An Airborne Infrared Spectrometer for Coronal Observations: Development, Characterization, and First Science Results from the 2017 Solar Eclipse

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An Airborne Infrared Spectrometer for Coronal Observations: Development, Characterization, and First Science Results from the 2017 Solar Eclipse

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BY
JENNA ELIZABETH SAMRA
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An Airborne Infrared Spectrometer for Coronal Observations: Development, Characterization, and First Science Results from the 2017 Solar Eclipse

Abstract

The solar magnetic field enables the heating of the corona and provides its underlying structure. Energy stored in coronal magnetic fields is released in flares and coronal mass ejections and ultimately drives space weather. Therefore, direct measurements of the coronal magnetic field have the potential to significantly enhance understanding of coronal dynamics and improve solar forecasting models. High-precision measurements are difficult to make due to the low field strengths that characterize most of the corona, but previous work suggests that emission lines in the shortwave and mid-infrared are a promising target for future magnetometers. Characterizing these magnetically sensitive emission lines is an important first step in developing the next generation of instrumentation.

A new imaging spectrometer has just taken a step toward the direct observation of coronal magnetic fields by measuring infrared emission in the corona at high spectral resolution. On August 21, 2017, the Airborne Infrared Spectrometer (AIR-Spec) observed the total solar eclipse at an altitude of 14.3 km from aboard the NSF/NCAR Gulfstream V research aircraft. The instrument successfully observed the five coronal emission lines that it was designed to measure: Si X/1.43 \( \mu \)m, S XI/1.92 \( \mu \)m, Fe IX/2.84 \( \mu \)m, Mg VIII/3.03 \( \mu \)m, and Si IX/3.94 \( \mu \)m. This thesis describes the instrument design and development, the data processing and calibration, and the first science results from the 2017 eclipse observation.

AIR-Spec is a slit spectrometer that measures light over a 1.55 solar radius field of view in four spectral passbands between 1.4 and 4 \( \mu \)m. The package includes an image stabilization system, feed telescope, grating spectrometer, and slit-jaw imager. The instrument development encountered a number of challenges, centered around maintaining adequate resolution and signal-to-noise ratio in a compact and inexpensive package on a moving platform. Meeting all of the engineering challenges resulted in a
successful mission.

During the eclipse observation, AIR-Spec measured the average linewidths, peak intensities, and center wavelengths of all five lines radially outward from the limb at four positions in the corona. The observation of Fe IX at 2.84 µm was the first of that line. The radial intensity gradient of Si X was measured with high sensitivity, providing information on the dominant excitation processes for that line. The relative Doppler velocity of Si X was measured with a resolution of 5 km/s, revealing variations across different coronal structures and an interesting case of bimodal velocities near the solar prominence.

Several follow-on experiments are being proposed to expand on the results from the 2017 eclipse. These include a re-flight of AIR-Spec during the 2019 total eclipse, development of a spectropolarimeter operating at AIR-Spec wavelengths, and a laboratory study of infrared coronal emission lines.
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Author List

The following authors contributed to Chapter 5: Philip Judge, Edward DeLuca, and James Hannigan.
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The Infrared Corona as a Magnetic Field Diagnostic

Figure 1.0.1 shows the sun’s outer atmosphere, the solar corona, at wavelengths of 530 and 637 nm (left) and in white light (right) during two different solar eclipses. A close look at the images reveals three interesting features. First, the corona is highly structured, with loops and radial features corresponding to different wavelengths (left). Second, coronal structures extend several solar diameters in the radial direction (right). Third, a large bubble-like formation appears to move toward the corner of the white light image, suggesting that the corona is dynamic (right). Together, these observations hint at the
intricate relationship between coronal plasma and magnetic field.

An explanation of this relationship begins and ends with the magnetic field. Magnetic flux emerges from the opaque, dense plasma at the base of the atmosphere and expands into the corona, where the density is $\sim 9$ orders of magnitude lower. Emerging fields heat the coronal plasma to over 1 million Kelvin by transferring energy from subsurface convection, and the high magnetic pressure distributes the low-density plasma along field lines. As the hot plasma expands into space it pulls the magnetic field with it, creating the structures seen in Figure 1.0.1. The form of the underlying field is revealed by ions and electrons along the field lines. In the figure, multiply ionized iron at 0.9 and 1.8 MK emits red and green light (left), and electrons scatter broadband light from the photosphere (right). The plasma conducts heat and electrical current along the field lines, introducing stresses which trigger abrupt reconfigurations of the magnetic field. The stored energy is released in solar flares and coronal mass ejections (right), the source of earth-effective “space weather”.

Figure 1.0.1: Eclipse observations of the solar corona. Left: Composite image of emission from Fe X/Fe XI (red) and Fe XIII/Fe XIV (green) during the August 1, 2008 eclipse [22]. Right: White light image from the November 3, 2013 eclipse, Credit: C. Emmanouilidis, M. Druckmüller
As we will see in Section 1.1, direct measurements of the coronal magnetic field have the potential to enhance our understanding of coronal heating, structure, and dynamics and to improve solar forecasting models. Unfortunately, precise magnetic field measurements are very difficult to make due to the weak fields typical of the corona. Two promising techniques rely on polarization measurements of infrared emission lines (Section 1.2), but the candidate lines must be characterized before spectropolarimeters can be designed around the most useful ones (Section 1.3). In particular, the modeled intensities described in Section 1.3.1 must be confirmed by observations.

One such observation was made recently by the Airborne Infrared Spectrometer (AIR-Spec), a new imaging spectrometer developed to identify magnetically sensitive infrared (IR) coronal lines and assess their suitability for future spectropolarimetric observations (Section 1.3.2). During the 2017 solar eclipse, AIR-Spec identified five IR emission lines in the corona from an airborne platform at 14.3 km. The instrument and observation are the subject of this thesis.

1.1 THE CORONAL MAGNETIC FIELD

The solar corona begins approximately 3000 km¹ above the photosphere (the “surface” of the sun where the plasma becomes opaque) and is characterized by temperatures around 1 MK and electron densities of $10^8$ to $10^9$ cm$^{-3}$ (Figure 1.1.1). In contrast, the average temperature and density of the photosphere are around 6000 K and $10^{17}$ cm$^{-3}$. In the absence of magnetic energy input, the low-density corona would have to be cooler than the photosphere to satisfy thermodynamic equilibrium [21]. The magnetic field provides the energy that heats the corona and allows it to expand over 20 AU into the interstellar medium, forming the sun-dominated region of space known as the heliosphere [21]. The energy to heat the corona comes from convective motions below the solar surface [31], but the exact mechanism by which this energy is dissipated is unknown. The subsurface fluctuations may induce magnetohydrodynamic waves in

¹This approximate value assumes a spherically symmetric, plane parallel atmosphere, neglecting the structure and dynamics apparent in Figure 1.0.1.
the coronal plasma or reconfigure the coronal field through magnetic reconnection \([31]\). In a 2012 review on the subject, Parnell and De Moortel argue that both processes are important and the dominant mechanism depends on the coronal structure \([54]\).

![A Model Solar Atmosphere](image)

**Figure 1.1.1:** Modeled temperature and density of a spherically symmetric, plane parallel solar atmosphere \([21]\).

At coronal temperatures of \(\sim 1\) MK, hydrogen and helium are fully ionized and heavier elements such as iron, magnesium, and silicon are partially ionized. In 1942, Edlén established the high temperature of the corona by identifying four visible coronal emission lines as transitions in highly ionized iron and calcium \([17]\). Today, observations of emission from partially ionized species provide detailed measurements of plasma temperature and density throughout the corona. The plasma density can also be measured by observing the brightness of the coronal continuum, the broadband light produced when photons from the photosphere are scattered by coronal electrons. In addition to temperature and density,
observations of emitted and scattered light reveal the underlying magnetic structure of the corona, where the low-density plasma is distributed along field lines due to the high magnetic pressure. An example of this relationship is shown in Figure 1.1.2. By modeling the configuration of the coronal magnetic field (left), Predictive Science Inc. predicted the appearance of the 2017 solar eclipse (middle) one week before it occurred [39]. The model accurately reproduces the major features in the eclipse observation (right).


Magnetic flux is generated inside the sun by convection of the electrically conducting plasma and eventually emerges into the solar atmosphere. The coronal magnetic field evolves continuously as it is twisted and sheared by convective motions below the solar surface. These stresses can cause instabilities in the field and eventually trigger magnetic reconnection, by which the field is reorganized into a stable configuration with lower energy. The stored energy may be released in a solar flare, producing light across the electromagnetic spectrum and accelerating particles to relativistic speeds [20, 61]. The X-class flare shown in Figure 1.1.3 (left) is over 10,000 times brighter than the coronal background. Magnetic reconnection is also the source of energy for coronal mass ejections (CMEs) of plasma and magnetic flux traveling at hundreds of kilometers per second, as shown in Figure 1.1.3 (right) [7]. As earth-directed
CMEs can induce geomagnetic storms intense enough to damage communications satellites and disrupt power distribution, predicting these events becomes ever more critical as societies grow more dependent on technology.

Predicting coronal dynamics and space weather is especially challenging because routine, high-precision measurements of the coronal magnetic field are impeded by the low field strengths that characterize most of the corona. Without measurements, we attempt to model coronal activity using the measured photospheric field as a boundary condition and observations of coronal plasma to constrain the evolution. Magnetic field models vary in complexity [71]. The eclipse prediction in Figure 1.1.2 was made by a model that solves the full set of magnetohydrodynamic (MHD) equations (e.g. the form posed by Mikić and Linker [46]). MHD models make few approximations and can therefore accommodate a wide range of coronal conditions, but they have many free variables that are difficult to constrain with
observations. Due to their complexity, they are computationally intensive and therefore limited in spatial scale and/or resolution [71].

For modeling magnetically active regions of the corona, the force-free field approximation is often used [41]. The assumption that the Lorentz force is zero, i.e. plasma currents are aligned parallel to the field, is accurate in regions where the magnetic field is strong enough to dominate the force balance equation and a stable equilibrium exists [71]. In the example shown in Figure 1.1.4, x-ray images of three coronal active regions (top) agree qualitatively with magnetic fields derived from a nonlinear force-free model (bottom) [59].

![Figure 1.1.4: X-ray images of three coronal active regions observed by the X-Ray Telescope (top) and the corresponding magnetic fields derived from a nonlinear force-free model (bottom) [59].](image)

Force-free models have several limitations, most importantly the fact that the measured photospheric fields which provide the boundary conditions are not force-free [15, 44]. Even when these models appear to match the plasma observations (Figure 1.1.4), the accuracy of the extrapolated field cannot be assessed.
without direct measurements of the coronal field. Liu and Lin have successfully demonstrated the process
of validating a magnetic field model with observations \[40\], but model validation cannot become
standard until high-precision field measurements are made routinely.

1.2 Magnetic field measurements from emission line polarization

In a 2001 feasibility study, Judge et al. review techniques for measuring the coronal magnetic field \[27\].
Two of the most promising methods involve measuring the Zeeman and Hanle effects in polarized
emission lines. The Zeeman effect describes the polarization induced due to the splitting of degenerate
energy levels in the presence of a magnetic field, while the Hanle effect describes the magnetic
depolarization of emission lines polarized by resonant scattering. The two phenomena offer a means to
measure the line-of-sight (LOS) magnitude and plane-of-sky (POS) direction of coronal magnetic field,
but the measurements are very challenging.

1.2.1 The Zeeman effect

The Zeeman effect \[57\] refers to the magnetically-induced splitting of energy levels with the same total
angular momentum, which are degenerate in the absence of a magnetic field. When a magnetic field is
present, the levels depend on the component of angular momentum along the magnetic field vector in
addition to the total angular momentum. In the simplest case, a single transition at \(\lambda_o\) splits into a triplet
with components at \(\lambda = \lambda_o\) and \(\lambda = \lambda_o \pm \Delta \lambda_B\), where

\[
\Delta \lambda_B = \lambda_o^2 B g \left( \frac{e}{4\pi m_e c^2} \right)
\]

\(B\) is the magnitude of the magnetic field vector, \(g\) is the Landé factor, \(e\) is the electric charge, \(m_e\) is the
electron mass, and \(c\) is the speed of light. In the corona, where magnetic fields are only a few Gauss but
temperatures $T$ are on the order of $10^6$ K, $\Delta \lambda_B$ is typically hundredths of Å while thermal broadening

$$\Delta \lambda_T = \lambda_0 \sqrt{\frac{8kT \ln 2}{mc^2}}$$

is on the order of several Å. It is therefore impossible to measure the Zeeman splitting from the line profile alone [63].

The line polarization offers a more sensitive diagnostic for magnetic field. Polarization can be described by the Stokes vector $[I \ Q \ U \ V]^T$, where $I$ is the total polarized and unpolarized radiation, $Q$ is the amount of horizontal and vertical polarization, $U$ is the amount of $\pm 45^\circ$ polarization, and $V$ is the amount of circular polarization [5]. The line-of-sight component of $\vec{B}$ induces circular polarization ($V$) in the lines at $\lambda_0 \pm \Delta \lambda_B$, while the transverse component of $\vec{B}$ induces linear polarization ($Q$, $U$) in all three components of the triplet. In the absence of a magnetic field (and other sources of polarization), the emission line is unpolarized ($Q = U = V = 0$) [63]. Figure 1.2.1 shows an example of Stokes absorption profiles modeled by Solanki [63] for the 525 nm transition in Fe I. The magnetic field ranges from 0 to 2000 Gauss in steps of 200. The profiles are different from coronal Stokes spectra, which are emission lines with less perceptible Zeeman splitting and more significant thermal broadening. However, the magnetic field dependence of the profiles follows the same trends in the corona.

At the low magnetic field strengths typical of the corona, $\Delta \lambda_B \ll \Delta \lambda_T$ and the relationship between Stokes $I$ and $V$ can be approximated by

$$V(\lambda) \approx \cos \gamma \Delta \lambda_B \frac{\partial I(\lambda)}{\partial \lambda},$$

where $\gamma$ is the angle between the magnetic field vector and the instrument line of sight. Measurements of Stokes $I$ and $V$ can therefore provide an estimate of the line-of-sight magnetic field. In practice, these measurements are very challenging due to the high spectral resolution required to resolve the line profile.
Figure 1.2.1: Modeled Stokes spectra for the 525 nm absorption line of Fe I for magnetic fields of 0, 200, 400, 600, 800, 1000, 1200, 1400, 1600, 1800 and 2000 Gauss [63].

and the small circular polarization signal at coronal field strengths. For a 1 G field, the amplitude of Stokes \( V \) is about four orders of magnitude smaller than that of Stokes \( I \) in the bright Fe XIII line at 1.0746 \( \mu \)m [68]. For a hypothetical instrument with a 40 cm aperture and 10 arcsec pixels, Judge et al. predict that an exposure time of 100 seconds is required to detect Stokes \( V \) with a 3\( \sigma \) signal-to-noise ratio in this line [27].

Unsurprisingly, few Zeeman effect observations of the coronal magnetic field have been made. In 1969, Harvey measured the magnetic field in solar prominences, but was unable to detect the field in the corona [24]. Observations by Kuhn in 1995 did not precisely measure the coronal field strength but established an upper limit of 40 G [33]. The first high-precision measurements were made by Lin et al. early in this
century \([37, 38]\). Today, regular magnetic field measurements are made by the Coronal Multichannel Polarimeter (CoMP) \([68]\) located on Mauna Loa. Figure 1.2.2 (right) shows a CoMP measurement of the line-of-sight field. The 10–20 G measurements have errors around a few Gauss.

**Figure 1.2.2:** Magnetic field observation made by the Coronal Multichannel Polarimeter (CoMP) \([68]\). Left: Field azimuth in the plane of the sky. Right: Field magnitude along the line of sight.

1.2.2 Resonant scattering and the Hanle effect

Resonant scattering refers to the radiative excitation of an electron followed by its radiative decay back to the initial energy level, so that the incident and emitted photons have the same wavelength \([63]\). The emission line polarization is parallel to the polarization of the incident light and perpendicular to the direction of scatter. The linearly polarized coronal continuum, created when photospheric light is
scattered by free electrons in the corona, induces resonant scattering in visible and infrared transitions of coronal ions.

The Hanle effect occurs when resonant scattering takes place in the presence of a magnetic field. In this case, the angular momentum of the excited electron precesses about the magnetic field vector at the Larmor frequency

\[ \omega_L = \frac{eB}{2m_e}. \]

Due to this precession, the average electric field vector of the emitted light has a non-zero component perpendicular to the initial polarization direction. This has the effect of reducing the amount of polarization in the emission line and rotating the polarization direction relative to the \( B = 0 \) case \( [25] \).

Along an axis parallel to the magnetic field vector, the magnitude and angle of the emission line polarization are given by

\[
P = \frac{P_0}{1 + (2g\omega_L \tau)^2},
\]

\[
\Omega = \frac{1}{2} \tan^{-1} \left( 2g\omega_L \tau \right) [63],
\]

where \( P_0 \) is the amount of linear polarization when \( B = 0 \), \( g \) is the Landé factor of the upper level, and \( \tau \) is the lifetime of the upper level. The linear polarization (Stokes \( Q, U \)) measured by an observer depends on the magnitude of the magnetic field vector and its direction with respect to the observer.

In the corona, the magnetic field strength of several Gauss is strong enough that \( \omega_L^{-1} \ll \tau \). Because the precession completes many cycles over the lifetime of the upper level, the Hanle effect is saturated (\( P \to 0 \) and \( \Omega \to 45^\circ \)) and Stokes \( Q \) and \( U \) are not sensitive to the magnitude of the magnetic field vector \( [47] \). However, their ratio yields the magnetic field angle in the plane of the sky,

\[
\beta = \frac{1}{2} \tan^{-1} \left( \frac{U}{Q} \right) [64].
\]
The Hanle effect is easier to measure than the Zeeman effect, in part because it is not sensitive to the width of the emission line. The signal generated in Stokes $Q$ and $U$ is $1 - 10\%$ of Stokes $I$ \cite{68}, and the exposure time for a $3\sigma$ signal-to-noise ratio is on the order of tens of milliseconds \cite{27}. CoMP regularly measures the POS field angle by observing the Hanle effect in the 1074.7 and 1079.8 nm lines of Fe XIII, see Figure 1.2.2 (left) \cite{68}. Earlier polarization measurements in the 1970s and 1980s focused on the 530.3 nm line of Fe XIV and the 1074.7 nm line of Fe XIII \cite{1, 45, 56}.

1.3 Magnetically Sensitive Emission Lines in the Infrared Corona

In principle, the Zeeman effect provides a means of measuring the LOS magnitude of the coronal magnetic field and the Hanle effect a way to measure the POS field direction. Both types of measurements are limited in practice by the weak polarization signals which encode the field information. Infrared wavelengths, especially the shortwave and mid-IR regions from 1.4 to $5\,\mu$m, have advantages for both techniques \cite{27}. Zeeman splitting varies with wavelength as $\lambda^2$ while thermal broadening goes as $\lambda$. The Hanle effect relies on polarization by resonant scattering, which occurs in visible and infrared lines where the incident light from the photosphere is brightest. In addition, the effects of instrumental and atmospheric scattering are less significant at longer wavelengths.

Historically, the corona has been observed only infrequently in the shortwave infrared (SWIR) and midwave infrared (MWIR) \cite{11}. As a result, emission lines in these regions are not as well-understood as their visible and near-IR counterparts. Recent advances in detector technology are finally making this region available for observation. Before describing the AIR-Spec mission to survey and characterize SWIR and MWIR coronal emission lines, we explore the general properties of promising lines in the visible and infrared.
1.3.1 Predictions and previous observations

The brightest visible and infrared coronal lines are magnetic dipole (M1) transitions [28], often called “forbidden” lines because they are forbidden by the selection rules for electric dipole (E1) transitions [57]. M1 transitions occur within a configuration, in contrast to E1 transitions which require the electron to move to a new configuration [32]. In the highly ionized species that exist in the corona, a change in configuration is associated with a large energy drop, consistent with extreme ultraviolet and x-ray wavelengths. M1 transitions within a configuration have wavelengths in the visible and infrared (Figure 1.3.1).

![Figure 1.3.1: Term diagram illustrating the 637.4 nm forbidden magnetic dipole transition (red) in Fe X [21]. The allowed electric dipole transitions (black) produce extreme ultraviolet emission due to the large energy difference between configurations.]

Judge narrows the list of M1 transitions to those most likely to be useful for magnetic field measurements. He first discards ions with abundances less than 1% of iron, the most abundant coronal
species after hydrogen and helium [28]. He also eliminates all transitions except those that occur in ground and metastable terms, because excited electrons rapidly decay to these terms via electric dipole transitions [28]. (Metastable states are those which have long lifetimes because selection rules prevent decay to the ground state.) He models the intensity of the remaining lines assuming a distance of 1.1 R⊙ from sun center and a linewidth of 30 km/s. The predicted spectrum is shown in Figure 1.3.2 [28].

![Figure 1.3.2: Predicted spectrum of M1 lines at 1.1 R⊙ [28]. Black dots are intensity values for collisional de-excitation only, straight lines include radiative contributions. The smooth baseline is the coronal continuum produced by Thomson scattering by free electrons. Lines outlined in red were measured by AIR-Spec during the 2017 eclipse.](image)

The modeled intensities decrease with wavelength due to a decrease in the rates of both radiative decay and collisional de-excitation. The radiative rate decreases because the incident photospheric photons are distributed as a 5800 K blackbody, which peaks at about 0.5 μm and decreases at longer wavelengths. The collisional probability and emitted wavelength both decrease with the ion charge, so collisional probability actually increases with wavelength. This makes electric dipole transitions more likely at long wavelengths, resulting in fewer M1 transitions from the same upper level [28].

In their feasibility study on measuring coronal magnetic fields, Judge et al. list the most promising candidates for magnetic field measurements based on the modeled intensities in Figure 1.3.2 [27]. Their list is reproduced in Table 1.3.1. The first four columns give the ion, transition wavelength, transition
wavenumber, and electron temperature corresponding to the maximum population of each ion. The next three columns list the estimated flux from the emission line \(F_E\), photospheric light scattered by the atmosphere \(F_{\text{scat}}\), and 250 K atmospheric thermal emission \(F_{\text{th}}\) integrated over the emission line bandwidth and the solid angle of the corona \(F_E\) or photosphere \(F_{\text{scat}}, F_{\text{th}}\). The last two columns list the main atmospheric absorber and predicted transmission at 8 km elevation [27].

The emission line flux \(F_E\) decreases with wavelength for the reasons discussed earlier. The scattered light \(F_{\text{scat}}\) varies as \(\lambda^{-4}\) because the dominant process is Rayleigh scattering by molecules in the atmosphere. The thermal emission \(F_{\text{th}}\) increases exponentially with wavelength to its peak at 11.6 \(\mu\)m [27]. Although it is not shown in the table, the ratio of Zeeman splitting to thermal broadening varies as \(\lambda\) (Section 1.2.1). The SWIR and MWIR lines near the center of the table are good candidates for making magnetic field measurements because they balance the short wavelength advantages of high line intensity and low thermal emission with the long-wavelength benefits of high sensitivity to magnetic field and low scattered light.

A summary of previous observations of candidate M1 lines is given by Del Zanna and DeLuca [11]. Visible and near-IR lines are generally better observed than longer wavelength transitions due to greater detector availability and a lower probability of atmospheric interference. At the time of the 2017 eclipse, five of the promising lines in Table 1.3.1 had never been observed: Si IX/2.58 \(\mu\)m, Fe IX/2.86 \(\mu\)m, and the three lines with \(\lambda > 5 \mu\)m [11]. The SWIR and MWIR lines that had been measured were not well-characterized spatially or temporally (e.g. [29, 34, 51]).

1.3.2 An infrared pathfinder for the 2017 solar eclipse

This chapter has established the importance of coronal magnetic field measurements and explained why shortwave and mid-IR emission lines show particular promise for spectropolarimetric observations of magnetic field. As described in the previous section, the corona is not well-observed at these wavelengths.
Table 1.3.1: Candidate M1 lines for coronal magnetic field measurements [27].

<table>
<thead>
<tr>
<th>Ion</th>
<th>$\lambda$</th>
<th>$\tilde{\nu}$</th>
<th>log $T_e$</th>
<th>$F_{E}$</th>
<th>$F_{scat}$</th>
<th>$F_{th}$</th>
<th>Absorber</th>
<th>Transm. % 8 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe XIV</td>
<td>0.530</td>
<td>1.885+4</td>
<td>6.30</td>
<td>2.57+8</td>
<td>2.78+8</td>
<td>8.22–32</td>
<td>...</td>
<td>100</td>
</tr>
<tr>
<td>Fe X</td>
<td>0.637</td>
<td>1.568+4</td>
<td>6.03</td>
<td>1.77+8</td>
<td>1.37+8</td>
<td>3.96–24</td>
<td>...</td>
<td>100</td>
</tr>
<tr>
<td>Fe XI</td>
<td>0.789</td>
<td>1.267+4</td>
<td>6.10</td>
<td>1.48+8</td>
<td>5.48+7</td>
<td>7.21–17</td>
<td>...</td>
<td>100</td>
</tr>
<tr>
<td>Fe XIII</td>
<td>1.075</td>
<td>9.305+3</td>
<td>6.22</td>
<td>4.91+8</td>
<td>1.26+7</td>
<td>7.27–9</td>
<td>...</td>
<td>100</td>
</tr>
<tr>
<td>Si X</td>
<td>1.430</td>
<td>6.993+3</td>
<td>6.13</td>
<td>1.57+8</td>
<td>2.88+6</td>
<td>1.85–3</td>
<td>H$_2$O + 0.2 cm$^{-1}$</td>
<td>50</td>
</tr>
<tr>
<td>S XI</td>
<td>1.920</td>
<td>5.208+3</td>
<td>6.25</td>
<td>3.59+7</td>
<td>5.85+5</td>
<td>2.21+1</td>
<td>H$_2$O</td>
<td>50</td>
</tr>
<tr>
<td>Si IX</td>
<td>2.584</td>
<td>3.870+3</td>
<td>6.04</td>
<td>6.07+7</td>
<td>1.11+5</td>
<td>2.01+4</td>
<td>H$_2$O</td>
<td>0</td>
</tr>
<tr>
<td>Fe IX</td>
<td>2.855</td>
<td>3.503+3</td>
<td>5.94</td>
<td>1.60+7</td>
<td>6.31+4</td>
<td>1.23+5</td>
<td>H$_2$O/CO$_2$/N$_2$O</td>
<td>60</td>
</tr>
<tr>
<td>Mg VIII</td>
<td>3.027</td>
<td>3.303+3</td>
<td>5.92</td>
<td>2.73+7</td>
<td>4.51+4</td>
<td>3.27+5</td>
<td>H$_2$O + 0.6 cm$^{-1}$</td>
<td>100</td>
</tr>
<tr>
<td>Si IX</td>
<td>3.935</td>
<td>2.545+3</td>
<td>6.04</td>
<td>5.67+7</td>
<td>1.01+4</td>
<td>1.17+7</td>
<td>N$_2$O</td>
<td>60</td>
</tr>
<tr>
<td>Mg VII</td>
<td>5.502</td>
<td>1.818+3</td>
<td>5.80</td>
<td>3.20+6</td>
<td>1.42+3</td>
<td>2.80+8</td>
<td>H$_2$O</td>
<td>10</td>
</tr>
<tr>
<td>Fe XI</td>
<td>6.081</td>
<td>1.644+3</td>
<td>6.10</td>
<td>2.61+6</td>
<td>7.88+2</td>
<td>5.62+8</td>
<td>H$_2$O</td>
<td>50</td>
</tr>
<tr>
<td>Mg VII</td>
<td>9.031</td>
<td>1.107+3</td>
<td>5.80</td>
<td>9.53+5</td>
<td>7.66+1</td>
<td>3.79+9</td>
<td>O$_3$</td>
<td>90</td>
</tr>
</tbody>
</table>

From left to right, the columns list the ion, transition wavelength, transition wavenumber, electron temperature for maximum ion population, emission line flux, scattered light, thermal emission, main atmospheric absorbers, and atmospheric transmission at 8 km. The highlighted rows correspond to transitions measured by AIR-Spec during the 2017 eclipse.

Before spectropolarimeters can be designed around SWIR or MWIR emission lines, the lines need to be characterized to determine which are useful probes of coronal magnetism. This thesis describes a new imaging spectrometer that was developed by a team from Harvard University and Smithsonian Astrophysical Observatory to identify and characterize magnetically sensitive infrared coronal lines and assess their suitability for future ground-based, airborne, and space-based spectropolarimetric observation.

During the total solar eclipse of August 21, 2017, the Airborne Infrared Spectrometer (AIR-Spec) surveyed the infrared corona and identified five magnetically sensitive emission lines between 1.4 and 4 µm. The instrument observed the eclipse from a research aircraft owned by the National Science Foundation (NSF) and operated by the National Center for Atmospheric Research (NCAR). The airborne observation was made at 14.3 km, above most of the atmospheric absorption. The spectral passbands were chosen to target five lines that show promise for future magnetic field observations: Si X
at 1.43 \( \mu m \), S XI at 1.92 \( \mu m \), Fe IX at 2.84 \( \mu m \), Mg VIII at 3.03 \( \mu m \), and Si IX at 3.93 \( \mu m \). The lines are highlighted in Figure 1.3.2 and Table 1.3.1, and the transitions and energy levels are listed in Table 1.3.2. The Fe IX transition occurs in a metastable triplet term; all other lines arise from ground term transitions. During the four-minute eclipse measurement, the intensities and center wavelengths of all five lines were measured radially outward from the limb at four positions in the corona. An early success of the program was the first observation of Fe IX at 2.84 \( \mu m \) [58].

**Table 1.3.2:** Transitions and energy levels for AIR-Spec target lines.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Configuration</th>
<th>Term</th>
<th>Level (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si X</td>
<td>[He] 2s(^2)2p(^2)</td>
<td>(^3\text{P}_1\to\text{o}^\text{3})</td>
<td>6,990.6 → 0.0</td>
</tr>
<tr>
<td>S XI</td>
<td>[He] 2s(^2)2p(^2)</td>
<td>(^3\text{P}_1\to\text{J}^\text{4})</td>
<td>5,208.0 → 0.0</td>
</tr>
<tr>
<td>Fe IX</td>
<td>[Ne] 3s(^2)3p(^3)3d</td>
<td>(^3\text{F}_1\to\text{J}^\text{4})</td>
<td>429, 310.9 → 425, 809.8</td>
</tr>
<tr>
<td>Mg VIII</td>
<td>[He] 2s(^2)2p(^2)</td>
<td>(^3\text{P}_1\to\text{J}^\text{2})</td>
<td>3,302 → 0</td>
</tr>
<tr>
<td>Si IX</td>
<td>[He] 2s(^2)2p(^2)</td>
<td>(^3\text{P}_1\to\text{J}^\text{4})</td>
<td>2,545.9 → 0.0</td>
</tr>
</tbody>
</table>

Electron configurations, terms, and energy levels come from the National Institute of Standards and Technology (NIST) spectroscopic database [32]. The LS coupling scheme assumes negligible spin-orbit interaction. The term symbol is \(^{S+1}L_J\), where \(S\) is the total spin angular momentum, \(L\) is the total orbital angular momentum, and the total angular momentum \(\vec{J} = \vec{L} + \vec{S}\). Odd parity is indicated by a superscript ‘o’.

This thesis presents the development and characterization of AIR-Spec as well as the first science results from the eclipse observation. Chapters 2 and 3 present the AIR-Spec instrument and serve as a guide to the eclipse data. Chapter 2 describes the mission science goals and explains how the instrument was designed and built to meet those goals. The optical alignment procedure is described, and the chapter ends with a description of the eclipse flight. Chapter 3 picks up the story with a summary of the eclipse observations, followed by the details of the data processing and calibration schemes. The chapter ends with a description of the available data.
Chapters 4 and 5 describe the first scientific results from the 2017 eclipse observation. Chapter 4 focuses on the 1.43 µm transition of Si X, the brightest coronal line observed by AIR-Spec. The first half discusses the Si X intensity gradient and its interpretation in terms of line excitation processes. The second half examines the Doppler velocity variations across different coronal structures and presents an interesting case study of bimodal velocities observed after an eruption. Chapter 5 describes the Fe IX detection, the first of that line.

Chapter 6 summarizes the early findings from the 2017 eclipse and then presents some avenues for future exploration of the observations. It concludes with a discussion of follow-on missions, including a re-flight of AIR-Spec and development of a spectropolarimeter to make airborne measurements of the coronal magnetic field.
The Airborne Infrared Spectrometer (AIR-Spec) is an imaging spectrometer that was designed to search for infrared emission lines of Si X, S XI, Fe IX, Mg VIII, and Si IX in the solar corona during the total solar eclipse on August 21, 2017. Results from the 2017 measurement will inform the design of future instruments to measure the coronal magnetic field. AIR-Spec was funded by a Major Research Instrumentation grant from the NSF with cost-sharing by Smithsonian Institution. It observed the eclipse from the NSF/NCAR Gulfstream V High-performance Instrumented Airborne Platform for Environmental Research (GV HIAPER).
This chapter describes the instrument design, implementation, and deployment. Section 2.1 presents the mission science goals and frames the instrument specifications in the context of meeting those goals. The instrument design and implementation are presented in Section 2.2, including the optical design and the practical considerations of image stabilization and thermal background reduction. Section 2.3 describes the optical alignment of each subsystem and the instrument as a whole. Finally, Section 2.4 discusses the eclipse flight and timeline of operations.

2.1 Goals and specifications

In addition to the basic success criterion of identifying one or more of its five target emission lines, AIR-Spec had three science goals focused on exploring the spatial and spectral characteristics of each line:

1. Measure line wavelengths and intensities in different regions of the corona.

2. Measure intensity gradient as a function of distance from the limb to provide information on the radiative excitation of each line \(^{23}\).

3. Search for time-varying Doppler velocities in the lines, including high frequency velocity oscillations which are thought to be the signatures of waves or flows \(^{10, 67}\).

The upper half of Table 2.1.1 lists the predicted rest wavelengths, intensities, and linewidths of the five AIR-Spec lines. The instrument performance, shown in the lower half of the table, ensured that each science goal was met for one or more lines. The spectral range extends from each predicted central wavelength \(\pm 200\ \text{Å}\), allowing for the 0.1% wavelength uncertainty \(^{28}\) plus a 500% margin. The spectral resolution broadens each line by only a factor of 2–3. The spectral dispersion provides 5–6 pixels across each measured full width half maximum (FWHM), allowing centroid performance to be determined by signal-to-noise ratio (SNR) alone. The 1.55 \(R_\odot\) field of view (FOV) is sufficient to sample different coronal conditions with a single slit position, while the 11–13 arcsec spatial resolution is sufficient to
distinguish between different coronal features. Near the limb where the corona is brightest, a 30 second exposure provides SNR sufficient to detect all of the lines and a 1 second exposure provides 5 km/s velocity resolution on SiX.

**Table 2.1.1:** Predicted emission line properties and measured instrument performance.

<table>
<thead>
<tr>
<th></th>
<th>SiX</th>
<th>S XI</th>
<th>Fe IX</th>
<th>Mg VIII</th>
<th>Si IX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest wavelength (^1) (µm)</td>
<td>1.43</td>
<td>1.92</td>
<td>2.86</td>
<td>3.03</td>
<td>3.93</td>
</tr>
<tr>
<td>Thermal linewdith (^2) (Å)</td>
<td>2.3</td>
<td>3.1</td>
<td>4.6</td>
<td>4.9</td>
<td>6.3</td>
</tr>
<tr>
<td>Intensity (^1) at 1.1R(\odot) (ph s(^{-1}) cm(^{-2}) sr(^{-1}))</td>
<td>12 × 10(^{12})</td>
<td>2.4 × 10(^{12})</td>
<td>1.2 × 10(^{12})</td>
<td>1.7 × 10(^{12})</td>
<td>3.0 × 10(^{12})</td>
</tr>
<tr>
<td>Spectral range (µm)</td>
<td>1.42 – 1.54</td>
<td>1.87 – 1.99</td>
<td>2.83 – 3.07</td>
<td>2.83 – 3.07</td>
<td>3.75 – 3.98</td>
</tr>
<tr>
<td>Spectral dispersion (Å/pixel)</td>
<td>1.19</td>
<td>1.17</td>
<td>2.37</td>
<td>2.37</td>
<td>2.33</td>
</tr>
<tr>
<td>Spatial FOV (R(\odot))</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
<td>1.55</td>
</tr>
<tr>
<td>Spatial sampling (arcsec/pixel)</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
<td>2.31</td>
</tr>
<tr>
<td>Spectral resolution (Å)</td>
<td>7.5</td>
<td>7.5</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Spatial resolution (arcsec)</td>
<td>11</td>
<td>13</td>
<td>11</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>SNR (^3) of line center</td>
<td>140</td>
<td>10</td>
<td>7</td>
<td>7</td>
<td>12</td>
</tr>
</tbody>
</table>

\(^1\) Rest wavelengths and intensities were predicted by Judge [28].

\(^2\) Thermal line widths were extrapolated from measurements of the 530.3 nm Fe XIV [8].

\(^3\) SNR is specified for a 30 second exposure over 35 arcsec at the limb.

### 2.2 Design and Implementation

AIR-Spec consists of an image stabilization system, telescope, infrared spectrometer, and visible slit-jaw imager (Figure 2.2.1). The image stabilization system keeps the sun fixed in the telescope field of view as the airplane moves. The telescope focuses onto a mirrored slit-jaw, where the light is divided into two channels. Visible light reflected by the slit-jaw is imaged by a slit-jaw camera, while infrared light passing
Figure 2.2.1: AIR-Spec on-board GV HIAPER. The instrument is installed on the floor at the front left of the cabin. The image stabilization system, telescope, spectrometer, and slit-jaw camera are mounted on a vibration-isolated optical bench (1). Light enters through a small viewport on the upper right of the fuselage and is reflected into the telescope by a fast steering mirror (2). The optical bench is translated fore–aft and left–right (3) and the mirror rotated about two axes (4) to facilitate alignment of the sun, window, mirror, and telescope. The spectrometer optics are contained in a vacuum chamber (5) and cooled with liquid nitrogen (6). Through the slit is dispersed by a diffraction grating and focused onto an infrared detector.

2.2.1 Optical system

Figure 2.2.2 shows a raytrace of the AIR-Spec telescope and spectrometer. Light is collected by the f/1.5 Cassegrain telescope (10 cm primary, 1.5 m focal length) and focused onto a 70 μm entrance slit. The light exiting the slit is collimated by a 0.7 m focal length spherical mirror, and the collimated light is incident on a planar diffraction grating with 10 μm groove spacing. The grating is used in a near-Littrow configuration, so that the diffracted wavelengths are nearly coincident with the incoming light. The five wavelengths of interest are diffracted in two groups, second order 1.92 μm rays near first order 3.94 μm rays, and second order 1.43 μm rays near first order 2.84 μm and 3.03 μm rays. Two 0.5 m focal length spherical mirrors focus the two wavelength groups onto the top and bottom of the detector. The 3 μm and 4 μm channels include second order light at 1.5 μm and 2 μm, respectively. The detector layout is shown in
Figure 2.2.2. The spectral and spatial characteristics of each channel are listed in Table 2.1.1.

Figure 2.2.2: Raytrace of the AIR-Spec telescope and spectrometer (left), including the layout of emission lines on the infrared detector. Raytrace of the slit-jaw camera optics (right).

The infrared camera is an IRC912 from IR Cameras, modified to include a non-standard focal plane with 50,000 electron well depth. The indium antimonide (InSb) detector is sensitive from 1 – 5.3 µm, with a quantum efficiency of about 95%. The focal plane has 1024 pixels along the spectral dimension and 1280 pixels along the spatial dimension (640 pixels per channel). The pixel pitch is 12 µm, providing a linear dispersion of about 2.4 Å/pixel in first order (1.2 Å/pixel in second order) and a plate scale of 2.3 arcsec/pixel. The spectral width of each channel is about 2400 Å in first order and 1200 Å in second order. The slit length is 0.4 degrees (1.5 R⊙). During the eclipse, the IR camera operated at a cadence of 15 frames/sec. The coronal data were collected with a 60 ms exposure time.

The white light slit-jaw camera provides context imagery for the infrared spectra. Light from the mirrored slit-jaw is re-imaged by a monochrome visible camera, in which the slit appears as a dark line superimposed on the corona. Both the white light camera and its lens are commercially available products. The camera is a Prosilica GC 1290 from Allied Vision Technologies, with 1280 × 960 3.75 µm pixels. The f/1.4, 35 mm camera lens is a Fujinon CF35HA-1. A field lens ensures that the off-axis rays
from the slit-jaw are not vignetted at the camera lens. The field lens is a 150 mm achromat that serves as the vacuum chamber exit window for the light reflected from the slit-jaw. The slit-jaw camera has a plate scale of 2.3 arcsec/pixel (equivalent to the IR camera plate scale), a 2.3 R⊙ field of view (1.5 times larger than the IR camera FOV), and a cadence of 33 frames/sec (about twice the IR camera cadence). During totality, a the exposure time was set to 1 ms to provide a well-exposed inner corona. A ray trace of the slit-jaw camera optics is shown in Figure 2.2.2.

The two main challenges of implementing the AIR-Spec optical design were (1) pointing the telescope at the sun stably and continuously and (2) minimizing the level of the dark instrument background. Pointing and stabilization were achieved by actively controlling the line of sight (LOS) with a fast steering mirror and manually adjusting the mirror and table to compensate for changes in viewing geometry. The instrument background was reduced by cooling the spectrometer optics and infrared camera. Figure 2.2.1 shows AIR-Spec installed in the GV cabin with image stabilization and cooling system components identified.

2.2.2 Pointing and Image Stabilization

During the 2017 eclipse, AIR-Spec observed through a 150 × 220 mm sapphire viewport on the top right side of the aircraft cabin. The instrument was mounted to the floor on the left side of the cabin, where a fast-steering mirror on the optical bench directed sunlight from the window into the telescope (Figure 2.2.1). Since both the field of view through the window and the mirror range of travel were limited, the instrument was positioned fore–aft and left–right using linear sliders and the mirror normal was aligned using two manual rotary adjusters on its mount. A custom alignment tool similar to a telescope reflex sight was used to place the sun in the telescope through the window as the instrument was translated and the mirror was rotated. The alignment tool superimposed an LED referencing the telescope LOS onto a view of the sun through the aircraft window.

Image stability was addressed in two ways. First, the optical bench was isolated from the effects of
high-frequency airframe vibration by six tuned isolators placed between it and the aircraft floor. Second, the remaining low-frequency perturbations were compensated by a closed-loop fast steering mirror that fed a stabilized beam into the telescope. The mirror was dynamically positioned so that the line of sight from the sun was normally incident on the telescope. The image stabilization requirement was 4.6 arcsec (2 pixels) RMS over each 60 ms camera exposure. During the four minute eclipse observation, 92% of exposures achieved this requirement (Figure 2.2.3).

**Figure 2.2.3:** Image stabilization system block diagram (left) and performance (right). RMS jitter for each 60 ms exposure is plotted in blue. The 2 pixel Nyquist limit is the red line. 92% of exposures have jitter below the Nyquist limit.

The image stabilization is shown schematically in Figure 2.2.3. Computations are performed at 500 Hz by a real-time computer. The mirror command is calculated from three inputs: the eclipse ephemeris (computed using GPS location and time), aircraft attitude given by the integrated gyroscope rates, and slit position coordinates from the operator. In order to position the slit, the operator monitors a video of the white light corona from the slit-jaw camera.
2.2.3 Thermal background reduction

Because of their close proximity to the focal plane, the slit-jaw, collimator, grating, focus mirrors, and camera fold mirror emit enough radiation at room temperature to overwhelm the coronal signatures. Radiation from the slit-jaw is especially significant because it is imaged onto the focal plane by design. In order to maximize signal-to-noise ratio, the slit-jaw and all subsequent optics are cooled to 150 K. To achieve this while keeping the optics dry and stable, the entire spectrometer is housed in a vacuum chamber at a pressure below $10^{-3}$ Torr. The optics are mounted to thermally isolated plates and attached with copper straps to the chamber floor, which is the top of a liquid nitrogen dewar. Chilled wall guards shield the detector from thermal radiation from the warm walls, and the wall guards and floor are blackened to reduce reflectivity. Figure 2.2.4 shows the inside of the vacuum chamber, including the spectrometer optics, liquid nitrogen ports, and chilled wall guards. Two feedthrough micrometers on the focus mirrors (not shown) allow cold alignment of the two channels on the detector. The inset shows in more detail how the optics are mounted and cooled.

The infrared camera includes several features that help minimize its dark background. The focal plane is chilled to 59 K by a closed-cycle cooler, providing a dark current of about 20,000 DN/sec. The thermal background is reduced by a cold aperture, which limits the field of view, and a cold bandpass filter, which removes light outside the instrument passbands. Packing the camera–spectrometer interface in dry ice provides a 2x further reduction in the background.

Compared to room temperature operation, the thermal background is 400x lower when the spectrometer and camera are chilled with liquid nitrogen and dry ice (Figure 2.2.4). At cold equilibrium, the background level is on the order of $10^5$ DN/sec, and a 60 ms exposure time limits the background to half the 15,000 DN well depth. The target exposure time for the 2019 eclipse is 1 second, which will require an additional 10x–15x reduction in the dark background. To achieve this, a three-pronged approach will reduce light from inside the spectrometer, light from the camera, and the detector dark
Figure 2.2.4: Thermal background reduction. Left: Top-down view of the AIR-Spec vacuum chamber before it was blackened to reduce stray light. The spectrometer optics and IR camera are labeled. Liquid nitrogen enters through the LN$_2$ fill port and nitrogen gas is released through the vent. Copper straps connect the optics to the floor, which is the top of the liquid nitrogen dewar. Inset: Detail of the collimator mount and cooling strap. To maximize stability, each optic is mounted to the warm chamber wall with G10, a thermally isolating fiberglass composite. A thermally conducting copper strap attaches the optic to the cold spectrometer floor. Inner and outer wall guards block radiation from the warm chamber wall. Right: Effect of cooling the instrument.

Current. The focal plane will be more effectively shielded from the spectrometer, the camera body will be cooled to a lower temperature, and the detector temperature will be reduced to below 55 K.

2.3 Optical alignment

The AIR-Spec alignment took place in five steps. First, the telescope secondary was aligned to the primary. The internal spectrometer optics were aligned next, and then the slit-jaw camera was aligned to the slit-jaw. Finally, the telescope was aligned and focused relative to the spectrometer, and the image stabilization components were aligned to the telescope.

The purpose of the optical alignment was to minimize the instrument point-spread function (PSF) and center and focus the image on each camera. Because small misalignments could be compensated by adjusting focus, it was sufficient to align each optic to several hundred microns in centration and several...
arcminutes in tilt. With the system aligned to this level, misalignment had a negligible effect on PSF compared to imperfections in the mirror surfaces.

2.3.1 Telescope mirrors

The method for aligning the AIR-Spec telescope was modeled on the alignment procedure for the Atmospheric Imaging Assembly (AIA) telescopes (W. Podgorski private communication to V. Marquez, 2017). Before the primary and secondary mirrors were aligned, a corner cube was positioned to reference the mechanical boresight of the telescope tube. Two cross-hair reticles were mounted at either end of the tube, one in the primary mirror hole and the other in place of the secondary. An alignment telescope was used to find the line through both reticles, and this line was defined as the mechanical boresight. With the alignment telescope in auto-collimation mode, a retro-reflecting flat mirror was aligned to both telescopes. Finally, the corner cube was aligned to the retro flat using a theodolite and bonded into place.

The secondary mirror was aligned to the primary with the telescope in the double-pass configuration shown in Figure 2.3.1 (left), from a Zygo application note on typical interferometer setups [72]. A Zygo interferometer (model GPI-4-XP 512, 633 nm wavelength) fed the telescope and precisely measured the tip, tilt, and defocus of the returned wavefront, which was reflected back through the system by the retro flat. The focal point was defined by the center of a removable retro-reflecting ball mounted to the back of the telescope.

The interferometer was outfitted with an f/7.2 DynaFlect transmission sphere, suitable for aligning reflective surfaces, and the focus of the spherical beam was placed at the nominal telescope focus by translating the interferometer until the wavefront was approximately flat. The final wavefront had a peak-to-valley height of 0.76 waves and a power term of 0.13 waves, corresponding to about 3 \( \mu \text{m} \) lateral displacement and 30 \( \mu \text{m} \) axial displacement of the focal point from the center of the retro ball.

Next, the retro ball assembly was removed from the rear telescope flange and mounted upside down,
Figure 2.3.1: Telescope alignment. Left: Optical setup, including the Zygo interferometer, retro ball, AIR-Spec telescope, and retro flat [72]. Center: Aligning the secondary mirror. The retro ball is off-axis, allowing the Zygo laser beam to pass through the system. The secondary is tilted and focused by shimming with washers at the three points indicated. Right: Double-pass wavefront for the final telescope alignment, after zeroing tip and tilt. The phase variations are due to a combination of defocus and the λ/20 RMS surfaces of the primary and secondary.

maintaining the tilt of the telescope while allowing the interferometer beam to pass through it (Figure 2.3.1, center). The secondary mirror was shimmed with washers at its three mounting points, resulting in a final tilt of 28 waves (270 µm lateral displacement) and defocus of 0.23 waves (260 µm axial displacement). The right plot in Figure 2.3.1 shows the double-pass wavefront after zeroing tip and tilt by adjusting the retro flat. In addition to defocus, the variations across the wavefront come from imperfections in the mirror surfaces.

2.3.2 Spectrometer optics

The spectrometer alignment was complicated by the number of optical elements and the non-axial light path. However, the long depth of focus (0.5 mm) and the use of spherical mirrors provided relatively loose alignment tolerances that were achieved using shims and measurement tools such as a shear plate, a ruler, and the IR camera. Because all of the spectrometer optics were either planar or spherical, decenter could be compensated by tilt with little effect on PSF. Therefore, it was sufficient to center the light path on each optic to about 0.5 mm and precisely align the image on the detector by tilting the focus mirrors with a set of micrometers.

Two input assemblies were constructed to allow alignment in both visible and infrared light (Figure
Figure 2.3.2: Input options for spectrometer alignment. The focusing optics are fed by either two visible lasers or a broadband IR lamp. The focusing optics image the object (microscope objective spot or IR-illuminated field stop) onto the slit through the vacuum chamber window (lower right).

2.3.2). The visible laser assembly combined red (635 nm) and blue (405 nm) lasers with a 50:50 beamsplitter. A 40x microscope objective was used to create a fast divergent beam. The infrared assembly consisted of a field stop (iris aperture) illuminated by a diffuse broadband IR source. One of several exchangeable filters could be included to tailor the spectral output. A 50 mm MgF\textsubscript{2} lens focused light from the operational assembly, imaging the object (microscope objective spot or IR-illuminated field stop) onto the spectrometer slit-jaw. The lens was placed approximately 75 mm from the object and 150 mm from the slit, providing a magnification of about 2. The f number was set by another iris, which acted as an aperture stop. The spectrometer was aligned according to the following procedure:

1. A 50 µm pinhole was mounted in place of the slit-jaw. The laser input assembly (with the blue laser off) was aligned through the pinhole to the center of the collimating mirror, defining the optic axis.

2. Pinhole focus: A shear plate was used to check the beam from the collimating mirror. The mirror was shimmed until the shear plate fringes were parallel to the fiducial line, indicating that the
pinhole was coincident with the mirror focal point (Figure 2.3.3a).

Figure 2.3.3: Alignment of the spectrometer optics. (a) Pinhole focus. The shear plate fringes are parallel to the fiducial line, indicating that the pinhole is at the focus of the collimator. (b) Collimator tilt. The collimator has been tilted to center the collimated beam on the grating. (c) Grating tilt. The grating has been tilted to properly align the red and blue dispersed beams on the focus mirrors. (d) Feedthrough micrometers for tilting the focus mirrors. (e) Focus mirror tilt. Each focus mirror has been tilted to center the pinhole image vertically and properly align the passbands horizontally. (f) Grating rotation. The grating has been clocked so that the broadband image of the pinhole is approximately horizontal in both channels. (g) Slit rotation. The slit has been clocked so that the atmospheric absorption features are approximately vertical in both channels. (h) Cold alignment. Screen-shot from the IR visualization software during in-flight alignment of the focus mirrors. The lower plot shows the 3 µm spectral × spatial image and the upper a spectral cross-section of the image. Spectral alignment is achieved when photospheric absorption features in the measured spectrum (1) overlap with those in the library spectrum (2). Spatial alignment is achieved when light from the slit is centered vertically in the detector, resulting in a dark band at the top (3) and bottom (4).

3. **Collimator tilt:** The 50 µm pinhole was replaced by a 400 µm pinhole and the blue laser was turned on. The collimating mirror was tilted about two axes until the beam was centered on the diffraction grating (Figure 2.3.3b).
4. *Grating tilt*: The grating was tilted about two axes until the 6th order beam from the red laser \((m\lambda = 3.81 \, \mu m)\) and the 7th order beam from the blue laser \((m\lambda = 2.835 \, \mu m)\) landed in their intended locations on the two focus mirrors (Figure 2.3.3c).

5. The laser assembly was replaced by the IR assembly. The field stop was adjusted to fully illuminate the pinhole while underfilling the 25 mm pinhole substrate, to prevent stray light from reaching the detector. The illuminated pinhole produced a bright line in each channel of the IR camera.

6. *Focus mirror tilt*: Narrowband filters centered at 1480 nm and 1900 nm were added one at a time. Using the feedthrough micrometers (Figure 2.3.3d), each focus mirror was tilted about two axes until the line was centered vertically in the channel and the spectral passband was centered at the intended horizontal pixel (Figure 2.3.3e).

7. *Grating rotation*: The narrowband filters were removed. The grating was rotated in-plane until the line in each channel was approximately horizontal (Figure 2.3.3f).

8. *Camera focus*: The 400 \(\mu m\) pinhole was replaced by the 50 \(\mu m\) pinhole (an approximate point source). The focus of the pinhole image was checked in both channels. The point-spread function was about as wide as predicted, so the focus mirrors were not moved.

9. *Slit rotation*: The 400 \(\mu m\) pinhole was removed and the slit-jaw was mounted in its place. The field stop was adjusted to overfill the slit while underfilling the slit-jaw. The slit-jaw was rotated in-plane until the observed atmospheric absorption features were approximately vertical in both channels (Figure 2.3.3g). Although the alignment was performed indoors, the absorption was measurable due to the long path length in the open vacuum chamber.

10. *Slit focus*: The top and bottom edges of the slit image were checked in the IR camera. The top edge was well-focused, indicating that the slit-jaw did not need to be adjusted. Light from the bottom of the slit was vignetted by the slit-jaw mount, reducing the slit length by 10% (Figure 2.3.3g). This issue will be corrected before the 2019 eclipse.
11. **Cold alignment:** The spectrometer was sealed, pumped down, and chilled. As designed, the image focus, spatial rotation, and spectral rotation remained unchanged. The image shifted spectrally and spatially, and this was corrected by tilting the focus mirrors. The final alignment of the focus mirrors was performed in flight, using absorption lines in the solar photosphere to place the spectrum on the detector (Figure 2.3.3h).

2.3.3 **Slit-jaw camera**

Once the position of the slit-jaw was finalized, the slit-jaw camera was aligned to it. Figure 2.3.4 shows the slit-jaw camera and associated optics, with the available adjustments labeled. The slit-jaw itself is out of sight inside the vacuum chamber. The fold mirror was tilted about two axes to center the slit in the image. The plate scale was set by translating the camera and lens as a unit, and the image was focused using the focus adjustment on the camera lens. The target plate scale was 2.31 arcsec/pixel, equivalent to that of the IR camera. Due to limited travel in the translation stage, the maximum available plate scale was 2.26 arcsec/pixel (Section 3.3.2).

![Slit-jaw camera and associated optics.](Figure 2.3.4)
Figure 2.3.5: Aligning the telescope to the spectrometer. (a) Diagram of components. The theodolite was used to align tip, tilt, and focus, while the IR collimator was used to check centration. (b) Slit-jaw image of the theodolite crosshair. The green plus sign marks the center of the slit, 40 arcsec from center of the theodolite crosshair. The slit and theodolite crosshair are both in focus. (c) Slit-jaw image of a concentric circle target from the IR collimator. (d) 4 µm IR image of the concentric circle target. The intensity is uniform over the length of the slit, confirming that the telescope pupil is centered on the spectrometer mirrors.

The telescope was aligned to the spectrometer in tip, tilt, focus, and horizontal and vertical translation. Alignment took place with the spectrometer evacuated, cold, and internally aligned, ensuring that all
optical elements were in their flight positions. Tip, tilt, and focus were aligned using a theodolite, and translation was checked using an infrared collimator. Figure 2.3.5 shows the alignment scheme and results.

The telescope was placed in its nominal location in front of the spectrometer and fed with a collimated beam from the theodolite. A piece of the theodolite beam was retro-reflected by the telescope alignment cube, allowing the theodolite to be precisely aligned to the telescope line of sight. The theodolite output was focused onto the slit-jaw by the telescope and re-imaged by the slit-jaw camera (Figure 2.3.5a).

The telescope was adjusted in tip, tilt, and focus until the image of the theodolite crosshair was centered and focused on the slit (Figure 2.3.5b). Each time the telescope moved, the theodolite had to be realigned to the telescope alignment cube. This iterative process continued until the center of the theodolite crosshair was less than one arcminute from the center of the slit. In Figure 2.3.5b, the green plus sign marks the center of the slit. The center of the theodolite crosshair is displaced by 40 arcsec.

Next, the infrared image was checked for vignetting resulting from decenter of the telescope pupil on the spectrometer mirrors. Due to diffraction at the slit, the telescope overfilled the spectrometer mirrors horizontally but not vertically. As the vertical direction was more sensitive to decenter, centration was assessed by checking the intensity of the IR image along the slit. The theodolite was replaced with an infrared collimator (Figure 2.3.5a), which fed the telescope with collimated light from a concentric circle target illuminated by a broadband IR lamp. Figure 2.3.5c shows the slit-jaw image of the target with the slit through the center. Figure 2.3.5d shows the 4 μm infrared image and the spectrally integrated intensity at each bright circle sampled by the slit. In the intensity plot, variations in the light source have been removed by dividing by the intensity in the slit-jaw image and the result has been normalized. The intensity is relatively constant along the slit, indicating that the nominal telescope position adequately centered the pupil in the spectrometer mirrors. The slit vignetting discussed in Section 2.3.2 is apparent near the bottom of the intensity plot in Figure 2.3.5d.
2.3.5 IMAGE STABILIZATION SYSTEM

In the final step of the optical alignment, the fiber-optic gyroscope and fast steering mirror were aligned to the telescope. The three gyroscope axes were referenced by a corner cube aligned to x arcmin using a coordinate measuring machine. Two alignment holes in the bottom surface of the gyroscope package provided a precise reference for the gyroscope axes.

Figure 2.3.6a shows the alignment of the gyroscope to the telescope. The theodolite was aligned to the telescope line of sight by centering its crosshair on the center of the slit. Part of the theodolite beam was retro-reflected by the gyro corner cube. The gyroscope was tilted about its x and z axes until the y axis was aligned to the theodolite, and therefore to the telescope line of sight. The final alignment error between the gyroscope and telescope was less than 10 arcsec in each axis.

The fast steering mirror was installed and the theodolite was rotated 90 degrees to feed this mirror (Figure 2.3.6b). The theodolite was aligned along gyro x using the alignment cube. Using the adjustments in Figure 2.3.6c, the mirror assembly was rotated in azimuth and zenith until the image of the theodolite crosshair was centered at slit center. In this orientation, the fast steering mirror reflected the theodolite.
beam from gyro $x$ to gyro $y$ (the telescope line of sight), performing a 90 degree rotation about gyro $z$.
The resulting azimuth and zenith stage positions defined the origin from which all future positions were measured.

2.4 Eclipse flight

AIR-Spec observed the total eclipse from GV HIAPER between 18:22 and 18:26 UTC. The observation took place over western Kentucky, near maximum duration. The eclipse flight started and ended in Chattanooga, TN in order to minimize the fuel requirements and allow the Gulfstream V to fly at 14.3 km altitude, as high as possible above the IR-absorbing water vapor. To bring the spectrometer optics to thermal equilibrium, the instrument was cooled with liquid nitrogen beginning six hours before takeoff and ending 30 minutes before takeoff.

The flight path was designed to maximize the time spent in totality while optimizing the orientation of the aircraft before and during totality. Before entering the eclipse path, the GV flew a series of headings that compensated for the changing azimuth of the sun. This allowed the sun to be acquired well before second contact with the instrument optimally positioned for totality. The predetermined instrument position accounted for the likely wind direction, allowing the GV to fly along the eclipse path while remaining in an orientation that kept the total eclipse in the telescope.

Figure 2.4.1 shows the three hour eclipse flight. The aircraft took off two hours before second contact (18:22 UTC), flew northwest for about 50 minutes, and entered a holding pattern. The partial eclipse began, and the crew began adding dry ice to the IR camera interface. About 25 minutes before totality, the GV exited the holding pattern and the sun was acquired. The final spectral and spatial alignment was performed as described in Section 2.3.2. AIR-Spec observed totality for four minutes, collecting dark frames before and after and photospheric calibration data near the end of the flight. The GV landed in Chattanooga about 45 minutes after totality.
Figure 2.4.1: Eclipse flight and operations. The GV flight path is shown in blue, the totality center-line is marked by red dashes, and the totality swath appears in light red. The start time of each operation is noted with respect to second contact (C2) at 18:22 UTC. (1) Take off from Chattanooga, C2–130 min. (2) Enter holding pattern, C2–80 min. (3) Begin dry ice, C2–30 min. (4) Acquire the sun, C2–20 min. (5) Set wavelength range, C2–10 min. (6) Collect darks, C2–2 min. (7) Observe totality, C2–0 min. (8) Collect darks, C2+4 min. (9) Collect calibration data, C2+10 min. (10) Land in Chattanooga, C2+45 min.
The August 21, 2017 Eclipse Data

The carefully planned flight and operations resulted in four minutes of data at four positions in the corona as well as a five second observation of the chromosphere. All five target lines were observed (Table 3.1.2). Prior measurement campaigns have confirmed the existence of Si X at 1.43 μm [34, 55], S XI at 1.92 μm [30, 51], Mg VIII at 3.03 μm [48, 51], and Si IX at 3.93 μm [29, 35]. AIR-Spec made the first detection of Fe IX at 2.84 μm [58].

A summary of the observations and coronal line characteristics is given in Section 3.1. The next two sections describe the data processing and calibration. The post-processing scheme includes dark
subtraction, defective pixel replacement, and image rectification and registration (Section 3.2).

Observations of the photosphere and chromosphere are used to calibrate wavelength, pointing, plate scale, throughput, and resolution (Section 3.3). Section 3.4 outlines the structure and organization of the available data.

3.1 **Summary of observations**

AIR-Spec observed the corona at four positions, sampling the west limb, a solar prominence, and the east limb (including an active region). A fifth position measured the chromosphere at third contact.

Table 3.1.1 lists the time spent at each position and the number of frames acquired in each camera. Most of totality was spent on the west limb to coordinate with other observatories.

<table>
<thead>
<tr>
<th>Slit Position</th>
<th>Duration</th>
<th>IR Frames</th>
<th>SJ Frames</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. West limb</td>
<td>63.5 sec</td>
<td>953</td>
<td>2083</td>
</tr>
<tr>
<td>2. Prominence</td>
<td>41.5 sec</td>
<td>622</td>
<td>1359</td>
</tr>
<tr>
<td>3. East limb</td>
<td>35.7 sec</td>
<td>536</td>
<td>1171</td>
</tr>
<tr>
<td>4. Prominence &amp; west limb</td>
<td>82.4 sec</td>
<td>1236</td>
<td>2702</td>
</tr>
<tr>
<td>5. Chromosphere</td>
<td>5.0 sec</td>
<td>75</td>
<td>164</td>
</tr>
</tbody>
</table>

Figure 3.1.1 shows the average slit position for each observation superimposed on a composite of images from the slit-jaw camera (left) and the mean infrared spectrum corresponding to each slit position (right). Each baseline-subtracted spectrum was averaged completely in time and over 35 arcsec at the limb. All five target lines were observed in all of the coronal positions. Neutral hydrogen was observed in the prominence and chromosphere. The chromospheric (flash) observation was used in the wavelength calibration (Section 3.3.1) and point-spread function (PSF) measurement (Section 3.3.4). H I lines in the
prominence were also used to measure PSF. Gaussian fits to each line (Figure 3.1.2) provided the center wavelength, FWHM, and intensity (Table 3.1.2).

<table>
<thead>
<tr>
<th>Ion</th>
<th>( \lambda_o ) (( \mu m ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si X</td>
<td>1.43030 ± 0.00004</td>
</tr>
<tr>
<td>S XI</td>
<td>1.92088 ± 0.00004</td>
</tr>
<tr>
<td>Fe IX</td>
<td>2.84262 ± 0.00009</td>
</tr>
<tr>
<td>Mg VIII</td>
<td>3.02789 ± 0.00006</td>
</tr>
<tr>
<td>Si IX</td>
<td>3.93381 ± 0.00005</td>
</tr>
</tbody>
</table>

Observed wavelengths \( \lambda_o \) (in air) are from a 30 second measurement at the east limb. They have been corrected for solar rotation. The wavelength calibration is described in Section 3.3.1.

3.2 IMAGE PROCESSING

Each infrared camera frame was processed to remove the dark background, replace defective pixels, align the spatial and spectral axes with the image, register to other frames along the slit, and remove interference fringes from the 4 \( \mu m \) channel. Two-dimensional image registration was performed on the slit-jaw images.

3.2.1 DARK SUBTRACTION

Because of the significant thermal background discussed in Section 2.2.3, it was necessary to subtract a dark frame from each infrared data frame in order to see the IR corona. Dark frames were collected before and after totality by blocking light from the telescope at the vacuum chamber entrance window.
Figure 3.1.1: Observation overview. Slit positions (top) and corresponding IR spectra (bottom).
Figure 3.1.2: Gaussian fits to the coronal lines in slit position 3 (east limb).

Figure 3.2.1 shows the dark frame immediately after totality (a) and the time variation of the mean dark frame over the 6 minutes following totality (b). The background image has a mean of about 10,000 DN and significant structure resulting from bright regions inside the spectrometer. In comparison, the measured intensity of the brightest coronal line is about 150 DN. The background increases with time at a rate of about 80 DN/minute as the liquid nitrogen evaporates and the dry ice sublimes.

Figure 3.2.1: Behavior of the dark background. (a) Dark frame at the end of totality. (b) Six minute time series of the spatial average.

For pixels near the center of the array, a 4.2 minute sinusoidal trend is superimposed on the warm-up. The sine wave comes from the Stirling cooler used to chill the detector. The cold piston of the cooler is in contact with the middle of the focal plane and moves toward and away from the focal plane at 60 Hz, the
operating frequency of the cooler. This generates a time-varying acceleration in the pixels near the center of the detector, introducing a piezoelectric effect that changes the intensity in those pixels. The 4.2 minute period is a result of aliasing the \( \approx 60 \) Hz fluctuation by sampling at the 15 Hz frame rate. The amplitude \( A \) and phase \( \phi \) of the aliased sine wave are given by

\[
A = A_o \sin \left[ \pi \frac{T_{\text{exp}} \cdot 60 \text{ Hz}}{} \right]
\]

\[
\phi = \phi_o + \pi \frac{T_{\text{exp}} \cdot 60 \text{ Hz}}{}
\]

where “frac” denotes the fractional part of the argument, \( T_{\text{exp}} \) is the exposure time, and \( A_o \) and \( \phi_o \) are the amplitude and phase of the original (unaliased) 60 Hz wave. \( A_o \) and \( \phi_o \) vary from pixel to pixel but remain constant in time. They were measured after the eclipse and are shown in panels (a) and (b) of Figure 3.2.2.

\[\text{Figure 3.2.2: Fit parameters for the time evolution of the dark background. (a) Initial intensity in DN. (b) Rate of change in DN/minute. (c) Sine wave amplitude in DN. (d) Sine wave phase in radians.}\]

Because the background varied significantly over the four minutes of totality, its time evolution was modeled using an eight minute series of dark frames from before and after totality. 90 frames (6 seconds) of data were averaged to produce each sample in the time series. The signal in each pixel was assumed to
have the form

\[ I(t) = I_0 + r(t - t_0) + a(t - t_0)^2 + A \sin \left( \frac{2\pi(t - t_0)}{4.2 \text{ min}} + \phi \right), \tag{3.3} \]

where \( I \) is the pixel intensity in DN, \( t \) is the time each frame was collected, \( t_0 \) is an arbitrary start time, \( I_0 \) is the initial intensity in DN, \( r \) is the linear rate of change in DN/minute, \( a \) is the acceleration in DN/minute\(^2\), \( A \) is the sine wave amplitude in DN, and \( \phi \) is the sine wave phase in radians. \( A \) and \( \phi \) were calculated using Equations 3.1 and 3.2, and \( t_0 \) was selected such that the observed phase of the dark time series was equal to \( \phi \) at \( t = t_0 \). The sinusoidal term was subtracted from the time series and \( I_0, r, \) and \( a \) were estimated for each pixel using a least-squares fit. Maps of \( I_0 \) and \( r \) are shown in panels (c) and (d) of Figure 3.2.2.

3.2.2 Defective pixel replacement

At 60 ms exposure time, defective pixels made up about 2% of the focal plane array. Bad pixels were identified as outliers in the distributions of initial intensity, rate, or acceleration or as pixels with poor fits to Equation 3.3. They were replaced using bilinear interpolation. Figure 3.2.3 shows the histograms for initial intensity (a), rate (b), acceleration (c), and \( \chi^2 \) (d), with black vertical lines marking the cutoff values for good pixels. Defective pixels are shown in white in Figure 3.2.3e.

3.2.3 Geometric correction

After dark subtraction and defective pixel replacement, a geometric correction was applied to remove spectral and spatial shear in the infrared images. The shear was produced by the optical design and is apparent in Figure 3.2.4a, which shows IR data from scattered photospheric light just before totality. The structure along the spectral dimension comes from photospheric and atmospheric absorption, while the spatial structure comes from dust on the slit and variations in the scattered intensity. The spectral shear is
Figure 3.2.3: Defective pixels. Histograms are used to identify outliers in initial intensity (a), rate (b), acceleration (c), and goodness of fit (d). Good pixels lie between the black vertical lines. Defective pixel map (e). Bad pixels are shown in white and make up 2% of the array.

Shear was removed by computing a coordinate transformation to align the image axes with the sheared features and then interpolating the data from sheared coordinates to Cartesian coordinates. A gradient filter was used to detect lines along the spectral and spatial features. Each line was defined by two \((x, y)\) coordinate pairs, which were mapped to corrected coordinates \((u, v)\) corresponding to horizontal and vertical lines. Because the sheared lines were straight and parallel, the \(2 \times 3\) affine transformation \(T\) was used to map each \((x, y)\) to \((u, v)\) according to

\[
\begin{bmatrix}
  u \\
  v
\end{bmatrix} = T
\begin{bmatrix}
  x \\
  y \\
  1
\end{bmatrix}
\]
Figure 3.2.4: IR image processing: geometric correction, image registration, and fringe removal. The optical design shears spectral and spatial features with respect to the detector (a). After geometric correction, the spectral and spatial axes are aligned with the detector axes in both channels (b). Due to pointing jitter, the lunar limb crosses the slit at a different place in each frame (c). The high-contrast limb is used to detect the jitter, and each frame is shifted an integer number of pixels to align with the others (d). In the 4 µm channel, interference fringes obscure the emission lines (e). The fringes are removed using a notch filter at the fringe frequency (f).
A least squares estimate for $T$ is given by

$$\tilde{T} = UX^T (XX^T)^{-1}, \quad (3.5)$$

where $U = \begin{bmatrix} u_1 & u_2 & \ldots & u_n \\ v_1 & v_2 & \ldots & v_n \end{bmatrix}$, $X = \begin{bmatrix} x_1 & x_2 & \ldots & x_n \\ y_1 & y_2 & \ldots & y_n \\ 1 & 1 & \ldots & 1 \end{bmatrix}$, and $n \geq 3$ is the number of features (lines) extracted.

$\tilde{T}$ was used to produce a sheared grid aligned with the spectral and spatial features, and the IR data was mapped from the sheared grid to a Cartesian grid using bilinear interpolation. Separate transformations were used to correct the 3 \(\mu\)m and 4 \(\mu\)m channels. Figure 3.2.4b shows the IR data after geometric correction. The spectral and spatial features are aligned with the image axes.

### 3.2.4 Image Registration

In order to remove residual pointing jitter, image registration was performed on frames from both cameras. The slit-jaw images were registered in $x$, $y$, and rotation to place solar north up and moon center at the same location in all frames (Figure 3.2.5). The rotation angle was found by comparing the IR corona to the 193 \AA{} channel of the Atmospheric Imaging Assembly (AIA) [36], after enhancing features by applying a radial filter and computing the image gradients. Moon center was found by fitting the limb of the moon to a circle.

The IR images were registered along the spatial dimension by placing the limb of the moon at the same pixel in all frames. First, each frame was summed along the spectral dimension to produce the integrated intensity at every pixel along the slit. Figure 3.2.4c shows the spectrally integrated intensity as a function of spatial pixel and time. The inner corona appears as a wavy bright line in each channel, with a sharp intensity change at the limb of the moon. The spectrally integrated intensity was differentiated with
Figure 3.2.5: Slit-jaw image registration. By matching features in AIR-Spec (a) and AIA 193 (b), the slit-jaw frames are rotated to orient solar north up. Moon center is found by fitting the lunar limb to a circle (c). Each frame is shifted horizontally and vertically to place moon center in the same location.

respect to the distance from sun center, and the pixel with the largest derivative was defined as the limb of the moon. Each frame was shifted an integer number of spatial pixels to align the location of the limb. Figure 3.2.4d shows the spectrally integrated intensity after alignment.

3.2.5 Fringe removal

Interference fringes of unknown origin appeared in the 4 μm channel of the infrared data. The fringes were oriented vertically on the image and had a period of about 14 pixels (170 μm) and a peak-to-peak amplitude of 5–10 DN. Figure 3.2.4e shows a sample 4 μm image and its spatial (row) mean. The fringes are bright enough to obscure the two emission lines in the image.

The fringes were removed by applying a notch filter at the fringe frequency. Figure 3.2.6 shows the power spectral density (blue) of the mean row in the 4 μm channel. A peak appears at the fringe frequency of 6 mm$^{-1}$. The notch filter (black) attenuates frequencies between 5 and 7 mm$^{-1}$. Figure 3.2.4f shows the sample 4 μm image after fringe removal. The emission lines are clearly visible.
Figure 3.2.6: Power spectral density of the mean row in the 4 µm channel (blue). Fringes with a period of 14 pixels (170 µm) appear as a peak at 6 mm$^{-1}$. The notch filter (black) attenuates frequencies between 5 and 7 mm$^{-1}$, removing the fringes.

3.3 CALIBRATION

The AIR-Spec wavelength, plate scale, pointing, and throughput were calibrated to map spectral pixel to wavelength, spatial pixel to solar coordinates, and image intensity to spectral radiance. A calibration of the point-spread function provided a measurement of the spectral and spatial instrument resolution.

3.3.1 WAVELENGTH

The 3 µm channel wavelength calibration was obtained from a measurement of the chromosphere at third contact, which contained a number of strong hydrogen lines (Figure 3.3.1a). Gaussian fits to the measured H I lines gave the center of each line in pixels. The mapping from pixel to wavelength was estimated using a weighted linear least squares fit of the measured line centers to H I rest wavelengths from the NIST spectroscopic database (Figure 3.3.1b). As the chromosphere was measured on the west limb at a solar latitude of +10°, reference wavelengths were scaled by $1 + v_r/c$ ($v_r = 2.04$ km/s) to account for the redshift due to solar rotation. The regression weights were given by the inverse of the
variance for each line center estimate, and residuals were on the order of a few Å (Figure 3.3.1c).

In the 4 µm channel, only two unblended lines were observed in the chromospheric spectrum. A measurement of the photosphere provided a more accurate wavelength calibration (Figure 3.3.1d). The strong HI (Paschen) line at 1.875 µm was used to align the photospheric and chromospheric spectra, as it was observed in absorption in the photosphere and emission in the chromosphere. The photospheric reference spectrum was synthesized by R. Kurucz (http://kurucz.harvard.edu/stars/sun) and smoothed to $R = 5000$ to approximate the AIR-Spec resolution. Absorption features in the AIR-Spec and reference spectra were fit to convex third order polynomials to precisely measure their centers. The reference wavelengths were scaled to remove redshift. All points were weighted equally in the linear regression (Figure 3.3.1e). Residuals were on the order of several Å (Figure 3.3.1f).

The linear fit coefficients and their uncertainties are listed in Table 3.3.1. Uncertainties in the wavelengths of the observed coronal lines (for example, in Table 3.1.2) arise from a combination of the coefficient uncertainties and the centroid error in the Gaussian fit to the coronal lines. The variance of each observed wavelength $\lambda_o$ is given by

$$Var(\lambda_o) = Var(a + \beta x_o)$$

$$= Var(a) + \beta^2 Var(x_o) + \bar{x}_o^2 Var(\beta)$$

$$+ Var(\beta) Var(x_o) + 2\bar{x}_o Cov(a, \beta),$$

(3.6)

where $a$ and $\beta$ are the coefficients of the linear fit and $x_o$ is the observed coronal line center in pixels. Table 3.1.2 reports the mean and standard deviation of $\lambda_o$. 

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Figure 3.3.1: Wavelength calibration. Chromospheric spectrum (a), linear fit (b), and fit residuals (c) for 3 µm channel. Photospheric spectrum (d), linear fit (e), and fit residuals (f) for 4 µm channel.

Table 3.3.1: Wavelength calibration coefficients and uncertainties.

<table>
<thead>
<tr>
<th></th>
<th>3 µm</th>
<th>4 µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>First Pixel $a$ (Å)</td>
<td>30724.5</td>
<td>39849.8</td>
</tr>
<tr>
<td>Dispersion $\beta$ (Å/pixel)</td>
<td>-2.370</td>
<td>-2.331</td>
</tr>
<tr>
<td>Uncertainty, $a$ (Å)</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Uncertainty, $\beta$ (Å/pixel)</td>
<td>0.001</td>
<td>0.001</td>
</tr>
</tbody>
</table>

3.3.2 Plate scale and pointing

The slit-jaw camera plate scale and slit length were measured using a solar observation from two days before the eclipse. The solar diameter was measured by fitting the limb of the disk (Figure 3.3.2a), and the
plate scale and slit length were found to be 2.26 arcsec/pixel and 1.55R⊙. The effective slit length was 10% shorter because the slit-jaw mount clipped light from the slit, as mentioned in Section 2.3.2.

The IR camera plate scale was computed by comparing simultaneous observations of the partial eclipse in the slit-jaw camera (Figure 3.3.2b) and IR camera (Figure 3.3.2c). From the width of the intensity profiles along the slit, the IR plate scale was found to be 2% larger than that of the slit-jaw camera. The IR camera achieved the designed plate scale of 2.31 arcsec/pixel, while the slit-jaw camera was restricted by the range on its translation stage, as described in Section 2.3.3.

![Figure 3.3.2: Measuring plate scale.](image)

The plate scales were used to map spatial pixel to solar coordinates in both sets of images. Once the slit-jaw frames were aligned with respect to moon center as described in Section 3.2.4, the solar coordinates of each pixel were computed by accounting for the drift of the moon relative to the sun. The time-varying offset between sun center and moon center was computed by cross-correlating on a solar prominence over the four minute observation. In each IR image, the spatial pixel of the lunar limb crossing was determined using the method explained in Section 3.2.4. The limb crossing was mapped to solar coordinates using the corresponding slit-jaw image, and the coordinates for the other spatial pixels
were determined using the IR plate scale.

3.3.3 Throughput

We define throughput as the product of overall optical efficiency, geometric area, slit width in wavelength units, and solid angle subtended by a pixel. The AIR-Spec throughput was estimated using both bottom-up (forward) and top-down (inverse) approaches. The forward model was computed by simply multiplying the slit width, solid angle, and geometric area from the optical design by the estimated efficiency of each element in the optical train, from the aircraft window to the bandpass filter immediately in front of the detector. The results are shown in the dashed lines in Figure 3.3.3.

![Throughput Graph](image-url)

**Figure 3.3.3:** Forward and inverse modeled throughput.
The top-down throughput calibration relied on photospheric measurements acquired during a test flight four days before the eclipse. In order to separate the contributions from first and second order, bandpass filters were used to isolate light near 1.5, 2, 3, and 4 \( \mu m \). All observations were acquired with a broadband solar filter (\( T \approx 10^{-3} \)) in place. The AIR-Spec data was compared with the expected spectrum at the entrance to the instrument, which was taken as the product of the radiance from the photosphere, the transmission through earth's atmosphere, and the transmission through the bandpass and solar filters. The photospheric library spectrum came from a combination of ground-based [70] and space-based [18] measurements and a model from R. Kurucz (http://kurucz.harvard.edu/stars/sun). The ATRAN model (https://atran.sofia.usra.edu) was used to provide an estimate of the atmospheric transmission. The transmission of each filter was measured by J. Hannigan of NCAR ACOM.

The throughput was modeled as a function of wavelength by fitting a smoothing spline to the quotient of the measured spectrum and library spectrum. The result is shown in the solid lines in Figure 3.3.3. Figure 3.3.4 shows the agreement between the AIR-Spec data and library spectrum after the latter was multiplied by the throughput and first and second order were summed together.

The top-down throughput estimate is 2–3 times smaller than the bottom-up estimate (Figure 3.3.3). We are still exploring possible causes for this discrepancy, but we suspect a combination of factors. The geometric area of the instrument was likely smaller than designed due to the angle of the sun on the feed mirror and misalignments inside the spectrometer. In addition, the solar filter transmission measurement is subject to error due to the high attenuation in that filter. Finally, the AIR-Spec measurements may have been influenced by limb darkening, in which case the library spectrum would have overestimated the intensity of the photosphere. In the future, we will use a calibrated lamp to measure throughput in the laboratory, where we have fewer sources of error and greater control over the experimental conditions.
Figure 3.3.4: Checking the inverse-modeled throughput. The black line is AIR-Spec data, converted from DN to photons s$^{-1}$. The red line shows the photospheric library spectrum after multiplication by the inverse-modeled throughput.

### 3.3.4 Point-spread function

The AIR-Spec point-spread function (PSF) was measured using an observation of the photosphere immediately after third contact. At the time of the observation, the exposed photosphere was a bright point source, and single frame at an exposure time of 0.3 ms provided a high-SNR measurement of the resolution in both channels. The raw data are shown in Figure 3.3.5. The photosphere appears as a bright line spanning all wavelengths but only a few spatial pixels.
The PSF full width at half maximum (FWHM) was measured by fitting a Lorentzian to the data in each spectral channel. The FWHM is plotted as a function of wavelength in Figure 3.3.6. Due to the optical design, the point-spread function is about 1 pixel broader in the 4 µm channel than in the 3 µm channel. The FWHM of 4.8–5.6 pixels corresponds to a spatial resolution of 11–13 arcsec and a spectral resolution of about 14–15 Å in first order (half that value in second order), once the effect of the slit is included. Measurements of a narrow, bright hydrogen line (Section 4.3.1/Figure 4.3.1) confirm the value for spectral resolution.

3.4 DATA DESCRIPTION

The AIR-Spec data have been organized by slit position into five separate observations (Table 3.1.1) and will be made available on the Virtual Solar Observatory (https://sdac.virtualsolar.org). Each data set contains three 3D arrays with images from the slit-jaw camera and 3 µm/4 µm channels of the IR camera, as depicted in Figure 3.4.1.

In the slit-jaw camera data, all frames have been aligned with respect to moon center and rotated to orient solar north up. Each data point is described by solar coordinates \((h_x, h_y)\) and time \(t\), where \(h_x\) varies
Figure 3.3.6: Point-spread function FWHM across the detector. The dotted lines represent 95% confidence intervals.

along columns, $h_y$ varies along rows, and $t$ varies along the third dimension. Because the moon drifts with respect to the sun, $h_x$ and $h_y$ are different for every frame.

In the IR camera data, all frames have undergone dark subtraction, defective pixel replacement, and geometric correction. Frames have been co-aligned spatially so that the limb crossings coincide, and fringes have been removed from the 4 $\mu$m channel. Each data point is described by wavelength $\lambda$, time $t$, and solar coordinates $(h_x, h_y)$, where $h_x$ and $h_y$ refer to the solar position of each pixel along the slit. $h_x$ and $h_y$ vary along rows, $\lambda$ varies along columns, and $t$ varies along the third dimension. Unique $h_x$ and $h_y$ arrays exist for every frame.
Figure 3.4.1: Illustration of data from one of the five eclipse observations. The data set consists of three 3D arrays from the slit-jaw camera (left) and both channels of the IR camera (right). In the slit-jaw image array, each data point is characterized by time and solar coordinates. Each IR data point is described by time, wavelength, and solar coordinates.
This chapter explores the radial behavior of the two silicon lines measured by AIR-Spec and the spectral properties of our strongest line, Si X at 1.43 \( \mu \text{m} \). With appropriate averaging, the Si X SNR was sufficient to measure intensity up to 0.6 \( R_\odot \) above the limb and Doppler velocities as low as 5 km/s. The east limb observation of Si IX at 3.93 \( \mu \text{m} \) was bright enough to reveal spatial structure 0.25 \( R_\odot \) above the limb.
4.1 Infrared, Visible, and Extreme Ultraviolet Observations

Images at four different wavelengths were used to explore the physical conditions in the corona and line formation properties in the IR. The 171 and 193 Å channels of AIA [36] (12 second cadence, 1.3 × 1.3 R⊙ FOV, 0.6 arcsec/pixel) provided information on global coronal structure and dynamics. The EUV emission, assumed to be collisionally-dominated, was also used as a control for comparing excitation processes in the AIR-Spec lines. In addition, ground-based eclipse images at 789.2 nm (Fe XI) and 530.3 nm (Fe XIV) from Shadia Habbal provided 4 arcsec sampling of coronal structures up to 1 R⊙ above the limb. The wavelengths, ions, and temperatures of the AIR-Spec, AIA, and ground-based data are compared in Table 4.1.1. Figure 4.1.1 shows the average location of the AIR-Spec slit superimposed on each of the images.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Wavelength (nm)</th>
<th>Ion</th>
<th>log(T_e(K))</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIA</td>
<td>17.1</td>
<td>Fe IX</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>19.3</td>
<td>Fe XII, Fe XXIV</td>
<td>6.1, 7.3</td>
</tr>
<tr>
<td>Ground-based¹</td>
<td>530</td>
<td>Fe XIV</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>789</td>
<td>Fe XI</td>
<td>6.0</td>
</tr>
<tr>
<td>AIR-Spec</td>
<td>1430</td>
<td>Si X</td>
<td>6.1</td>
</tr>
<tr>
<td></td>
<td>1920</td>
<td>S XI</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>2840</td>
<td>Fe IX</td>
<td>5.8</td>
</tr>
<tr>
<td></td>
<td>3030</td>
<td>Mg VIII</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>3930</td>
<td>Si IX</td>
<td>6.0</td>
</tr>
</tbody>
</table>

¹ Ground-based images were provided by S. Habbal, © 2017 Miloslav Druckmüller, Shadia Habbal, Pavel Štarha, Judd Johnson, Jana Hoderová.
4.2 Intensity Gradient in the Inner Corona

Above the limb, the EUV lines are expected to decrease in intensity as density squared \([28]\), while visible lines excited by photospheric radiation remain bright much further into the corona. Because charge states freeze once the electron density drops low enough to prohibit collisions \([53]\), comparing the relative importance of the two excitation processes provides information on the frequency of charge exchange as a function of height above the limb \([23]\). Habbal et al. have performed this comparison using observations
of Fe X at 637.4 and 17.4 nm [23].

Like visible transitions, lines in the shortwave and mid-infrared are predicted to have a greater radiative excitation component than their EUV counterparts [11, 28]. This behavior is apparent in the AIR-Spec data in Figure 4.2.1, which shows the time-averaged spectrum of observation 3 (east limb) from the limb to 0.5 R⊙. Similar measurements exist for the other three observations. We compare our AIR-Spec observations of Si IX and Si X with visible/EUV observations and models to probe plasma properties in the inner corona.

<table>
<thead>
<tr>
<th>First Order Wavelength (µm)</th>
<th>Second Order Wavelength (µm)</th>
<th>Distance from Solar Limb (R⊙)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si X 1.43 µm</td>
<td>Mg VIII 3.03 µm</td>
<td>1.44</td>
</tr>
<tr>
<td>Fe IX 2.84 µm</td>
<td>Si IX 3.94 µm</td>
<td>2.93</td>
</tr>
</tbody>
</table>

**Figure 4.2.1:** Mean AIR-Spec spectrum of observation 3 (east limb), 0–0.5 R⊙ above the solar limb. The continuum and dark background have been removed. Si X, the brightest line, is detectable out to 0.5 R⊙.

4.2.1 Si X measurements and predictions

To maximize SNR, we average the Si X intensity in time over each observation and perform a weighted mean over the line profile. The resulting intensities are plotted in Figure 4.2.2 (left) as a function of distance from the limb. The black line is the mean over all four observations. The measurements agree
well with the trends predicted by Judge [28] and Del Zanna & DeLuca [11] (right). The Si X intensity falls two orders of magnitude from the limb to 0.6 R⊙.

Figure 4.2.2: Normalized Si X intensity as a function of height above the limb. The left plot shows the measured mean for each AIR-Spec observation (same color scheme as Figure 4.1.1) and the mean of the four observations (black). The right plot compares the overall AIR-Spec mean (black) with predictions from Judge [28] (red) and Del Zanna & DeLuca [11] (blue). All intensities have been normalized to 0.02 R⊙.

To estimate the relative importance of collisional and radiative excitation in Si X, we compare the 1.43 μm AIR-Spec measurements with 193 Å data from AIA. The two wavelengths probe different ions with similar formation temperatures (Table 4.1.1). For each of the four AIR-Spec observations, the 193 Å intensity is averaged in time over six minutes (18:21–18:27 UTC) and in space over all slit positions in the observation. The resulting intensities are plotted in Figure 4.2.3 (left) as a function of distance from the limb. The EUV intensity falls two orders of magnitude in about 0.4 R⊙, 50% faster than the IR intensity.

Judge models the Si X line strength with and without radiative excitation from the photosphere [28]. He predicts a ratio of 2 (equal importance of collisional and radiative excitation) 0.1 R⊙ above the limb and a ratio of 12 (11 parts radiative to 1 part collisional) 1 R⊙ above the limb. In Figure 4.2.3 (right), we compare his predictions with the Si X 1.43 μm/AIA 193 Å intensity ratio. Because the IR and EUV
Figure 4.2.3: Effect of radiative excitation on intensity gradient. The left plot shows the mean AIA 193 Å intensity at the AIR-Spec slit positions, normalized to 0.01 R☉. The right plot shows the Si X 1.43 µm/AIA 193 Å intensity ratios (colored lines) and Judge’s prediction for the intensity ratio of Si X with and without radiative excitation (black line) [28]. The measured ratios have been scaled to match Judge’s prediction at 0.03 R☉.

Intensities have different units, their ratio is scaled to match Judge’s prediction at 0.03 R☉. The relative change with height above the limb is similar for the measured and predicted ratios.

4.2.2 Si IX enhancement at 0.25 R☉

Although the AIR-Spec measurements of Si IX (3.93 µm) were noisier than the observations of Si X, the bright active region in observation 3 demonstrated the high off-limb sensitivity of this mid-IR line. A comparison of data at 171 Å, 789 nm, and 3.93 µm reveals that the 3.93 µm and 789 nm intensities follow the same trend above the limb, while the 171 Å intensity gradient is markedly different. The AIR-Spec and EUV measurements were averaged using the procedure described in the previous section. Data from the 789 nm (Fe XI) still frame was averaged over all slit positions on the east limb.

The right panels in Figure 4.2.4 show the 3.93 µm AIR-Spec measurement in black. An enhancement in Si IX appears 0.2–0.3 R☉ from the limb and is highlighted in light red. The images provide spatial context for the source of the enhancement. In the left panels of the figure, the AIR-Spec slits are overlaid on the
789 nm frame (a) and the average 171 Å frame (b). The region of enhancement is shown in red, and clearly corresponds to an active region structure in the 789 nm image. No corresponding structure appears at 171 Å. The average 789 nm and 171 Å intensities are plotted in blue in (c) and (d). As expected, the enhancement appears at 789 nm but not 171 Å.

Figure 4.2.4: Si IX enhancement 0.25 R☉ from the east limb. Left: AIR-Spec east limb slit positions overlaid on Fe XI 789 nm (a) and AIA 171 Å (b). The region of enhanced Si IX is marked in red. It corresponds to an active region loop in Fe XI, but no structure is visible at 171 Å. Right: Si IX intensity as a function of distance from the limb, compared with Fe XI 789 nm (c) and AIA 171 Å (d). The enhancement is highlighted in light red. It appears in the 789 nm data but not the 171 Å data.
4.3 **Line-of-sight velocities in Si X**

Emission line profiles provide information on the line-of-sight velocity of the plasma. Center wavelength shifts are interpreted as Doppler velocities, while linewidths have contributions from the instrument point-spread function, thermal broadening, and unresolved velocity shifts due to turbulence or flows. The mapping from wavelength shift $\Delta \lambda$ to velocity $v$ is given by $v = c (\Delta \lambda / \lambda)$, where $c$ is the speed of light and $\lambda$ is the rest wavelength. For Si X, the vacuum rest wavelength is taken to be 14305 Å [55].

In Si X, we see line shifts of tens of km/s that appear to correspond to spatial structures. We measure surprisingly large linewidths throughout the corona, corresponding to 120–240 km/s after the instrumental and thermal broadening are removed. In some observations, we see two peaks separated by a velocity of up to 150 km/s. We therefore speculate that the line broadening is caused by fast flows instead of turbulence, even when multiple velocity components are not resolved. Pointing jitter and low SNR make it difficult to unravel the spatial and temporal dependence of the velocity components, but we find evidence that an eruption on the west limb increased the measured velocities $\sim 20$ km/s around 18:24 UTC.

4.3.1 **Analysis of observations**

Figure 4.3.1 shows the mean Si X profile for each of the four AIR-Spec observations in blue. Each profile represents an average of 30–90 seconds in time, 35 arcsec (15 pixels) along the slit, and $\sim 200$ arcsec along the limb of the sun, due to pointing jitter. To put the linewidth in context, two measurements of the instrument resolution are included in the plots. The spatial point-spread function, from a measurement of the photosphere at third contact, is shown in black. For observations that sample the prominence, the H I line at 1.875 µm is shown in red. The two PSF measurements have widths of about 7 Å (150 km/s), while the FWHM of Si X is 10–11 Å. The additional width cannot be explained by thermal motion. With an
average temperature of 1.26 MK, Si X has a thermal linewidth of only about 2 Å.

To minimize the blur introduced by averaging in time and space, we analyze each of the four observations in Figure 4.3.1 as a series of sub-observations. A single 60 ms exposure does not have sufficient SNR to allow the line profiles to be fit accurately, so we average 15 pixels (35 arcsec) at the limb, sort the exposures by solar latitude, and apply a 15-exposure moving average. We apply the moving
average over latitude instead of time because we expect the spatial variation in the line profiles to be greater than the temporal variation. We fit each sub-observation as a single Gaussian with line center $\lambda_c$ and FWHM $w$, then subtract the mean from each line center ($\lambda_c - \bar{\lambda}_c$) and the $7.5$ Å instrument/thermal linewidth from each FWHM ($\sqrt{w^2 - 7.5^2}$). Figure 4.3.2 shows the mean-subtracted line centers and non-thermal linewidths for observations 1–4 in velocity units.

![Histograms of SiX Gaussian fit parameters for all sub-observations in each AIR-Spec observation. Left: Line-of-sight velocity for observations 1 (a), 2 (b), 3 (c), and 4 (d). Velocities are relative to the mean for each observation. Right: Non-thermal linewidths for observations 1 (e), 2 (f), 3 (g), and 4 (h).](image)

**Figure 4.3.2**: Histograms of SiX Gaussian fit parameters for all sub-observations in each AIR-Spec observation. Left: Line-of-sight velocity for observations 1 (a), 2 (b), 3 (c), and 4 (d). Velocities are relative to the mean for each observation. Right: Non-thermal linewidths for observations 1 (e), 2 (f), 3 (g), and 4 (h).

We measure line shifts from -20 to 40 km/s, which partially explain the large widths of the average profiles in Figure 4.3.1. The shifts appear to be correlated with spatial structure in Fe XIV and may be
related to the angle between the coronal structures and the line of sight (Figure 4.3.3). The resolved velocity shifts do not completely explain the large Si X linewdths, as we observe large non-thermal widths of 120–240 km/s even after reducing the number of exposures averaged (Figure 4.3.2). The widths are independent of spatial structure but vary significantly across observations 1–4 (Figure 4.3.3).

Figure 4.3.3: Spatial distribution of Si X Gaussian fit parameters for all sub-observations in each AIR-Spec observation. AIR-Spec lunar limb crossings are overlaid on the FeXIV image and colored according to the scales on the right. Top: Line-of-sight velocity for observations 1 (a), 2 (b), 3 (c), and 4 (d). Velocities are relative to the mean for each observations. Bottom: Non-thermal linewidths for observations 1 (e), 2 (f), 3 (g), and 4 (h).

Non-thermal widths of 120–240 km/s are too large to be caused by turbulence, which is usually on the order of 20 km/s in the corona [16, 60]. Furthermore, we note that some of the profiles in Figure 4.3.1 are poorly described by a single Gaussian because they exhibit broad peaks (b), asymmetry (c), or double peaks (d). For these two reasons, we suspect that flows are producing two velocity components in Si X,
making the lines appear broad when the components are unresolved and bimodal when they are resolved.

If the Si X profiles can be described as the sum of two velocity components, we expect each component to have a FWHM of slightly more than 7 Å (the quadrature combination of the ~7 Å instrumental linewidth and the 2 Å thermal linewidth). We check this by fitting the mean profiles in observations 2 and 4 (where the velocity separation is most pronounced) as the sum of two Gaussians, allowing the FWHM to vary. In both cases, we find that a FWHM of 7.5 Å provides the best fit (Figure 4.3.4).

![Figure 4.3.4: Two-component fit to observations 2 and 4. (a) RMS fit error vs. FWHM of the two Gaussians. A FWHM close to the PSF FWHM provides the best fit. Right: Red and blue velocity components for observations 2 (b) and 4 (c).](image)

Based on the results of the FWHM search, we fit all sub-observations in observations 1–4 as the sum of two Gaussian components with FWHM 7.5 Å. Figure 4.3.5 shows the amplitude fraction of the red component (left) and the velocity separation between the components (right). The blue component dominates in observation 3 (east limb), while the two components have similar amplitudes in the three west limb observations. The 120–240 km/s non-thermal linewidths correspond to velocity separations of
100–150 km/s.

Figure 4.3.5: Histograms of SiX two-component fit parameters for all sub-observations in each AIRSpec observation. Left: Amplitude of the red velocity component for observations 1 (a), 2 (b), 3 (c), and 4 (d). The red and blue amplitudes sum to one. Right: Velocity separation of components for observations 1 (e), 2 (f), 3 (g), and 4 (h).

The two velocity components may arise from flows in spatially separate structures that lie along the same line of sight in the optically thin corona. However, because our averaging scheme combines observations from different times, the components may be separated in time instead of (or in addition to) along the line of sight. We attempt to set an upper limit for the temporal and angular separation of the components by analyzing three test cases on the east limb, where we have the highest SNR. For each test case, we average 5 pixels along the slit in 15–19 exposures separated by less than 2 seconds. The total
angular separation, including the effect of point-spread function, is about $15 \times 15$ arcsec for each test case. Figure 4.3.6 plots the three locations over the Fe XIV image (a) and shows the average line profile in each location (b–d). The red and blue velocity components are both present at all three locations, indicating that in these three test cases, the two components are separated by less than $15 \times 15$ arcsec and less than 2 seconds. The velocity separation and amplitude partitioning fall near the center of the distributions in Figure 4.3.5, suggesting that this spatial and temporal separation is typical, and the general presence of two components is not a result of the averaging scheme.

### 4.3.2 Interpretation and limitations

The presence of two velocity components explains the large Si X linewidths and the double peak in observation 4, but it also raises additional questions. First, the observed velocities of 100–150 km/s are faster than the typical flows in the corona. Marsch et al. report continuous downflows near the legs of coronal loops and upflows at the base of open field lines, indicating a general “coronal circulation” [42]. However, they measure a maximum velocity separation of around 40 km/s. Tian et al. measure two velocity components separated by 50–150 km/s near the footpoints of loops [66], but the blueshifted component has an amplitude of only a few percent, while our amplitudes are close to equal. The combination of low SNR and pointing jitter makes the AIR-Spec line profiles difficult to interpret, and we do not currently have an explanation for the anomalously high velocities. We will search again for velocity signatures during the 2019 eclipse, after improving the AIR-Spec sensitivity and image stabilization. Chapter 6 details the planned instrument improvements and the science they will enable.

In addition to the large velocity separations observed throughout the corona, we measure an enhancement of about 20 km/s between observations 2 and 4, which sample the same region of the west limb 1–2 minutes apart. We speculate that the 20 km/s velocity increase is caused by a small eruption that occurred north of the AIR-Spec slit positions shortly before our observation. We study the eruption using
Figure 4.3.6: Bounding the angular and temporal separation of the velocity components.

the Fe XIV 530 nm image and a series of of AIA 171 Å difference images smoothed over 5 minutes and $4 \times 4$ arcsec (Figure 4.3.7). The Fe XIV image (a) shows a 200 arcsec loop on the west limb. The AIR-Spec slit crosses the limb near the southern end of the loop. The eruption occurs at the northern end, and the front appears to propagate south and west along the loop (b–d). Although the front fades from view before reaching the AIR-Spec slit positions, we speculate that it is responsible for the 20 km/s velocity increase observed between AIR-Spec observations 2 (blue, 18:23:00–18:23:45) and 4 (red,
Figure 4.3.7: Eruption in AIA 171 Å and Fe XIV 530 nm. (a) Fe XIV eclipse image showing a loop structure on the west limb. Lunar limb crossings of the AIR-Spec slit are overlaid in blue (observation 2, 18:23:00–18:23:45) and red (observation 4, 18:24:30–18:26:00). (b–e) AIA 171 Å five-minute difference images showing a small eruption near the AIR-Spec observations. The front is indicated by an arrow in each frame. It appears to travel along the loop in (a).
Discovery of New Coronal Lines at 2.843 and 2.853 µm

AIR-Spec detected two new coronal emission features during its observation of the 2017 solar eclipse. We derive wavelengths in air of 2.8427 ± 0.00009 µm and 2.8529 ± 0.00008 µm.

One of these lines belongs to the $3p^53d^3F_3 \rightarrow 3p^53d^3F_4$ transition in Ar-like Fe IX. This appears to be the first detection of this transition from any source, for two reasons. First, the transition occurs between two levels within the excited $3p^53d$ configuration, 429,000 cm$^{-1}$ above the ground level. The line is therefore absent in photo-ionized coronal-line astrophysical sources such as the Circinus Galaxy. Second, the 2.85 µm wavelength region is significantly attenuated by telluric H$_2$O, as shown by data from a Fourier
Minimization of residual wavelength differences using both measured wavelengths, together with NIST extreme ultraviolet wavelengths, does not clearly favor assignment of either line to Fe IX. However, the shorter wavelength line appears more consistent with other observed features formed at similar temperatures to Fe IX. We have been unable to identify the longer wavelength transition.

5.1 CORONAL FORBIDDEN LINES OF IRON IONS

Forbidden lines of ions of iron were among those first identified by Edlén [17] in his demonstration of the anomalously high temperature of the solar corona. These lines from Fe IX to Fe XV are given in Table 5.1.1. Particularly strong in the solar corona were the “red line” of Cl-like Fe X at 6376 Å, the “green line” of Al-like Fe XIV at 5304 Å, and the two infrared lines of Si-like Fe XIII at 10747 Å and 10798 Å. Edlén’s work on these lines, which are of magnetic dipole (M1) character, confirmed the 1 MK temperature of the corona and posed the problem of coronal heating, which is still unsolved today.

Because Fe IX is from the noble gas sequence of Ar, it is abundant in the solar atmosphere over an unusually large range of temperatures in collisional ionization equilibrium ($\approx 10^{5.6} - 10^{6.1}$ K, depending on which set of calculations are adopted [2, 14, 26]). In the corona ($T_e \approx 10^6$ K), significant fractions of the Maxwellian electron distributions can therefore excite metastable triplet levels such as $3p^5 3d \ ^3F_4$.

Table 5.1.1 lists those forbidden lines of Fe IX that have large branching ratios which should be seen in the corona. There are only two such transitions, with predicted wavelengths of 2.218 and 2.856 µm.

5.2 PREVIOUS OBSERVATIONS OF THE 2.85 µm REGION

We have been unable to find any previous reference to observations of emission lines near 2.85 µm in any astrophysical object. We attribute this to two effects:
Table 5.1.1: Coronal forbidden lines of iron ions.

<table>
<thead>
<tr>
<th>Ion</th>
<th>IES¹</th>
<th>j</th>
<th>i</th>
<th>$E_j$ cm⁻¹</th>
<th>$E_i$ cm⁻¹</th>
<th>$\lambda$ Å</th>
<th>BR²</th>
<th>$E_j/kT_{IE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe XV</td>
<td>Mg</td>
<td>3s3p ¹P₂ o</td>
<td>3s3p ¹P₁ o</td>
<td>253 820</td>
<td>239 660</td>
<td>7058.6</td>
<td>0.92</td>
<td>0.18</td>
</tr>
<tr>
<td>Fe XIV</td>
<td>Al</td>
<td>3p ²P₂ o</td>
<td>3p ²P₁ o</td>
<td>18 852.5</td>
<td>0</td>
<td>5302.86</td>
<td>1</td>
<td>0.014</td>
</tr>
<tr>
<td>Fe XIII</td>
<td>Si</td>
<td>3p² ³P₁</td>
<td>3p² ³P₀</td>
<td>9 302.5</td>
<td>0</td>
<td>10746.8</td>
<td>1</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3p² ³P₂</td>
<td>3p² ³P₁</td>
<td>18 561</td>
<td>9 302.5</td>
<td>10797.9</td>
<td>1</td>
<td>0.017</td>
</tr>
<tr>
<td>Fe XII</td>
<td>P</td>
<td>3p³ ³D₅/₂</td>
<td>3p³ ³D₃/₂</td>
<td>46 075</td>
<td>41 566</td>
<td>22178³</td>
<td>0.34</td>
<td>0.04</td>
</tr>
<tr>
<td>Fe XI</td>
<td>S</td>
<td>3p⁴ ³P₁</td>
<td>3p⁴ ³P₂</td>
<td>12 667.9</td>
<td>0</td>
<td>7891.79</td>
<td>1</td>
<td>0.014</td>
</tr>
<tr>
<td>Fe X</td>
<td>Cl</td>
<td>3p⁵ ²P₅/₄</td>
<td>3p⁵ ²P₃/₄</td>
<td>15 683.1</td>
<td>0</td>
<td>6374.51</td>
<td>1</td>
<td>0.023</td>
</tr>
<tr>
<td>Fe IX</td>
<td>Ar</td>
<td>3p³ ³F₃ o</td>
<td>3p³ ³F₄ o</td>
<td>429 310.9</td>
<td>425 809.8</td>
<td>28555</td>
<td>0.91</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3p⁶ ³F₂ o</td>
<td>3p³ ³F₃ o</td>
<td>433 818.8</td>
<td>429 310.9</td>
<td>22177</td>
<td>0.60</td>
<td>0.88</td>
</tr>
</tbody>
</table>

Energy levels are from the NIST spectroscopic database. The accompanying wavelengths are in air. The final column lists the ratio of the excitation energy of the upper level to the energy in the Boltzmann factor for a plasma formed in coronal ionization equilibrium, using the calculations of [26].

¹ Isoelectronic sequence.
² Branching ratio, $A_{ji}/\Sigma A_{ji}$. The Einstein $A$ coefficients come from CHIANTI 8.0 [13].
³ For Fe XII, the energy levels have been revised by Del Zanna and Mason [12], and the wavelength is closer to 22057 Å.

1. H₂O molecules in the Earth’s troposphere almost completely absorb radiation in this spectral region (see Figure 5.2.1).

2. Excited levels of Fe IX lie $\nu \gtrsim 400,000$ cm⁻¹ above the ground (‘S₀) state. In photo-ionized astronomical plasmas, electron temperatures $T_e$ are too low to populate these levels ($12,000 < T_e < 150,000$ K, $1$ cm⁻¹ $\equiv 1.44$ K, [e.g. 19, 52]). Such objects do emit coronal lines such as Mg VIII, which have lower excitation energies [e.g. 50].

A measurement of the atmospheric absorption was provided by a Fourier transform interferometer that observed the eclipse from an altitude of 2400 m. The NCAR Airborne Interferometer (NAI) was designed for airborne measurements of the Earth’s atmosphere and was adapted observe the sun during
the total eclipse. Although initially intended for deployment on the GV aircraft, the NAI was ultimately deployed to Camp Wyoba on Casper Mountain, Wyoming.

Figure 5.2.1 compares the east limb AIR-Spec spectrum (red) with an NAI observation (blue) from just before totality, when about 0.4% of the solar disk was visible. The upper panel highlights the 2.2–3.2 μm region, which includes the astronomical K and L windows and the AIR-Spec 3 μm wavelength band. The lower panels focus on two narrower wavelength ranges containing the 2.218 and 2.856 μm lines of Fe IX. The NAI measures zero light near the new coronal lines detected by AIR-Spec. The near-total absorption at 2400 m indicates that we are unlikely to find data from ground-based observatories. We therefore seek these lines in observations from space.

The relatively high excitation energies of Fe IX levels are accessible in collisionally-ionized plasmas such as the corona (last column in Table 5.1.1), but such excitations are rarer in photo-ionized plasmas. We search for Fe IX in data from the Short Wavelength Spectrometer (SWS) on the Infrared Space Observatory. SWS obtained over 1000 spectra of various objects in this wavelength region [62]. While NASA’s SOFIA facility obtains spectra only above 4.5 μm (see www.sofia.usra.edu), SWS is sensitive between 2.4 and 45.4 μm. We find no sign of a line at either 2.843 or 2.853 μm in approximately 1200 SWS spectra.

The 2.218 μm line of Fe IX lies outside the wavelength range of SWS. However, the atmospheric transmission is near 100% at this wavelength (Figure 5.2.1b), so this line can in principle appear in ground-based observations. We focus on observations of star forming galaxies, in which collisional ionization dominates [49]. Using the SpeX spectrograph at the NASA Infrared Telescope Facility, Martins et al. [43] have compiled a 0.8–2.4 μm atlas of 23 H II and starburst galaxies. The 2.218 μm Fe IX line does not appear in these data, either because it was not present or because the instrument was not sensitive enough to detect it.
Figure 5.2.1: Spectra from the NAI and AIR-Spec instruments. The NAI data (blue) are from a measurement of the solar photosphere taken 17 to 40 seconds before second contact. The AIR-Spec data (red) show the coronal emission above the east limb over 30 seconds during totality. Intensity values are dark-subtracted NAI counts. The AIR-Spec data are scaled arbitrarily. The NAI instrument has a resolving power close to 20,000 and its spectrum shows absorption features from H$_2$O and other gases in the Earth’s atmosphere. The AIR-Spec data show almost no absorption as they were taken from the GV aircraft at 14 km, above essentially all of the water vapor. (a) 2.2–3.2 μm wavelength band. The limits of the astronomical K and L bands are shown at the top. AIR-Spec detections of Fe IX, Si X, and Mg VIII are labeled. (b) 2.2–2.3 μm wavelength band. No AIR-Spec data exist for this wavelength range. The atmospheric absorption is minimal in this region, as shown by the NAI data. Lines of Fe IX and Fe XII are predicted to lie in this region near 2.218 μm (Table 5.1.1). (c) 2.8–2.9 μm wavelength band. The NAI spectrum has zero light near the coronal lines detected by AIR-Spec. The black lines mark reference wavelengths for the coronal lines, from a previous observation of Si X and the NIST energy levels of Fe IX. “Emission” features in the NAI data are gaps in absorption of photospheric light.
5.3 The unidentified and known lines of Fe IX

We have tried unsuccessfully to identify unambiguously these lines purely on the basis of known energy levels. We discarded candidate lines matching the following criteria:

1. Elements with abundances below 1% of iron.

2. Ions that are not abundant in the typical corona (e.g., complex ions with less than 5 and more than 14 electrons removed).

3. IR lines with small branching ratios (e.g. those of H-, Li- or Na-like ions whose excited levels all decay via electric dipole transitions at shorter wavelengths).

In searching the NIST database, we found the $3p^5 3d^3F_3 \rightarrow 3p^5 3d^3F_4$ line of Fe IX to be the only credible candidate. Therefore, one of the lines remains unidentified. The uncertainties in energy levels from the NIST database preclude a definitive identification of one of the two lines as belonging to Fe IX. To illustrate this clearly, we performed two optimizations of the system of known energy levels of Fe IX in the NIST database, one for each AIR-Spec wavelength. In each case, the optimized energy levels provided a set of $n$ transition wavelengths $\lambda_i,\text{NIST}$ that minimized

$$\chi^2 = \frac{1}{n - 1} \sum_i^n \left( \frac{\lambda_i - \lambda_{i,\text{NIST}}}{\Delta \lambda_i} \right)^2.$$  \hfill (5.1)

The observed wavelengths $\lambda_i$ included one of the two AIR-Spec wavelengths as well as 47 NIST wavelengths corresponding to transitions between levels that are radiatively connected to the $3p^5 3d^3F_4$ and $3p^5 3d^3F_3$ levels of Fe IX (Figure 5.3.1). For each observed wavelength from NIST, the uncertainty $\Delta \lambda_i$ was taken to be ten times the last significant figure in $\lambda_i$. The optimization procedure consisted of a genetic algorithm-driven Monte Carlo search of NIST energy levels, using an IDL translation of PIKAIA [6] kindly provided by S. McIntosh. Each level energy $\tilde{\nu}$ was perturbed by a random number between
\( \nu \pm 2\Delta \nu \) where \( \Delta \nu \) is the tabulated uncertainty in the energy level.

![Term diagram for Fe IX](image)

**Figure 5.3.1**: Term diagram for Fe IX, showing the levels that are radiatively connected to \( 3p^5 3d^3 F^o \) and \( 3p^5 3d^3 F^o \) [32]. These levels were used in the energy level optimization described in Section 5.3.

The optimal values of \( \chi^2 \) were

\[
\chi^2(2.843) = 1.12
\]

\[
\chi^2(2.853) = 1.05.
\]
Thus we have no strong statistical evidence to select one line over the other. Table 5.3.1 shows only minor relative wavelengths shifts from the NIST data, with one exception (the level at $1302840 \text{ cm}^{-1}$). Note that for Fe XII, Del Zanna and Mason [12] revised the energy levels such that the listed IR transition moved by 121 Å from 22057 to 22178 Å (see also Figure 5.2.1). Version 8.0 of the CHIANTI atomic database [13] contains updated energy levels for Fe IX (listed in the table where different from NIST). The revised energies in this work shift in the direction of the CHIANTI values, in all cases but the level at $1304600 \text{ cm}^{-1}$.

In the next section, we argue that the $2.843 \mu \text{m}$ line belongs to Fe IX on the basis of its behavior in relation to other IR and extreme ultraviolet (EUV) lines observed during, or close to, the eclipse. On this basis, Table 5.3.1 shows our optimized set of energy levels for Fe IX.

5.4 LINE IDENTIFICATIONS

In our AIR-Spec data, the feature at $2.843 \mu \text{m}$ is clearly an emission line belonging to the corona, as opposed to emission from the chromosphere or a “gap” in telluric absorption. The line appears in observations at all four slit positions with an intensity and width similar to those of the identified Mg VIII line (Figure 5.4.1), which has a similar temperature in ionization equilibrium. In contrast, the $2.853 \mu \text{m}$ line appears only at slit position 3 over the east limb, and it is fainter and narrower than Mg VIII. The width of the $2.853 \mu \text{m}$ line is 12 Å, on the order of the instrument resolution. The $2.843 \mu \text{m}$ and Mg VIII lines have widths of about 20 Å. Intensities are compared in Table 5.4.1.

The similarity of the $2.843 \mu \text{m}$ line to Mg VIII suggests that this line is Fe IX. However, the wavelength of the $2.853 \mu \text{m}$ line is much closer to the theoretical wavelength predicted for Fe IX, and the differences in intensity, width, and spatial distribution between the Fe IX and Mg VIII lines may be due to the excited energy levels of the Fe IX transition. (The Mg VIII line arises from a transition to the ground state.)
Table 5.3.1: Revised energy levels for Fe IX.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Term</th>
<th>NIST (CHIANTI) cm⁻¹</th>
<th>This work cm⁻¹</th>
<th>Δ cm⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>3s²3p⁶</td>
<td>1S⁰</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3P⁰</td>
<td>405772.0</td>
<td>405771.1</td>
<td>-0.9</td>
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<tr>
<td>3s³3p³</td>
<td>3P¹</td>
<td>408315.1</td>
<td>408317.3</td>
<td>2.2</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3P₂</td>
<td>413669.2</td>
<td>413671.3</td>
<td>2.1</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3F⁴</td>
<td>425809.8</td>
<td>425803.1</td>
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</tr>
<tr>
<td>3s³3p³</td>
<td>3P₃</td>
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<td>429319.8</td>
<td>8.9</td>
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<tr>
<td>3s³3p³</td>
<td>3F²</td>
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<td>433818.4</td>
<td>-0.4</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3D⁵</td>
<td>455612.2</td>
<td>455617.5</td>
<td>5.3</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3D₁</td>
<td>460616.0</td>
<td>460615.9</td>
<td>-0.1</td>
</tr>
<tr>
<td>3s³3p³</td>
<td>3D₂</td>
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<td>462618.8</td>
<td>2.2</td>
</tr>
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<td>3s³3p³</td>
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</tr>
<tr>
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</tr>
<tr>
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</tr>
<tr>
<td>3s³3p⁶(2P₀)⁶⁴s</td>
<td>½1/2</td>
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<td>(950498.0)</td>
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<td>3s³3p⁶(2P₁)⁶⁴s</td>
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<td>9655570.0</td>
<td>(965568.0)</td>
<td>-10.4</td>
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<tr>
<td>3s³3p⁶(2P₃)⁴f</td>
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<td>1198220.0</td>
<td>(1198222.0)</td>
<td>3.3</td>
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<tr>
<td>3s³3p⁶(2P₅)⁴f</td>
<td>½1/2</td>
<td>1213150.0</td>
<td>1213150.8</td>
<td>0.8</td>
</tr>
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<td>3s³3p⁶(2P₇)⁴f</td>
<td>½1/2</td>
<td>1300920.0</td>
<td>(1300923.0)</td>
<td>58.8</td>
</tr>
<tr>
<td>3s³3p⁶(2P₉)⁴f</td>
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<td>1302840.0</td>
<td>(1302841.0)</td>
<td>359.6</td>
</tr>
<tr>
<td>3s³3p⁶(2P₁₁)⁴f</td>
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<td>1304600.0</td>
<td>(1304598.0)</td>
<td>0.5</td>
</tr>
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<td>3s³3p⁶(2P₁₃)⁴f</td>
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<td>1306320.0</td>
<td>(1306319.0)</td>
<td>-1.3</td>
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<tr>
<td>3s³3p⁶(2P₁₅)⁴f</td>
<td>½1/2</td>
<td>1305760.0</td>
<td>(1305762.0)</td>
<td>3.4</td>
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</tbody>
</table>

The optimization routine used the NIST levels as input and produced the revised levels. Updated levels from version 8.0 of CHIANTI [13] are shown in parentheses where different from NIST. The last column shows the difference between revised and NIST levels, with the difference between revised and CHIANTI levels in parentheses. In seven out of eight cases the CHIANTI energies are closer than NIST to the revised energies.
Figure 5.4.1: Summary of observations from the 3 µm channel of AIR-Spec, corresponding to slit positions in 3.1.1. The average AIR-Spec spectrum at each slit position is shown in blue. SiX, Mg VIII and a coronal line at 2.843 µm are seen in all four slit positions, while a 2.853 µm line appears only in position 3 (east limb). H I appears in the prominence in position 2. The black dashed line indicates the theoretical wavelength of Fe IX, with a ±2σ error bar.

Therefore compare the AIR-Spec measurements to simultaneous EUV observations from the Atmospheric Imaging Assembly (AIA) [36], which provide additional evidence in favor of the 2.843 µm line.

We group the east limb AIR-Spec data into four observations based on how far north the slit crosses the limb and compare the average spectrum for each observation to data from the 171 Å (Fe IX, 0.63 MK) and 94 Å (Fe XVIII, 6.3 MK) channels of AIA. Figure 5.4.2 shows the limb crossings for positions 1–4 superimposed on the AIA images, and Figure 5.4.3 shows the mean AIR-Spec spectrum at each position. The 2.843 µm line is equally bright in all four positions, which cover 250 arcsec of the east limb. This is consistent with the AIA 171 Å observations from the same time, which show little brightness variation above the limb. In contrast, the 2.853 µm line appears only in slit positions that sample the active region loop shown in AIA 94 Å. Therefore, we conclude that the Fe IX wavelength is 2.843 µm and the 2.853 µm line is due to a hotter coronal ion that has not yet been identified.
Figure 5.4.2: East limb crossings for the AIR-Spec slit superimposed on (a) AIA 94 Å and (b) AIA 171 Å, ordered from south to north. Each of positions 1, 2, 3, and 4 consists of 134 frames. The slit samples hot plasma (94 Å channel) from an active region loop in observations 2 and 3 and cooler plasma (171 Å channel) in all four positions.

We find support for this identification in a comparison of modeled and measured line ratios. Table 5.4.1 compares the Fe IX/Mg VIII line ratios predicted by Judge [28] and Del Zanna & DeLuca [11] with the 2.843 μm/Mg VIII and 2.853 μm/Mg VIII line ratios measured by AIR-Spec. The measured ratios were computed for each position on the east limb. Relative to the observed Mg VIII line, the 2.843 μm line is about as bright as [28] and [11] predict. The four 2.843 μm ratios span the modeled values, while the 2.853 μm ratios are low compared to both models and vanish at east limb positions 1 and 4. The line ratio of zero at two positions indicates that the 2.583 μm line is not Fe IX. Fe IX and Mg VIII form at similar temperatures ($T_e \approx 10^5$) in ionization equilibrium. While their ratio may vary, it should not approach zero.

From the NIST energy level uncertainties, we calculate a 7 nm uncertainty in the theoretical wavelength of Fe IX. The difference between the measured and theoretical wavelengths is less than 2σ (Figure 5.4.1. The measured wavelength is close to the 2.847 μm result from Svensson et al. [65]. Their energy for the $3p^3d^4F_4$ level is only 3 cm$^{-1}$ less than the revised energy in Table 5.3.1.
Figure 5.4.3: Mean AIR-Spec spectrum for east limb positions 1–4. All east limb positions show an equally strong line at 2.843 µm. East limb positions 2 and 3, which sample a hot active region loop, show evidence of a line at 2.853 µm.

We have measured two new emission lines in the solar corona in the 2.85 µm region, one of them from the $3p^5 3d^3 F_3 \rightarrow 3p^5 3d^3 F_4$ transition in Fe IX. We have identified the shorter wavelength line (2.843 µm) as Fe IX because its spatial distribution is more consistent with EUV emission at a similar temperature. The observed wavelength is 12 nm shorter than the theoretical wavelength predicted by NIST, and we have revised the energy levels accordingly. The longer wavelength line (2.853 µm) remains unidentified. A second flight of the AIR-Spec instrument with improved signal-to-noise ratio will be able to confirm the identification and provide additional information on the longer wavelength feature.
Table 5.4.1: Ratio with Mg VIII.

<table>
<thead>
<tr>
<th>East Limb Position</th>
<th>2.843 µm, measured</th>
<th>2.853 µm, measured</th>
<th>Fe IX, Judge</th>
<th>Fe IX, Del Zanna</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.4</td>
<td></td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>2</td>
<td>1.3</td>
<td>0.3</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>3</td>
<td>1.4</td>
<td>0.4</td>
<td>0.7</td>
<td>1.7</td>
</tr>
<tr>
<td>4</td>
<td>0.8</td>
<td></td>
<td>0.7</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Fe IX/Mg VIII line ratios predicted by Judge [28] and Del Zanna & DeLuca [11] are compared with the measured 2.843 µm/Mg VIII and 2.853 µm/Mg VIII line ratios for all four AIR-Spec slit positions on the east limb. The 2.853 µm/Mg VIII ratio vanishes at positions 1 and 4, indicating that Fe IX lies at 2.843 µm.
Conclusions and Future Work

During the 2017 solar eclipse, AIR-Spec opened an IR window in the solar corona and laid the groundwork for future measurements of coronal magnetic fields. In an observation lasting four minutes, the instrument successfully measured its five target emission lines and satisfied its three scientific objectives. Several follow-on experiments are planned to expand on the results from the 2017 eclipse. These include a re-flight of AIR-Spec during the 2019 total eclipse, development of a spectro-polarimeter operating at AIR-Spec wavelengths, and a laboratory study of infrared coronal emission lines.
6.1 Summary of 2017 eclipse results

AIR-Spec was carefully designed and constructed to meet three science goals. After post-processing and calibration, the 2017 eclipse data revealed that the experiment met all three goals. A paper describing the AIR-Spec instrument and 2017 data (Chapters 2 and 3) will be submitted to The Astrophysical Journal during the summer of 2018. The scientific objectives are restated below with an explanation of how each one was met.

1. Measure line wavelengths and intensities in different regions of the corona.

AIR-Spec measured the average linewidths, peak intensities, and center wavelengths of its five target lines radially outward from the limb at four positions in the corona. Our observation of Fe IX at 2.84 µm was the first of that line (Chapter 5) and has been published in a discovery paper [58].

2. Measure intensity gradient as a function of distance from the limb to provide information on the radiative excitation of each line [23].

AIR-Spec measured the intensity of Si X (1.43 µm) up to 0.6 R⊙ above the limb. We have compared our observations with 193 Å data from AIA (Chapter 4), and the measured ratios support Judge’s theoretical predictions for the radiative contribution to the 1.43 µm line [28]. We plan to compare the IR measurements of Si X, Si IX, and SXI with simultaneous EUV observations from the EUV Imaging Spectrometer (EIS) [9] and publish a paper on the results.

3. Search for time-varying Doppler velocities in the lines, including high frequency velocity oscillations which are thought to be the signatures of waves or flows [10, 67].

AIR-Spec measured the center wavelength of Si X with a precision of about 5 km/s, sufficient to measure high-frequency waves and fast flows. The observations reveal Doppler velocity variations that appear to be correlated with spatial structures and the ubiquitous presence of two velocity components separated by 100–150 km/s (Chapter 4). Due to a combination of pointing jitter and
thermal noise, we have been unable to determine the origin of the bimodal velocities. We are improving the instrument’s pointing stability and sensitivity in order to make a more conclusive velocity measurement during the 2019 eclipse. With higher SNR in our other lines, we will be able to search for the presence of multiple velocity components in plasma of different temperatures.

6.2 **Planned 2019 Eclipse Flight**

We have received NSF funding to fly an improved version of AIR-Spec in the July 2, 2019 eclipse over the South Pacific (Figure 6.2.1). The GV aircraft will provide nearly 7 minutes of coronal observation time. The length of the eclipse and our improved instrumentation will allow us to sample a greater variety of coronal conditions, including active regions, prominences, the quiet sun, and coronal holes, which were too dim for us to measure in 2017. The location of the eclipse will enable the possibility of simultaneous observations with coronagraphs at solar observatories on the Hawaiian Islands.

![AIR-Spec observation path](image)

**Figure 6.2.1:** AIR-Spec flight path for the 2019 eclipse.

In order to make AIR-Spec flight-ready in time for the 2017 eclipse, we installed the instrument without the benefit of several performance improvements that were identified before the flight. Other
upgrades are possible now that we have eclipse observations in hand. We will increase the instrument sensitivity and reduce the pointing jitter to obtain measurements higher above the limb with improved spatial and temporal resolution. By streamlining the instrument operation, we will reduce risk in the critical moments leading up to totality.

1. **Improved signal-to-noise ratio:** Due to the high thermal instrument background, the 2017 data were acquired with a maximum exposure time of 60 ms. Improvements to thermal shielding in the IR camera and spectrometer dewar/vacuum chamber will allow us to increase the exposure time to about 1 second, increasing the SNR of our observations by a factor of 4.

2. **Improved stability:** By design, AIR-Spec uses a fiber-optic gyroscope to remove high frequency aircraft motion. In 2019, our visible light slit-jaw imager was not used to provide an error signal because we were unable to test that approach under eclipse conditions before the eclipse. We are now using the 2017 eclipse observations to design a closed-loop image stabilization algorithm that will allow us to maintain our spatial resolution over the longer 1 second exposure time. By closing the loop around the motion of the lunar limb, we predict that we can reduce the RMS jitter below the 4.6 arcsec Nyquist limit in 100% of 1 second exposures [69]. Figure 6.2.2 shows the predicted closed-loop stability compared with the measured open-loop stability.

3. **Improved operability:** We have identified improvements to the mirror adjusters that will simplify the in-flight spectral alignment procedure. Improvements to the dewar/vacuum chamber will allow it to maintain vacuum longer, expediting the pump-down process. A flight-certified dewar and pump will allow us to add liquid nitrogen to the spectrograph in-flight to maintain the lowest possible thermal background.
Figure 6.2.2: Image stabilization performance, open-loop (measured) and closed-loop (predicted).

6.3 Future experiments

The December 2020 eclipse over South America is the last easily accessible total solar eclipse for four years. We plan to fly a spectro-polarimeter or high resolution spectrometer operating at one of the AIR-Spec wavelengths, in addition to providing a stabilized feed for another instrument. We will propose for a Major Research Instrumentation grant from the NSF to build the 2020 eclipse instrumentation.

We are exploring several options for the second instrument (Table 6.3.1). Our first choice is the Coronal Multichannel Polarimeter (CoMP) [68], which currently measures coronal magnetic field and LOS velocity from the Mauna Loa Solar Observatory in Hawaii (Figure 6.3.1, left). Before 2020, CoMP will undergo an upgrade to expand its wavelength coverage, field of view, and spatial resolution, leaving the original optics available for integration into the GV platform (S. McIntosh private communication to E. DeLuca, 2018). If CoMP is not available, a Bruker Fourier Transform Interferometer could provide high-resolution spectroscopy over the 1–5 μm range (Figure 6.3.1, right). Alternately, we could fly a broadband or narrowband imager provided by Habbal’s group at the University of Hawaii, which has a
long heritage in ground-based eclipse observation.

**Table 6.3.1**: List of possible GV instruments for the 2020 eclipse observation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Institution</th>
<th>Description</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASPIRE¹</td>
<td>SAO³</td>
<td>Imaging spectrometer or spectro-polarimeter, AIR-Spec successor</td>
<td>Near-IR lines TBD</td>
</tr>
<tr>
<td>CoMP²</td>
<td>HAO⁴</td>
<td>Imaging polarimeter, currently on Mauna Loa, HI</td>
<td>Fe XIII 10747/10798 Å and He I 10830 Å</td>
</tr>
<tr>
<td>Bruker EM 27</td>
<td>SAO³</td>
<td>Fourier Transform Interferometer</td>
<td>1–5 μm emission and continuum</td>
</tr>
<tr>
<td>Various</td>
<td>UH IfA⁵</td>
<td>Visible and near-IR imagers, currently ground-based</td>
<td>Fe IX/ XI/ XIII/ XIV, Ar X, and/or white light</td>
</tr>
</tbody>
</table>

¹ Airborne Spectro-Polarimetry in the InfraREd
² Coronal Multichannel Polarimeter
³ Smithsonian Astrophysical Observatory, Cambridge, MA
⁴ High Altitude Observatory, National Center for Atmospheric Research, Boulder, CO
⁵ University of Hawaii Institute for Astronomy, Honolulu, HI

We plan to complement the airborne effort with a laboratory study of infrared coronal lines. A rebuild of SAO’s electron beam ion trap (EBIT) is underway; the instrument will be able to produce plasma of a single atomic species (e.g. Fe, Si, Mg) at coronal density and temperature. EBIT measurements have successfully verified EUV wavelengths in iron and other coronal ions [3, 4]. Infrared spectroscopy is possible if appropriate measures are taken to mitigate atmospheric absorption and thermal emission, e.g. from the EBIT electron gun (R. Hutton private communication to P. Judge, 2018). IR emission spectra produced by the SAO EBIT will be measured by the Bruker Fourier Transform Interferometer (Figure 6.3.1, right) to provide line wavelengths and temperature-dependent ratios. Such an experiment might allow us to identify the AIR-Spec line at 2.853 μm.
Figure 6.3.1: Possible GV instruments for 2020: Coronal Multichannel Polarimeter [68] (left) and Bruker EM27 Fourier Transform Interferometer (right). The EM27 will be used in the EBIT study of coronal lines.
References


