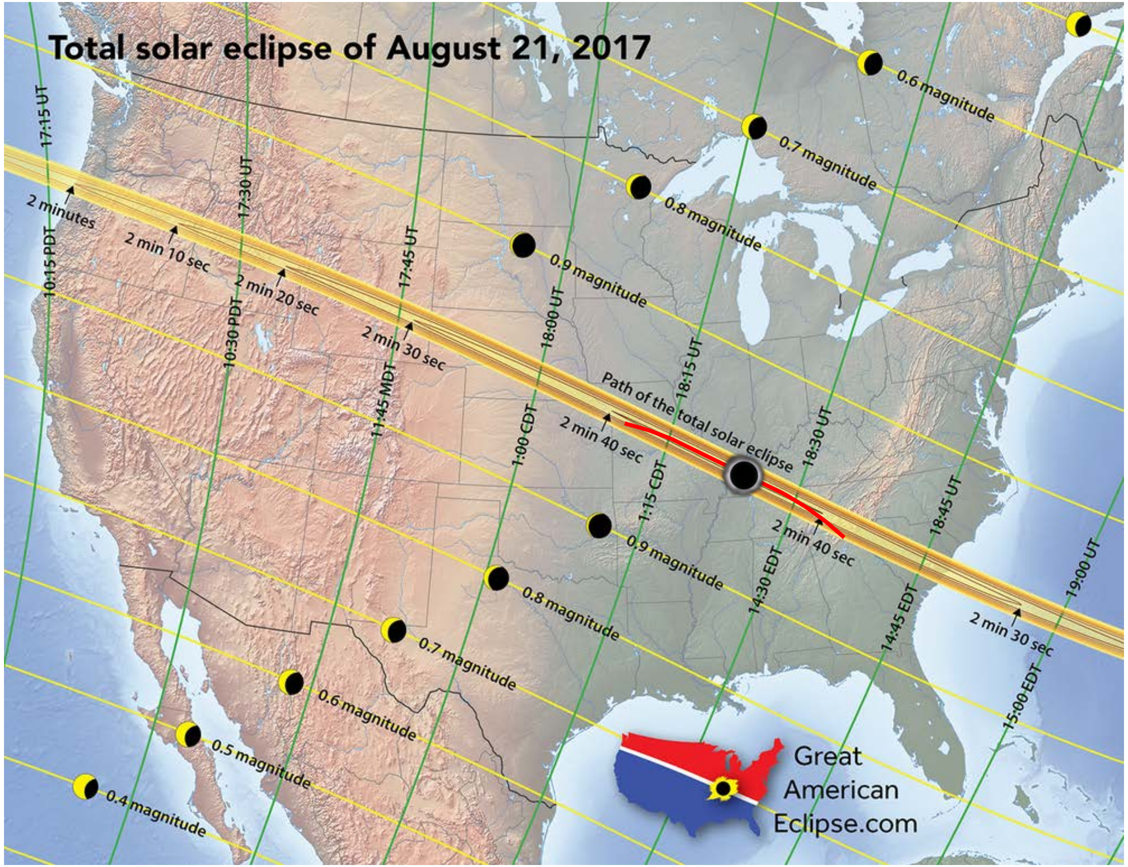
- Exposure time limited to 60 ms (goal: 1 sec)
- Mean dark background = 10,000 DN (vs. 150 DN line intensity)
- Dark background changes significantly during eclipse
  - 80 DN/minute increase + sinusoidal trend
  - Different behavior at image center vs. edges







Flight Planning



Observation Requirements

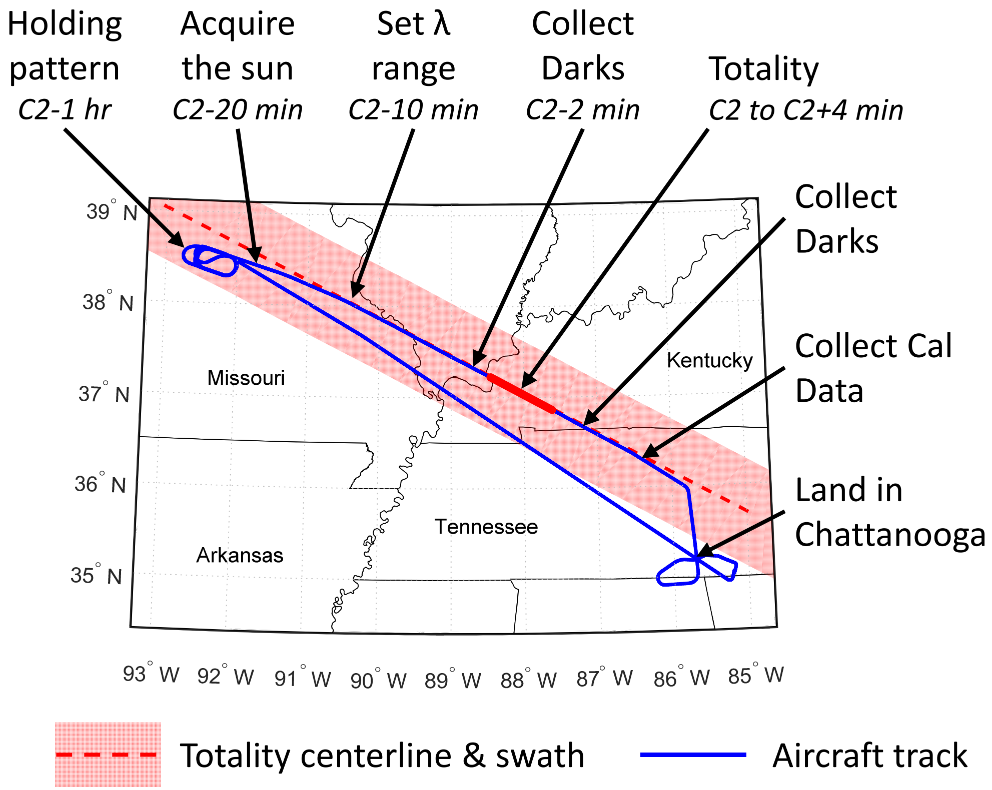
- Observe near longest duration and highest elevation (local noon)
- Acquire sun >20 min before totality
- Enter the eclipse track >15 min before totality
- During totality:
  - Fly straight and level at a fixed heading
  - Stay within 13 km of the eclipse centerline

→ *Observe over western Kentucky*

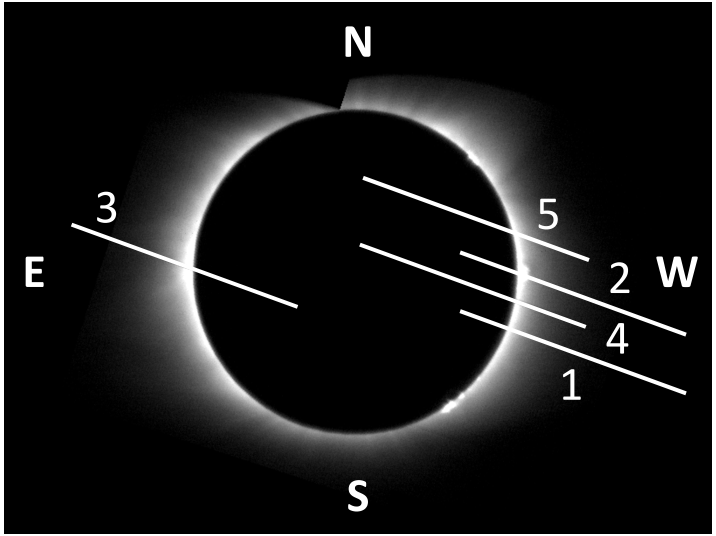
→ *Curve into/out of eclipse track to adjust for sun angle*

Eclipse Observation

*2nd Contact (C2) = **18:22 UTC***

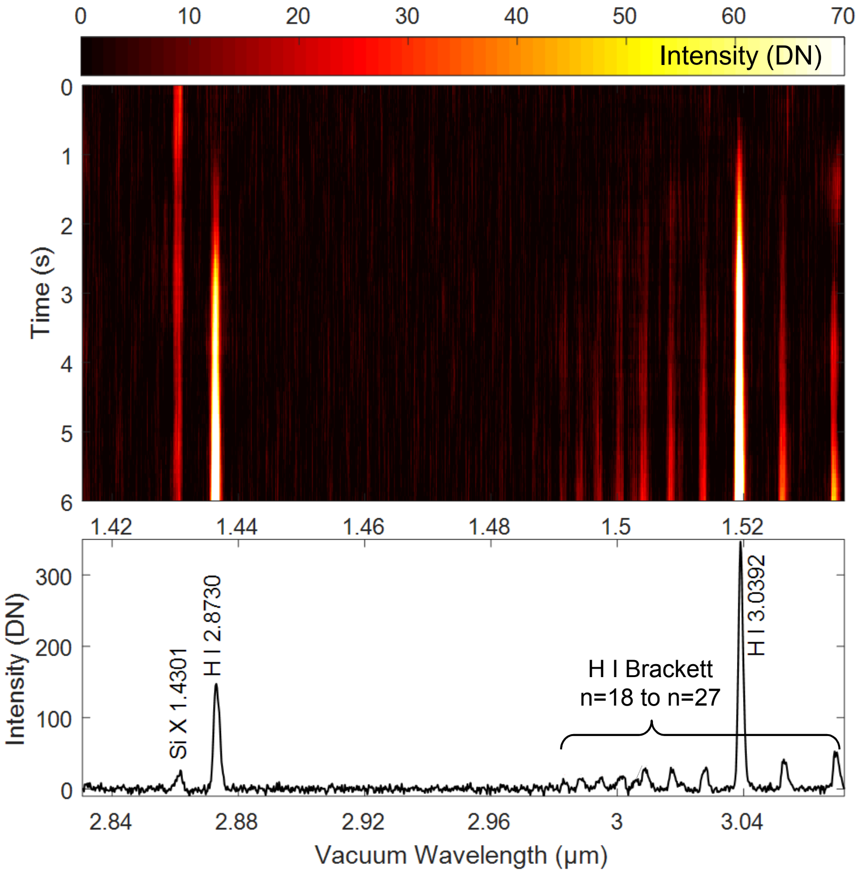


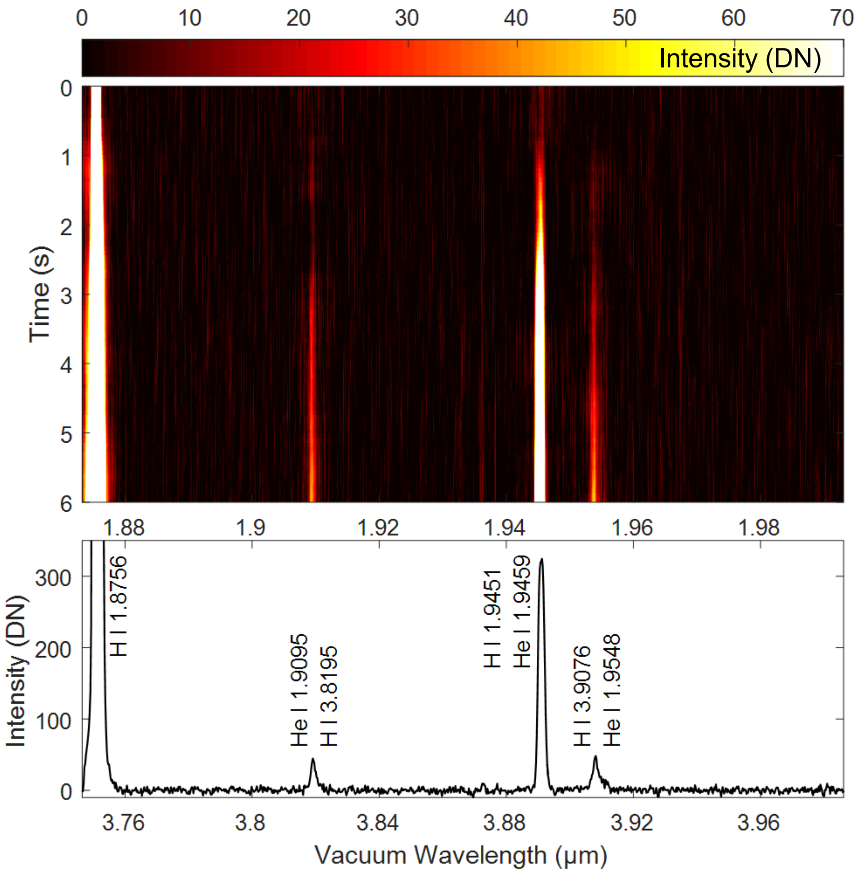
Slit Positions During Totality



1. West Limb	63.5 sec	953 frames
2. Prominence	41.5 sec	622 frames
3. East Limb	35.7 sec	536 frames
4. Prominence/West Limb	52.1 sec	782 frames
5. Chromosphere (Flash)	6 sec	90 frames

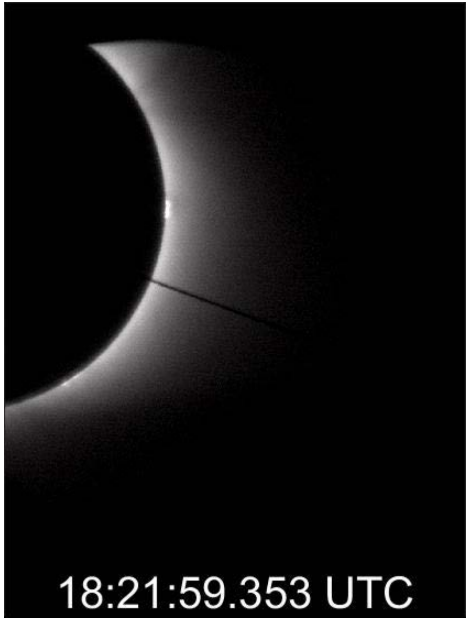
Position 5: Flash Spectrum



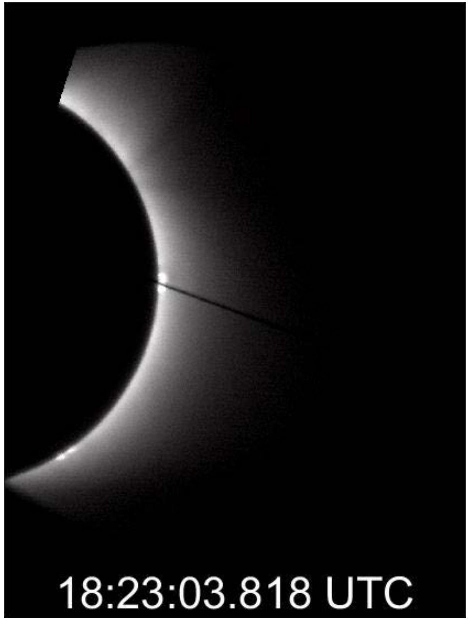


Positions 1 – 4: Slit-jaw Camera

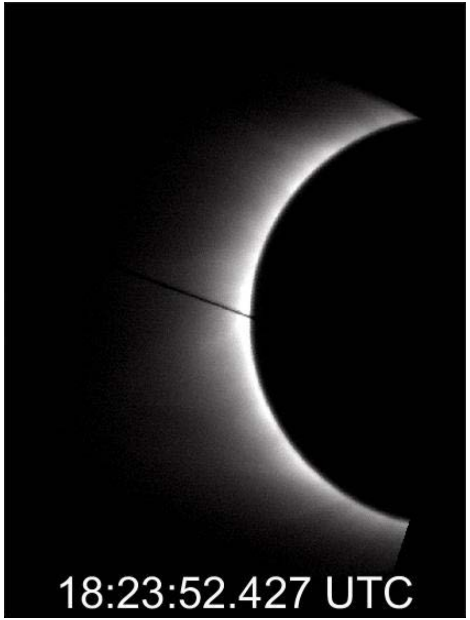
Obs. 1: West Limb
63.5 sec, 953 frames



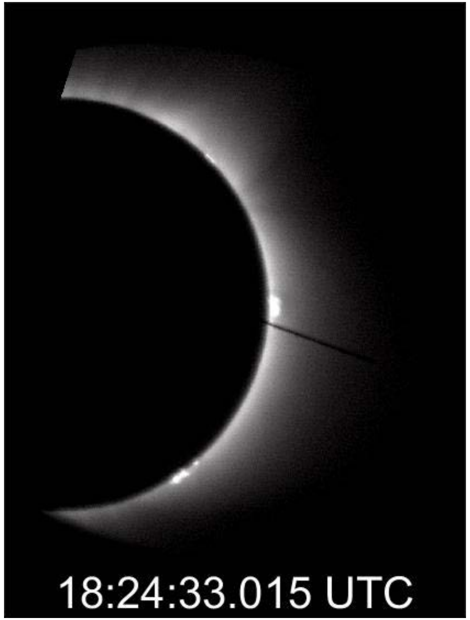
Obs. 2: Prominence
41.5 sec, 622 frames



Obs. 3: East Limb
35.7 sec, 536 frames

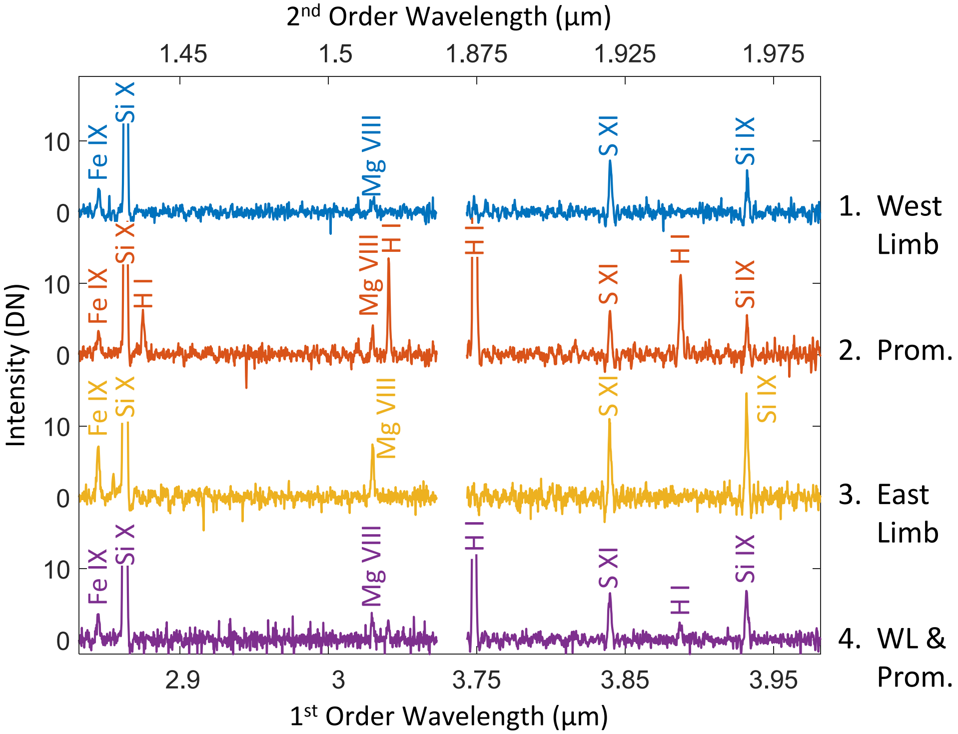


Obs. 4: Prominence & West Limb
52.1 sec, 782 frames



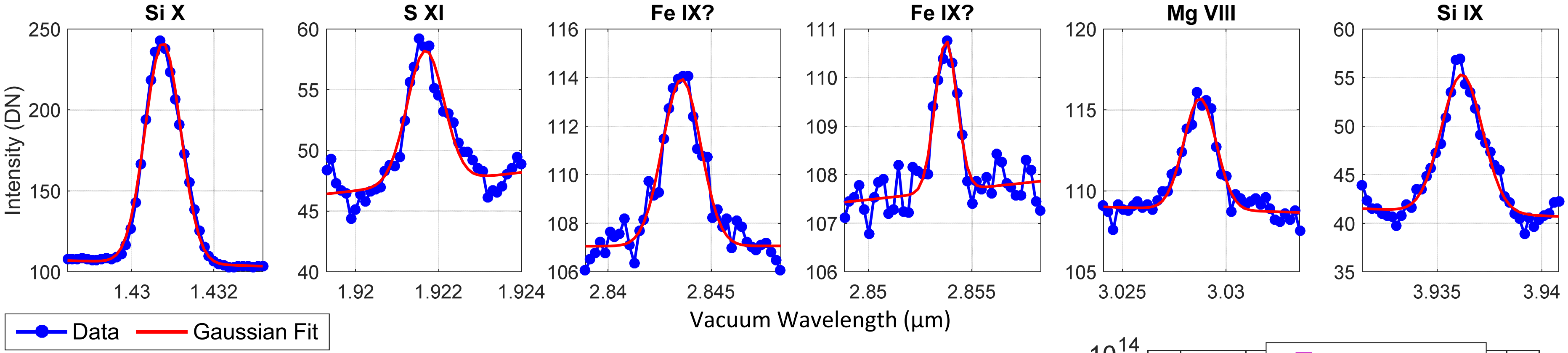
Positions 1 – 4: Coronal Spectra

Mean Spectra by Slit Position



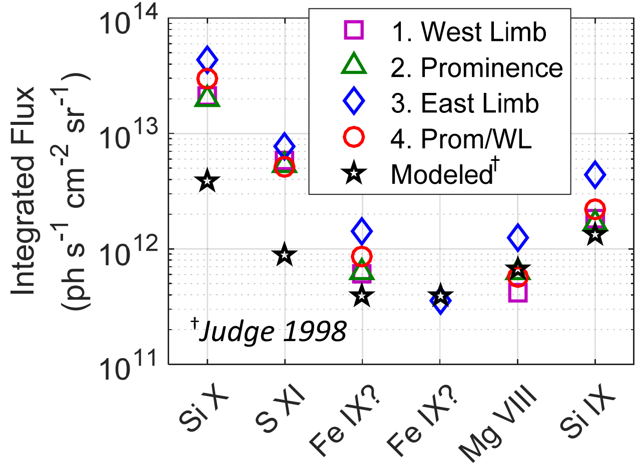
- *Results:*
  - Emission line parameters
  - Radial intensity gradient
  - First detection of Fe IX
- *In progress:*
  - Search for waves/flows
    - Si X: 5 km/s resolution at 60 ms exposure time, 1 km/s at 1 sec
  - Ground-based collaborations

Emission Line Parameters

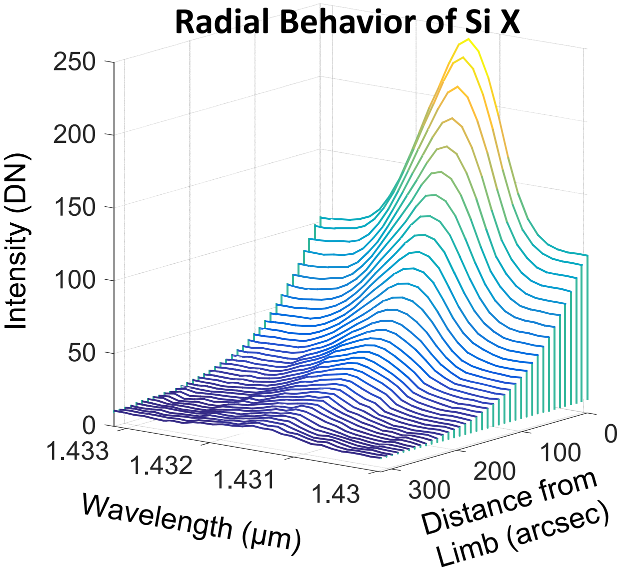


Obs. 3 Summary

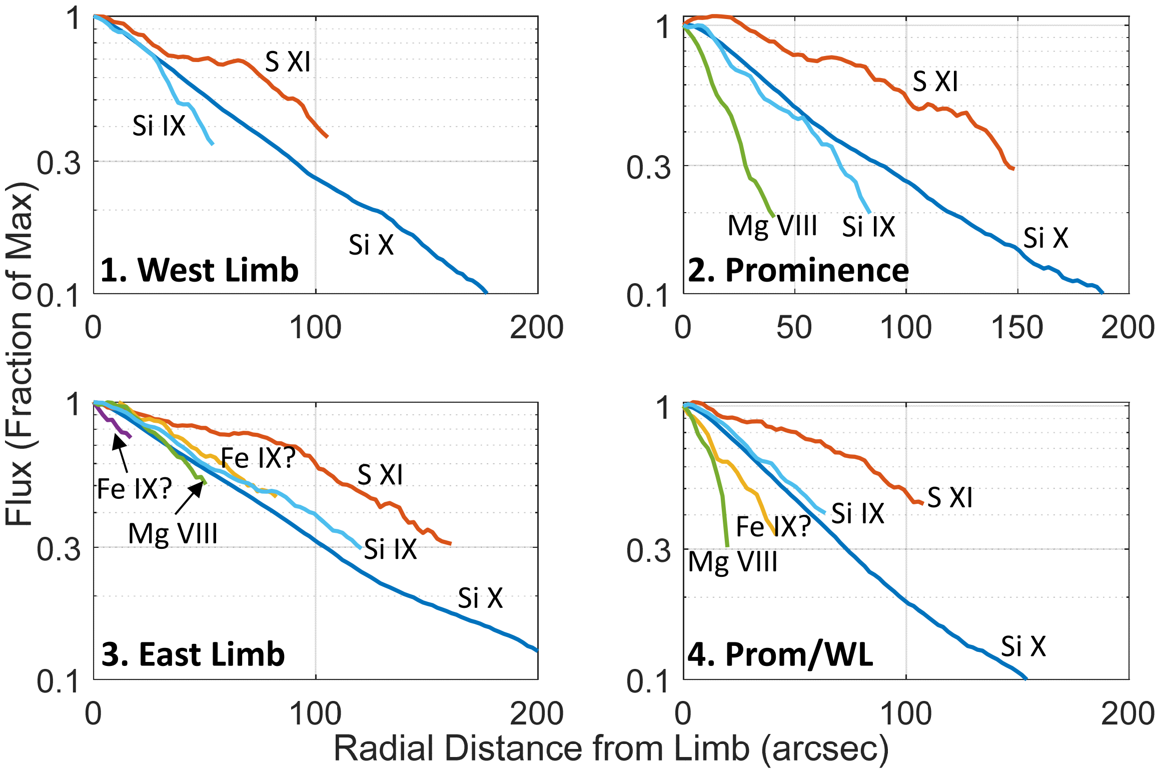
	Vacuum Wavelength (μm)	FWHM (Å)	Amplitude (σ)	Integrated Flux (10^{12} ph s^{-1} cm^{-2} sr^{-1})
Si X	1.4308	10.1	185	44
S XI	1.9217	10.8	13	7.8
Fe IX?	2.8436	21.8	9.3	1.4
Fe IX?	2.8537	12.3	4.2	0.36
Mg VIII	3.0287	18.4	9.3	1.3
Si IX	3.9362	23.1	17	4.4



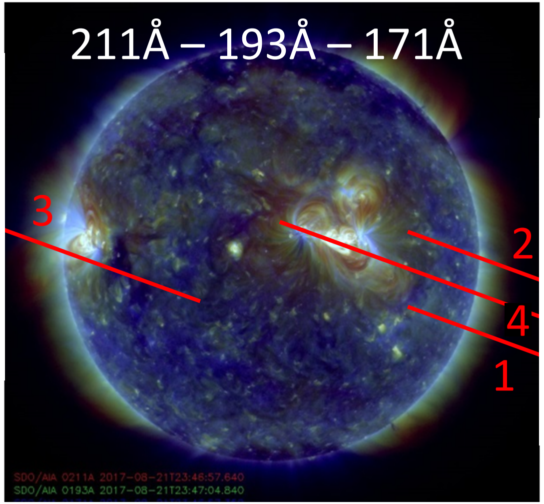
Radial Intensity Gradient



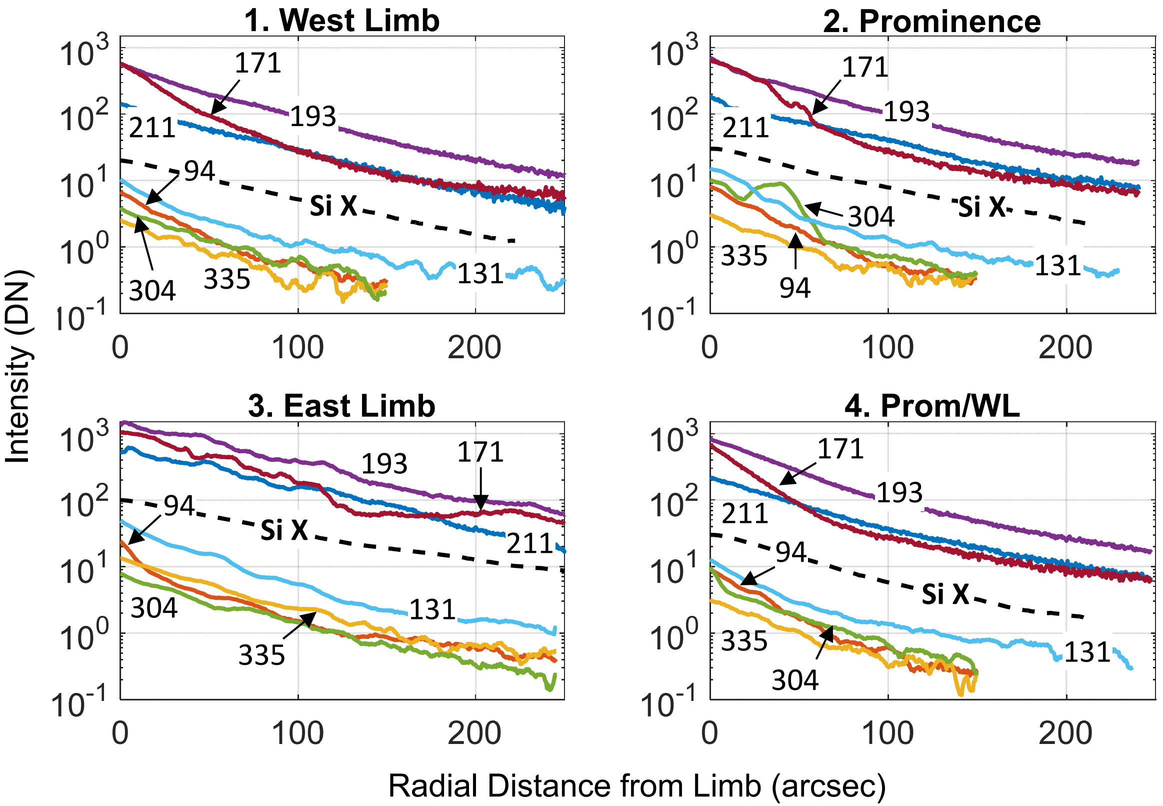
λ (µm)	Ion	log T_e
1.43	Si X	6.1
1.92	S XI	6.3
2.86	Fe IX	5.8
3.03	Mg VIII	5.9
3.93	Si IX	6.0



Si X Gradient, AIA Comparison



λ (Å)	Ion	$\log T_e$
304	He II	4.7
171	Fe IX	5.8
193	Fe XII, XXIV	6.1, 7.3
211	Fe XIV	6.3
335	Fe XVI	6.4
94	Fe XVIII	6.8
131	Fe VIII, XX, XXIII	5.6, 7.0, 7.2

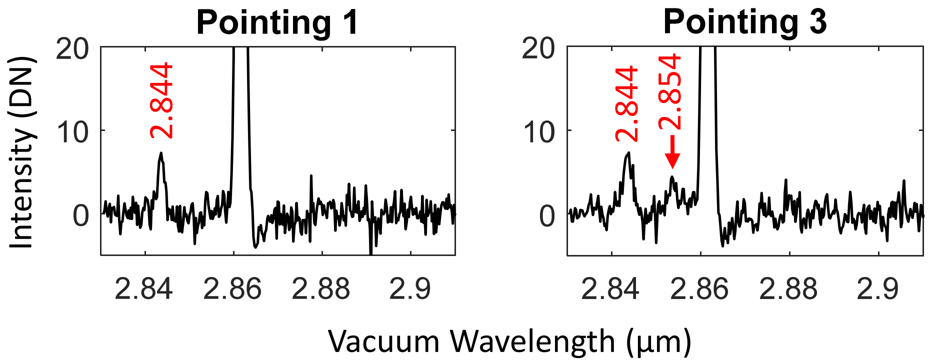


First Detection of Fe IX

Why first?

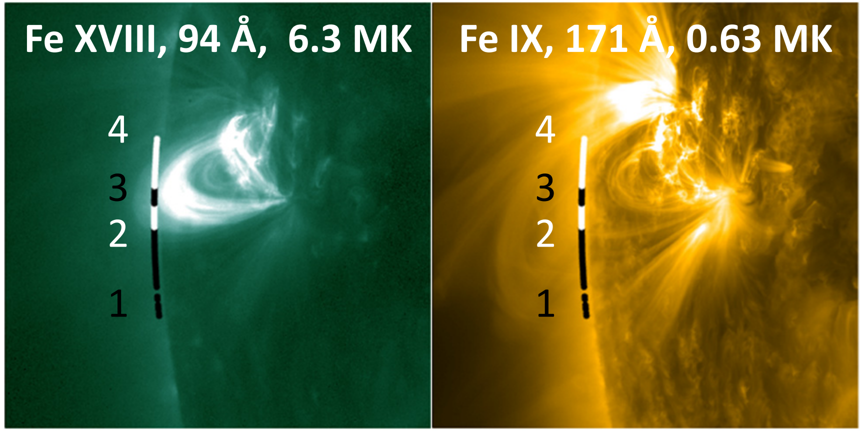
- Completely absorbed from the ground
- Energy of the transition levels too high for photo-ionized plasmas
  - Level $\tilde{\nu} \sim 429{,}000\ \mathrm{cm}^{-1} \rightarrow T = \frac{hc\tilde{\nu}}{k} \sim 6\times10^5$ K
  - T ~ 12,000 K – 150,000 K in photo-ionized plasmas

➔ Limit search to space-based observations of collisionally-ionized plasmas



Which line?

- 2.854 µm is closer to NIST wavelength *(2.8562 µm)*
- 2.844 µm is more similar to identified coronal lines *(intensity, radial gradient, and spatial distribution)*

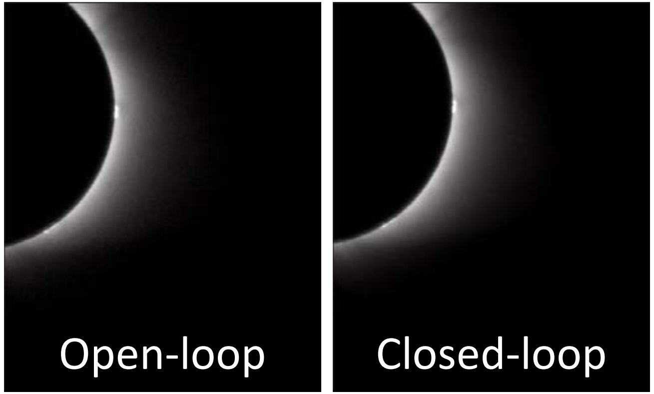


Preliminary conclusion:

- **2.844 µm** is Fe IX → *revise NIST energy levels*
- **2.854 µm** is something hotter

Instrument Improvements

- Closed-loop image stabilization
  - Improve RMS jitter to allow 1 second exposures

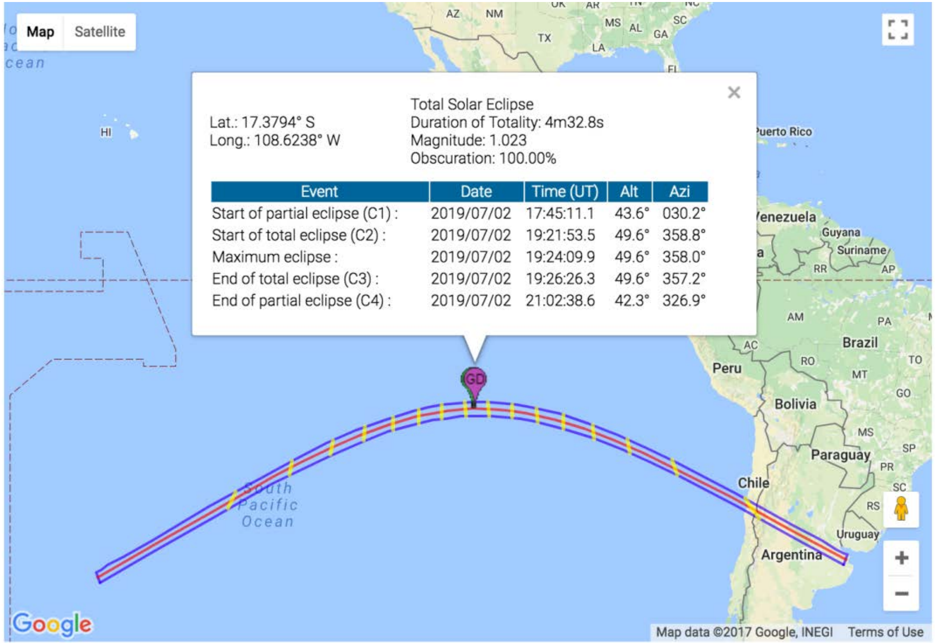


- 10 – 15x reduction in dark background
  - Reduce dark current (lower detector temp)
  - Reduce thermal contributions (camera & chamber)
  - Allow 0.5 – 1 sec exposures
- Refine pre-eclipse operations

Follow-on Experiments

- AIR-Spec re-flight, 2019
  - Closed-loop image stabilization
  - 10 – 15x background reduction for 0.5 – 1 second exposures
- Spectro-polarimeter flight, 2020
  - 1 or 2 lines from AIR-Spec design
  - Broadband FTS on-board
- Laboratory study of IR coronal lines
  - Source: Electron Beam Ion Trap (EBIT)
  - Single species plasma (e.g. Fe, Si, Mg, S) at coronal density and temperature
  - Confirm Fe IX wavelength, and more

July 2, 2019 Total Solar Eclipse



Acknowledgements

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