

The Optical Aurora of Jupiter's Galilean Satellites; or, What They Do in the Shadows

Thesis by
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The Caltech logo, featuring the word "Caltech" in a bold, orange, sans-serif font.

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“To sit in solemn silence in a dull, dark dock,
In a pestilential prison, with a life-long lock,
Awaiting the sensation of a short, sharp shock,
From a cheap and chippy chopper on a big black block!”

—from Act I of *The Mikado* by W. S. Gilbert and Arthur Sullivan

When people ask me what I do, I often respond with “professional *Star Trek*.” However, being a scientist in the present is more difficult than in the glorious, socialist utopia of the 24th century. This quote from *The Mikado* nicely sums up the experience of a contemporary scientist whose research is supported by government grants. But, it isn’t all bad; my work over these past five years has been supported by both financial and personal relationships, and I’ll do my best to acknowledge each of them here.

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To the Hawai'ian community, the opportunity to use the telescopes on Maunakea is a rare gift and I am grateful for the opportunity to visit and observe from this sacred mountain.

Finally, though this official Caltech thesis template does not include a dedication page, I would like to dedicate my thesis to the memory of George Austin-Martin (October 24, 1939–November 21, 2020). George was my high school math teacher. He recognized something in me very early in my freshman year and soon thereafter got me involved in the very same kind of academic work I do now. We wrote and published a paper together about the development of problem solving skills in math students and gave presentations about the geometric constructions of the Ancient Greeks at seven math conferences, including two out of state. George showed me early on that I had what it took to be a professional scientist, and I will be forever grateful for his kindness, intelligence, encouragement and support.

ABSTRACT

When electrons from Jupiter's rapidly rotating magnetosphere collide with the thin atmospheres of the Galilean satellite—Io, Europa, Ganymede and Callisto—they create faint auroras like Earth's northern and southern lights. However, reflected sunlight from their icy surfaces overwhelms these faint auroral emissions at visible wavelengths. Fortunately, the satellites transit Jupiter's large shadow once per synodic orbit. When Jupiter is near elongation, we can view these transits from Earth and observe the satellites' faint auroral emissions in the absence of reflected sunlight. Over the past five years, we have used the High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope at the summit of Maunakea to observe the optical wavelength auroras of these four satellites during the eclipse phase of their orbits. My analysis of the auroras and the modulation of their brightnesses over five- to ten-minute timescales has provided new insight into the composition and density of their atmospheres and how they interact with the local plasma environment.

At Io, I found 13 auroral emissions not previously detected. I compared these detections to optical wavelength images taken through a variety of narrowband filters during the Cassini flyby to understand the morphology of the different auroral emissions. Using an auroral emission model, I showed that the oxygen emissions were consistent with electron impact on an atmosphere composed of O, SO and SO₂, disagreeing with prior studies which posited the oxygen emissions came from electron impact on its extended atomic oxygen corona. The brightest oxygen emissions did not vary with ambient upstream electron density, suggesting the electron flux into Io's atmosphere is more complex.

At Europa, the oxygen emissions varied systematically with the upstream electron density, indicating a simpler electron precipitation process than that at Io. This allowed me to use the variability in the auroral emissions as a proxy to understand variability in Europa's plasma environment. I evaluated how the brightnesses changed on short timescales during single eclipses as well as systematically on longer timescales over the four years we made the observations. I validated the results by comparing to *in situ* measurements taken during the Galileo mission. I also considered the timescale under which a sublimated water atmosphere would need to freeze back onto the surface as Europa passed into Jupiter's shadow.

At Ganymede, I showed the brightness had a hemispheric asymmetry that correlated with the geometry between the satellite and the centrifugal equator of Jupiter's magnetosphere. The brightness ratio between the northern and southern hemispheres

suggested that its auroras are triggered by the bounce motion of electrons along Jovian magnetic field lines rather than by ram flux from the upstream plasma population. I compared the results to model simulations of Ganymede's O_2 and H_2O atmospheres at different times during the eclipse to understand the detectability of a sublimated water atmosphere which, like with Europa, would need to collapse rapidly at the onset of the eclipse.

Finally, at Callisto, detections of auroral emission have been challenging because of the very low magnetospheric electron densities at its orbital distance from Jupiter. However, through careful data processing I was able to retrieve brightnesses of the 630.0 nm [O I] emission from individual spectra, allowing for the first time-series analysis of Callisto's aurora. Like Europa, I found the brightness modulated with distance from the centrifugal equator as expected for excitation by the upstream ram electron flux. This indicated the absence of a substantial ionosphere and supported the paradigm that the ionosphere exists only over the trailing hemisphere when it is illuminated by sunlight. I did not detect enough emission lines to perform the atmospheric compositional analysis I did with the other satellites, but I forward-modeled the expected brightness of the O, O_2 , H_2O and CO_2 atmospheres inferred or measured by other studies and found agreement with the aurora brightnesses and upper limits I observed with HIRES.

PUBLISHED CONTENT AND CONTRIBUTIONS

Milby, Z., K. de Kleer, and C. Schmidt (2026a). “Variability of Callisto’s Optical Aurora in Eclipse”. *The Planetary Science Journal* 7, 5. DOI: 10.3847/PSJ/ae650c

Contributions: I participated in the observing campaign, reduced and calibrated the data using pipelines I developed, analyzed the results and wrote the draft manuscript.

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TABLE OF CONTENTS

Acknowledgments	iii
Abstract	vii
Published Content and Contributions	ix
Table of Contents	ix
List of Illustrations	xii
List of Tables	xvi
Chapter 1: Introduction	1
1.1 Project Overview	1
1.2 Aurora	2
1.3 Jupiter's Magnetic Field and Space Plasma Environment	4
1.4 Observations	17
1.5 Housekeeping	31
1.6 Auroral Emission Model	35
1.7 Preview	39
Chapter 2: Io	45
2.1 Introduction	45
2.2 Observations and Data Reduction	48
2.3 Analysis	51
2.4 Results and Discussion	63
2.5 Conclusions	76
Chapter 3: Europa	85
3.1 Introduction	85
3.2 Observations and Data Reduction	88
3.3 Analysis	91
3.4 Results and Discussion	100
3.5 Conclusions	111
Chapter 4: Ganymede	119
4.1 Introduction	119
4.2 Observations and Data Reduction	122
4.3 Analysis	128
4.4 Results and Discussion	132
4.5 Conclusions	153
Chapter 5: Callisto	161
5.1 Introduction	161
5.2 Observations and Data Reduction	168
5.3 Analysis and Discussion	169
5.4 Conclusions	177
Chapter 6: Conclusion	183
References	185

Appendix A: Technical Drawings	203
Appendix B: Additional Atomic Energy Level Diagrams	207

LIST OF ILLUSTRATIONS

<i>Number</i>	<i>Page</i>
1.1 <i>L'Aurore</i> (1881) by William-Adolphe Bouguereau (1825–1905).	2
1.2 A photograph of Earth's aurora taken from Delta Junction, Alaska at midnight on April 10, 2015.	3
1.3 Family portrait of Jupiter's "Galilean satellites" taken by the <i>Galileo</i> spacecraft's Solid State Imaging experiment (SSI).	4
1.4 Cartoon depiction of Jupiter's magnetic field, incorporating solar wind modification.	5
1.5 Angular difference between centrifugal and magnetic latitudes in Jupiter's magnetosphere.	8
1.6 Geometric relationships between the centrifugal equator of the Jovian plasma sheet and an arbitrary Galilean satellite depicted at one of the maximum displacements between the magnetic and planetographic equators.	9
1.7 Distance to the closest point on the centrifugal equator as a function of distance from Jupiter and System III east longitude.	10
1.8 Traces along Jovian magnetospheric field lines intersecting the four Galilean satellites.	11
1.9 Electron densities in the Io plasma torus.	14
1.10 Modeled plasma scale height as a function of radial distance from Jupiter.	15
1.11 Maxwell-Boltzmann electron energy distributions for each Galilean satellite used in my auroral emission model.	16
1.12 The W. M. Keck Observatory with adjacent telescopes.	17
1.13 Cutaway diagram of the W. M. Keck Observatory showing the Keck I (right) and Keck II (left) telescopes within their respective domes and the support facility connecting them. Image credit: W. M. Keck Observatory/Tom Connell.	18
1.14 Keck I pointing limits.	19
1.15 A photo of what I am pretty sure is the room containing HIRES.	20
1.16 HIRES optical system schematic.	21
1.17 HIRES throughput measured by the observatory in late 2005.	24
1.18 Example HIRES mosaic detector image of Io in eclipse on 2024-09-12 at 14:05:46 UTC.	25

1.19	Example HIRES pointing and tracking for the observations of Ganymede on 2021-06-08 at the eclipse midpoint time of 14:31 UTC.	26
1.20	Durations of Galilean satellite umbral eclipses over one Jovian year. . . .	27
1.21	Relative velocity necessary to shift wavelength by ± 15 spectral pixels. . .	29
1.22	Partial energy level diagram for neutral oxygen (O).	33
1.23	Emission cross sections for electron impact on atomic oxygen (O) and the oxygen-bearing molecules O ₂ , H ₂ O, CO ₂ and SO ₂	37
2.1	Example viewing geometry of the apparent motion of Io in eclipse relative to Jupiter.	48
2.2	Calibrated example images for all 19 detected auroral emissions listed in Table 2.2.	54
2.3	Morphological features of Io's optical emission in eclipse.	57
2.4	<i>Cassini</i> /ISS NAC filter transmission and locations of identified auroral emission features.	58
2.5	Images of each <i>Cassini</i> /ISS filter and filter combination containing discrete auroral emissions identified in the HIRES spectra.	59
2.6	<i>Cassini</i> /ISS imaging filter sequence displayed in Figure 2.5 sorted by the exposure midpoint time.	60
2.7	Dependence of the 630.0 nm/557.7 nm [O I] brightness ratio on electron energy and density assuming electron impact on an atmospheric column of atomic oxygen.	64
2.8	Best-fit emission model column densities for O, O ₂ as a proxy for SO and SO ₂	67
2.9	Best-fit emission model O/SO ₂ mixing ratio calculated from the column densities in Figure 2.8.	69
2.10	Relationship between Io's 630.0 nm auroral brightness and distance from the centrifugal equator.	72
2.11	Dependence of the 671.6 nm/673.1 nm [S II] brightness ratio on electron number density assuming excitation by 5 eV electrons.	74
3.1	Example HIRES data showing the three oxygen emission lines identified in individual five-minute integrations.	92
3.2	Calibrated auroral brightnesses for 557.7 nm [O I], 630.0 nm [O I], 636.4 nm [O I] and 1 σ detectability thresholds for 656.3 nm H α , 777.4 nm O I and 844.6 nm O I sorted by time since partial eclipse ingress.	93

3.3	Geometric relationships between the centrifugal equator of the Jovian plasma sheet and Europa depicted at one of the maximum displacements between the magnetic and planetographic equators.	96
3.4	Three-dimensional projection of Europa's minimum distance from the centrifugal equator.	98
3.5	Relative ambient electron density as a function of System III east longitude for a plasma scale height of $1.7 R_J$, calculated at Europa's orbital distance from Jupiter ($9.4 R_J$) assuming azimuthal homogeneity in electron density along the centrifugal equator.	99
3.6	Best-fit component column densities for molecular oxygen (O_2) and 1σ detectability thresholds for atomic oxygen (O) and water (H_2O).	101
3.7	Weighted average nightly 630.0 nm [O I] brightness over the five years of observations as observed and after correcting for ambient plasma density with a scale height of $1.7 R_J$	105
3.8	Fit of the nominal ambient electron density (Figure 3.5) to Europa's 630.0 nm [O I] brightnesses assuming equal covariance between electron density and emission brightness.	106
3.9	Electron density scale height fits to observations of Europa's 630.0 nm [O I] auroral brightnesses assuming direct proportionality between electron density and emission brightness.	108
3.10	Correlation between Europa's normalized 630.0 nm [O I] brightness and distance from the plasma sheet centrifugal equator for an electron scale height of $1.7 R_J$	110
4.1	Line-of-sight observing geometry of Ganymede during eclipse by Jupiter on 2021-06-08 UTC.	123
4.2	Hemispheric observing geometry of Ganymede on 2021-06-08 between 12:58 and 15:08 UTC.	124
4.3	Geometric relationships relevant to the retrieval of electron properties.	132
4.4	Disk-integrated brightness of Ganymede's 630.0 nm [O I] aurora as a function of distance from the plasma sheet mid-plane.	133
4.5	Calibrated images of Ganymede's 630.0 nm [O I] auroral emission.	135
4.6	Ratio of Ganymede's 630.0 nm [O I] auroral emission between its northern and southern hemispheres.	138
4.7	Ratio of Ganymede's 630.0 nm [O I] auroral emission between its dusk and dawn hemispheres.	139

4.8	Time series of the ratio of the [O I] aurora brightness at 630.0 nm to the brightness at 557.7 nm.	141
4.9	H ₂ O/O ₂ column density ratio derived from MCMC fits to retrieved aurora brightnesses.	143
4.10	Simulation of Ganymede's O ₂ and H ₂ O atmospheric column densities before, during and after eclipse by Jupiter as observed from Earth.	145
4.11	Comparison between 557.7 nm [O I] and 656.3 nm H α disk-integrated brightness observations and predicted brightnesses from modeled column densities.	148
4.12	Simulated sub-solar surface temperature and number of simulated H ₂ O molecules before, during and after eclipse.	149
4.13	Simulation of Ganymede's 630.0 nm [O I] auroral emission from electron impact on O ₂ incorporating an updated electron energy distribution and emitting region.	151
5.1	Jovian magnetic field lines (M-shells) intersecting the Galilean satellites.	164
5.2	M-shells intersecting Callisto over one full rotation of Jupiter's magnetic field.	165
5.3	Callisto's 630.0 nm [O I] emission on 2021-07-04 and 2025-11-29.	170
5.4	Observational sampling of Jovian magnetic latitudes.	176
5.5	Change in Callisto's 630.0 nm [O I] emission with distance from the plasma sheet centrifugal equator.	177
A.1	Topographic map of the summit of Maunakea with annotated observatory locations.	204
A.2	Schematic plan diagram of the Keck I telescope and the HIRES instrument on the right Nasmyth platform.	205
A.3	Schematic section diagram of the Keck I telescope and the HIRES instrument on the right Nasmyth platform.	206
B.1	Partial energy level diagram for neutral hydrogen (H).	208
B.2	Partial energy level diagram for singly ionized oxygen (O ⁺).	209
B.3	Partial energy level diagram for neutral sodium (Na).	210
B.4	Partial energy level diagram for neutral sulfur (S).	211
B.5	Partial energy level diagram for singly ionized sulfur (S ⁺).	212
B.6	Partial energy level diagram for neutral potassium (K).	213

LIST OF TABLES

<i>Number</i>	<i>Page</i>
1.1 Harmonic coefficients and magnetic field angles for three Jovian magnetic field models.	6
1.2 Phipps et al. (2017) Io plasma torus model parameters.	12
1.3 Upstream electron population parameters assumed in our modeling for each Galilean satellite.	15
1.4 HIRES mosaic detector properties.	23
1.5 HIRES observations summary.	30
1.6 Auroral transitions in neutral oxygen (O).	34
1.7 Auroral emission model cross section sources.	38
2.1 Overview of the Keck I/HIRES observations of Io in eclipse.	49
2.2 Average auroral emission line brightnesses.	53
2.3 Emission morphologies in <i>Cassini</i> /ISS images and contributing auroral emissions identified in HIRES spectra.	61
2.4 Best-fit auroral emission model oxygen emissions for different atmospheric compositions.	65
2.5 File names of <i>Cassini</i> /ISS images.	84
3.1 Overview of the Keck I/HIRES observations of Europa in eclipse.	89
3.2 Emission model auroral brightness predictions.	102
4.1 Overview of the Keck/HIRES observations of Ganymede in eclipse on 2021-06-08 UTC.	129
4.2 Retrieved optical aurora brightnesses for emission from atomic oxygen and atomic hydrogen.	130
4.3 630.0 nm [O I] brightnesses calculated for the northern, southern, dawn (leading) and dusk (trailing) hemispheres.	137
4.4 Modeled emission ratios relative to 557.7 nm [O I] for Ganymede's optical aurora, assuming an electron population with a Maxwell-Boltzmann distribution centered at 100 eV and a number density of 20 cm^{-3}	142
4.5 MCMC median atmosphere column densities using retrieved brightnesses listed in Table 4.1.	144
4.6 Modeled emission ratios relative to 557.7 nm [O I] for Ganymede's optical aurora, assuming the Juno-derived electron population with a Maxwell-Boltzmann distribution at 200 eV and a number density of 950 cm^{-3}	153

5.1	Summary of measured and inferred atmospheric column densities for oxygen-bearing constituents.	166
5.2	Individual 630.0 nm [O I] brightness measurements.	169
5.3	Average Measured Optical Auroral Brightnesses	171
5.4	Modeled auroral emission brightnesses.	174

Chapter 1

INTRODUCTION

1.1 Project Overview

My first project in graduate school was the development of a data reduction and calibration pipeline for spectra taken with the High Resolution Echelle Spectrometer (HIRES; Vogt et al., 1994), an optical wavelength spectrograph on the Keck I telescope at the summit of Maunakea. The motivation for this project was the production of flux-calibrated spectra of auroral emission from Jupiter’s Galilean satellites—Io, Europa, Ganymede and Callisto—while they passed through Jupiter’s shadow. The completion of these pipelines and the small bit of analysis I did on the resulting spectra contributed to the de Kleer et al. (2023) paper.

Soon thereafter, I took over leading the aurora project from my advisor Katherine, which included the acquisition of additional spectra through the HIRES observing campaign and more granular analysis of the emissions from each satellite. Over the course of my five years in graduate school, we observed Io’s aurora over 7 separate nights, Europa’s over 11 nights, Ganymede’s over 5 nights and Callisto’s over 4 nights (though not all of these resulted in usable data, see Table 1.5). I took the many spectra, which sampled a variety of Jovian magnetic field geometries and plasma parameters, and over the course of four papers (Milby et al., 2024; Milby et al., 2025; Milby et al., 2026b; Milby et al., 2026a) I looked at the short-timescale variability (typically on the order of 5 to 7 minutes) in auroral emission brightnesses and their implications for the composition of the satellite atmospheres and how they interact with the Jovian plasma environment.

In the sections that follow, I’ll try to set up the science common to each of the four satellite aurora papers (Chapters 2 through 5). Some of this material will be repeated in the individual paper introductions, but I figure it is still useful to have it all together in one place, especially since my own understanding of some of these concepts has changed (and I hope improved) with time. I’ll briefly describe the basic physical process generating the aurora and the oxygen emissions we searched for (Section 1.2), Jupiter’s magnetic field and the space plasma environment bound within it (Section 1.3), the observations we took and how we took them (Section 1.4), the confounding unit for brightness used by auroral scientists and the quantum mechanics of auroral emission (Section 1.5), and finally how we modeled and interpreted the auroral brightnesses we observed (Section 1.6).

1.2 Aurora

Defining exactly what an *aurora* is seems like a good place to start. Scientists have split non-anthropogenic photon emission from the night sky into two categories: *airglow* and *aurora* (Chamberlain et al., 1987). Auroras occur when exogenous charged particles (typically electrons) interact with atmospheric atoms and/or molecules, resulting in photon emission. Airglow is a blanket term encompassing everything else which might make the atmosphere glow, either in broadband or at discrete wavelengths. This includes things like scattered sunlight (which makes the cloudless Earth sky appear blue during daytime), dynamic processes producing or removing charged particles in the ionosphere and photochemical reactions between neutral atoms and molecules in the atmosphere.

The word “aurora” comes from the Latin word *aurōra*, meaning “dawn.”¹ In Roman mythology, Aurora is the personification of the dawn (her Greek mythological counterpart is Eos). According to her Wikipedia page, Sol (the Sun) is her brother and Luna (the Moon) is her sister, and she flies across the sky each morning announcing the impending arrival of her brother. In mythological literature, she most frequently appears in erotic poetry with a mortal companion lover.

On Earth, auroras typically occur near the poles where magnetic field lines provide a pathway for charged particles from the Sun to precipitate into the atmosphere. Under quiescent solar conditions, the “auroral zones” occur in a 600 km-wide band coincidentally centered (within 1° of latitude) on the arctic/antarctic circles, though magnetic pressure from the solar wind generates subsolar-antisolar asymmetry, pushing the region to higher latitudes on the dayside and lower latitudes on the nightside.

Auroras appear in different colors at different altitudes, each resulting from excitation of a different atom or molecule. At about 200 km and higher, charged particle collisions with atomic oxygen produce red aurora. Between 100 and 200 km, the denser



Figure 1.1: *L'Aurore* (1881) by William-Adolphe Bouguereau (1825–1905).

¹Consequently there's some disagreement about the plural form of the word: some use *aurorae* in its proper Latin form, others use *auroras* in familiar English form. I typically use the latter since I am writing in English.



Figure 1.2: A photograph of Earth's aurora taken from Delta Junction, Alaska at midnight on April 10, 2015. Image credit: NASA/Sebastian Saarloos.

atmosphere suppresses the emission of the red aurora; in this region collisions with atomic oxygen produce green aurora. Below 100 km atomic oxygen concentration is low, and the density of other atmospheric molecules like nitrogen (N_2) is high enough to effectively suppress all of the green and red emission. At these altitudes, blue and pink auroras result from the excitation of neutral and ionized N_2 . However, these low-altitude aurora require a larger solar flux and generally occur only when the Sun is particularly active, either near solar maximum or during coronal mass ejection events that impact the Earth. Figure 1.2 is a photo of Earth's aurora taken by photographer Sebastian Saarloos from Delta Junction, Alaska at midnight on April 20, 2015, showing its ribbon-like structure and the altitude dependence of the colors.

Auroras also occur in the thin atmospheres (some say exospheres) of Jupiter's "Galilean satellites": Io, Europa, Ganymede and Callisto (see Figure 1.3 for a *Galileo*-era family portrait). Interestingly, some of their brightest auroral emissions are the same green and red oxygen emissions seen here on Earth.

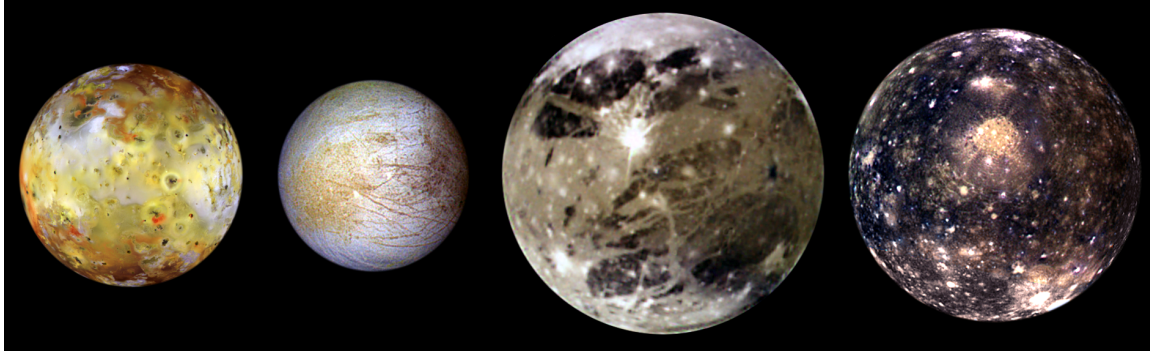


Figure 1.3: Family portrait of Jupiter’s “Galilean satellites” taken by the *Galileo* spacecraft’s Solid State Imaging experiment (SSI). From left to right: Io, Europa, Ganymede and Callisto. Image credit: NASA/JPL/DLR.

1.3 Jupiter’s Magnetic Field and Space Plasma Environment

The Galilean satellites each orbit close enough to Jupiter to be well within the influence of its magnetosphere. Consequently, the geometry of Jupiter’s magnetic field influences the distribution and trajectories of the electrons exciting the satellite auroras (though the story gets more complex at Ganymede, where its own internally generated magnetic field complicates its interaction with Jupiter’s magnetic field). Knowing the position of a satellite within Jupiter’s magnetic field is important for analyzing and interpreting variability in auroral brightnesses, especially over short, several-hour timescales given Jupiter’s magnetospheric rotation rate (approximately 10 hours) relative to the orbital periods of the satellites (from 1.77 days for Io up to 16.7 days for Callisto; Archinal et al., 2018).

In situ magnetometer measurements by spacecraft within the Jovian system have allowed researchers to develop spherical harmonic models of Jupiter’s magnetic field. Connerney et al. (1998) developed the “VIP4” model by fitting *Voyager 1* and *Pioneer 11* magnetometer measurements constrained by the position of Io’s flux tube footprint in Jupiter’s atmosphere. Scientists associated with the *Juno* mission developed two follow-up magnetic field models: the “JRM09” model using the first 9 orbits of *Juno* (Connerney et al., 2018), and the “JRM33” model using 32 of the first 33 orbits of *Juno* (Connerney et al., 2022). The best-fit harmonic coefficients from each of these three magnetic field models indicate that Jupiter’s magnetic field is primarily dipolar, though they do not incorporate the effect of the solar wind (illustrated qualitatively in Figure 1.4).

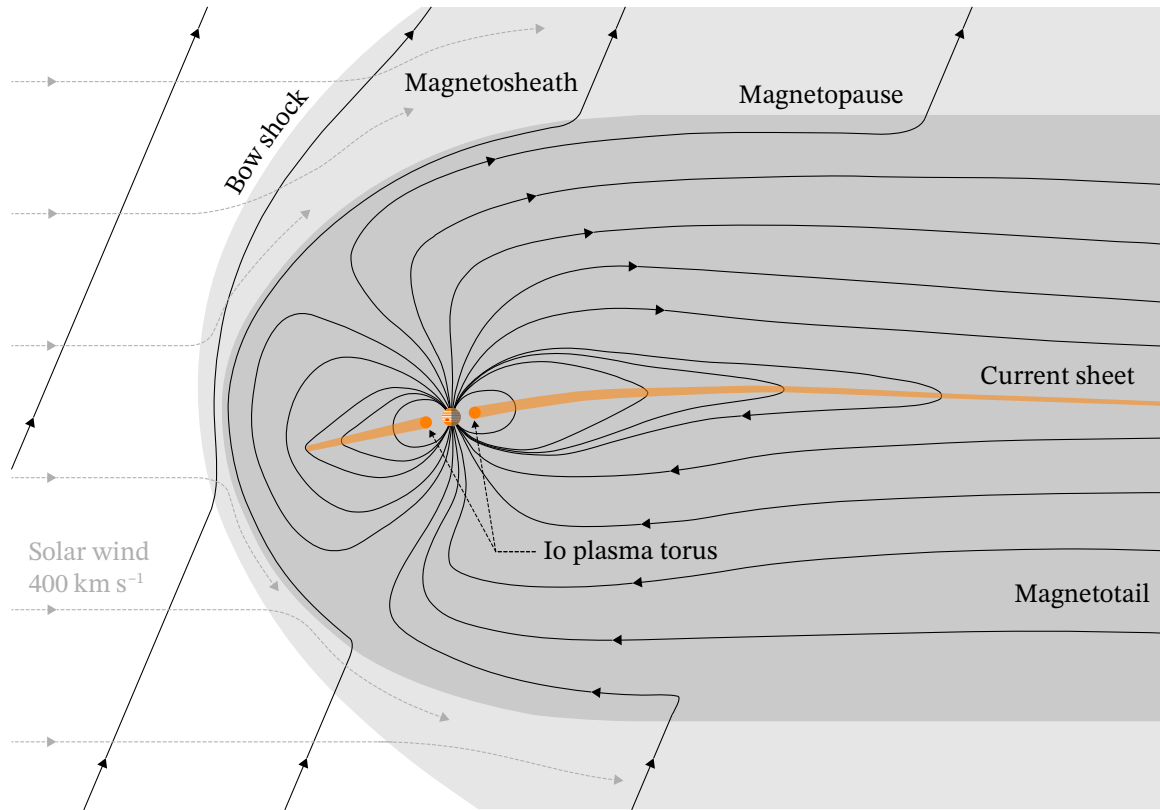


Figure 1.4: Cartoon depiction of Jupiter’s magnetic field, incorporating solar wind modification. Image credit: Fran Bagenal/Steve “Crusher” Bartlett/Mitchell Deans.

1.3.1 The Planetocentric/Planetographic Equator

This feels like a good opportunity to introduce the Jovian coordinate systems I have had to think about for this project. Since Jupiter does not have a solid surface and its cloud bands rotate at different velocities, a reasonable question to ask is “just how exactly is longitude defined for Jupiter?” Conventionally, it is based on the orientation and rotation of the magnetic field, which can be measured externally. This coordinate system is called System III, and it is conventionally left-handed, meaning longitudes increase positively to the west (a planetographic coordinate system). This is mathematical nonsense and I won’t have anything to do with it, so I always convert to east-positive longitude (a planetocentric coordinate system), which is easily done using

$$\phi_{\text{east}} = 360^\circ - \phi_{\text{west}}. \quad (1.1)$$

I also pretty strongly believe the “north” pole of a planet should be its rotational angular momentum pole, but I fortunately don’t need to argue that point for Jupiter as I would for Venus or Uranus.

Table 1.1: Harmonic coefficients and magnetic field angles for three Jovian magnetic field models.

Model	Coefficient [nT]			Field Angle [deg]		Reference
	g_1^0	g_1^1	h_1^1	θ_B	ϕ_B	
VIP4	420 543.0	−65 920.0	24 992.0	9.516406	159.236969	Connerney et al. (1998)
JRM09	410 244.7	−71 498.3	21 330.5	10.307870	163.388276	Connerney et al. (2018)
JRM33	410 993.4	−71 305.9	20 958.4	10.250332	163.620757	Connerney et al. (2022)

Note. Copied from Wang et al. (2023), Table A1.

1.3.2 The Magnetic Equator

The magnetic field’s rotation axis does not align with the axis of the dipole moment. Khurana et al. (2004) provided two equations (their Equations numbers 4 and 5) for the tilt θ_B and orientation ϕ_B of the magnetic field pole relative to the rotation axis as functions of the first-order dipole harmonic coefficients. (I have changed the symbols from his to keep consistency with my own notation herein.) Wang et al. (2023) converted Khurana et al. (2004)’s arctangent form of θ_B to an arccosine (presumably to change the range from exclusive $(-90^\circ, 90^\circ)$ to inclusive $[-90^\circ, 90^\circ]$) and the arctangent form of ϕ_B to the four-quadrant piecewise arctangent2 function (for the full $[-180^\circ, 180^\circ]$ range of longitudes):

$$\theta_B = \arccos \left(\frac{g_1^0}{\sqrt{(g_1^0)^2 + (g_1^1)^2 + (h_1^1)^2}} \right), \text{ and} \quad (1.2)$$

$$\phi_B = \arctan2(h_1^1, g_1^1), \quad (1.3)$$

where θ_B is the colatitude, convertible from ordinary latitude λ_B by

$$\theta_B = 90^\circ - \lambda_B, \quad (1.4)$$

ϕ_B is the east longitude of the magnetic pole in the right-handed (east-positive) version of System III coordinates, and g_1^0 , g_1^1 and h_1^1 are the dipole spherical harmonic components.

Converting from System III latitude (λ) to magnetic latitude (λ_B) involves a simple cosine modulation using the tilt and orientation parameters:

$$\lambda_B = \theta_B \cos(\phi - \phi_B) - \lambda. \quad (1.5)$$

Most of the papers I referenced for my analysis used the VIP4 model, so I likewise assumed a dipolar magnetic field offset from Jupiter’s rotational axis by approximately

9.5° toward 159.2° System III east longitude and calculated magnetic latitudes accordingly. Table 1.1 lists the dipole coefficients and corresponding tilt and orientation of the magnetic field axis for the three magnetic field models.

1.3.3 The Centrifugal Equator

So far that's two coordinate systems (planetocentric and magnetic). But, there's a third equator to consider, and its location depends on both System III longitude and radial distance from Jupiter. This third equator arises due to the coupling of the plasma to Jupiter's rotating magnetic field, which affects the distribution of the plasma (Michel et al., 1974). If the magnetic field did not rotate, the gravity field would produce a density gradient perpendicular to the magnetic field equator (similar to the density profile in protoplanetary disks). However, because of the relatively fast rotation period of the magnetic field (9h 55m 29.711s or $870.536^\circ \text{ day}^{-1}$, Archinal et al., 2018) and the offset between the magnetic field and rotation poles, the coupled plasma experiences centripetal acceleration, deflecting the high-density plasma away from the magnetic equator toward the rotational equator. The location of the high-density center of the plasma is called the "centrifugal equator" or "centrifugal symmetry surface" (Gledhill, 1967; Hill et al., 1974). So, the third latitude to consider is the centrifugal latitude λ_c , defined geometrically as the furthest point from Jupiter's spin axis along a magnetic field line.

Phipps et al. (2021) used the VIP4 magnetic field model and the Connerney et al. (2020) "CON2020" current sheet model to calculate the planetocentric latitude of the centrifugal equator as a function of both distance from Jupiter and System III magnetic east longitude. They fit a nonphysical hyperbolic tangent model modulated by sinusoidal variation with azimuth and found agreement within $\pm 1\%$ of the input latitudes from the magnetic field model. I've modified their equation by adding an additional digit of precision to the longitude of the magnetic pole (from 159° to 159.2° ; Connerney et al., 1998) and converted the sine function to a cosine function for consistency with other equations used herein. The System III latitude λ_{ceq} of the centrifugal equator at a distance r from Jupiter's barycenter can be calculated as

$$\lambda_{\text{ceq}}(r, \phi) = \left(1.66^\circ \tanh\left(0.131 \text{ rad} \frac{r}{R_J} - 1.62 \text{ rad}\right) + 7.76^\circ \right) \cos(\phi - 159.2^\circ) \quad (1.6)$$

where the angular quantities (with the exception of the cosine argument) are their best fit values, r is the radial distance from Jupiter and ϕ is System III east longitude. Consequently, the centrifugal latitude λ_c of a satellite can be calculated as

$$\lambda_c = -\lambda_{\text{ceq}} - \lambda, \quad (1.7)$$

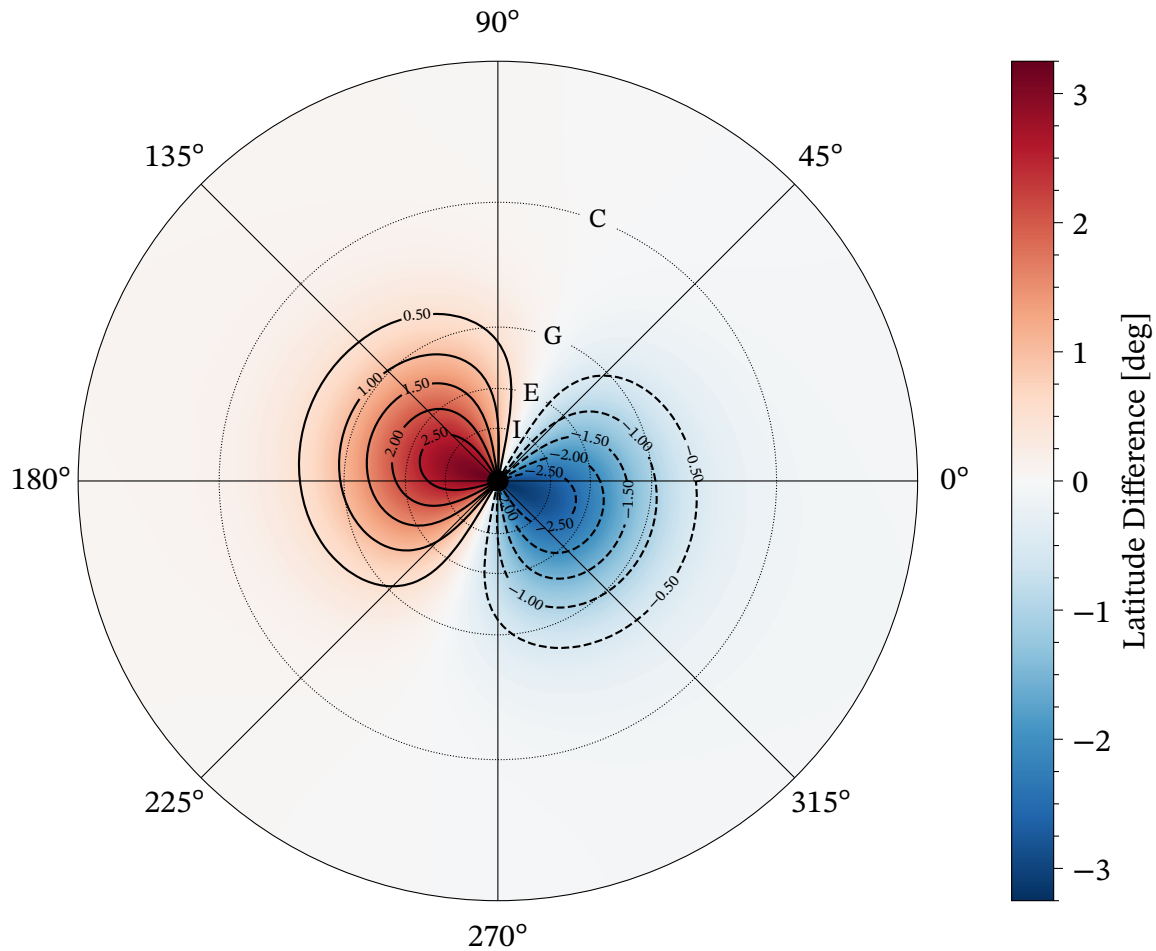


Figure 1.5: Angular difference between centrifugal and magnetic latitudes in Jupiter's magnetosphere. Positive (red) indicates the magnetic equator is at a more positive latitude than the centrifugal equator, while negative (blue) indicates the magnetic equator is at a more negative latitude than the centrifugal equator. Radial coordinates are distance from Jupiter's barycenter in units of the standard Jupiter equatorial radius (71 492 km; Archinal et al., 2018). The four dotted circles show the locations of the semimajor axes of Io (I), Europa (E), Ganymede (G) and Callisto (C). Angular coordinates are in System III east longitude.

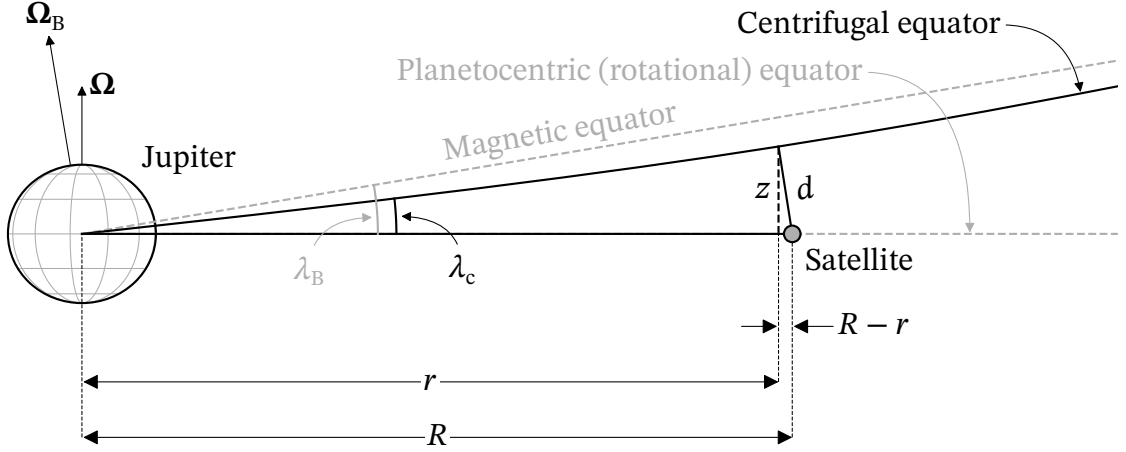


Figure 1.6: Geometric relationships between the centrifugal equator of the Jovian plasma sheet and an arbitrary Galilean satellite depicted at one of the maximum displacements between the magnetic and planetographic equators. Ω is the magnetic field rotation axis and Ω_B is the magnetic field north pole axis. R is the satellite's instantaneous orbital distance from Jupiter. r is the distance along the orbital plane which minimizes the length of the hypotenuse d of the right triangle with legs $z(r)$ and $(R - r)$, corresponding to the ray perpendicular to the centrifugal equator which intersects the satellite and minimizes the distance between the satellite and the centrifugal equator.

where λ is the System III latitude of the satellite and λ_{ceq} is negative because when the centrifugal equator appears at a positive latitude, the orbital plane in which the satellites orbit is below the equator. Figure 1.5 shows the difference between the centrifugal equator latitude and magnetic equator latitude as a function of radial distance from Jupiter and System III east longitude.

Figure 1.6 shows the angles and distances relevant to calculating the minimum distance from a satellite to the centrifugal equator, which is the position from which the ambient plasma density scales perpendicularly with distance. The minimum distance d of each Galilean satellite from the centrifugal equator is

$$d(r, \phi) = \sqrt{(R - r)^2 + z(r, \phi)^2} \quad (1.8)$$

where R is the satellite's instantaneous orbital distance from Jupiter,

$$z(r, \phi) = r \tan(-\lambda_c(r, \phi)) \quad (1.9)$$

is the height of the centrifugal equator from the rotational equator and r is the solution to

$$\frac{\partial}{\partial r} d(r, \phi) = 0. \quad (1.10)$$

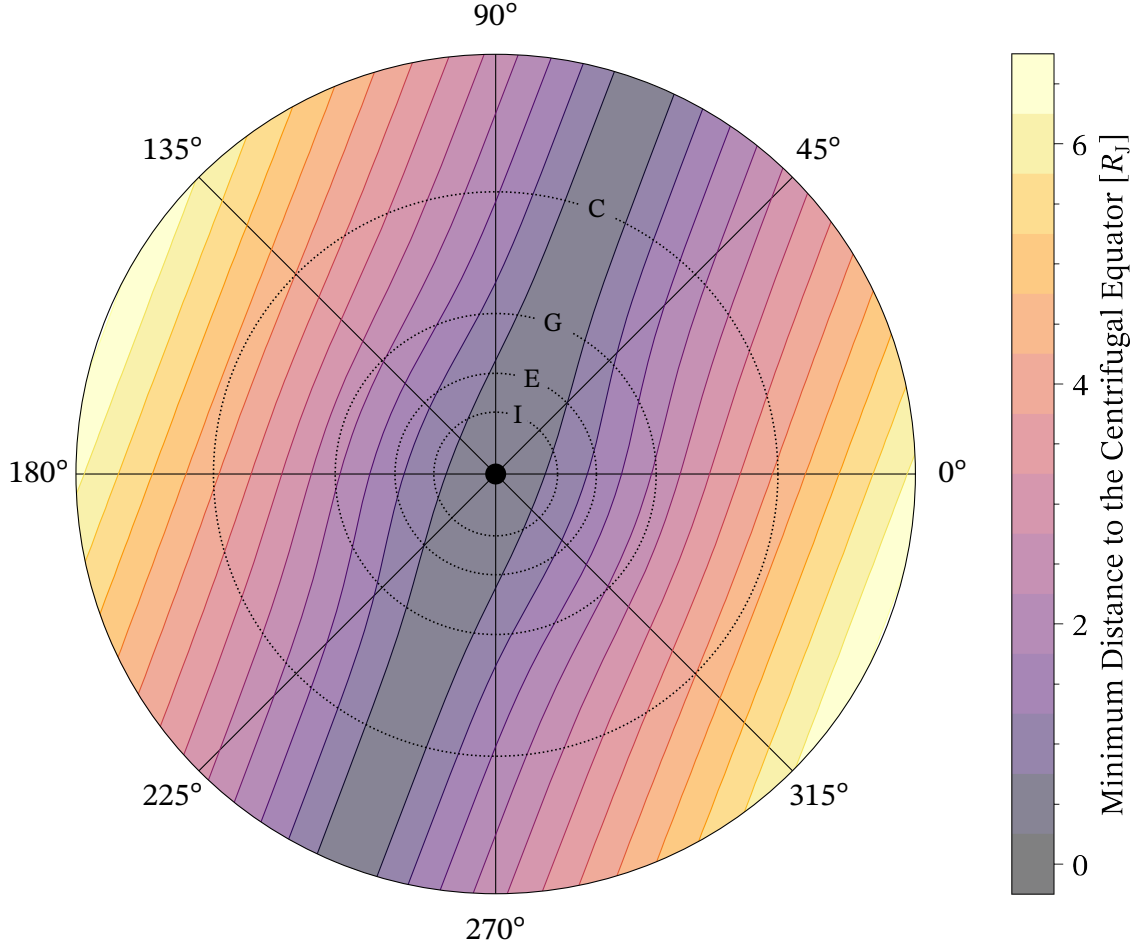


Figure 1.7: Distance to the closest point on the centrifugal equator as a function of distance from Jupiter and System III east longitude. Distances shown in discrete contours with $0.5 R_J$ spacing. The slight deviation from the tangent approximation (Equation 1.11) is clearest near the orbits of Io and Europa.

While this is the mathematically rigorous way to calculate the distance, it's probably unnecessarily complicated. I did a quick back-of-the-envelope calculation and found the maximum relative difference between z and d is at most about 2%. So, as an alternative, a simple tangent approximation can be used where

$$d \approx R \tan \lambda_{\text{ceq}}. \quad (1.11)$$

Figure 1.7 shows the minimum distance to the centrifugal equator as a function of distance from Jupiter and System III east longitude. The difference between the tangent approximation and more mathematically rigorous calculation I've detailed above is most evident in the slight deflection from parallel contours near the orbits of Io and Europa.

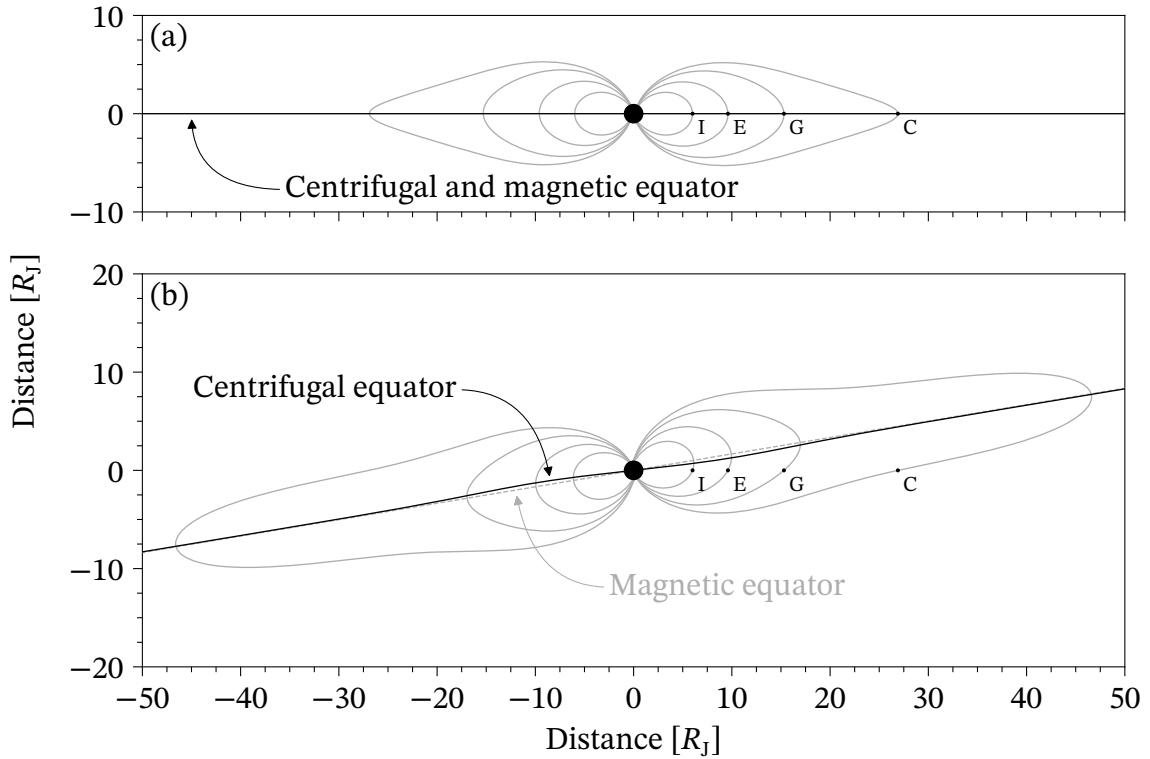


Figure 1.8: Traces along Jovian magnetospheric field lines intersecting the four Galilean satellites. The four black dots show the locations of the semimajor axes of Io (I), Europa (E), Ganymede (G) and Callisto (C). (a) shows the field lines when the magnetic and joviographic equators align (in the plane intersecting 69.2° and 249.2° in System III east longitude). (b) shows the field lines at the maximum displacement between the joviographic and magnetic equators (in the plane intersecting 159.2° and 339.2° in System III east longitude). Distances are in the standard Jupiter equatorial radius of 71 492 km (Archinal et al., 2018). These field lines do not include distortions from either Ganymede’s internally generated magnetic field or the induced fields present at each satellite.

The last thing to consider is how the magnetic field lines intersect each of the satellites. The current sheet “stretches” out the field lines in the radial direction. For Io and Europa the effect is minimal and the field lines intersect near their north and south poles for all System III longitudes. However, for Ganymede and Callisto, this stretching of the field lines shifts the latitude at which the field line intersects the satellite substantially. At its maximum displacement from the centrifugal equator, the field lines intersect Callisto almost at its equator! Figure 1.8 shows this effect graphically. However, keep in mind this is a fairly simplified approximation. The geometry of the field is modified by the exogenous solar wind (recall Figure 1.4), such that field line tracing

Table 1.2: Phipps et al. (2017) Io plasma torus model parameters.

Region	Parameter			
	n_0 [cm ⁻³]	r_0 [R_J]	w [R_J]	H [R_J]
Cold torus	1710	5.23	0.2	0.1
Ribbon	2180	5.6	0.08	0.6
Warm torus	2160	5.89	0.32	1
Extended torus	1601	5.53	1.88	1

becomes increasingly unreliable with greater distance from Jupiter when assuming only an internal field and current sheet model, which this simulation does.

1.3.4 Electrons

Ions constitute most of the mass in the Jovian magnetospheric plasma, and consequently their properties determine the plasma scale height. Bagenal et al. (2011) modified Equation (3) of Hill et al. (1976) to obtain the plasma scale height

$$H = 0.64 R_J \sqrt{\xi \frac{\langle E_{\text{ion}} \rangle}{\langle m_{\text{ion}} \rangle}} \quad (1.12)$$

where $\langle m_{\text{ion}} \rangle$ is the average ion mass, $\langle E_{\text{ion}} \rangle$ is the average ion energy and ξ is the ratio of the atomic mass unit (u) to the electron volt (eV). This form assumes that the magnetic field is primarily dipolar and that the ion energy is significantly larger than the electron energy (which is true for Jupiter at radial distances greater than $5.6 R_J$).

While ions may dominate the mass of the plasma, it's the electrons I care about since they provide the energy exciting the auroral emissions. Within the plasma torus near Io the radial energy and density structure is more complicated than it is further out at Europa and beyond.

Phipps et al. (2017) provided a model for electron density in the plasma torus near Io. Though traditionally the plasma torus is split into three regions (the cold torus, the ribbon and the warm torus), their model further subdivides the warm torus into two separate components: one region localized to Io's semi-major axis (the "warm torus") and one extended region (you guessed it, the "extended torus"). Table 1.2 lists the model values for each of these component parameters. Interestingly, their model scale height of $1 R_J$ in the warm torus is significantly larger than the $0.77 R_J$ scale height of Bagenal et al. (2011) (see Figure 1.10), though the finer radial structure of the their model near Io may simply average out to the Bagenal et al. (2011) value. Mathematically, their model

is

$$n(r, z) = \begin{cases} \sum_{i=1}^3 n_i e^{-((r-r_{0,i})/w_i)^2 - (z/H_i)^2} & \text{if } r < 6.089 R_J, \text{ and} \\ n_4 e^{-((r-r_{0,4})/w_4)^2} e^{-(z/H_4)^2} & \text{if } r \geq 6.089 R_J, \end{cases} \quad (1.13)$$

where r is the radial distance from Jupiter, z is the height above or below the centrifugal equator, n_0 is the density at the center of the component region, r_0 is the radial center of the component region, w is the radial width of the component region, H is the scale height of the component region and $i \in [1, 4]$ refers to the different component regions of the torus: 1 is the cold torus, 2 is the ribbon, 3 is the warm torus and 4 is the extended torus.

When I evaluated their model I noticed that the boundary densities did not match at the transition from the warm torus to the extended torus. I used a numeric root finder and found that the more accurate boundary is $r = 6.089 R_J$ in contrast to the $6.1 R_J$ they reported. Regardless, their model still produces a sharp (and likely non-physical) discontinuity at the boundary between the two warm torus regions. Figure 1.9 (a) shows the modeled radial density profile along the centrifugal equator and Figure 1.9 (b) shows the two-dimensional model near Io's orbital distance from Jupiter.

For Io's semi-major axis of $5.9 R_J$ and eccentricity of 0.004 (Archinal et al., 2018), Io experiences a maximum modeled plasma density of 2160 cm^{-3} along the centrifugal equator at an orbital distance of $5.9 R_J$ and a minimum modeled plasma density of 1347 cm^{-3} at its apoapsis orbital distance of $5.9236 R_J$ and its maximum displacement of $0.679333 R_J$ from the centrifugal equator.

Energy-wise, inward of the cold torus things fall off pretty quickly. However, from the cold torus through the ribbon, electron energies are pretty steady at around 4 eV. For the warm torus it jumps up to 5 eV, and more or less steadily increases toward approximately 20 eV at Europa's orbit (see Figure 1 in Bagenal, 1994).

In my modeling work (see Section 1.6), I generally use the same electron densities and energy distributions as the UV studies to allow for easy comparison of our results. For the densities, I assumed a nominal value at the centrifugal equator n_0 which I then scaled with the Hill et al. (1976) Gaussian profile

$$n(r, d) = n_0(r) e^{-(d/H(r))^2}, \quad (1.14)$$

where d is satellite's instantaneous displacement from the centrifugal equator and H is the scale height at its semimajor axis r assumed for each satellite as indicated in Figure 1.10 (Bagenal et al., 2011). For the electron energies, I assumed a Maxwell-Boltzmann

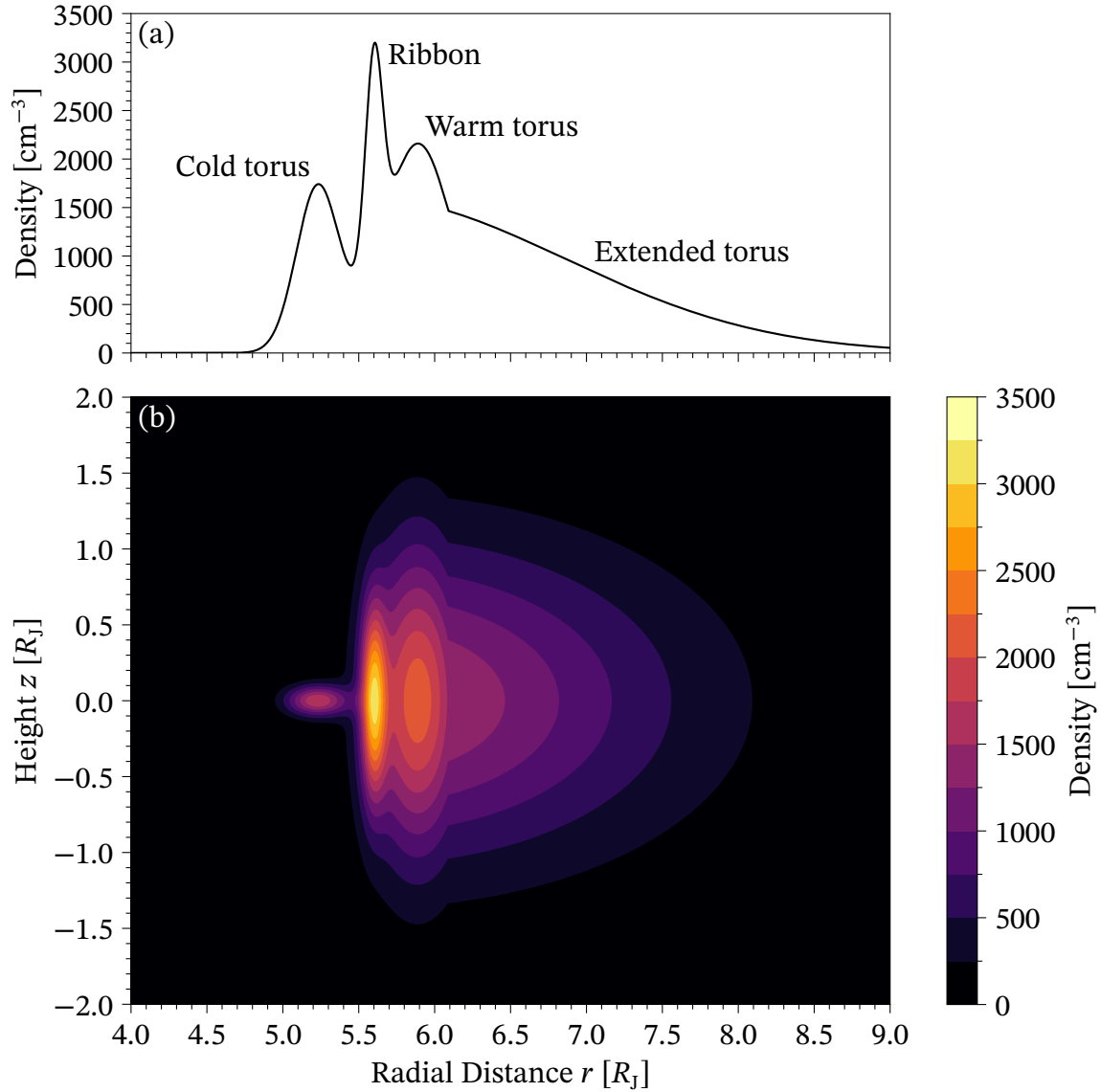


Figure 1.9: Electron densities in the Io plasma torus based on the model of Phipps et al. (2017). (a) Radial profile showing the density maximum along the centrifugal equator at $z = 0 R_J$. (b) Two-dimensional electron density cross section through the plasma torus, displayed using 250 cm^{-3} contours. Io's semi-major axis falls at the center of the warm torus region.

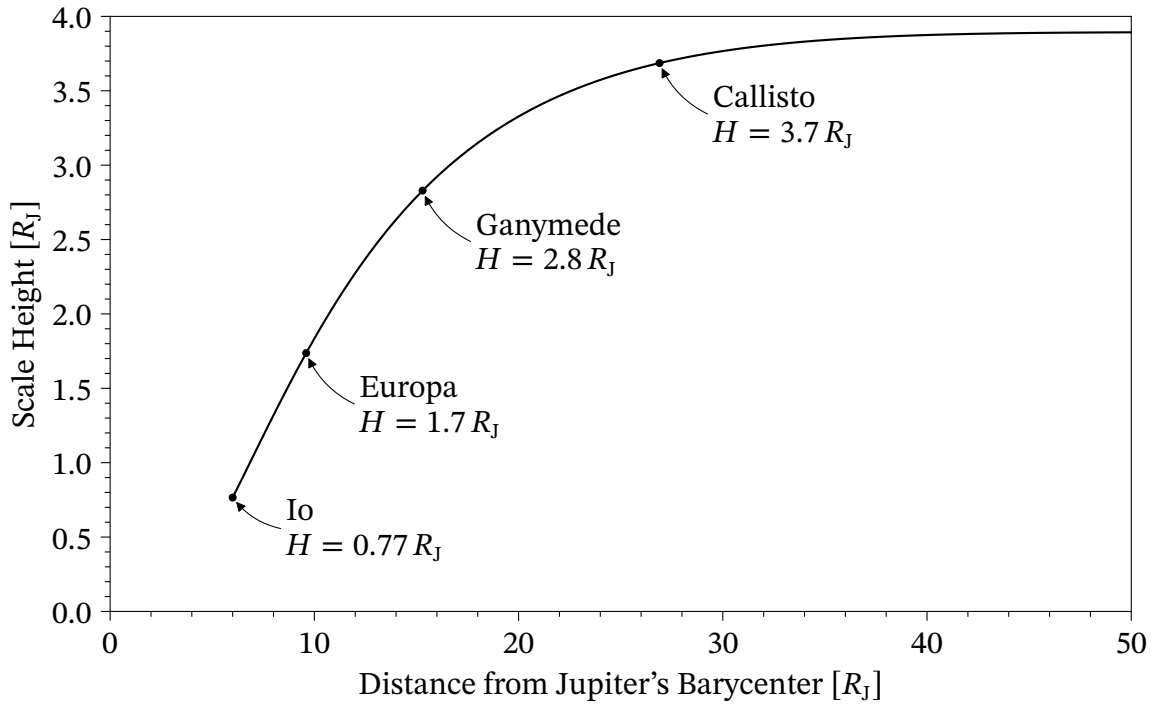


Figure 1.10: Modeled plasma scale height as a function of radial distance from Jupiter (Bagenal et al., 2011).

Table 1.3: Upstream electron population parameters assumed in our modeling for each Galilean satellite.

Satellite	Thermal		Suprathermal		Reference(s)
	n_0 [cm^{-3}]	E_0 [eV]	n_0 [cm^{-3}]	E_0 [eV]	
Io	2500	5	—	—	Kivelson et al. (2004)
Europa	150	20	8	300	Bagenal et al. (2015)
Ganymede	20	100	—	—	n_0 : Scudder et al. (1981) E_0 : Eviatar et al. (2001)
Callisto	0.11	35	0.04	1500	Cunningham et al. (2015)

Notes. Densities n_0 are at the centrifugal equator. Europa and Callisto have measured, non-negligible suprathermal electron populations.

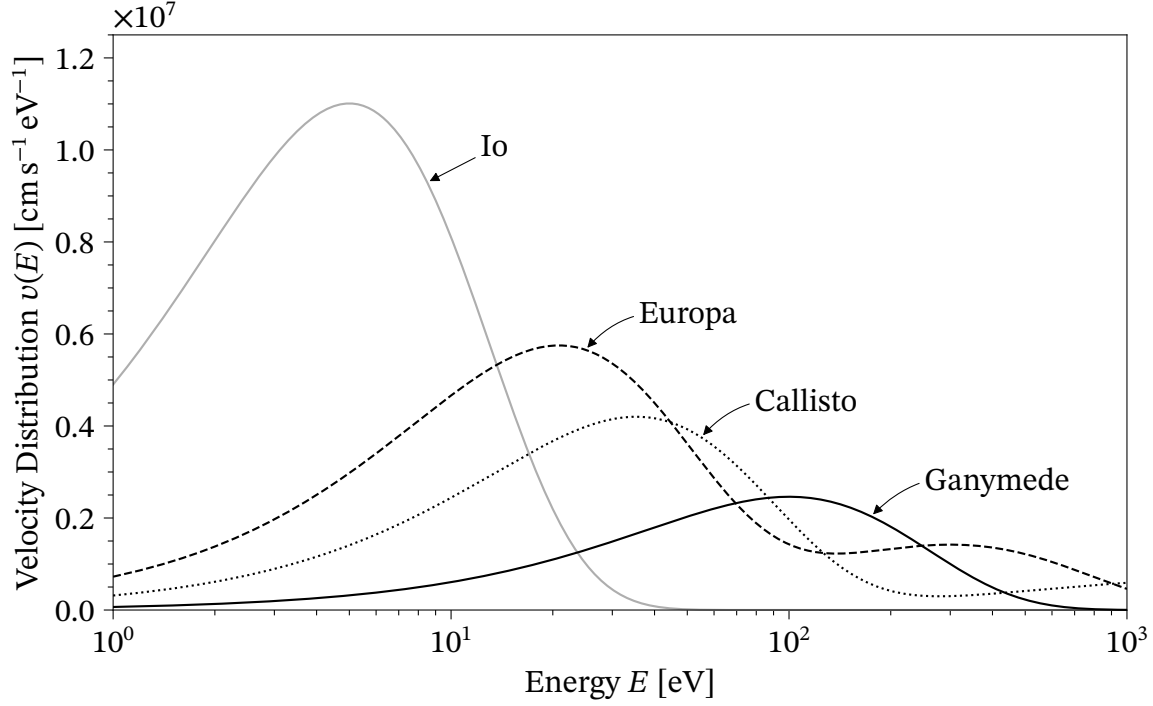


Figure 1.11: Maxwell-Boltzmann electron energy distributions for each Galilean satellite used in my auroral emission model. Europa and Callisto have non-negligible high energy electron populations which result in secondary peaks outside of the core population.

thermal velocity distribution v as a function of electron energy E s

$$v(E) = \frac{4}{\sqrt{2\pi m_e E_0^3}} E e^{-E/E_0} \quad [\text{cm s}^{-1} \text{ eV}^{-1}], \quad (1.15)$$

where E_0 is the core electron energy and m_e is the mass of the electron (Mohr et al., 2025). Table 1.3 lists the densities and core energies I assumed in my modeling for each satellite. Figure 1.11 shows what each of these velocity distributions looks like as a function of electron energy. For Europa and Callisto, you can see the prominent secondary bumps from the suprathermal populations in the high-energy tails.

The conclusion to take away from this section is that Jupiter's magnetic field is complex and dynamic, and the distribution and energies of the electrons coupled to it are not well understood. Unfortunately this requires us to make a bunch of assumptions when we use these properties to interpret the aurora brightnesses. Hopefully joint observation campaigns with *in situ* spacecraft like the *Juice* mission run by the European Space Agency (ESA) and the *Europa Clipper* mission run by the United States National Aeronautics and Space Administration (NASA) can help provide simultaneous constraints on more of these properties in the not-too-distant future.



Figure 1.12: The W. M. Keck Observatory with adjacent telescopes. Photo taken on February 6, 2026; photo credit: me.

1.4 Observations

The data I analyzed for my thesis consist of telescope observations of the Galilean satellites during the eclipse phase of their orbits when they transited through Jupiter’s shadow. Figure 4.1 in Chapter 4 shows an example of the orientation of the Solar System for the observations we took of Ganymede in eclipse on 2021-06-08. Many people helped take these observations over the years, including Mike Brown, Maria Camarca and Katherine de Kleer from Caltech and Patrick Lierle, Emma Lovett, Luke Moore, and Carl Schmidt from Boston University. We made most of the observations from our homes in California and/or Massachusetts, but on one occasion in early February 2026 Katherine, Carl and I traveled to the W. M. Keck Observatory headquarters in Waimea² to observe a Callisto eclipse in person.

1.4.1 The W. M. Keck Observatory and the Keck I Telescope

We made all of the observations using the Keck I telescope (see Figure 1.12), which is a part of the W. M. Keck Observatory at the summit of Maunakea on the (big) island of Hawai‘i. Figure A.1 in Appendix A shows a topographical map of the summit area detailing the location of the telescopes which make up the Maunakea Observatories complex. The W. M. Keck Observatory consists of two identical altitude-azimuth telescopes (Keck I and Keck II), separated from each other by about 85 m; see Figure 1.13

²The United States Postal Service calls it Kamuela because of the town of Waimea on Kauai; this caused me a lot of confusion when trying to look up the weather forecast.

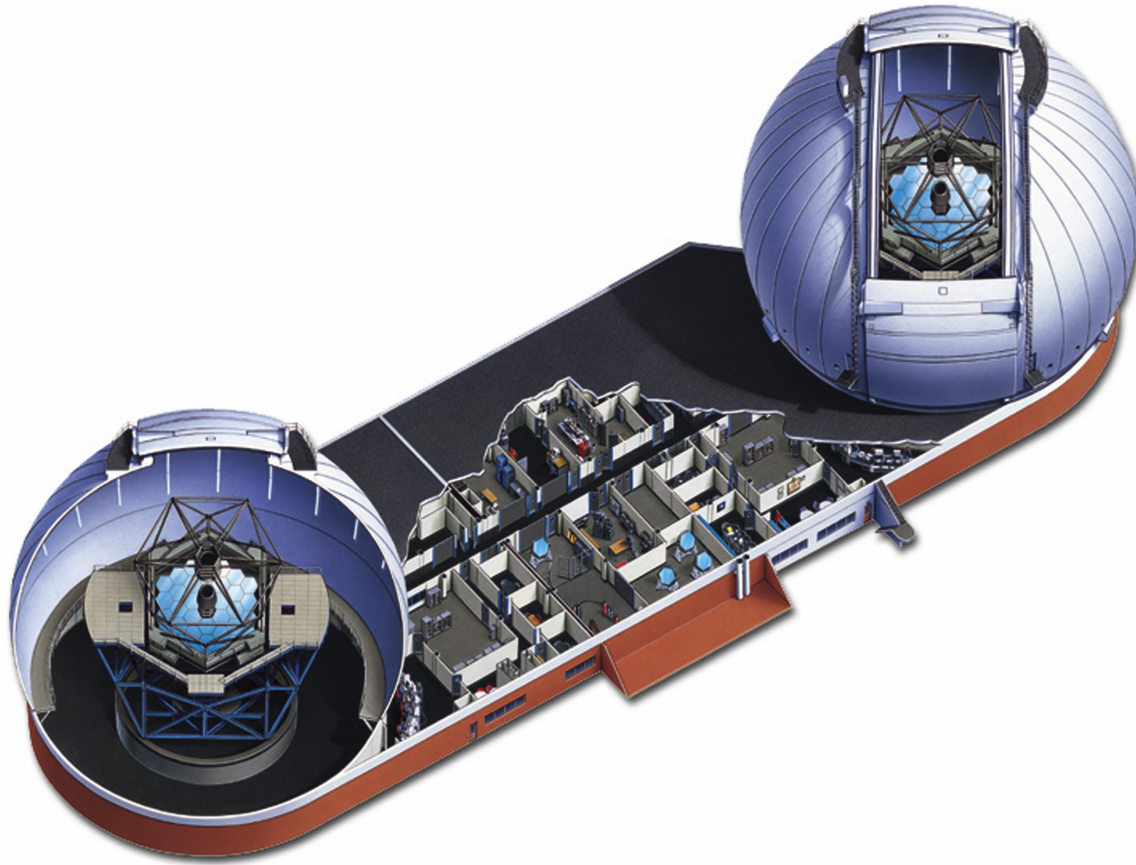


Figure 1.13: Cutaway diagram of the W. M. Keck Observatory showing the Keck I (right) and Keck II (left) telescopes within their respective domes and the support facility connecting them. Image credit: W. M. Keck Observatory/Tom Connell.

for a cutaway graphic of the facility showing the scale of the telescopes within their respective domes and the support facility connecting them.

Keck I achieved first light on November 24, 1990, while Keck II achieved first light six years later on October 23, 1996. Keck I science operations commenced in May of 1993. NASA's Infrared Telescope Facility (IRTF) reports the precise coordinates of the Keck I telescope are latitude $19^{\circ}49'33.40757''$ N, longitude $-155^{\circ}28'28.98665''$ E at an altitude of 4159.58 m (13 646.92 ft) above sea level, based on an aerial survey made on September 25, 1996.³ I compiled the following technical information about the observatory primarily from the Keck Telescope and Facility Instrument Guide (W. M. Keck Observatory, 2002).

Each telescope has a 10.95 m corner-to-corner hexagonal primary mirror with a 17.5 m focal length composed of 36 smaller hexagonal mirror segments. Each of the

³<https://irtfweb.ifa.hawaii.edu/observing/telescopeCoordinates.php>

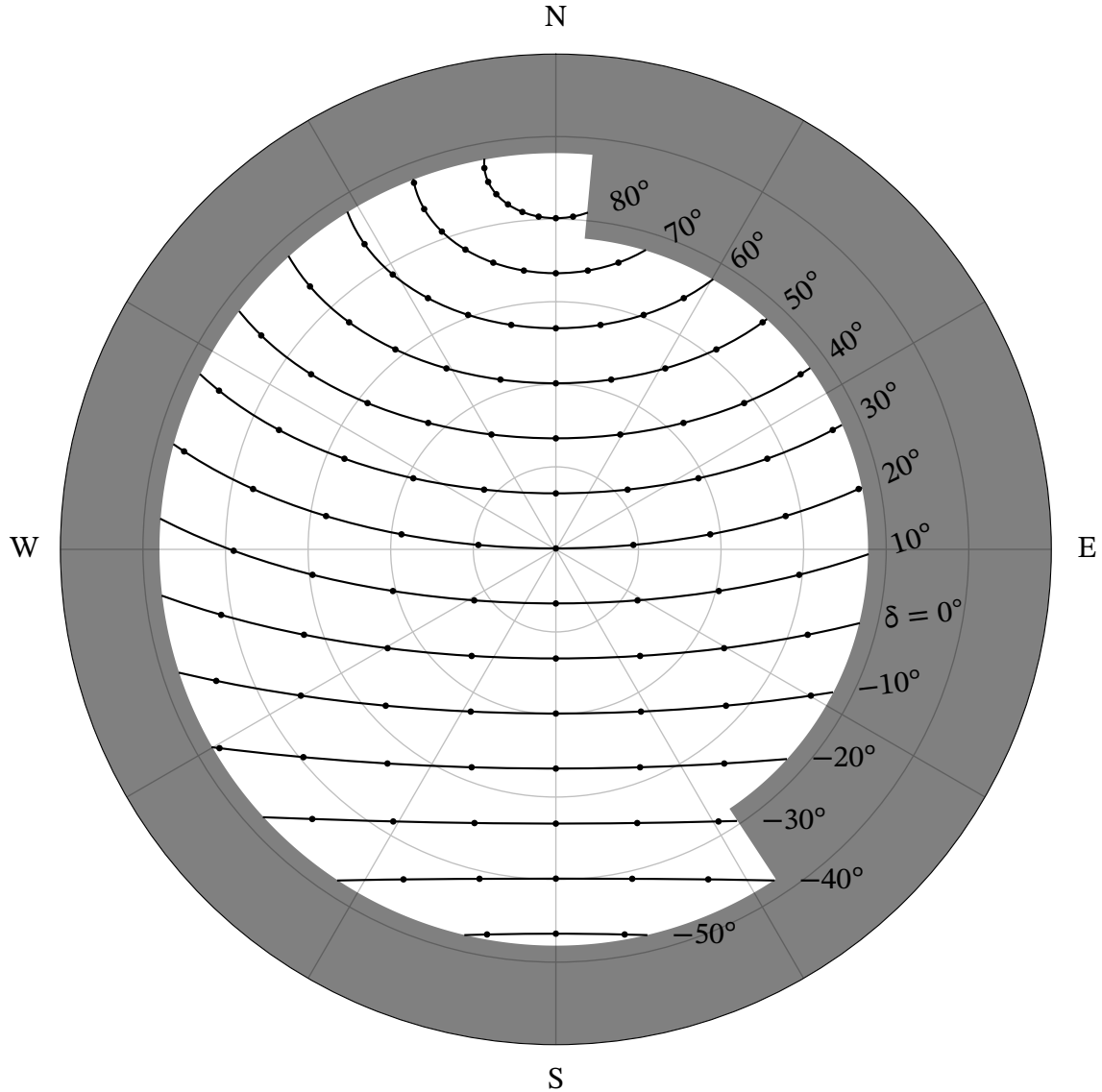


Figure 1.14: Keck I pointing limits. The dark gray shaded region shows the altitude/azimuth combinations excluded by the bottom shutter or Nasmyth deck. Black lines show J2000 declinations every 10° (annotated to the right of each path); points on each line show the hour angle in 1 hr increments. The gray polar grid in the background shows elevation in 15° increments and azimuth in 30° increments. Based on Figure 1 in the Keck Telescope and Facility Instrument Guide (W. M. Keck Observatory, 2002).

segments has a corner-to-corner width of 1.8 m, a thickness of 7.5 cm and weighs approximately 500 kg. The hexagonal mirror is equivalent to a circular mirror with a diameter of 9.96 m. The total weight of each telescope is around 300 tons.

The telescopes have low-elevation pointing limits due to the presence of the Nasmyth deck between the two domes and the dome shutters. For Keck I, the Nasmyth platform



Figure 1.15: A photo of what I am pretty sure is the room containing HIRES. Photo taken on February 6, 2026; photo credit: me.

limits pointing to elevations above 33.3° for azimuths between 5.3° and 146.2° . At all other azimuths the bottom shutter vignettes at elevations below 18° . The zenith blind spot, which arises due to mechanical limitations from the altitude-azimuth design, is a circle with a radius of approximately 0.5° . Figure 1.14 shows the declinations, hour angles and pointing limits of the Keck I telescope. Jupiter more-or-less falls somewhere along the ecliptic, so its declination varies between $\pm 23^\circ$ or so, and as a result if an eclipse occurs near the time the Jupiter system rises, the 33.3° Nasmyth limit will delay the time at which we can begin to observe it.

1.4.2 The High Resolution Echelle Spectrometer (HIRES)

The scientific instrument we used for our observations was the High Resolution Echelle Spectrometer (HIRES; Vogt et al., 1994), a room-sized, in-plane optical wavelength echelle spectrograph with grating cross-dispersion permanently mounted on the right Nasmyth platform of the Keck I telescope (see Figure 1.15). It has a spectral range from the atmospheric UV cutoff near 300 nm to about 1000 nm. It was originally conceived in

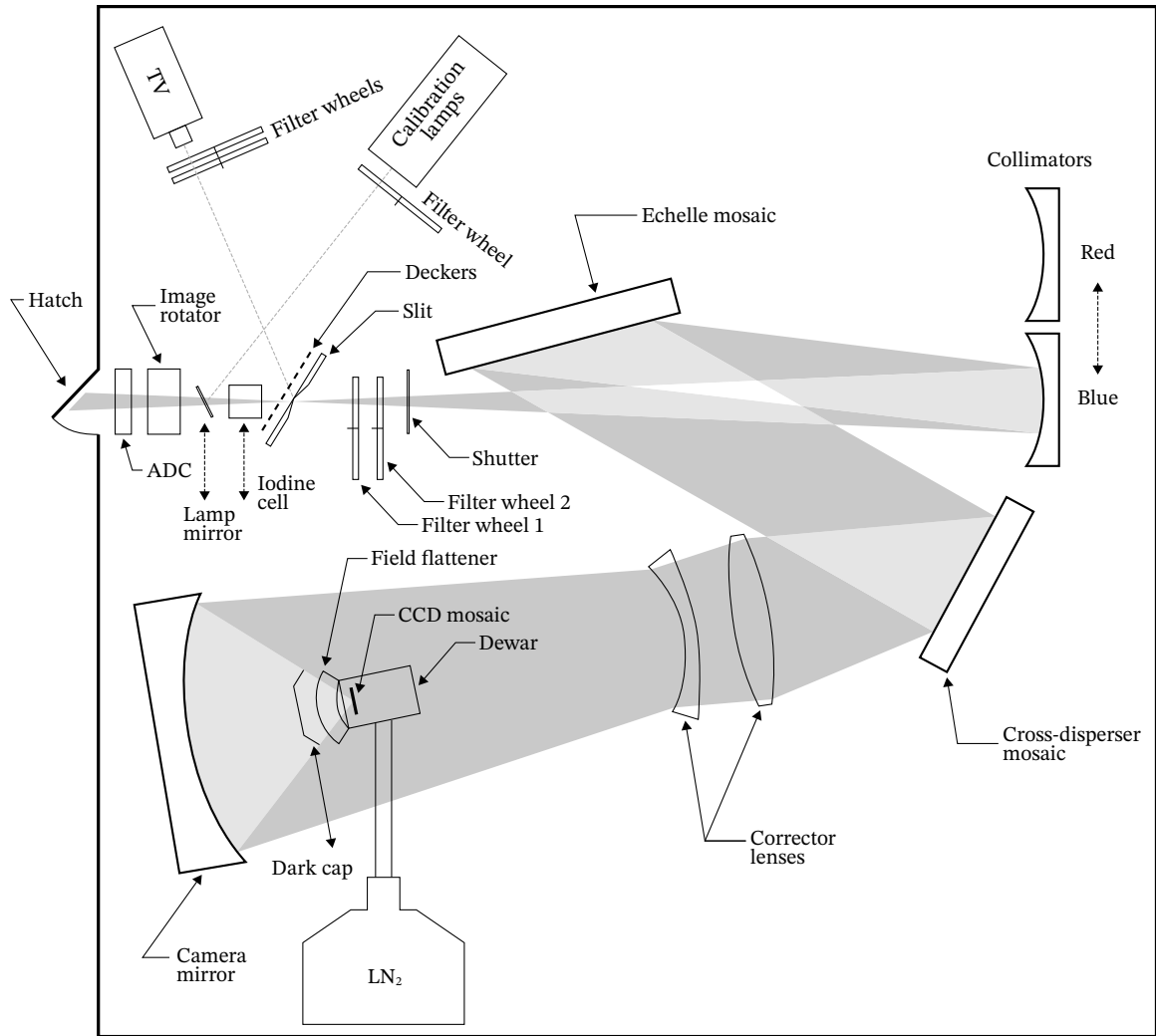


Figure 1.16: HIRES optical system schematic (Vogt, 1994). Redrawn by Mitchell Deans.

1987 in response to the call for first-light instruments for the soon-to-open observatory. The project officially began in September 1988 (the year and month of my birth) and achieved first light on July 16, 1993 at a total cost of about \$4.1 million USD. I scraped together the following technical summary of HIRES based on details of the mechanical design of HIRES (Osborne et al., 1993), the original instrument paper (Vogt et al., 1994), the original user's manual (Vogt, 1994), the Keck Telescope and Facility Instrument Guide (W. M. Keck Observatory, 2002) and the most recent edition of the HIRES instrument website (Doppmann et al., 2025). Figures A.2 and A.3 in Appendix A shows a schematic detailing the relative scale of the telescope and the size and location of the HIRES instrument.

Figure 1.16 provides a schematic of the HIRES light path. After reflecting off of the $f/15$ secondary and the flat tertiary mirror, the light beam enters the instrument

through a hatch and converges on the slit placed at the Nasmyth focus. Between the hatch and the slit it apparently passes through an Atmospheric Dispersion Compensator (ADC; which accounts for slit losses when the slit angle is not set to the parallactic angle), though it was not installed at the instrument commissioning and I have never explicitly activated it nor do I know if it was ever installed. The light beam then passes through an image rotator which allows for the slit to be oriented at arbitrary angles on the sky. It then optionally passes through an iodine cell (which allows for high-precision Doppler shift measurements) and finally the decker plate. A guider camera (labeled “TV” in Figure 1.16) is pointed at the slit plane to allow for precise object targeting. There are also quartz flat lamps and a thorium-argon (ThAr) arc lamp which can be directed toward the slit through the placement of a mirror into the light path.

HIRES has a variable slit width and a moveable decker plate which gives an observer the option to choose from 20 different apertures with varying lengths and widths. We initially took spectra using the D3 slit which has an angular size on the sky of $1.722'' \times 7''$. However, due to the strong scattered-light continuum from Jupiter, we eventually changed to using the longer D4 slit which has an angular size on the sky of $1.722'' \times 14''$. This provided more signal with which to characterize and remove the scattered-light background from the monochromatic auroral emissions. The slit width of $1.722''$ provides a resolving power $R = \lambda/\Delta\lambda$ of about 24 000. Figure 1.19 shows the sizes of these two slits on the sky during the Ganymede eclipse on 2021-06-08.

After the decker/slit, the light passes through two filter wheels before encountering the shutter. Beyond the shutter the light encounters the primary optical components: first, a collimator optimized for observations at the shorter “blue” end or the longer “red” end of the wavelength range, producing a light beam with a diameter of 12 in. The collimated beam then encounters the 12 in $\times$ 48 in echelle grating mosaic with 52.68 grooves mm^{-1} and a 70.5° blaze angle.

The dispersed beam reflects off of the echelle grating towards the 16 in $\times$ 24 in cross disperser mosaic. Originally, HIRES was only supposed to have one cross disperser, designed to be used in the first order for “red” and the second order for “blue”. This original cross disperser was specified with 250 grooves mm^{-1} , a blaze angle of 5.3° and a first-order peak of 700 nm and a second-order peak of 350 nm. However, the grating as delivered had a blaze of 4.3° which changed the first order blaze peak from 700 to 560 nm and the second order blaze peak at from 350 to 280 nm. As a result, the observatory ordered a second cross disperser optimized for second order “blue” observations with 400 grooves mm^{-1} , a blaze peak at 380 nm (Greg Doppmann, private communication).

After cross dispersion, the light beam passes through the “camera” optics, which

Table 1.4: HIRES mosaic detector properties.

Model	CCID20
Manufacturer	MIT/Lincoln Labs
Dimensions:	
Physical	30.72×61.44 mm
Pixel	2048×4096 pix
Pixel size	15×15 μ m
Plate scale	$0.179'' \times 0.119''$ pix ⁻¹
Layout	3×1 mosaic, 6144×4096 pix
Material	Silicon (Si)
Readout time	~1 min (no binning) ~40 s (2×1 binning) ~30 s (3×1 binning) ~24 s (2×2 binning)
Read noise	2.8, 3.1 and 3.1 e ⁻
Dark current	$2 \text{ e}^- \text{ pix}^{-1} \text{ hr}^{-1}$
Operating temperature	-130 °C
Gain:	
Low	$1.9, 2.2$ and $2.2 \text{ e}^- \text{ DN}^{-1}$
High	$0.78, 0.86$ and $0.84 \text{ e}^- \text{ DN}^{-1}$
Full well capacity	65 535 DN
Linearity	39 800, 37 900 and 38 400 DN

Note. A list of three values refer to the blue, green and red CCDs, respectively.

include two corrector lenses and the spherical $f/0.76$ camera mirror. After reflecting off of the camera mirror, the light beam passes through a field-flattening lens before finally falling onto the charge-coupled device (CCD) sensor. A beam-blocking dark cap can be placed between the camera mirror and field flattener to take dark frames.

The original CCD was a single engineering-grade 2048×2048 Tektronix 2048EB2 with $24 \mu\text{m}$ pixels. Despite its \$100,000 USD price tag, it contained a large felt tip pen mark near the center which had to be avoided by observers. Fortunately, a new three-CCD mosaic replaced this detector in 2004, providing both increased spectral and spatial resolution, larger wavelength sampling for a single instrument setting, better response at wavelengths less than 380 nm, lower readout noise, faster readout time and no felt tip pen marks!

Distortions introduced to the light beam by the optics cause the angular projection of the pixels on the sky to be rectangular rather than square; along the spectral axis the plate scale is $0.179'' \text{ pix}^{-1}$ while along the spatial axis the plate scale is $0.119'' \text{ pix}^{-1}$.

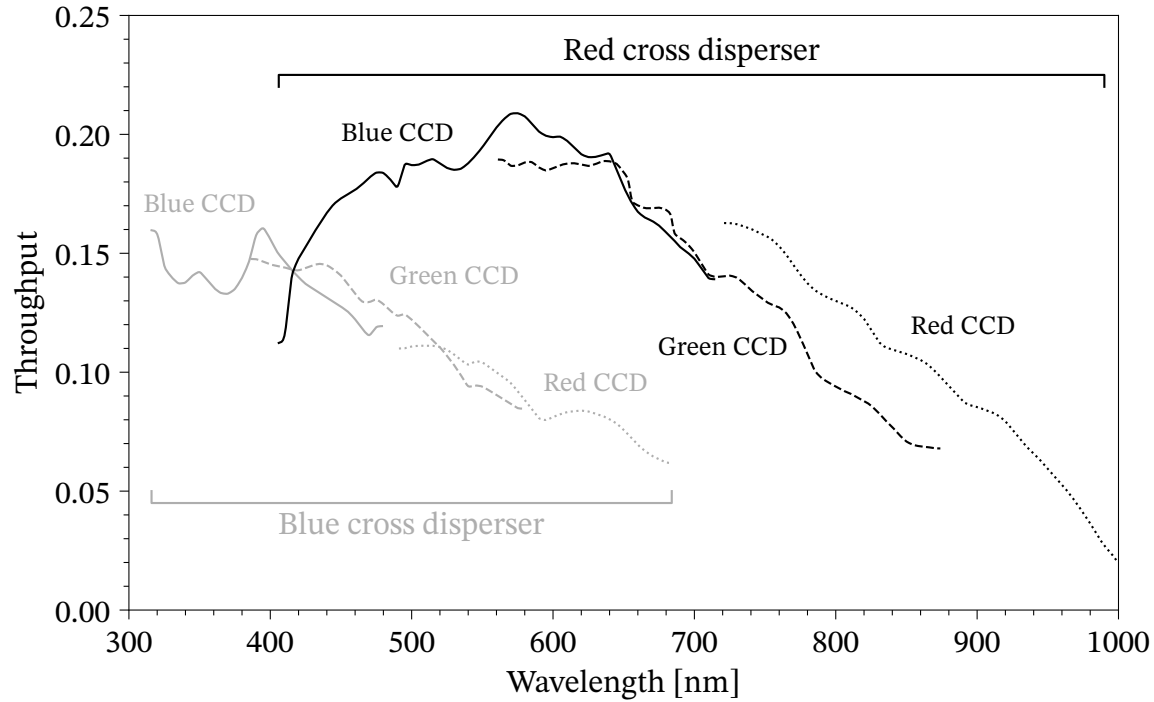


Figure 1.17: HIRES throughput measured by the observatory in late 2005. Line styles differentiate the blue (solid), green (dashed) and red (dotted) CCDs. Colors differentiate the blue (gray) and red (black) cross dispersers. Description of the observations and throughput calibration available from <https://www2.keck.hawaii.edu/inst/hires/throughput.html> (accessed April 8, 2026).

Table 1.4 lists key properties of the current mosaic detectors and Figure 1.17 shows the throughput from the primary mirror through to the CCDs measured shortly after the commissioning of the new detector mosaic.

The angular spacing between the orders depends on wavelength and is smaller for shorter wavelengths. Figure 1.18 shows an example of a HIRES mosaic detector image of Io in eclipse taken on 2024-09-12 UTC. With the D4 slit, some orders even overlap on the blue detector. For the red cross disperser, the order-to-order separation is about $4''$ at 300 nm, $11''$ at 500 nm, $21''$ at 700 nm and $42''$ at 1000 nm. For the blue cross disperser, the order-to-order separation is about $8''$ at 300 nm and $21''$ at 500 nm.

1.4.3 Observing Methodology and Procedures

Most telescope observations involve using either the target object (if it is effectively a point source) or field stars to maintain telescope tracking as the Earth rotates. Unfortunately, the nature of our observations provides two hurdles to this type of tracking:

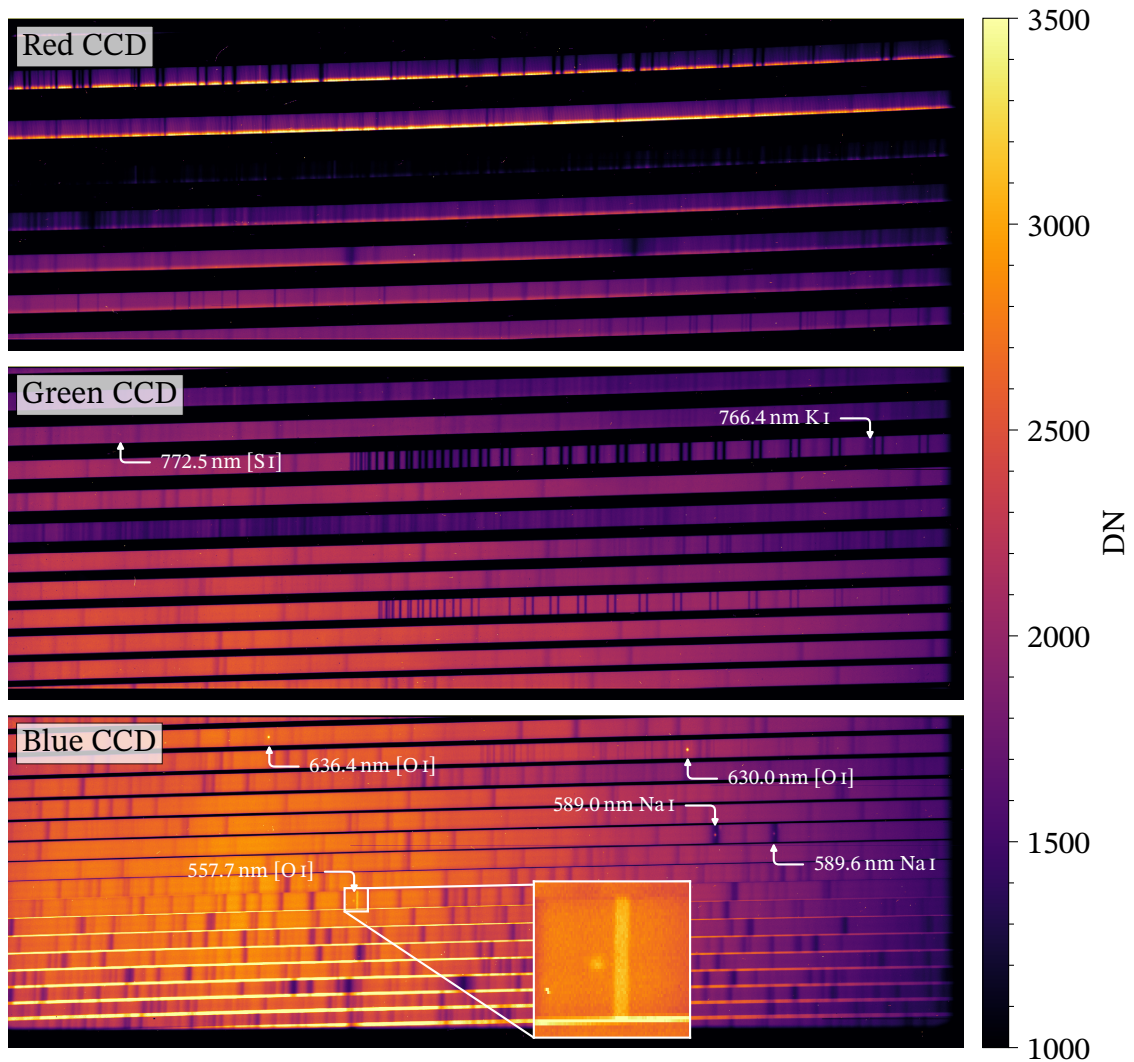


Figure 1.18: Example HIRES mosaic detector image of Io in eclipse on 2024-09-12 at 14:05:46 UTC. Each bright horizontal stripe is a different spectral order spanning different wavelengths from left to right. Annotations point to the locations of the brightest emissions. The inset axis zooms in on the 557.7 nm [O I] emission showing the slit-filling telluric emission line (the bright vertical stripe), Io's Doppler-shifted emission (the bright circle to the left side) and the order overlap due to the use of the long D4 slit (the bright horizontal stripe at the bottom). We used 3×1 spatial/spectral binning, so each bin has an angular size on the sky of $0.357'' \times 0.179''$; I consequently set the pixel aspect ratio of the images to 2 so that each bin maps physically to its aspect ratio on the sky.

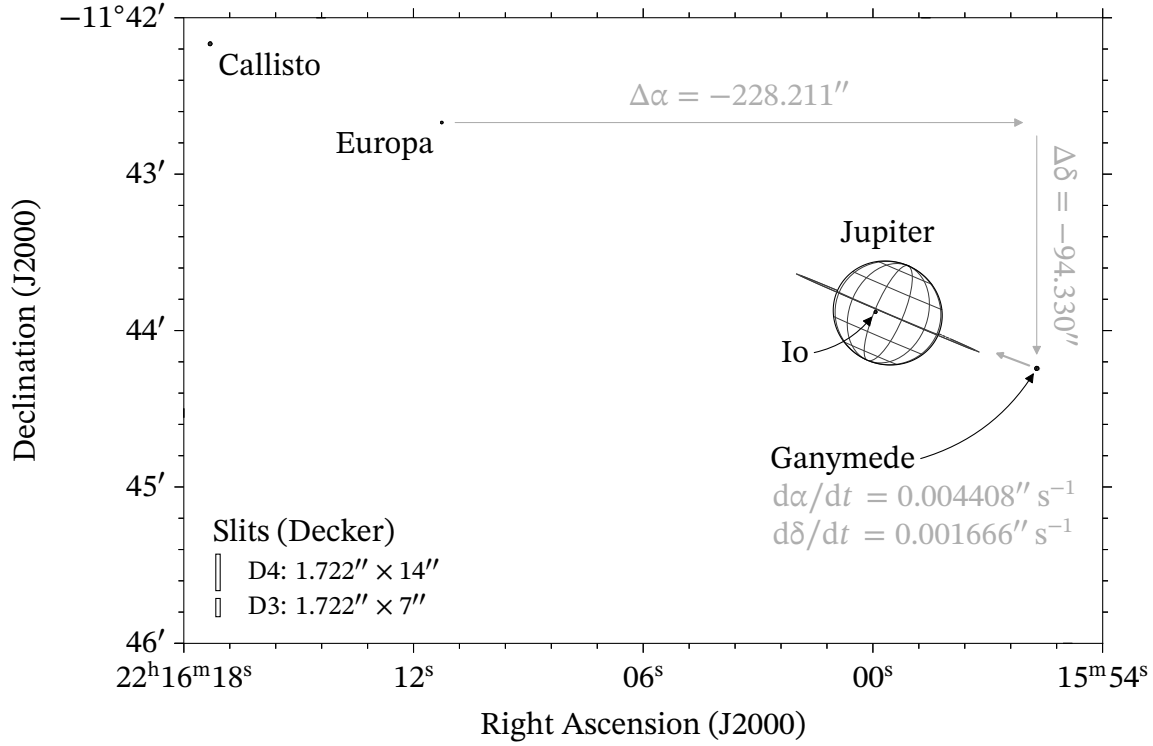


Figure 1.19: Example HIRES pointing and tracking for our observations of the eclipse of Ganymede on 2021-06-08 at the eclipse midpoint time of 14:31 UTC. The displayed field of view is $6' \times 4'$. Annotations with gray horizontal/vertical arrows illustrate the instantaneous angular offsets in right ascension (α) and declination (δ) between Europa (the sunlit guide satellite) Ganymede (eclipsed in Jupiter's shadow). The gray arrow pointing from Ganymede toward Jupiter illustrates its instantaneous angular velocity at the annotated rates. At this time, Io is transiting Jupiter. I've also drawn the on-sky sizes of the D3 and D4 slits we used over the observing campaign in the lower left corner; we typically rotated them to Jupiter's north pole angle.

1. The eclipsed satellite is in Jupiter's shadow and is therefore completely invisible to the guide camera, so tracking on the target object is not an option, and
2. Jupiter (and its satellites) move at non-sidereal rates across the sky which are significant even on five-minute timescales, so tracking on field stars will not keep the slit placed on the eclipsed satellite.

As a result, we had to use a more complicated method. We first centered the slit on a nearby sunlit Galilean satellite, which we referred to as the “guide satellite.” We then used the SPICE (Spacecraft Planet Instrument C-matrix Events) ancillary information system (Acton, 1996) to calculate both the instantaneous angular offset from the guide satellite to the eclipsed satellite and the eclipsed satellite's angular velocity across the

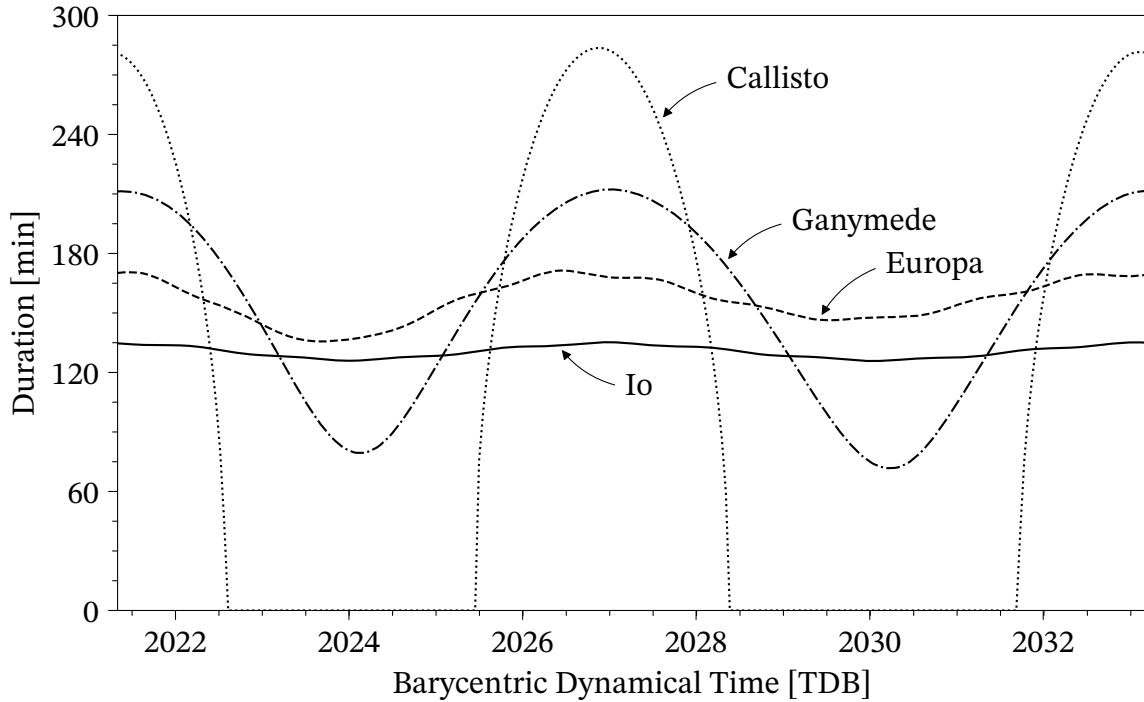


Figure 1.20: Durations of Galilean satellite umbral eclipses over one Jovian year. Timescale starts at the Jovian equinox on May 2, 2021 at 07:43:31 TDB and concludes one Jovian year later on the equinox which occurs on March 12, 2033 at 17:34:20 TDB. Calculated with SPICE ancillary information system (Acton, 1996).

sky. After manually offsetting the telescope to the eclipsed satellite's predicted position, we had the telescope track at its calculated non-sidereal rate. We took a five-minute exposure, then offset the telescope back to the guide satellite using equivalent SPICE calculations. We took a fiducial exposure of the sunlit satellite to check for drift along the slit, checking for how well the telescope tracked the eclipsed satellite. We repeated this sequence until the eclipse ended, either from the satellite re-emerging into sunlight, occulting behind Jupiter, or sunrise on Maunakea. Figure 1.19 illustrates this on-sky observing procedure at the midpoint of the Ganymede eclipse on 2021-06-08 UTC.

1.4.4 Eclipses

You might expect each satellite to enter eclipse once per synodic orbit. In fact, I said as much in the abstract. Well, this is true for Io, Europa and Ganymede, but Callisto orbits far enough from Jupiter that due to the slight tilt of the Jupiter system relative to its orbital plane it completely misses Jupiter's shadow for more than half of the Jovian year. I calculated the durations for each satellite over the course of one Jovian year, beginning on May 2, 2021 at 07:43:31 TDB and concluding one Jovian year later on the March 12,

2033 at 17:34:20 TDB equinox. The duration of Io's eclipses varied between 02:05:46 and 02:15:16; Europa's between 02:15:38 and 02:51:24, Ganymede's between 01:11:45 and 03:32:17 and Callisto's between 00:00:00 and 04:43:35. Figure 1.20 shows a plot of the durations over the same time period.

Using the SPICE ancillary information system (Acton, 1996), I found a total of 2448 eclipses of Io, 1219 eclipses of Europa, 605 eclipses of Ganymede and 123 eclipses of Callisto between the Jovian equinoxes on May 2, 2021 at 07:43:31 TDB and March 12, 2033 at 17:34:20 TDB. However, not all of them will be visible from Maunakea during astronomical twilight or night (solar elevation less than -12°). Applying this constraint, I determined that 1250 (51.1%) of the Io eclipses, 645 (52.9%) of the Europa eclipses, 310 (51.2%) of the Ganymede eclipses and 76 (61.8%) of the Callisto eclipses were at least partially observable from Maunakea.

Further, not all of these have a sufficient relative velocity to Doppler shift the satellite emissions off of Earth airglow lines or absorption features; this is particularly important for the 557.7 and 630.0 nm [O I] telluric emission lines (for example, see the inset axis in Figure 1.18) and the 589.0 and 589.6 nm Na I doublet telluric absorptions. The non-relativistic Doppler effect is

$$\lambda = \lambda_0 \left(1 + \frac{v}{c_0} \right), \quad (1.16)$$

where λ is the Doppler-shifted wavelength, v is the velocity of the emitter relative to the observer⁴, λ_0 is the rest wavelength and c_0 is the vacuum speed of light. The change in wavelength $\Delta\lambda$ is the difference between the Doppler-shifted and rest wavelengths $\lambda - \lambda_0$, which simplifies to

$$\Delta\lambda = \lambda_0 \frac{v}{c}. \quad (1.17)$$

For negative velocities (motion toward an observer), this results in a negative $\Delta\lambda$ and a blue-shifted emission. In contrast, for positive velocities (motion away from an observer), this results in a positive $\Delta\lambda$ and a red-shifted emission. Solving Equation (1.17) for the relative velocity,

$$v = c_0 \left(\frac{\Delta\lambda}{\lambda_0} \right). \quad (1.18)$$

Figure 1.21 shows the relative velocities necessary to shift the satellite emissions by 1.5 D3/D4 slit widths, or about 15 spectral pixels. A relative velocity (either toward or away from the observer) greater than about 21 km s^{-1} is sufficient to Doppler shift all emissions away from the equivalent rest wavelength and any Earth airglow lines for the D3 or D4 decker slit width of $1.722''$ (though we often used velocities as low as about

⁴Within the SPICE framework, a relative velocity toward an observer is negative.

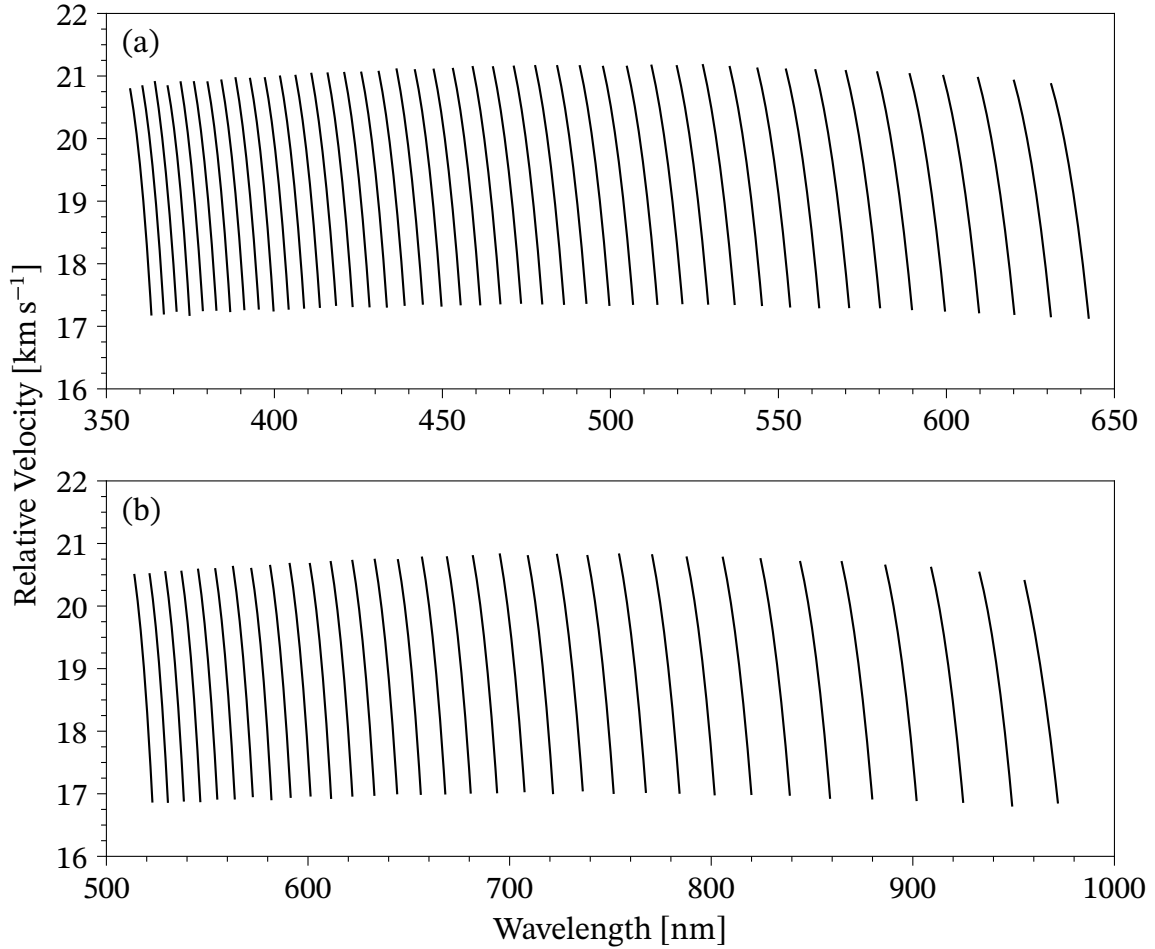


Figure 1.21: Relative velocity necessary to shift wavelength by ± 15 HIRES spectral pixels. Each line represents a different HIRES order. (a) shows the velocities for a typical setup of the HIRESb cross disperser. (b) shows the velocities for a typical setup of the HIRESr cross disperser.

18 km s⁻¹). This velocity restriction reduces the number of observable eclipses to 779 (31.8%) for Io, 422 (34.6%) for Europa, 224 (37.0%) for Ganymede and 47 (38.2%) for Callisto.

1.4.5 Data Overview

Table 1.5 gives an overview of the Galilean satellite eclipses we observed since May 2021, sorted by date. I excluded five nights from my analysis due to either non-photometric observing conditions (usually bad weather) or other systematic problems like detector artifacts or diffraction spikes by nearby satellites.

Table 1.5: HIRES observations summary.

Date [UTC]	Satellite Target		Cross Disp.	Notes
	Eclipsed	Guide		
2021-05-20	Europa	Io	HIRESr	Swapped guides after a few integrations because Io became occulted by Jupiter
2021-06-08	Ganymede	Io, Europa	HIRESr	
2021-06-21	Europa	Io	HIRESr	
2021-07-04	Callisto	Europa	HIRESr	Non-photometric
2021-07-16	Europa	Io	HIRESr	
2021-09-26	Callisto	Europa	HIRESr	
2021-10-01	Ganymede	Io	HIRESr	Non-photometric
2022-08-18	Europa	Io	HIRESr	Non-photometric
2022-11-24	Io	Ganymede	HIRESr	
2022-12-05	Ganymede	Io	HIRESr	
2023-08-09	Io	Europa	HIRESb	Blue cross-disperser!
2023-08-12	Europa	Io	HIRESr	Detector artifacts
2023-08-25	Io	Europa	HIRESr	
2024-09-12	Io	Europa	HIRESr	
2024-09-17	Ganymede	Europa	HIRESr	Detector artifacts
2024-10-05	Io	Europa	HIRESr	
2024-10-08	Europa	Ganymede	HIRESr	
2024-10-21	Io	Europa	HIRESr	Detector artifacts and diffraction spikes from Io
2024-10-30	Ganymede	Europa	HIRESr	
2024-11-02	Europa	Callisto	HIRESr	
2025-02-06	Europa	Ganymede	HIRESr	Observed after the publication of my Europa paper
2025-03-03	Europa	Ganymede	HIRESr	
2025-11-02	Io	Ganymede	HIRESr	
2025-11-10	Europa	Ganymede	HIRESr	Observed after the publication of my Europa paper
2025-11-29	Callisto	Io	HIRESr	
2026-02-04	Callisto	Europa	HIRESr	
2026-04-05	Europa	Io	HIRESr	Observed after the publication of my Europa paper

Note. Dates in **bold** font indicate data not used in this thesis.

1.5 Housekeeping

Before I discuss our emission model, I think it's probably important to go over the physical brightness units we use and the esoteric notation used to describe the auroral transitions.

1.5.1 The Rayleigh

Auroral brightnesses are often reported in a unit called the “rayleigh,” abbreviated symbolically as “R.” You’ll see a definition of this unit pop up in the chapters on Io, Europa and Ganymede (by the time I wrote my Callisto paper, I became tired of including it). The rayleigh is a photon irradiance unit first defined by Hunten et al. (1956) to describe apparent surface brightness. Under their definition, airglow brightnesses on Earth at the zenith are typically a few hundred rayleighs while aurora can vary between 1 kR and 1 MR. The unit and its uses were further refined during a session of the Fall Meeting of the American Geophysical Union, held at San Francisco, California in December of 1975 in memory of the unit’s namesake, Robert John Strutt, 4th Baron Rayleigh FRS (Baker et al., 1976).

In SI units, the rayleigh is defined as

$$1 \text{ R} \equiv 10^{10} \text{ ph s}^{-1} \text{ m}^{-2}. \quad (1.19)$$

Most observations of photon flux involve collecting over some solid angle; in that case, the rayleigh is defined in such a way as to integrate over 4π sr and convert to the equivalent of a column emission rate

$$1 \text{ R} \equiv \frac{10^{10}}{4\pi} \text{ ph s}^{-1} \text{ m}^{-2} \text{ sr}^{-1}. \quad (1.20)$$

Often these brightnesses are written in the form $4\pi B = \dots \text{ R}$ to indicate the brightness has been integrated over all solid angles. Either way, the base units always end up at $\text{ph s}^{-1} \text{ m}^{-2}$. I have been using data with this unit for the better part of 10 years now, and I still occasionally find myself perplexed by it despite its apparent simplicity.

1.5.2 Notation

At the icy satellites Europa, Ganymede and Callisto, we primarily looked for emissions from atomic oxygen (though we also looked in vain for $\text{H}\alpha$). At Io we additionally looked for emissions from O^+ , Na, S, S^+ and K, though we did not model their emissions or analyze them in as great of detail. Consequently, to keep things brief, I decided to focus on just atomic oxygen in this section. Appendix B contains additional energy level diagrams for other relevant atoms.

1.5.2.1 Aurora on the Quantum Scale

The emission of the auroral photon we observed ultimately requires the excitation of an atom. This can come from dissociative excitation of a molecule by an electron collision (e.g., an electron collides with SO_2 , breaks the molecule into SO and O, and imparts extra energy to the O atom), or by direct collision of an electron with an existing O atom. Physically, the collision transfers kinetic energy and angular momentum to the atom, causing its electrons to change to a higher energy configuration. These configurations are unstable, and eventually the configuration will return to the stable, lowest-energy ground configuration, emitting a photon with a wavelength λ equal to the energy difference ΔE between the levels

$$\Delta E = \frac{hc}{\lambda}, \quad (1.21)$$

where h is the Planck constant and c is the vacuum speed of light (Mohr et al., 2025). The transition to a lower energy configuration via photon emission changes the angular momentum of the atom because the photon itself carries away at least one $\hbar$ worth of angular momentum with it (the intrinsic angular momentum from its spin).

A term symbol is a spectroscopic notation used to describe the total electron angular momentum of an atom. Notationally, they are written as

$$^{2S+1}L_J^\pi \quad (1.22)$$

where S is the total electron spin quantum number ($1/2$ times the number of unpaired electrons following the Pauli exclusion principle), L is the total electron orbital angular momentum (the sum across all populated orbitals of ℓ times the number of electrons in the orbital m_ℓ), J is the total electron angular momentum quantum number (spin and orbital) and π is the parity. The term $2S + 1$ is called the “spin multiplicity” and its value is equal to the total number of different possible spatial orientations for an atom’s total electron spin. Values of L are written in spectroscopic notation, where each integer value of L corresponds to a different upright capital Latin letter: $S = 0$, $P = 1$, $D = 2$, etc. For even parity π is blank, for odd parity it is indicated by a superscript upright Latin lowercase letter “o,” though some people use a degree symbol ($^\circ$) for reasons that remain unknown to me.

There are three different types of transitions commonly observed in auroral emission: allowed electric dipole transitions (E1), forbidden electric quadrupole transitions (E2) and forbidden magnetic dipole transitions (M1). The use of the terms “allowed” and “forbidden” is unfortunate, because really they are driven by probability; forbidden

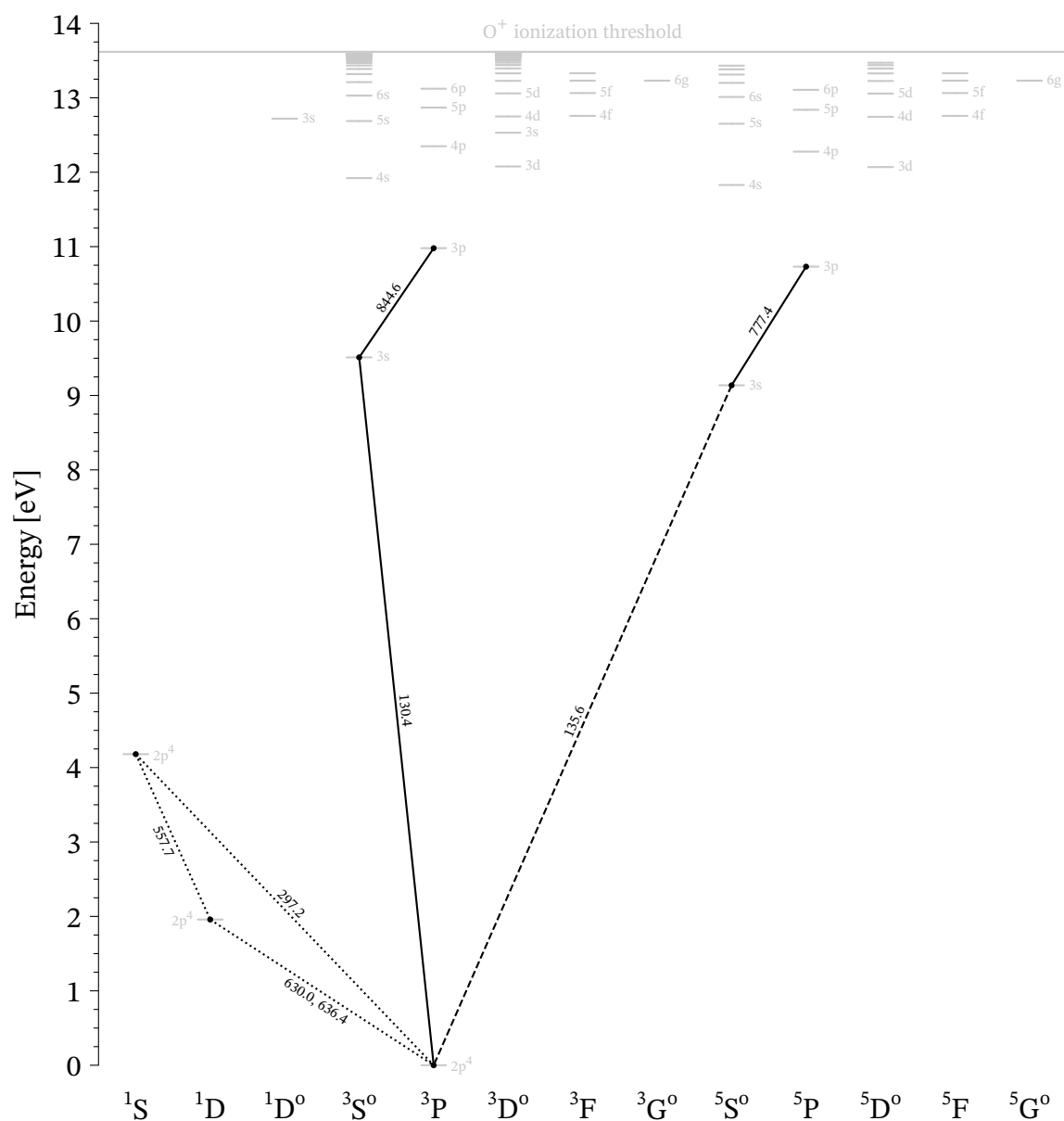


Figure 1.22: Partial energy level diagram for neutral oxygen (O). Wavelengths have units of nanometers (in air above 200 nm and in vacuum at and below 200 nm). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions. Table 1.6 gives details for the transitions shown.

Table 1.6: Auroral transitions in neutral oxygen (O).

Electron Configuration		Type	A_{ki} [s ⁻¹]	Wavelength [nm]		Energy Level [eV]	
Initial (<i>k</i>)	Final (<i>i</i>)			Air	Vacuum	Initial E_k	Final E_i
$2p^3(^4S^o)3s^3S_1^o$	$2p^4^3P_2$		3.41×10^8		130.2168	9.5213638	0.0
$2p^3(^4S^o)3s^3S_1^o$	$2p^4^3P_1$		2.03×10^8		130.4858	9.5213638	0.0196224
$2p^3(^4S^o)3s^3S_1^o$	$2p^4^3P_0$		6.76×10^7		130.6029	9.5213638	0.0281416
$2p^3(^4S^o)3s^5S_2^o$	$2p^4^3P_2$		4.20×10^3		135.5598	9.1460911	0.0
$2p^3(^4S^o)3s^5S_2^o$	$2p^4^3P_1$		1.36×10^3		135.8512	9.1460911	0.0196224
$2p^4^1S_0$	$2p^4^3P_1$	M1	7.54×10^{-2}	297.2286	297.3154	4.1897463	0.0196224
$2p^4^1S_0$	$2p^4^1D_2$	E2	1.26	557.7339	557.8887	4.1897463	1.9673642
$2p^4^1D_2$	$2p^4^3P_2$	M1	5.63×10^{-3}	630.0304	630.2046	1.9673642	0.0
		E2	2.11×10^{-5}				
$2p^4^1D_2$	$2p^4^3P_1$	M1	1.82×10^{-3}	636.3776	636.5536	1.9673642	0.0196224
		E2	3.39×10^{-6}				
$2p^3(^4S^o)3p^5P_3$	$2p^3(^4S^o)3s^5S_2^o$		3.69×10^7	777.1944	777.4083	10.7409314	9.1460911
$2p^3(^4S^o)3p^5P_2$	$2p^3(^4S^o)3s^5S_2^o$		3.69×10^7	777.4166	777.6305	10.7404756	9.1460911
$2p^3(^4S^o)3p^5P_1$	$2p^3(^4S^o)3s^5S_2^o$		3.69×10^7	777.5388	777.7527	10.7402250	9.1460911
$2p^3(^4S^o)3p^3P_0$	$2p^3(^4S^o)3s^3S_1^o$		3.22×10^7	844.6247	844.8568	10.9888811	9.5213638
$2p^3(^4S^o)3p^3P_2$	$2p^3(^4S^o)3s^3S_1^o$		3.22×10^7	844.6359	844.8680	10.9888616	9.5213638
$2p^3(^4S^o)3p^3P_1$	$2p^3(^4S^o)3s^3S_1^o$		3.22×10^7	844.6758	844.9079	10.9887923	9.5213638

Notes. Horizontal rules group multiplets. Empty entries in the “Type” column indicate allowed electric dipole (E1) transitions; “M1” indicates forbidden magnetic dipole transitions and “E2” indicates forbidden electric quadrupole transitions. All electron configurations assume the subshell configuration $1s^2 2s^2$. Information compiled from Wiese et al. (1996).

transitions occur, so obviously they are not actually forbidden! There is always some non-zero probability for a transition to take place between any two levels. Normally, the probability of an E1 transition is so high that no other transitions can take place. For E1 transitions, the lifetime between excitation and de-excitation is typically on the order of a few nanoseconds. However, under approximations like LS-coupling, the first order dipole transition probability may be effectively zero, in which case E1 transitions do not take place. Higher order probability terms, while comparatively small, can then occur. But, they do not take place as quickly, with the atom staying the excited state for milliseconds to tens of minutes or more! These are the so-called “forbidden” transitions. Forbidden transitions mostly occur between lower energy levels in an atom where no allowed transitions to lower energy levels otherwise exist. Figure 1.22 shows the energy levels of the oxygen atom and the various transitions (and their photon wavelengths) that have been observed from the Galilean satellites in both the ultraviolet, visible and

near-infrared. These types of diagrams are sometimes called “Grotrian” diagrams after inventor Walter Grotrian. You can see between the two lowest levels ($2p^4\ ^1D$ and $2p^4\ ^1S$) and the ground level ($2p^4\ ^3P$) there are only forbidden transitions.

Requirements for different transition types (E1, E2, M1, etc.) can be described by changes in S , L and J and can be readily found by looking up a summary table for quantum mechanical “selection rules.”⁵ Term symbols are often written following the electron configuration of an atomic state; see Table 1.6 for the electron configurations and total angular momentum of the upper and lower states of each of the oxygen auroral transitions observed between the UV and the near-infrared.

1.5.2.2 Spectroscopic Notation

Astronomers love to write out the ionization state of an atom and transition type together using a notation you will see a lot in the following chapters. This notation uses the conventional chemical symbol for an atom (e.g., H, O, Na) followed by a Roman numeral indicating the ionization state: “I” for the neutral state of an atom, “II” for singly ionized, etc. So, neutral oxygen is “O I” while singly ionized oxygen is “O II”.

The presence or absence of square brackets indicates the transition type: allowed (no brackets), forbidden (left and right brackets) or semi-forbidden (right bracket only). For example, “589.0 nm Na I” would refer to the D_2 allowed transition in neutral sodium, “671.6 nm [S II]” would refer to the 671.6 nm forbidden transition in singly ionized sulfur, and “135.6 nm O I]” would refer to the 135.6 nm semi-forbidden transition in neutral oxygen. Semi-forbidden transitions are still E1 electric dipole transitions, but they violate the selection rule requiring no change in the spin multiplicity. They have microsecond to millisecond lifetimes.

1.6 Auroral Emission Model

We developed an inverse model of auroral emission in order to analyze the brightnesses we observed. This model takes an assumed electron velocity distribution $v(E)$ (see Section 1.3.4 and Equation 1.15) and an emission cross section $\sigma(E)$ and integrates them over all electron energies E to calculate a volumetric photon production rate γ , where

$$\gamma = \int_0^{\infty} E\sigma(E)v(E) dE \quad [\text{ph m}^3 \text{s}^{-1}]. \quad (1.23)$$

⁵I pay \$10 per month to Wikipedia, so may I suggest reviewing the summary table at https://en.wikipedia.org/wiki/Selection_rule.

Because each excitation results in an emitted photon, I've added the photon unit to Equation (1.23). We then calculate photon irradiance from atomic or molecular species s by multiplying the photon production rate γ by the assumed electron number density n_{e^-} and specific atmospheric column density N_s of species s

$$n_{e^-} N_s \gamma \quad [\text{ph s}^{-1} \text{m}^{-2}]. \quad (1.24)$$

This rate can be converted to rayleighs (R) using Equation (1.19). We can then fit the observed brightnesses with simulated emission from different atmospheric components to determine what column densities are necessary to reproduce the observed aurora and even estimate uncertainties on those column densities. As an aside, though I prefer to use SI standard units whenever possible, for the purposes of modeling I begrudgingly used electronvolts (eV) rather than joules (J) for energy and centimeters (cm) rather than meters (m) for cross sections, though I eventually convert to SI units whenever it becomes feasible to do so.

1.6.1 Emission Cross Sections

A cross section is essentially an energy-dependent probability distribution describing either the excitation to a specific atomic state after the impact of an electron (an “excitation cross section”) or the emission of a particular photon after the impact of an electron (an “emission cross section”). Emission cross sections are the most useful in my work because they account for all the transitions that populate the upper state of an auroral transition. However, for practical reasons, many of the forbidden emissions we observe have not had their emission cross sections measured in laboratories, so we have had to make do by approximating emission cross sections with excitation cross sections under the assumption that few emissions populate these states and they are mostly excited directly from the ground state. For instance, to estimate the emission cross section for the 630.0 nm [O I] transition from electron impact on O, I added the excitation cross section for $\text{O}(^3\text{P}_2 \rightarrow ^1\text{S}_0)$ to the excitation cross section for $\text{O}(^3\text{P}_2 \rightarrow ^1\text{D}_2)$, then multiplied by the relative probability of emission of the 630.0 nm photon, calculated by dividing the Einstein A coefficient for the 630.0 nm transition by the total of the Einstein A coefficients for transitions from the $^1\text{D}_2$ state; effectively the branching ratio for the 630.0 nm emission.

In order to extrapolate laboratory measurements of cross sections to arbitrary electron energies, I've fit the cross section measurements with the following partially non-

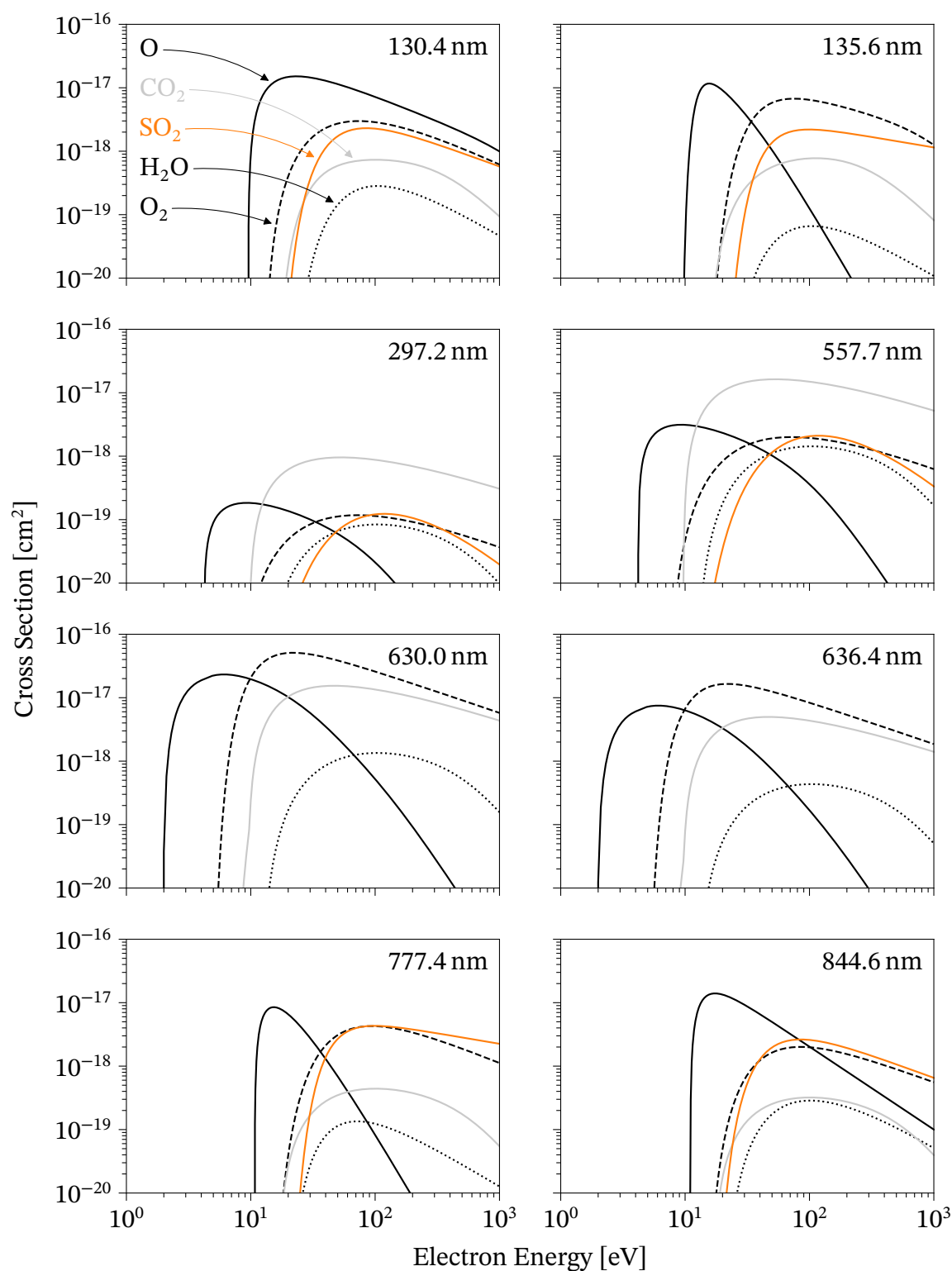


Figure 1.23: Emission cross sections for electron impact on atomic oxygen O and the oxygen-bearing molecules O_2 , H_2O , CO_2 and SO_2 . No emission or excitation cross sections have been measured or theoretically calculated for dissociative electron impact on SO_2 producing the 630.0 or 636.4 nm transitions. Forgive me for the units.

Table 1.7: Auroral emission model cross section sources.

Emission	Parent Atom/Molecule				
	O	O ₂	H ₂ O	CO ₂	SO ₂
121.6 nm Ly α			Makarov et al. (2004)		
130.4 nm O I	Julienne et al. (1976)	Kanik et al. (2003)	Itikawa et al. (2005)	Ajello (1971)	Vatti Palle et al. (2004)
135.6 nm O I]	Laher et al. (1990)^a	Kanik et al. (2003)	Makarov et al. (2004) ^f	Ajello (1971) ^h	Vatti Palle et al. (2004)
297.2 nm [O I]	Laher et al. (1990)^b	LeClair et al. (1993)^b	Kedzierski et al. (1998)^b	LeClair et al. (1994)^b	Kedzierski et al. (2000)^b
486.1 nm H β			Beenakker et al. (1974)		
557.7 nm [O I]	Laher et al. (1990)^b	LeClair et al. (1993)^b	Kedzierski et al. (1998)^b	LeClair et al. (1994)^b	Kedzierski et al. (2000)^b
630.0 nm [O I]	Laher et al. (1990)^c	Chung et al. (1980)^{c,e}	Kedzierski et al. (1998)^{c,g}	Strickland et al. (1969)^{c,i}	
636.4 nm [O I]	Laher et al. (1990)^c	Chung et al. (1980)^{c,e}	Kedzierski et al. (1998)^{c,g}	Strickland et al. (1969)^{c,i}	
656.3 nm H α			Möhlmann et al. (1979)		
777.4 nm O I	Laher et al. (1990)^d	Schulman et al. (1985)	Beenakker et al. (1974)	Zipf (1984)^j	Vatti Palle et al. (2004) ^k
844.6 nm O I	Laher et al. (1990)^d	Schulman et al. (1985)	Beenakker et al. (1974)	Zipf (1984)^j	Vatti Palle et al. (2004) ^k

Notes. **Bold** sources indicate excitation cross sections approximated as emission cross sections. Footnotes provide additional details if the source did not provide a measured emission cross section.

^a Equivalent to the emission cross section according to Johnson et al. (2003).

^b Emission cross sections estimated using Einstein *A* coefficient branching ratio of 0.954 (557.7 nm) and 0.056 (297.2 nm).

^c Relative excitation cross sections estimated using Einstein *A* coefficient branching ratio of 0.756 (630.0 nm) and 0.244 (656.3 nm). Emission cross sections estimated by adding the emission cross section for 557.7 nm.

^d Scaled to the peak of the emission cross section measured by Strickland et al. (1989).

^e Electron-impact dissociation of O₂ produces 90% O(¹D) and 10% O(³P), so I've scaled the dissociation cross section by 0.9 (Cosby, 1993).

^f Makarov et al. (2004) reports emission cross section at 100 eV and gives the total cross section for the 130.4 nm emission, so I scaled the Itikawa et al. (2005) 130.4 nm emission cross section by 0.7/3.

^g No excitation cross section available, but Bhardwaj et al. (2012) gives the rates for H₂O + e⁻ producing O(¹D) and O(¹S), so I scaled the Kedzierski et al. (1998) excitation cross section by this ratio. However, for O₂ the higher energy tail drops off more rapidly for O(¹D) than O(¹S), so this probably over-estimates the cross section at higher electron energies.

^h Ajello (1971) reports a lower limit "relative emission cross section" of 135.6 nm/130.4 nm = 1.05, so I scaled the 130.4 nm cross section by 1.05.

ⁱ Cross sections as reported by Seth et al. (2002), validated by comparing their CO₂ + e⁻ → O(¹S) excitation cross section to that of LeClair et al. (1994).

^j Zipf (1984) reports excitation cross sections, but then gives the value of the emission cross section at 100 eV in Table V, so I've scaled the excitation cross section to the emission cross section value.

^k In the last paragraph of Ajello et al. (2008), they claim the 130.4 and 135.6 nm emission cross sections can be scaled up by values they provide in Table 2 to produce a good approximation of the 844.6 and 777.4 nm cross sections, respectively.

physical equation from Laher et al. (1990)

$$\sigma(E) = \frac{qF}{W^2(1 + \gamma(E/W)^2)} \left(1 - \left(\frac{W}{E} \right)^\alpha \right)^\beta \left(\frac{W}{E} \right)^\Omega \quad [\text{cm}^2] \quad (1.25)$$

which is itself a modification of an equation from Jackman et al. (1977). The variables F , α , β , γ and Ω are the adjustable fit parameters. E is the electron energy and W is the excitation threshold. For atoms, I've set W to the energy of the upper level of the transition. For molecules, I've also included the dissociation energy necessary to produce the atomic fragment. The variable q is the constant

$$q = 4\pi a_0^2 (hc_0 R_\infty)^2 = 1.672 \times 10^{-55} \text{ kg}^2 \text{ m}^6 \text{ s}^{-4} \quad (1.26)$$

where a_0 is the Bohr radius, h is the Planck constant, c_0 is the vacuum speed of light and R_∞ is the Rydberg constant (Mohr et al., 2025). Figure 1.23 shows the emission cross sections used in the current version of the model for electron impact on O, O₂, H₂O, CO₂ and SO₂. As far as I can tell, no cross sections have been measured for electron impact on SO. Table 1.7 details the sources for the cross sections and the rather extensive table notes provide details on any approximations or assumptions I had to make.

1.7 Preview

Okay, that's more than enough introduction I think. The following four chapters are the four papers I published on the Galilean satellite optical aurora while I was a graduate student. As I now consider them all together while writing this introduction, it's retrospectively clear to me that the primary focus of my analysis was on how the auroral brightnesses varied on short timescales—essentially from spectrum to spectrum—and how those variations correlated with the incident plasma environment and potentially the rapidly changing atmosphere as the satellite moved into Jupiter's shadow. In the case of Europa, I also considered how the brightnesses changed systematically over longer, multi-year timescales. However, I did not write the papers in the logical, semi-major axis order in which I've presented them herein. The actual order in which I wrote them was Ganymede (Chapter 4, Milby et al., 2024), Io (Chapter 2, Milby et al., 2025), Europa (Chapter 3, Milby et al., 2026b) and Callisto (Chapter 5, Milby et al., 2026a).

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Chapter 2

IO

Milby, Z., K. de Kleer, and C. Schmidt (2025). “Detection of New Auroral Emissions at Io and Implications for Its Interaction with the Plasma Torus”. *The Planetary Science Journal* 6, 8. DOI: 10.3847/PSJ/ade0b1.

Abstract

We observed Io’s optical aurora in eclipse on six nights between 2022 and 2024 using Keck I/HIRES. Spectra revealed 13 new auroral emissions not identified previously, tripling the total number of optical emissions lines detected at Io. These included the O I lines at 777.4 and 844.6 nm, the Na I lines at 818.3 and 819.5 nm, the [S I] lines at 458.9 and 772.5 nm, the S I triplet at 922.3 nm, the [O II] lines at 732.0 and 733.0 nm and the [S II] lines at 406.9, 407.6, 671.6 and 673.1 nm. We leveraged these new detections by comparing with imaging data from the 2001 *Cassini* flyby to better understand the distribution of atmospheric species and their contribution to the observed auroral brightnesses. Our auroral emission model showed that the observed 557.7, 777.4 and 844.6 nm oxygen emission line brightnesses could be explained by excitation by electron impact of canonical 5 eV torus electrons on an atmosphere composed of O, SO₂ and an isoelectronic proxy for SO. The SO₂ emission did not decrease immediately after eclipse ingress, suggesting that the emitting column may be restricted to higher altitudes. The derived O/SO₂ mixing ratio was typically about 10%, but it also exhibited order-of-magnitude variance during some observations. Io’s 630.0 nm [O I] brightness did not strongly vary with plasma sheet distance, suggesting that electron flux at Io varies substantially beyond model predictions.

2.1 Introduction

A combination of volcanic outgassing and sublimation of surface frost by sunlight produces Io’s thin atmosphere. Although sulfur dioxide (SO₂) constitutes the bulk of the atmosphere (first detected by Pearl et al., 1979), observations have revealed the presence of smaller concentrations of sulfur monoxide (SO; Lellouch et al., 1996), atomic sulfur (S) and atomic oxygen (O; Ballester et al., 1987), in addition to the alkali compounds sodium chloride (NaCl; Lellouch et al., 2003) and potassium chloride (KCl; Moullet et al., 2013) and their dissociation products atomic sodium (Na; Schneider et al., 1987), atomic potassium (K; Brown, 2001) and atomic chlorine (Cl; Feaga et al., 2004). Spencer et al. (2000) detected S₂ on one occasion in a volcanic plume, but it has not yet been observed elsewhere in Io’s atmosphere. Observational results interpreted with photochemical models (e.g., Summers et al., 1996; Feldman et al., 2000b; Moses et al., 2002; Dols et al.,

2024) present Io's atmosphere as spatially variable in both density and composition, with global coronae made of S and O along with a higher-density molecular SO₂ and SO atmosphere concentrated near equatorial latitudes below $\pm 30^\circ$ with a column density 30 to 60 times larger than the SO₂ corona (Strobel et al., 2001). It remains uncertain what fraction of SO is nascent volcanic outgassing (de Kleer et al., 2019b) versus fragments of SO₂ dissociation (de Pater et al., 2020), though models of Io's atmosphere (e.g., Geissler et al., 2004; Roth et al., 2011; Dols et al., 2024) typically assume a 10% mixing ratio with SO₂ (McGrath et al., 2000), consistent with observed ratios between 3% and 10% (Lellouch et al., 1996; Moullet et al., 2010).

Solar insolation sublimates surface frost, producing collisional densities within the low-latitude equatorial atmosphere on the dayside, while on the nightside (and during eclipse) SO₂ can freeze back onto the surface, resulting in a thin exosphere (Saur et al., 2004; Tsang et al., 2016; de Pater et al., 2023). The differing spatial distributions between Io's molecular and atomic atmospheres help to explain spatially resolved observations of Io's aurora in eclipse which show three distinct morphological features: (1) a diffuse limb glow, (2) an extended coronal emission, and (3) bright, isolated emissions near the equator (e.g., Geissler et al., 1999; Geissler et al., 2004; Roesler et al., 1999; Retherford et al., 2000; Retherford et al., 2003; Retherford et al., 2007; Roth et al., 2011; Roth et al., 2014; Saur et al., 2000). Observations with finer spatial resolution also show emission from volcanic features like plumes and vents (Geissler et al., 1999; Geissler et al., 2004). The equatorial spots shift in latitude as Jupiter rotates, following tangents between Jupiter's magnetic field and Io's surface, with a small modification to the local field due to electromagnetic induction from within Io's core (Roesler et al., 1999; Roth et al., 2014; Roth et al., 2017). The limb glow has been most readily identified at the poles, where the observed north-south brightness asymmetry favors the hemisphere facing the centrifugal equator of the Io plasma torus (Retherford et al., 2003; Moore et al., 2010).

These different auroral morphologies are probably due to variation in both the spatial distribution and composition of Io's atmosphere as well as the properties of the excitation mechanisms for the specific emissions. However, no studies have yet quantitatively determined the relative contributions of atomic and/or molecular species responsible for the auroral emissions at optical wavelengths. Though the observed emissions are primarily from atoms and atomic ions (O, O⁺, S, S⁺, Cl, Na and K), dissociation of molecules and molecular ions can also produce excited fragments. For instance, at Europa and Ganymede, most of the optical atomic oxygen auroral emission in eclipse comes from dissociative electron impact on O₂; electron impact on O is only a minor contribution (de Kleer et al., 2018; de Kleer et al., 2019a; de Kleer et al., 2023; Milby

et al., 2024). Bouchez et al. (2000) found that the impact of 5 eV electrons on an atomic oxygen column of approximately 10^{19} m^{-2} could explain the auroral brightness ratios they observed at Io, though they note that Scherb et al. (1993) suggested that dissociative excitation of oxygen from electron impact on SO and SO₂ might constitute the majority of the forbidden oxygen emissions, an interpretation shared by Oliverson et al. (2001). Geissler et al. (2004) concluded that most of the emissions captured in their near-UV/blue broadband filter images likely came from electron-impact fluorescence of SO₂. Geissler et al. (2001) came to a similar conclusion earlier by observing emission enhancement near active volcanic vents in broadband clear filter images. Schmidt et al. (2023) concluded that the 557.7 nm/630.0 nm [O I] ratio could be explained by electron impact on atomic oxygen, but they also noted that the ratio required less energetic electrons than the 5 eV ambient population upstream of Io in the warm torus.

High-cadence observations leverage the large collecting areas of ground-based telescopes like the twin Keck telescopes on the summit of Maunakea to achieve high signal-to-noise ratios in short integration times, but atmospheric seeing limits their spatial resolution. In contrast, space-based observatories like the *Hubble Space Telescope* (HST) can achieve better spatial resolution at UV wavelengths, but its short orbital period and small mirror area limit the signal-to-noise ratio achievable over the brief satellite eclipses. Spacecraft flyby imaging of Io in eclipse by *Galileo* (Geissler et al., 1999; Geissler et al., 2001) and *Cassini* (Geissler et al., 2004) produced images with good spatial resolution, but the broad filter bandpasses made it difficult to identify individual emissions and their relative contributions. Nevertheless, these images allowed for the characterization of distinct emission morphologies. Bouchez et al. (2000) reported the first eclipse detections of individual components of Io’s optical aurora, including the 557.7, 630.0 and 636.4 nm [O I] lines and the sodium D lines at 589.0 nm (D₁) and 589.6 nm (D₂). Schmidt et al. (2023) reported the first eclipse detections of the potassium D lines at 766.5 nm (D₂) and 769.9 nm (D₁) and showed that the sodium D line brightness and line width exhibited a systematic temporal response to Io’s passage through Jupiter’s shadow.

We used high-resolution optical spectra of Io’s auroral emission in eclipse as a remote sensing window into the interaction between Io’s atmosphere and electrons within Jupiter’s magnetosphere. We compared both newly and previously identified atomic emission lines to broadband filter images of Io in eclipse taken during the *Cassini* flyby of the Jovian system on 2001-01-05 to determine which species contributed to which discrete aurora features and whether the atomic emissions identified in our spectra could reasonably account for all the brightness observed in the broadband images. We used

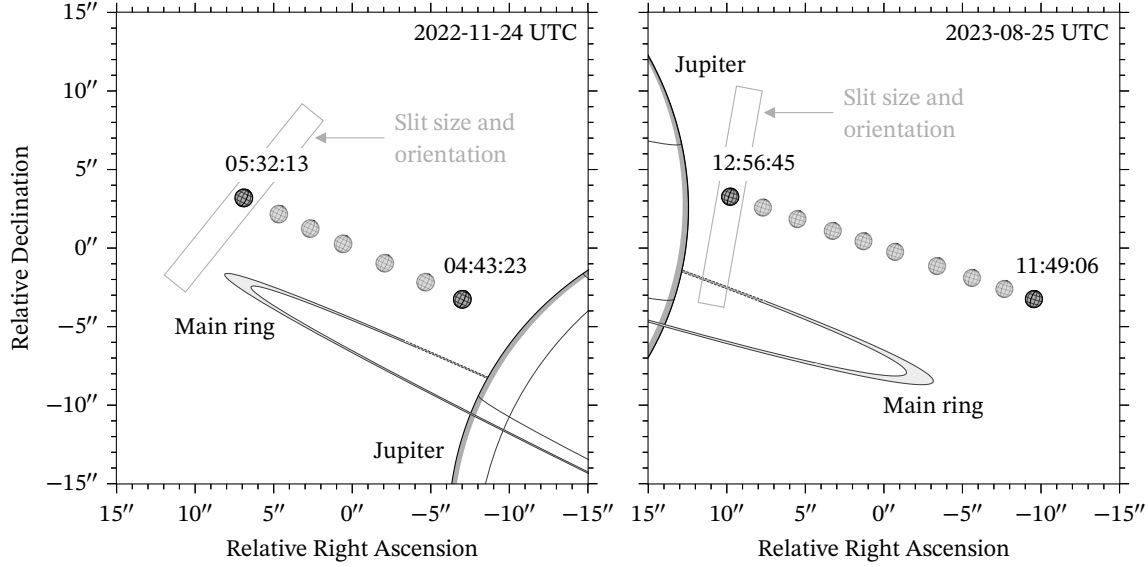


Figure 2.1: Example viewing geometry of the apparent motion of Io in eclipse relative to Jupiter for egress observations on 2022-11-24 (left) and ingress observations on 2023-08-25 (right). Each drawing of Io shows its position relative to Jupiter for each of the spectra taken on these nights, and the annotated times show the UTC time at the start of the first and last observations. The last observation also includes the angular projection of the slit on the sky and its orientation (the slit size and orientation were fixed for all observations on a given night).

an auroral emission model to evaluate the observed brightnesses under the assumption of electron-impact excitation to determine both the atmospheric species contributing to the observed atomic emissions (including both direct atomic excitation and electron-impact dissociation producing excited atomic fragments) and the energy of the electrons exciting the aurora. We evaluated the connection between Io's brightest oxygen aurora and Io's physical position within the plasma sheet to determine if the primary driver of the absolute magnitude of Io's aurora is the ambient density of the torus electrons. Finally, we evaluated whether certain ion emission lines could be used to probe electron density.

2.2 Observations and Data Reduction

We analyzed 40 spectra of Io in eclipse by Jupiter taken over six nights between 2022 and 2024, summarized in Table 2.1. These spectra were acquired with the High Resolution Echelle Spectrometer (HIRES; Vogt et al., 1994), an optical wavelength echelle spectrograph mounted on the Nasmyth platform of the Keck I telescope on the summit of Maunakea. HIRES has two cross-dispersers (called HIRESb and HIRESr) that permit observations at either end of the visible spectrum. The spectra acquired on 2023-08-09

Table 2.1: Overview of the Keck I/HIRES observations of Io in eclipse.

Date ^a [UTC]	Cross Disperser ^b	Used / Total ^c	λ_m^d [deg]	ϕ_m^e [deg]	r_I^f [R_J]	d^g [R_J]	v_{rel}^h [km s ⁻¹]
2022-11-24	HIRESr	7 / 7	-8.929 to -9.526	359.6 to 337.0	5.877	-0.633 to -0.676	21.0 to 19.1
2023-08-09	HIRESb	7 / 7	3.230 to 0.043	88.9 to 69.2	5.913	0.232 to 0.003	-21.3 to -23.0
2023-08-25	HIRESr	8 / 10	-3.628 to 1.479	271.5 to 240.1	5.910	-0.261 to 0.106	-19.7 to -22.4
2024-09-12	HIRESr	7 / 7	-5.936 to -8.259	30.0 to 8.1	5.921	-0.430 to -0.596	-21.4 to -23.3
2024-10-05	HIRESr	4 / 7	9.405 to 9.390	168.6 to 148.8	5.917	0.671 to 0.670	-19.1 to -20.7
2024-10-21	HIRESr	4 / 5	-9.441 to -9.093	342.8 to 323.0	5.913	-0.679 to -0.654	-15.9 to -17.6

Notes. Inaccuracies in telescope tracking at high elevations caused Io to move along and/or out of the slit during three observations on 2024-10-05 UTC, so we removed them from our analysis. These observations have UTC timestamps of 2024-10-05T14:02:13.000, 2024-10-05T14:23:11.000 and 2024-10-05T14:30:14.000. Strong Jovian scattered light background resulted in poor background subtraction for the first and last spectra taken on 2023-08-25 UTC and the first spectrum taken on 2024-10-21, so we removed those observations (2023-08-25T11:49:06.000, 2023-08-25T12:56:45.000 and 2024-10-21T12:04:28.000) as well.

^a UTC date on Maunakea at the start of the observations.

^b HIRES cross disperser used.

^c Number of spectra used out of total number of spectra taken.

^d Magnetospheric latitudes of Io over the range of observations.

^e Magnetospheric longitude of Io over the range of observations. This is the same as the System III west longitude, but converted here to east longitude.

^f Io's orbital distance from Jupiter.

^g Distance between Io and the plasma sheet centrifugal equator; positive when Io is above the midplane and negative when Io is below the midplane.

^h Velocity of Io relative to an observer on Earth (negative velocities indicate motion toward the observer).

UTC used the HIRESb cross-disperser, which was optimized for observations in the second order from about 300 to 700 nm. The data acquired on the other five nights used the HIRESr cross-disperser, which was optimized for observations in the first order from about 400 to 1000 nm. For all six nights, we used a slit with a projected angular size on the sky of $1.722'' \times 14''$.

We used the same observing methodology employed by previous HIRES optical aurora studies (Bouchez et al., 2000; de Kleer et al., 2018; de Kleer et al., 2023; Schmidt et al., 2023; Milby et al., 2024). During the 2022 observations, Jupiter was near eastern quadrature relative to Earth and the telescope line of sight captured Io as it emerged from behind Jupiter’s disk through eclipse egress. We used Ganymede as the guide satellite for these observations. During the 2023 and 2024 observations, Jupiter was near western quadrature and the line of sight captured Io during eclipse ingress until it eventually disappeared behind Jupiter’s apparent disk. On all of these nights we used Europa as the guide satellite. Figure 2.1 shows an example of the viewing geometry for both eclipse ingress and egress observations.

We reduced and calibrated the data using the latest versions of the data reduction and calibration pipelines described by Milby et al. (2024). When Io appears near to Jupiter’s limb, scattered solar continuum from Jupiter’s atmosphere can contribute a large background flux with variable Doppler shift along the slit. This makes the background very difficult to characterize and remove, especially at longer wavelengths greater than 875 nm where CCD fringing complicates the background structure. As a result, we were only able to retrieve the brightness of the 922.3 nm Si triplet from the 2022-11-24 data and we removed two spectra taken on 2023-08-25 (time stamps 2023-08-25T11:49:06.000 and 2023-08-25T12:56:45.000) and one spectrum taken on 2024-10-21 (time stamp 2024-10-21T12:04:28.000) from our analysis.

Keck I pointing and tracking become increasingly unreliable at high elevations near the zenith. Because we used manual offsets and tracking rates in order to observe the otherwise invisible eclipsed satellite, during some observations taken at high elevation the eclipsed satellite may move along the spatial axis of the slit or slip out of it all together. We identified this problem in three spectra taken on 2024-10-05 (time stamps 2024-10-05T14:02:13.000, 2024-10-05T14:23:11.000 and 2024-10-05T14:30:14.000) and subsequently removed them from our analysis.

In addition to the science exposures of Io in eclipse and the fully illuminated guide satellite, we took sets of CCD bias exposures, flat-lamp exposures, thorium-argon (ThAr) arc lamp exposures and a trace spectrum of a standard star for data reduction and wavelength calibration purposes. For calibration from detector counts to physical units,

we used a spectrum of Jupiter’s meridian following the same methodology as in de Kleer et al. (2018), de Kleer et al. (2019a), and de Kleer et al. (2023) and Milby et al. (2024). These data are available from the Keck Observatory Archive (KOA)¹.

2.2.1 Systematic Uncertainties

Milby et al. (2024) analyzed similar HIRES spectra of Ganymede in eclipse and found that the 630.0 nm/636.4 nm [O I] emission line ratio deviated from the optically thin ratio in a way that could not be explained by collisional de-excitation. As a result, they added a 9% systematic uncertainty to all of their auroral brightness measurements. We evaluated the same 630.0 nm/636.4 nm [O I] emission line ratio in the Io eclipse spectra to determine whether we needed to include any systematic error. However, we found that the ratio was within one standard deviation of the expected ratio of 3.09 (Wiese et al., 1996) and subsequently did not include any additional systematic uncertainty for any of the auroral brightnesses reported in this study.

2.3 Analysis

2.3.1 Average Brightnesses

All of the brightnesses listed in this study are disk-integrated and then averaged across all spectra used for each night. Though each measurement is independent, there is inherent variability in the brightnesses beyond expected Poisson noise due to short-timescale changes in the number density of the electrons exciting the auroral emissions and/or the atmospheric column densities. We therefore chose to calculate weighted brightness averages rather than arithmetic brightness averages so that measurements with relatively larger uncertainties are appropriately down-weighted. We calculated the weighed average brightness $\bar{B}$ of n brightness measurements as

$$\bar{B} = \frac{\sum_{i=1}^n B_i w_i}{\sum_{i=1}^n w_i}, \quad (2.1)$$

where B_i is the i th measurement and $w_i = 1/\sigma_i^2$ is the inverse of the square of its corresponding measured uncertainty σ_i (equivalently the inverse variance of B_i). The propagated uncertainty we report for the weighted average $\bar{\sigma}$ is

$$\bar{\sigma} = \frac{1}{\sqrt{\sum_{i=1}^n w_i}}. \quad (2.2)$$

¹<https://koa.ipac.caltech.edu/>

2.3.2 Auroral Emission Model

We have further expanded the auroral emission model used by de Kleer et al. (2023) and Milby et al. (2024) with additional cross sections relevant to Io's atmospheric composition. For electron impact on SO₂ we have included O I emission cross sections at 130.4 and 135.6 nm (Vatti Palle et al., 2004). Because the 777.4 and 844.6 nm O I emissions cascade into these UV lines, Ajello et al. (2008) indicated the 777.4 and 844.6 nm emission cross sections could be approximated by scaling the 130.4 and 135.6 nm cross sections using values they provided. We used the excitation cross section for electron impact on SO₂ producing O(¹S) from Kedzierski et al. (2000) to calculate emission cross sections for 297.2 and 557.7 nm [O I] using their relative emission probabilities (Wiese et al., 1996). To date, no measurements of excitation cross sections for electron impact on SO₂ producing O(¹D) or similar emission cross sections for 630.0 or 636.4 nm [O I] have been published, however, the Kedzierski et al. (2000) 557.7 nm [O I] cross section quantifies the cascade contribution, effectively setting a lower limit. No emission or excitation cross sections have been published for electron impact on SO (McConkey et al., 2008).

We also used ChantiPy, the Python interface to the CHIANTI atomic database v10.1 (Dere et al., 1997; Dere et al., 2023), to calculate photon emission line ratios from atomic and ionic columns as a function of electron energy and density. CHIANTI includes many of the emissions we detected, with the exception of those from the neutral alkali atoms Na I and K I and the electric dipole O I transitions at 777.4 and 844.6 nm and S I transition at 922.3 nm.

2.3.3 Auroral Emission Line Detections

Our analysis of the HIRES spectra revealed emission lines from a variety of neutral and singly ionized atoms including O, O⁺, Na, S, S⁺ and K. This complete set of emissions includes the first Io eclipse detections of the O I lines at 777.4 and 844.6 nm, the Na I lines at 818.3 and 819.5 nm, the [S I] lines at 458.9 and 772.5 nm, the S I triplet at 922.3 nm, the [O II] lines at 732.0 and 733.0 nm and the [S II] lines at 406.9, 407.6, 671.6 and 673.1 nm. Figure 2.2 shows examples of what these emissions (along with the previously identified emissions) look like in the reduced HIRES detector images. Io's angular width was nearly that of the slit (see Figure 2.1), so any emission from an extended corona would appear only in the vertical direction in the detector images.

Table 2.2 lists each of the emission lines for which we attempted to detect auroral emission along with the average brightness for those found at a signal-to-noise of 2 or greater. For non-detections (negative brightness or signal-to-noise ratio below 2) we have instead reported the 2 σ upper limit for the brightness. Brightnesses are in units of

Table 2.2: Average auroral emission line brightnesses.

Wavelength [nm]	Species	Disk-Integrated Brightness					
		2022-11-24 [R]	2023-08-09 [R]	2023-08-25 [R]	2024-09-12 [R]	2024-10-05 [R]	2024-10-21 [R]
388.4	[Na I]		<10				
406.9	[S II]		310 ± 18				
407.6	[S II]		87 ± 11				
458.9	[S I]		100 ± 8				
464.2	[K I]		15				
557.7 ^a	[O I]	395 ± 7	461 ± 12	417 ± 7	481 ± 10	440 ± 12	444 ± 12
589.0 ^a	Na I	16 200 ± 300	12 100 ± 300	18 820 ± 150	20 000 ± 200	14 220 ± 160	14 610 ± 180
589.6 ^a	Na I	6340 ± 180	5070 ± 140	8810 ± 90	9160 ± 110	7500 ± 90	7820 ± 110
630.0 ^a	[O I]	5430 ± 30	6090 ± 110	5630 ± 40	6700 ± 50	6130 ± 50	6160 ± 50
636.4 ^a	[O I]	1768 ± 15	2200 ± 20	1903 ± 12	2361 ± 19	2092 ± 18	1950 ± 20
671.6	[S II]	39 ± 6		61 ± 7	41 ± 9	60 ± 10	89 ± 12
673.1	[S II]	116 ± 7		133 ± 6	157 ± 9	143 ± 13	121 ± 12
732.0	[O II]	58 ± 6		48 ± 6	59 ± 8	53 ± 10	22 ± 16
733.0	[O II]	61 ± 6		47 ± 6	60 ± 10	76 ± 15	53 ± 15
751.5	[Na I]			<30	<40	<50	<70
766.4 ^b	K I	680 ± 30		982 ± 19	1240 ± 30	920 ± 30	1060 ± 40
772.5	[S I]	333 ± 7		361 ± 7	411 ± 12	351 ± 15	371 ± 16
777.4	O I	158 ± 7		166 ± 7	317 ± 11	190 ± 13	269 ± 14
818.3	Na I	—		117 ± 19	410 ± 30	210 ± 30	90 ± 20
819.5	Na I	—		360 ± 20	840 ± 30	350 ± 30	240 ± 40
844.6	O I	196 ± 7		266 ± 9	400 ± 15	281 ± 17	250 ± 20
922.3	Si	392 ± 10		—	—	—	—

Notes. Numbers preceded by a less-than symbol (<) are 2σ upper limits for non-detections. Uncertainties are representative of photon counting (Poisson) noise and do not capture additional systematic uncertainties (which are especially present for the 589.0 and 589.6 nm Na I doublet). Blank cells indicate wavelengths not captured by choice of cross-disperser and combination of cross-disperser and echelle angles. Order overlap prevented characterization and subtraction of backgrounds for wavelengths below approximately 380 nm. Background subtraction failed for 818.3 and 819.5 nm Na I on 2022-11-24. With the exception of 2022-11-24, fringing prevented proper background subtraction from all 922.3 nm Si data, though the emission was still visibly present in all spectra.

^a First detected in eclipse by Bouchez et al. (2000).

^b First detected in eclipse by Schmidt et al. (2023).

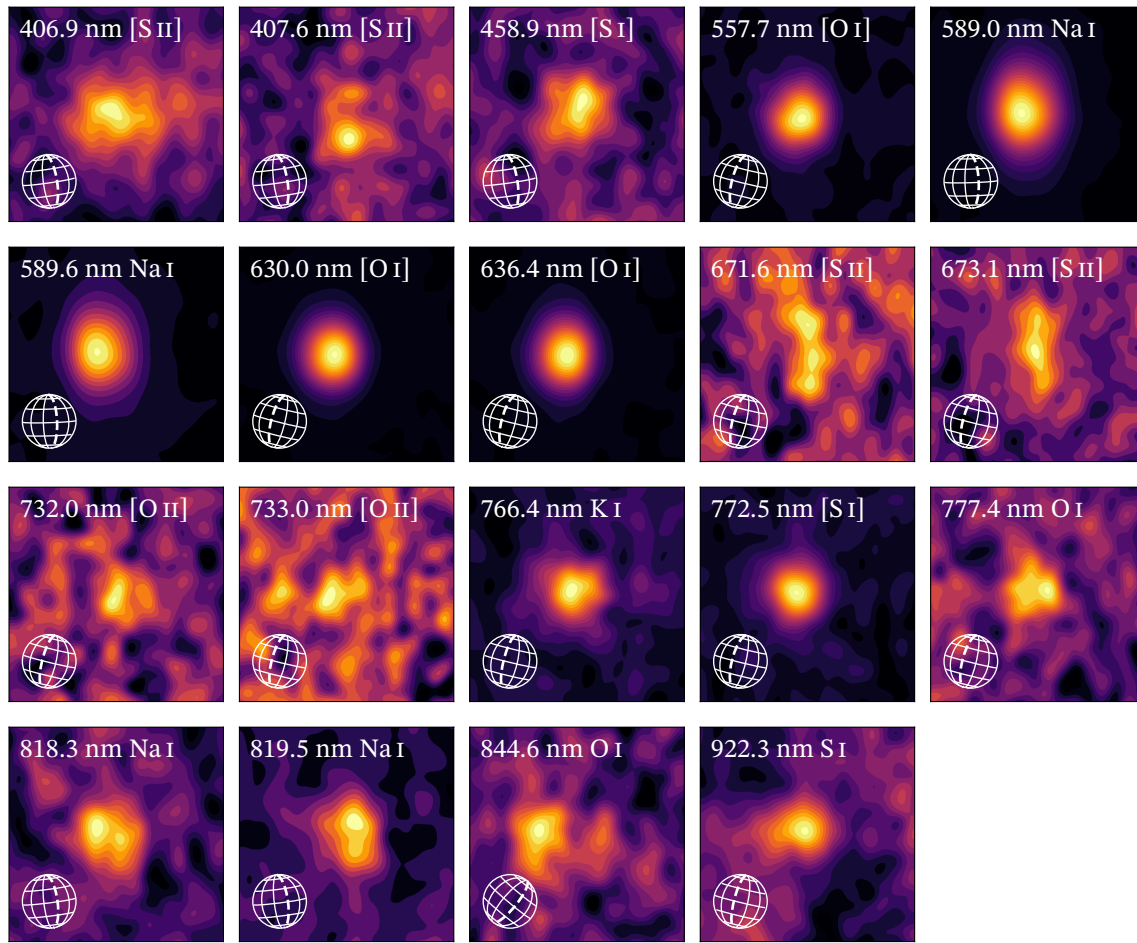


Figure 2.2: Calibrated example images for all 19 detected auroral emissions listed in Table 2.2 displayed using 20 discrete contours. Each image is a single, five-minute integration with the background subtracted. To better reveal the emissions, we smoothed the data using a two-dimensional Gaussian kernel with an FWHM of $0.5''$ approximating typical seeing conditions for Maunakea. Due to the large range of brightnesses, we scaled each image using its individual dynamic range, so comparing apparent brightnesses between images is not meaningful. Graticules in the lower left corner of each panel show the size and orientation of Io during the observation; the thicker dashed line shows the location of the prime meridian. (We chose not to display these directly over the emission in order to not interfere with interpretation of the dimmer emissions and to prevent the need to display three overlapping globes for the 844.6 nm O I triplet.) For the 777.4 nm O I and 922.3 nm S I triplets we have displayed only the brightest, shortest-wavelength component owing to the large separation of the three emissions on the HIRES detector. However, we used all three components simultaneously when retrieving the total brightnesses. The three components of the 844.6 nm O I triplet are somewhat blended at the HIRES detector resolution, so we centered that image on its average wavelength. The 732.0 and 733.0 nm [O II] emissions are both doublets and we chose the brighter components at 731.999 and 732.967 nm, respectively.

rayleighs (R), defined as

$$1 \text{ R} \equiv \frac{10^{10}}{4\pi} \text{ ph s}^{-1} \text{ m}^{-2} \text{ sr}^{-1}. \quad (2.3)$$

When comparing to brightnesses published by others, we occasionally used kilorayleighs (kR), where $1 \text{ kR} = 1000 \text{ R}$. Significant order overlap prevented us from calculating any emission brightness for wavelengths shorter than about 380 nm. Additionally, for our choice of echelle and cross-disperser angles, the K I emission at 769.9 nm did not fall onto the detector, though it should have been at a detectable brightness given the previously observed brightness ratio between the potassium D lines (Schmidt et al., 2023).

Because HIRES cannot operate with both HIRESr and HIRESb at the same time (or even on the same night), we were unable to simultaneously observe the shorter- and longer-wavelength emissions. Additionally, the inherent temporal variability in the total brightnesses precludes meaningful direct comparisons. However, when we compared the relative brightness of the 557.7 nm [O I] emission line and the [S I] electronic equivalent at 772.5 nm, we found that they had a Pearson correlation coefficient of 0.917 with a p -value of 0.0282, which qualifies as statistically significant beyond a standard 95% confidence threshold. We also compared the relative brightness of the 557.7 nm [O I] emission line to the 673.1 nm [S II] emission line and found that they had a Pearson correlation coefficient of 0.813 with a p -value of 0.0942, statistically significant for a 90% confidence threshold.

This indicates that the absolute brightnesses of the sulfur and oxygen emissions mostly co-vary and therefore the brightnesses and uncertainties derived from HIRESr observations can be scaled to approximate their expected values on 2023-08-09. Since we were able to retrieve the 557.7, 630.0 and 636.4 nm [O I] brightnesses with both cross-dispersers, we used the relative weighted average brightness of these three oxygen emissions to calculate scaling factors and uncertainties of 1.1 ± 0.2 for 2022-11-24, 0.92 ± 0.17 for 2023-08-25, 0.83 ± 0.15 for 2024-09-12, 0.73 ± 0.12 for 2024-10-05 and 0.88 ± 0.16 for 2024-10-21.

The brightnesses we retrieved from our HIRES observations vary substantially from those reported by Bouchez et al. (2000), potentially indicating large secular variability in aurora brightness. They found a 557.7 nm [O I] brightness of $(1.3 \pm 0.2) \text{ kR}$, a factor of 3.0 ± 0.5 larger than the weighted average brightness of $(0.429 \pm 0.004) \text{ kR}$ averaged over the six nights in our data. We found a similar factor of 3.0 ± 0.4 for the comparison of the 630.0 nm [O I] brightness and a slightly larger factor of 3.2 ± 0.5 for the 636.4 nm [O I] brightness. However, for the sodium doublet, their results were dimmer by a factor of 0.28 ± 0.04 for the 589.0 nm Na I D₁ line and 0.29 ± 0.04 for the 589.6 nm Na I D₂

line. These differences point to stochastic variability in atmospheric column density (discussed further in Section 2.4.5).

The weighted average brightness we found for the O(¹D) doublet was (7.75 ± 0.02) kR, which exceeds the 4.8 kR average reported by Schmidt et al. (2023) despite cross calibration of our two analysis routines (our pipeline and theirs produced comparable brightnesses when reducing the same HIRES data). This suggests that the difference is a real change in brightness and not a systematic difference in our respective flux calibrations. The eclipsed O(¹D) doublet brightness is less than the 10.5 kR average reported in the sunlit measurements by Oliverson et al. (2001). We found no evidence for time dependence of the O emissions during the eclipse phase, while the Na emissions do show a strong time dependence due to the sudden loss of solar photochemical production pathways (Schmidt et al., 2023). Both Oliverson et al. (2001) and Schmidt et al. (2023) found weak correlations between O(¹D) emission and Io’s location relative to the plasma torus, but they observed considerable variance by up to a factor of 3 in the brightness at a given magnetic longitude.

2.3.4 Comparison with *Cassini*/ISS Images

The identification of so many discrete emission features provided the opportunity to better understand Io’s species-dependent auroral morphology by comparing with images of Io taken in eclipse, first done by Bouchez et al. (2000) when they compared their five detected emission lines to images of Io in eclipse taken by the Solid State Imaging experiment (SSI) on the *Galileo* Orbiter spacecraft (Geissler et al., 1999).

On its way to Saturn, the Narrow Angle Camera (NAC) of *Cassini*’s Imaging Science Subsystem (ISS; Porco et al., 2004) took both broadband and narrowband images of Io in eclipse during its flyby of the Jovian system (see Figure 2.3 for a broadband clear filter example image and Figure 2.4 for a description of the filter bandpasses). ISS imaged Io’s trailing hemisphere, in contrast to the HIRES eclipse observing geometry which is restricted to the sub-Jovian hemisphere. Figure 5 of Geissler et al. (2004) shows images taken under 15 different filters and filter combinations on 2001-01-05, nine of which (shown in our Figure 2.5) had bandpasses that contained wavelengths of the auroral emissions we detected in the HIRES spectra. ISS took four sequences of images with exposure times of 12 seconds each. The sequences took about 14 minutes and 22 seconds to complete and they began and ended with clear filter images. We chose to display images taken during the second sequence in Figure 2.5 due to their high signal-to-noise ratio. Figure 2.6 shows the filter sequence sorted by the exposure midpoint time of each image relative to eclipse ingress, which occurred at 2001-01-05 11:03 UTC.

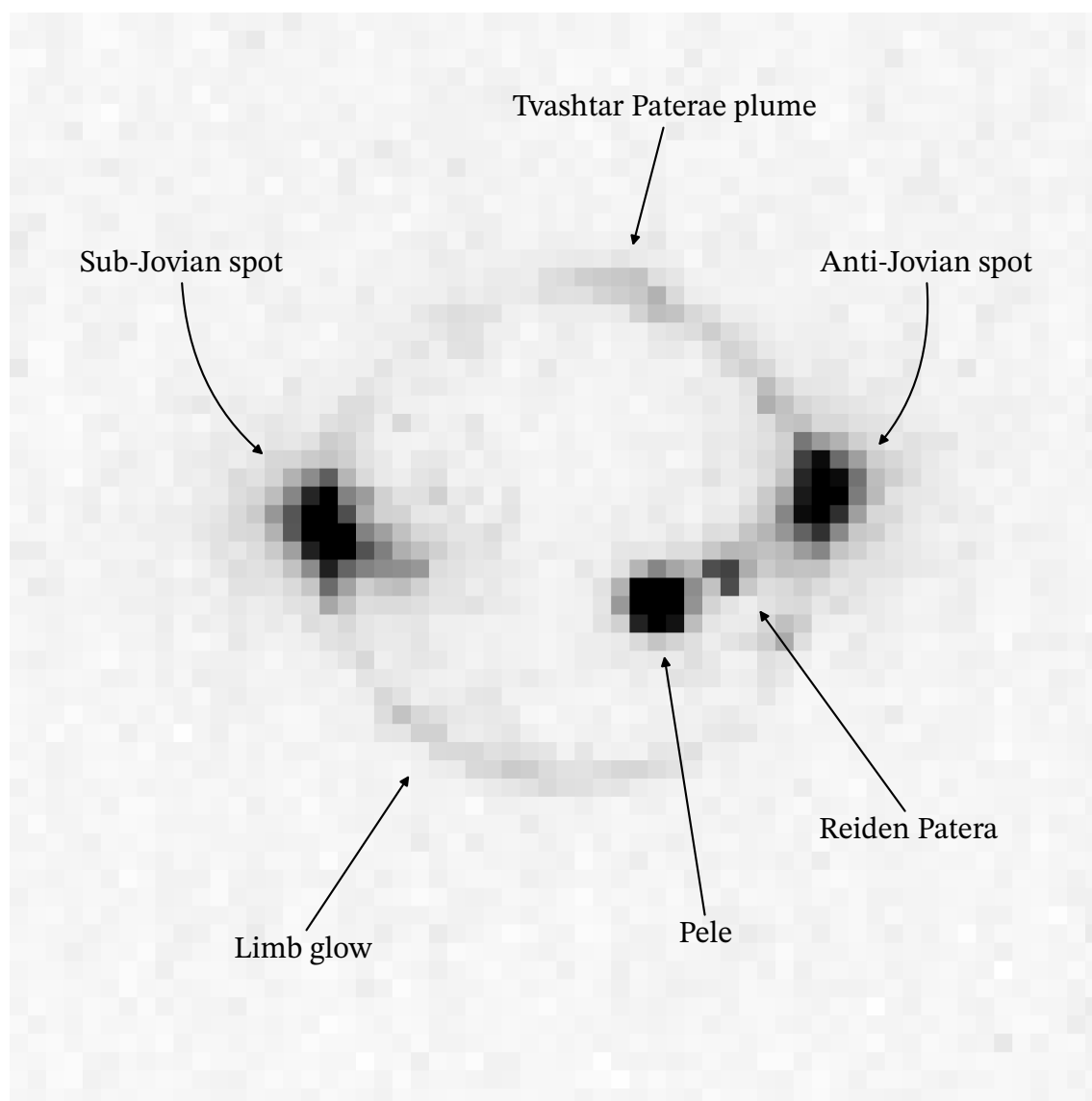


Figure 2.3: Morphological features of Io's optical emission in eclipse. This image was taken by the Narrow Angle Camera (NAC) on *Cassini's* Imaging Science Subsystem (ISS) with the CL1+CL2 (clear) filter combination, so it includes emission across the full detector sensitivity range from approximately 235 to 1100 nm. The volcanic features Pele and Reiden Patera also include thermal emission, especially at longer wavelengths. Table 2.5 lists the file name and observation time for this image.

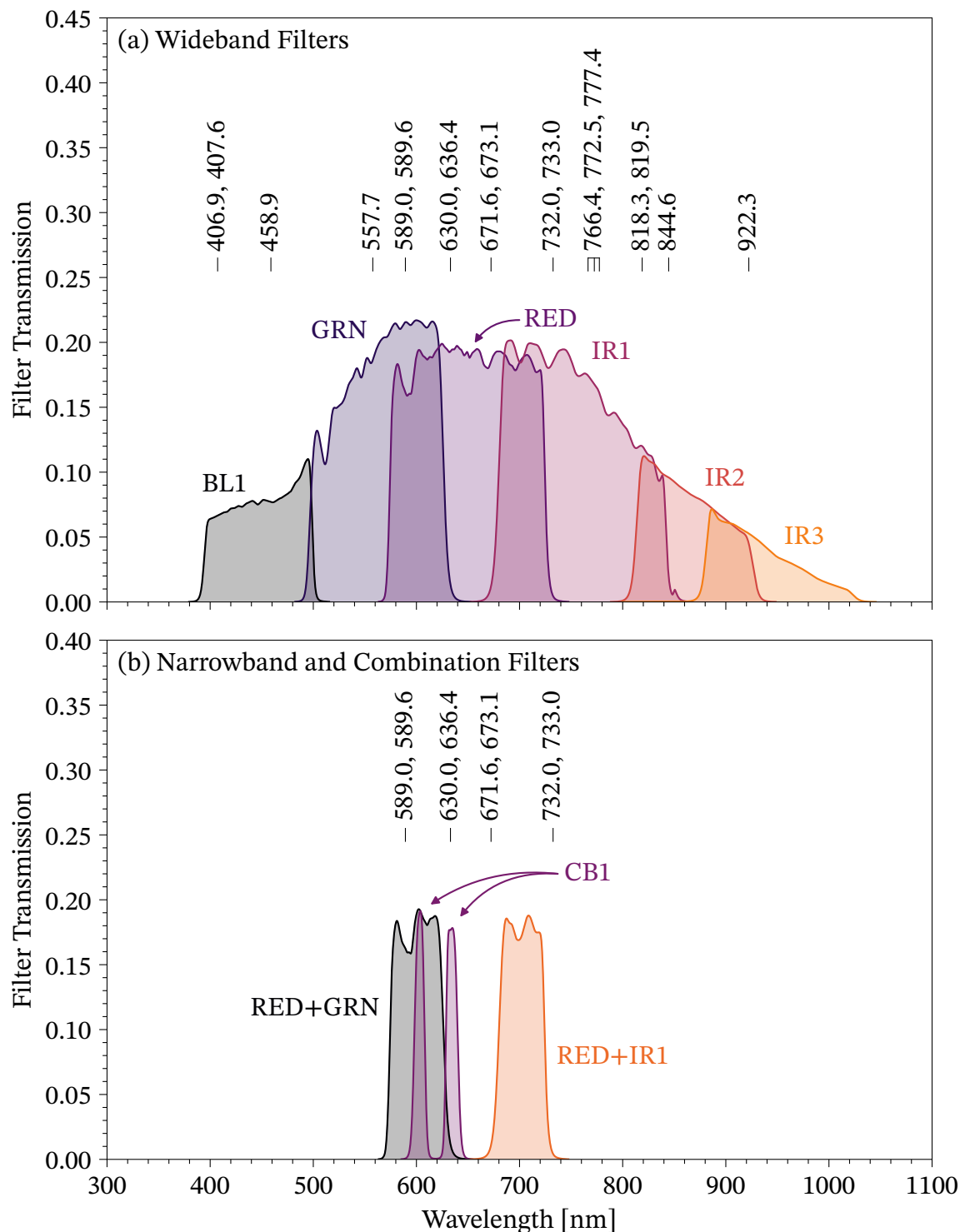


Figure 2.4: *Cassini*/ISS NAC filter transmission (Porco et al., 2004) and locations of identified auroral emission features. (a) shows all the wideband filters and the locations of all auroral lines, grouped as necessary to avoid overlap of the labels. (b) shows the narrowband filter CB1 and the filters made by the combination of two broadband filters, along with the emission features which correspond to those filter bandpasses.

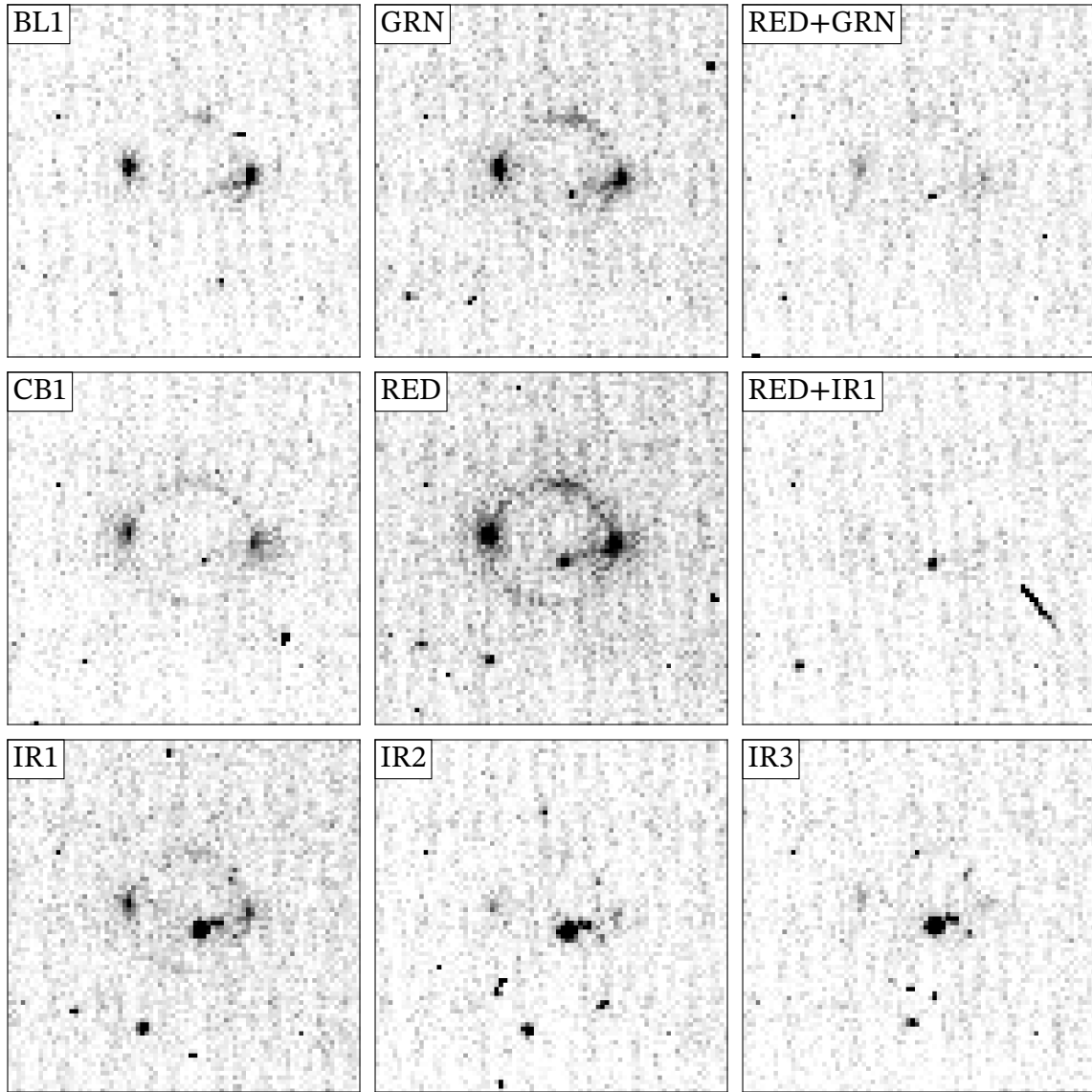


Figure 2.5: Images of each *Cassini*/ISS filter and filter combination containing discrete auroral emissions identified in the HIRES spectra. Labels in the upper right indicate the filter or filter combination. Table 2.5 lists the individual file names and observation time for the images displayed for each filter.

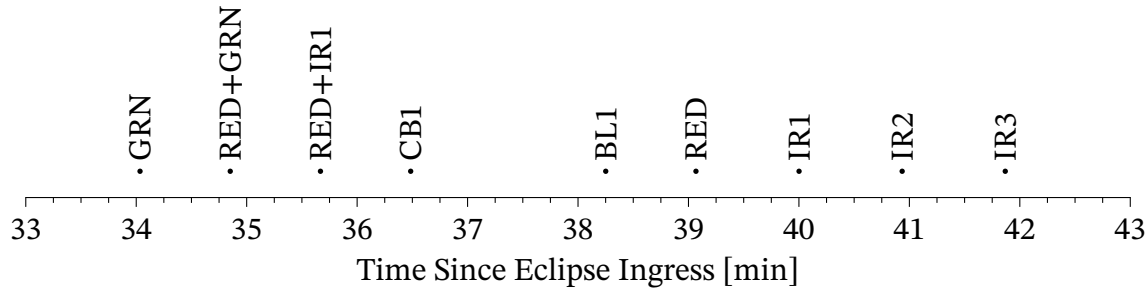


Figure 2.6: *Cassini*/ISS imaging filter sequence displayed in Figure 2.5 sorted by the exposure midpoint time (see Table 2.5) of each image relative to eclipse ingress, which occurred at 2001-01-05 11:03 UTC.

These images demonstrate that Io’s optical aurora exhibits some combination of two primary morphological features: the sub/anti-Jovian spots (also called the “equatorial glow”) that were first identified in UV imaging (e.g., Retherford et al., 2000; Retherford et al., 2003; Retherford et al., 2007; Roesler et al., 1999; Roth et al., 2011; Roth et al., 2014; Roth et al., 2017; Saur et al., 2000) and a diffuse limb glow (e.g., Retherford et al., 2003; Moore et al., 2010). Because the HIRES data do not have the spatial resolution to resolve spots versus a diffuse equatorial enhancement distributed across all visible longitudes, we used the term “equatorial glow” throughout our analysis instead of “sub-Jovian spot” when referring to emission features in the HIRES data (we still used the term for the ISS images). Further, despite its name, the sub-Jovian spot actually appears up to 20° west (wakeward) of the sub-Jovian longitude (Retherford et al., 2007; Moore et al., 2010). Regardless, the FWHMs of the bright emissions in Figure 2.2 are smaller than the angular size of Io’s disk (indicated by the graticules in the lower left corner of each panel), so the observed emissions are spatially isolated and likely to be primarily from the sub-Jovian spot.

The auroras also show transient thermal and/or thermally excited emissions from discrete volcanic features including Reiden Patera, the volcano Pele and a spot near the north pole that they identified as being associated with the Tvashtar Paterae volcanic plume. Reiden Patera and Pele appear in the CLR (clear) filter image (a combination of filters CL1 and CL2) and are increasingly more prominent at longer wavelengths owing to their thermal emission. The Tvashtar Paterae plume appears under most filters. Figure 2.3 shows an example ISS CL1+CL2 (clear) filter combination image containing each of these emission features, while Figure 2.4 shows the transmission bandpasses of the nine filters and the locations of the auroral emissions identified in the HIRES spectra.

Table 2.3: Emission morphologies in *Cassini*/ISS images and contributing auroral emissions identified in HIRES spectra.

Filter	Bandpass ^a [nm]	Equatorial Glow	Limb Glow	Plume	Disk-Integrated Brightness		
					HIRES ^b [kR]	ISS ^c [kR]	HIRES/ISS Ratio
BL1	390 to 500	[S I], [S II]	[S I]?	[S II]?	0.50 ± 0.02	25 ± 10	0.020 ± 0.008
GRN	495 to 635	[O I], Na I	[O I]	Na I	24.71 ± 0.09	15 ± 7	1.6 ± 0.8
RED+GRN	570 to 635	Na I	—	Na I	24.28 ± 0.09	4 ± 5	6 ± 8
CB1 ^d	625 to 645	[O I]	[O I]	—	7.845 ± 0.019	11 ± 4	0.7 ± 0.3
RED	570 to 730	[O I], Na I, [S II]	[O I]	Na I, [S II]	32.31 ± 0.09	19.1 ± 0.7	1.69 ± 0.06
RED+IR1	670 to 730	[O II], [S II]	—	[O II], [S II]	0.293 ± 0.007	—	—
IR1	670 to 850	O I, [O II], Na I, [S I], K I	O I? [S I]?	[O II]?, Na I?	2.49 ± 0.02	11 ± 3	0.23 ± 0.06
IR2	800 to 940	O I, Na I, S I	O I, S I?	Na I?	0.856 ± 0.019	—	—
IR3	880 to 1025	S I	S I?	—	0.392 ± 0.010	—	—

Note. Question marks indicate assumed contributions inferred but not unambiguously identified with the combination of ISS images and HIRES spectra.

^a From Table 1 of Geissler et al. (2004).

^b Weighted average of brightnesses from Table 2.2.

^c Converted from Table 4 of Geissler et al. (2004) as described in Section 2.3.4 of this paper.

^d The CB1 filter also included a second small bandpass from 595 to 615 nm, but this range contained no discrete emission feature in the HIRES spectra.

Geissler et al. (2004) reported the brightnesses of specific auroral morphologies like the anti-Jovian equatorial glow (their Tables 1 and 5) and the limb glow (their Table 3). They did not report disk-integrated brightnesses, which make comparisons with the disk-integrated HIRES brightnesses difficult. However, they did report disk-integrated total photon fluxes and uncertainties in their Table 4. They calculated these fluxes over apertures that included all apparent emission—the equatorial spots, the limb glow and any potential extended corona—and converted them to total photon flux emitted into 4π sr around the entire satellite. We took these flux values (they did not specify units, so we assumed ph s^{-1}), divided by the cross-sectional area of Io ($1.0514 \times 10^{12} \text{ m}^2$) and 4π sr, then converted to kR using Equation (2.3). We have included these brightnesses in Table 2.3.

The BL1 filter image brightness is significantly larger than that derived from the HIRES data. Geissler et al. (2004) attributed the brightness in the BL1 filter image to electron-impact quasi-continuum fluorescence of SO_2 , though they also proposed some contribution from the $\text{S}_2(\text{B } ^3\Sigma_g^- \longrightarrow \text{X } ^3\Sigma_u^-)$ band system to account for the larger-than-expected brightness in this filter relative to the UV1 filter. Trafton et al. (2012) also observed molecular emission bands in this wavelength region from Io in eclipse.

The GRN filter image contains both the 557.7 nm [O I] and 589.0 and 589.6 nm Na I doublet emissions, while the RED+GRN combination filter contains just the Na I doublet emissions. These images were taken only about 1 minute apart (see Figure 2.6), so the fact that they recorded nearly identical brightnesses suggests that the [O I] emission dominates in the GRN filter.

The CB1 filter image contains just the 630.0 and 636.4 nm [O I] emissions, which shows that the oxygen emission primarily comes from the equatorial and limb glows and does not seem to be correlated with the volcanic plume. This conclusion is further supported by the RED filter image, which contains the 589.0 and 589.6 nm Na I doublet, the 630.0 and 636.4 nm [O I] lines and the 671.6 and 673.1 nm [S II] lines. The strong plume emission must come from the Na I doublet and [S II] lines, suggesting that the plume emission in the GRN filter is probably from the Na I doublet and not from the 557.7 nm [O I] line, though the different lifetimes between the $\text{O}(^1\text{S})$ and $\text{O}(^1\text{D})$ states could lead to preferential quenching of the 630.0 and 636.4 nm [O I] lines in the high-density plume. The RED+IR1 filter combination image contains the 671.6 and 673.1 nm [S II] and 732.0 and 733.0 nm [O II] emissions, but they fall near the edges of the bandpass, accounting for the nearly featureless image.

The limb glow in the IR1 filter is likely from the 777.4 and 844.6 nm O I emissions and perhaps also from the 772.5 nm [S I] line (the sulfur electronic analog to the

557.7 nm [O I] line). Geissler et al. (2004) proposed that the largest contribution to the total brightness in the IR1 filter came from the 766.4 nm K I line, which agrees with the HIRES data, where it accounted for about half of the total disk-integrated brightness across the filter's bandpass. The IR2 and IR3 filters contain the emissions identified in the HIRES spectra at wavelengths greater than 800 nm, but the signal-to-noise ratio is quite low, and only the equatorial glows are significant.

Table 2.3 summarizes the species we attribute to the observed morphologies in each filter. Overall, the equatorial glow seems to include emission from all detected species, both neutrals and ions. The limb glow seems to be associated with the bright neutral oxygen emissions, though we cannot rule out contribution from neutral sulfur as well, which may be the species contributing to the extremely faint limb glows in the BL1, IR2 and IR3 filters. The concentration of molecular species at low to mid latitudes (Strobel et al., 2001) and global atomic coronae (Wolven et al., 2001) suggest that dissociative electron impact on molecules like SO₂ and SO produces the bright auroral spots while excitation of the atomic S and O coronae produces the limb glow. Emission from the Tvashtar plume is probably primarily from sodium but may also include emission from ionized atomic oxygen and sulfur.

2.4 Results and Discussion

2.4.1 Electron Energy

Emission line ratios are sensitive to different electron energy distributions because of their individual energy-dependent excitation cross sections. In contrast, absolute auroral brightnesses are sensitive to both electron energy distributions and the product of electron number densities and atmospheric column densities. Schmidt et al. (2023) evaluated the 630.0 nm/557.7 nm [O I] brightness ratio in observations taken primarily with the ARC Echelle Spectrograph (ARCES) at the Apache Point Observatory and found it was higher than expected from electron impact on a column of just atomic oxygen. They attributed the larger ratio to electrons losing energy as they precipitated through Io's SO₂ atmosphere, allowing them to preferentially excite the 630.0 nm red line emission (which has a lower excitation energy than the 557.7 nm emission). Models like those of Saur et al. (1999) and Dols et al. (2012) show electron energies decreasing from a typical upstream torus energy of 5 eV down to 0.2 eV near Io's surface. Figure 2.7 shows this brightness ratio for electron impact on atomic oxygen as a function of electron energy and density. For electron impact on O the emission line ratio is sensitive to energy but independent of plasma density for the range of values plausible for Io. Though the impact of 3 to 4 eV electrons on a column of atomic oxygen can explain

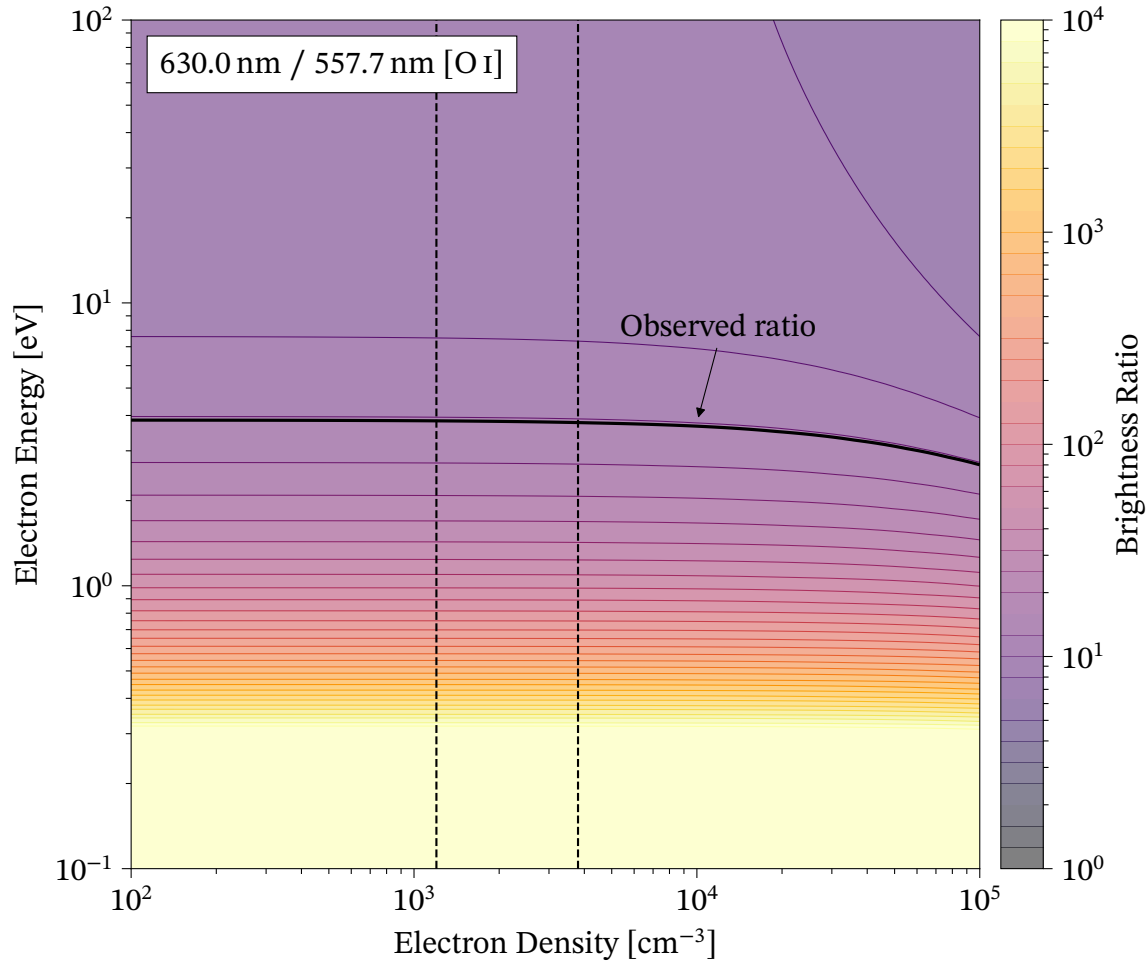


Figure 2.7: Dependence of the 630.0 nm/557.7 nm [O I] brightness ratio on electron energy and density assuming electron impact on an atmospheric column of atomic oxygen. The dashed vertical black lines show the typical electron density range of 1200 to 3800 cm^{-3} experienced by Io through one rotation of Jupiter's magnetosphere (Bagenal et al., 2020). The thick black line shows our average observed ratio of 13.64 ± 0.13 . This brightness ratio for electron impact on atomic oxygen is effectively insensitive to the range of typical electron densities, making it diagnostic of the energy of the exciting electrons. However, electron impact on atomic oxygen cannot account for the observed 777.4 and 844.6 nm O I brightnesses. Colored lines highlight contours at a spacing of 0.1 dex. Calculated using CHIANTI v10.1 (Dere et al., 1997; Dere et al., 2023).

Table 2.4: Best-fit auroral emission model oxygen emissions for different atmospheric compositions.

Date (Emission)	Observed [R]	Model Atmosphere Composition				
		O [R]	O + SO ₂ [R]	O + SO ₂ + O ₂ [R]	O + SO ₂ + CO ₂ [R]	O + SO ₂ + H ₂ O [R]
2022-11-24						
557.7 nm	395 ± 7	327	399	395	401	400
777.4 nm	158 ± 7	102	88	157	88	87
844.6 nm	196 ± 7	300	214	196	215	214
2023-08-25						
557.7 nm	417 ± 7	385	423	415	420	419
777.4 nm	166 ± 7	120	109	166	108	108
844.6 nm	266 ± 9	353	292	266	293	293
2024-09-12						
557.7 nm	481 ± 10	498	500	483	498	499
777.4 nm	317 ± 11	155	154	312	153	153
844.6 nm	400 ± 15	457	451	381	448	449
2024-10-05						
557.7 nm	440 ± 12	412	448	437	438	441
777.4 nm	190 ± 13	128	116	190	113	114
844.6 nm	281 ± 17	378	315	280	312	314
2024-10-21						
557.7 nm	444 ± 12	429	457	443	451	452
777.4 nm	269 ± 14	134	121	271	119	119
844.6 nm	250 ± 20	394	328	251	327	328

Note. Bold numbers indicate model brightness values within 2σ of the observed brightness.

the observed 630.0 nm/557.7 nm [O I] brightness ratios (Figure 2.7 shows the average ratio of 13.64 ± 0.13 , it cannot account for the ratios with the other oxygen emissions (777.4 and 844.6 nm) detected in the HIRES spectra. While we will present one potential explanation in Section 2.4.2, both quenching and electron energy variation with latitude, with altitude and within plumes are plausible alternative explanations.

2.4.2 Auroral Parent Species

In order to explore how the emissions change with other possible atmospheric compositions, we compared brightness calculations from our auroral emission model for three combinations: O alone (simulating emission from just the atomic oxygen column), an atmosphere of O and SO₂, and an atmosphere of O, SO₂ and a third molecular component. Because of the limited cross sections available for SO₂, we were only able to evaluate three of the five detected oxygen emissions: the forbidden 557.7 nm emission and the allowed 777.4 and 844.6 nm emissions. We used a Maxwellian electron energy

distribution centered at 5 eV to determine whether the observed brightness ratios could be explained through impact by the upstream electron population. Table 2.4 lists the results produced by our aurora model for the five different atmospheric compositions discussed below.

The single-component atmosphere composed of just O alone cannot replicate the observed brightness ratios of the three emission lines: the best fit under-predicts the 777.4 nm brightnesses and over-predicts the 557.7 and 844.6 nm brightnesses. Including SO₂ improves the fit overall but still fails to reproduce the observed brightnesses within their respective uncertainties, resulting in an over-prediction of the 844.6 nm emission and an under-prediction of the 777.4 nm emission. Including O₂ results in an excellent fit for all three emission features well within their observed uncertainties. However, this result yields O₂ column densities of approximately 10^{19} m^{-2} (see Figure 2.8), which is about 2 orders of magnitude larger than the estimated 1% mixing ratio between O₂ and SO₂ (Moses et al., 2002). This probably means that the observed auroral emissions are from a combination of electron impact on exospheric columns of O, SO₂ and a molecule that behaves like O₂ when dissociated into excited fragments by electron impact. The most likely candidate molecule is SO, which has a mixing ratio with SO₂ of around 10% (McGrath et al., 2000) and may be higher during eclipse when the SO₂ atmosphere condenses onto the surface (Tsang et al., 2016). Unfortunately, emission and/or excitation cross sections have not yet been published for SO (McConkey et al., 2008), so it cannot be explicitly included in our auroral emission model.

S and O occupy the same group in the periodic table, the valence electrons in the p orbitals are the same for both molecules, and therefore their overall state distribution is similar. They also have comparable dissociation energies: approximately 5.1 eV for O₂ and 5.4 eV for SO (Darwent, 1970). Theoretical calculations show similar excitation cross sections between O₂ and SO, though the SO cross sections tend to be larger owing to the physical size difference between the two molecules (Rajvanshi et al., 2010). We therefore chose to use the O₂ cross sections as a proxy for the SO cross sections. However, while the relative cross sections (and therefore the brightness ratios) between oxygen emission lines will be similar, the absolute cross sections may not be of the same magnitude. Consequently, while the modeled component from O₂ probably includes emission primarily from SO (along with any trace O₂ present), we cannot determine their relative contributions due to the inherent degeneracy. As a result, while the O and SO₂ column outputs are real, only the relative variability within the O₂ column density is real; the absolute column density magnitude is not physically meaningful and should not be interpreted as representative of either the modeled O₂ or SO column density. The

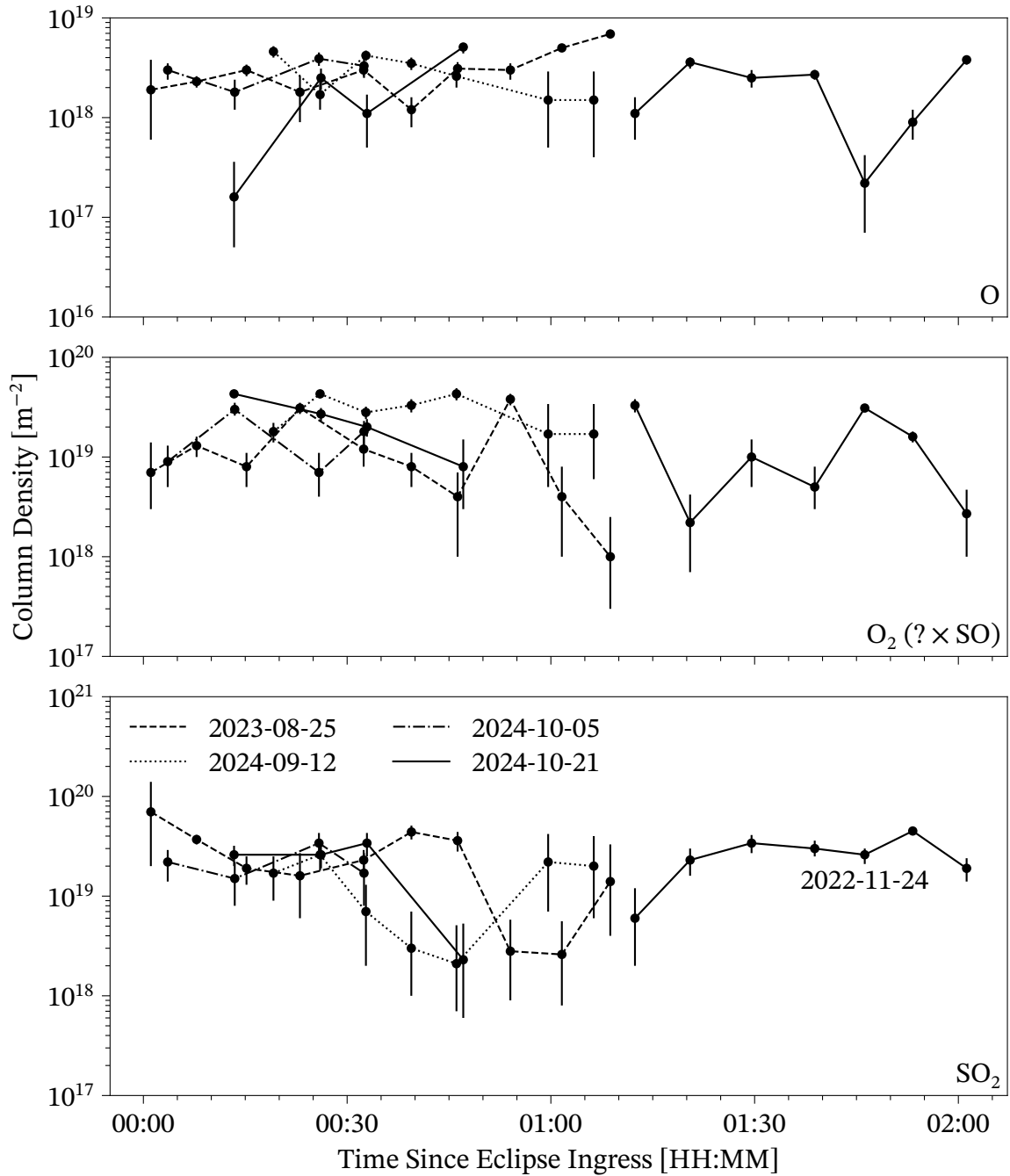


Figure 2.8: Best-fit emission model column densities for O (top), O₂ as a proxy for SO (middle) and SO₂ (bottom). These results assume only direct excitation of O and dissociative excitation of SO and SO₂ and do not include any recombination processes. We used a Maxwellian electron distribution centered at 5 eV with a density of 2500 cm⁻³. Line styles differentiate between the five observation nights as notated in the bottom panel. The variance in the O₂ column densities is physically meaningful, but the absolute magnitude is not necessarily representative of the SO column density (see the discussion in Section 2.4.1).

true SO column density is likely smaller than the modeled result if the SO cross sections are systematically larger than the O₂ cross sections (Rajvanshi et al., 2010).

To ensure that this exceptionally good agreement from the inclusion of the O₂ component was not an artifact from fitting three emission lines with a three species atmosphere, we fit two additional three-species atmospheres, substituting H₂O and CO₂ (the only other species for which we had 557.7, 777.4 and 844.6 nm emission cross sections) for the O₂ component. The other three-component atmospheres always resulted in a poor fit for at least one emission line. This could mean that the auroral emission is confined to high altitudes where electrons still maintain their 5 eV plasma torus energies. However, the *Cassini*/ISS images (specifically the CB1 image in Figure 2.5) seem to show the longest-lifetime 630.0 and 636.4 nm emissions all the way down to Io's surface. Hence, while the observed oxygen aurora brightness ratios can be explained by electron impact on Io's O, SO₂ and SO exospheres by 5 eV torus electrons without invoking the collisional cooling necessary for emission from a pure O column proposed by Schmidt et al. (2023), electron energies are much lower in the denser parts of the ionosphere near to Io's surface (Saur et al., 1999; Dols et al., 2008; Dols et al., 2012; Dols et al., 2024) and therefore there exists a degeneracy between electron energy and composition that cannot be resolved using forbidden oxygen emissions from Io.

Regardless, the disk-integrated 557.7, 777.4 and 844.6 nm brightnesses are consistent with electron impact on an atmosphere composed of O, SO and SO₂. For the 557.7 nm [O I] line, the fractional contribution to the total brightness from the SO component varies between 6 and 9%.

2.4.3 Atmosphere Collapse in Eclipse

It remains unclear what fraction of Io's SO₂ atmosphere comes from volcanic outgassing and what fraction comes from sublimation of surface ice. Some observations show a large decrease in column density during eclipse associated with the rapid drop in surface temperature, suggesting a predominantly sublimation-supported atmosphere where solar insolation maintains the vapor-pressure equilibrium between Io's SO₂ atmosphere and surface ice (Tsang et al., 2016; de Pater et al., 2020). If the atmosphere is primarily sublimation supported, then during the eclipse phase of Io's orbit a portion of the SO₂ atmosphere would freeze back onto the surface (Saur et al., 2004), perhaps even enough to change the near-surface bound atmosphere from collisional to non-collisional (Tsang et al., 2016).

Figure 2.8 shows the best-fit model column densities during eclipse for the three-species model containing O, O₂ (an unknown multiple of the SO column) and SO₂.

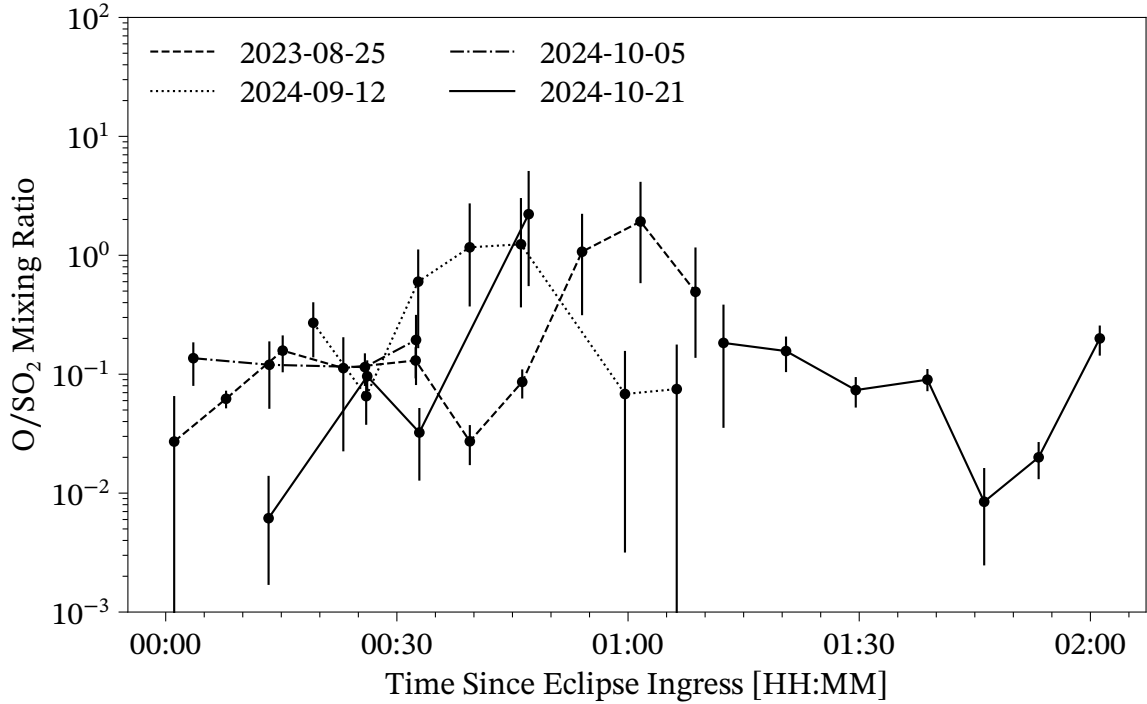


Figure 2.9: Best-fit emission model O/SO₂ mixing ratio calculated from the column densities in Figure 2.8. Points with lower uncertainty bounds intercepting zero are cut off by the lower axis limit. Though the mixing ratio just after eclipse ingress is typically about 10%, it can vary by more than an order of magnitude.

While the O and O₂ (SO) column densities exhibit some short-timescale variability, they are relatively constant over the duration of the eclipse. Further, though there are some decreases in SO₂ column density with time (primarily between 30 and 75 minutes after eclipse ingress), most are followed by a proportional increase well before eclipse egress (typically around 2 hours after ingress). Though this could be explained by the collapse and recovery of some fraction of the SO₂ atmosphere (Tsang et al., 2016; de Pater et al., 2020), the correlation between proximity to Jupiter’s limb and the relative decrease in brightness suggests that this may instead be a background subtraction artifact.

The average O column densities are on the order of $3 \times 10^{18} \text{ m}^{-2}$, about a factor of 4 larger than that in the Dols et al. (2024) model and a factor of 2 smaller than the column density derived by Schmidt et al. (2023). The maximum of the SO₂ column densities is approximately $2 \times 10^{19} \text{ m}^{-2}$, a factor of about 30 smaller than that in the Dols et al. (2024) model and around the lower end of typical observed column densities (see Table 19.1 and associated references in McGrath et al. 2004 and Table 1 in de Kleer et al. 2024). Figure 2.9 shows how the O/SO₂ column mixing ratio changes over the course of the eclipses. The ratio is typically around 10% but varies by an order of magnitude or

more and can approach parity owing to the drop in SO₂ column density near the eclipse midpoint.

However, the relative stability of the SO₂ column and its density at the low end of previously derived values suggest that the portion of the emission from dissociative excitation of SO₂ may originate from the high-altitude portion of the column, while the near-surface emission comes primarily from direct excitation of the atomic oxygen component. This would permit the near-surface SO₂ atmosphere to collapse while maintaining the emitting column. This could also explain the apparent delay in the drop in SO₂ emission, since the lower atmosphere would have to collapse first before the higher-altitude emitting column. However, as noted above, this does not account for the apparent “recovery” that occurs in most of the observations after one hour in eclipse.

In such a scenario, electron energies near Io’s surface may be insufficient to dissociate SO₂ but are able to excite the lower-energy forbidden emissions in the atomic O, and the much higher electron number density within the ionosphere is sufficient to produce measurable emission despite quenching. The presence of the 630.0 and 636.4 nm [O I] emissions at altitudes near Io’s surface in the ISS images (see Section 2.3.4) indicates that electrons are penetrating into Io’s ionosphere and therefore must be losing energy as they precipitate.

2.4.4 Quenching

Laboratory experiments show that SO₂ quenches O(¹D) with a rate coefficient of $(2.17 \pm 0.19) \times 10^{-16} \text{ m}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ (Zhao et al., 2010). The O(¹D₂ → ³P₂) 630.0 nm transition has a lifetime of 178 s (Wiese et al., 1996), so the critical density at which SO₂ quenches this emission (the density of SO₂ for which the collisional de-excitation rate equals the auroral photon emission rate) is $2.59 \times 10^{13} \text{ molecules m}^{-3}$. The O(¹D₂ → ³P₁) 636.4 nm transition has a much longer lifetime of 549 s (Wiese et al., 1996), so the critical density at which SO₂ quenches this emission is $8.39 \times 10^{12} \text{ molecules m}^{-3}$. For the atmospheric columns in the Dols et al. (2024) model, this quenching rate would limit the modeled atomic O column to $6.059 \times 10^{17} \text{ m}^{-2}$ for the emission of 630.0 nm photons (83.5% of the total column, corresponding to a minimum altitude for emission of approximately 200 km) and $5.761 \times 10^{17} \text{ m}^{-2}$ for the emission of 636.4 nm photons (79.4% of the total column, corresponding to a minimum altitude for emission of approximately 250 km).

No laboratory measurements have been published of rate coefficient for the quenching of O(¹S) by SO₂. However, measurements have been published for O₂ quench-

ing of both $O(^1D)$ (Streit et al., 1976) and $O(^1S)$ (Atkinson et al., 1972; Slanger et al., 1972). At a temperature of 115 K, O_2 quenches $O(^1D)$ with a rate coefficient of $5.2 \times 10^{-17} \text{ m}^3 \text{ molecule}^{-1} \text{ s}^{-1}$ and $O(^1S)$ with a rate coefficient of $2.9 \times 10^{-21} \text{ m}^3 \text{ molecule}^{-1} \text{ s}^{-1}$. These rates yield critical O_2 densities of $1.1 \times 10^{14} \text{ molecules m}^{-3}$ for collisional de-excitation of $O(^1D)$ preventing the 630.0 nm transition, $3.5 \times 10^{13} \text{ molecules m}^{-3}$ for collisional de-excitation of $O(^1D)$ preventing the 636.4 nm transition and $4.3 \times 10^{20} \text{ molecules m}^{-3}$ for collisional de-excitation of $O(^1S)$ preventing the 557.7 nm transition. The $O(^1S)$ quenching rate is different by more than four orders of magnitude compared to the $O(^1D)$ quenching rate; assuming that a similar difference in magnitude exists for SO_2 there should be effectively no collisional de-excitation of $O(^1S)$ along the entire O column.

The sulfur equivalent to the 630.0 nm/557.7 nm [O I] ratio is the 1082.0 nm/772.5 nm [S I] ratio. de Pater et al. (2025) calculated a disk-integrated 1082.0 nm [S I] brightness of 4.2 kR in eclipse in August 2023. When evaluated in conjunction with the 772.5 nm [S I] brightness we observed with HIRES in August 2023, the ratio is consistent with emission from an atomic S column impacted by electrons with energies between 4 to 5 eV. The near-surface emissions in the ISS images (see Figure 2.5) suggest little if any quenching of the emission, though the corresponding increase in electron density makes firm conclusions difficult and altitude estimates for the exobase vary substantially (Summers et al., 1996). See de Pater et al. (2025) for an in depth discussion of the near-infrared [S I] emissions.

2.4.5 Electron Scale Height

The electron number density in the Jovian magnetosphere forms a Gaussian-like vertical profile of the form

$$n(r, d) = n_0(r) e^{-(d/H)^2}, \quad (2.4)$$

where n_0 is the number density at the centrifugal equator, H is the scale height (equal to $0.77 R_J$ at Io's average orbital distance; Bagenal et al., 2011) r is Io's instantaneous orbital distance from Jupiter and d is Io's distance from the centrifugal equator (Hill et al., 1976). Figure 2.10 shows a fit of Equation (2.4) to the disk-integrated 630.0 nm [O I] brightnesses, assuming that the brightness is directly proportional to the local electron number density n . The six nights of observations captured Io at a variety of distances from the centrifugal equator, but some large gaps remain unobserved. Though the data between -0.4 to $-0.75 R_J$ show some correlation between auroral brightness and electron density, the complete data across all distances are characterized effectively as well by a constant (the horizontal line in Figure 2.10). While this could be interpreted

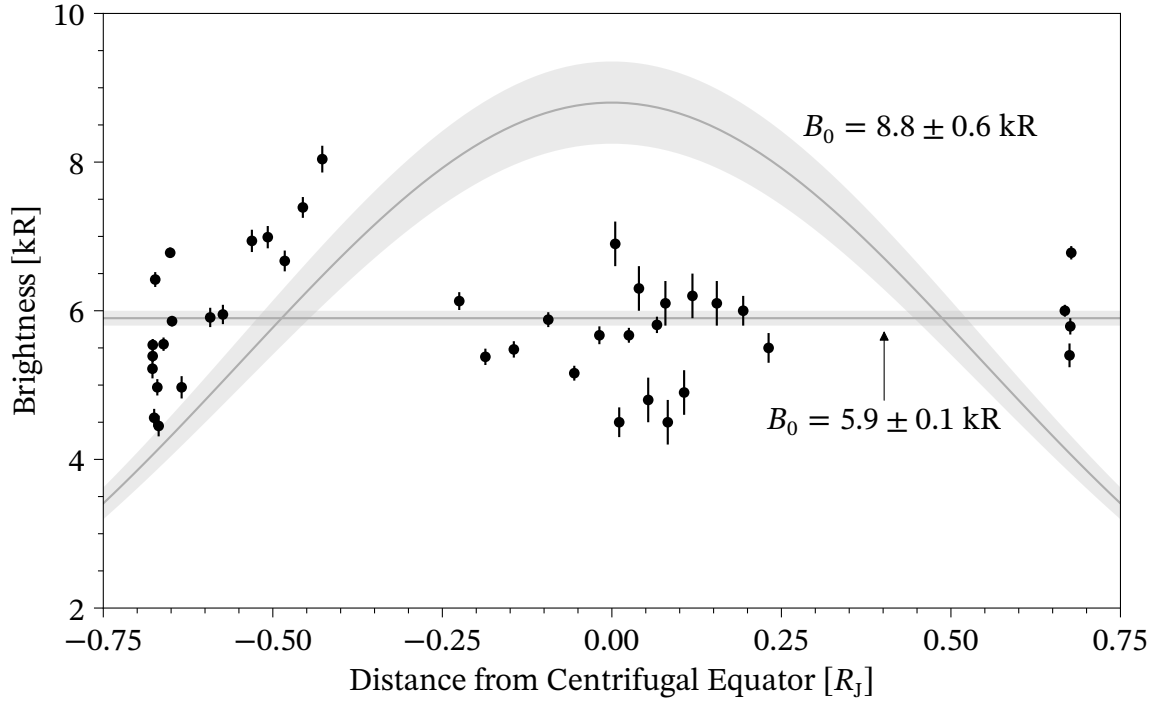


Figure 2.10: Relationship between Io's 630.0 nm auroral brightness and distance from the centrifugal equator. The gray lines show fits of both Equation (2.4) with the scale height fixed at $0.77 R_J$ and a simple constant model. The shaded regions show the uncertainty in the fit (for Equation 2.4 this corresponds to the amplitude n_0 , for the constant this corresponds to the uncertainty in its value). These data suggest that the inherent variability of torus electron density with both longitude and on secular timescales may be on the order of factors of 2 to 3. However, the small quantity of observed brightnesses and the gaps in sampling the distance from the centrifugal equator prevent firm conclusions regarding the connection between brightness and upstream plasma density. (Note that the reported uncertainties are from the weighted fit and do not reflect the standard deviation of the data.)

as suggesting that there may be no intrinsic connection between the density of the upstream electrons in the torus and the brightness of the auroral emission, it could also point to variability in the density of plasma torus electrons both longitudinally within the torus with System III longitude and in terms of bulk torus density on long-term secular timescales. The latter interpretation is consistent with the results of Steffl et al. (2006), Coffin et al. (2020) and Oliverson et al. (2001), the latter of which saw variability in Io's sunlit 630.0 nm [O I] emission by factors of 2 to 3 as a function of System III longitude (see their Figure 4). Regardless, the HIRES data do not show a strong correlation between the upstream electron plasma density and auroral brightness.

The connection between the ambient upstream plasma density and auroral bright-

ness has been evaluated before at Io, Europa and Ganymede. Roth et al. (2014) fit UV observations of Io's 130.4 nm O I, 135.6 nm O I] and 147.9 nm S I emissions and found electron scale heights between 0.8 to 1.0 R_J , though their observations exhibited considerable variance. At Europa, Roth et al. (2016) found some evidence of an exponential decrease in the 130.4 nm O I and 135.6 nm O I] brightnesses with distance from the centrifugal equator (see their Figures 5c and 5d), but their data also showed a large variance. de Kleer et al. (2023) observed a weak correlation between Europa's disk-integrated 630.0 nm aurora brightness and the plasma scale height at its orbit.

Others have shown a connection between the column densities of electrons in the flux tubes above and below a satellite at different positions within the plasma torus. Roth et al. (2016) showed a hemispheric asymmetry in the spatial distribution of the brightness that correlated with Europa's position above or below the plasma sheet centrifugal equator (see their Figure 10), suggesting either excitation from bounce motion along the flux tube or a strong gradient in plasma density within the magnetosphere between Europa's northern and southern hemispheres. Milby et al. (2024) showed that the north-south hemispheric brightness ratio on Ganymede was strongly correlated with its position within the plasma sheet, and specifically with the column density of the flux tube above/below each hemisphere using the Bagenal et al. (2011) plasma scale height at its orbital distance from Jupiter. Unfortunately, the HIRES Io data are likely dominated by emission from the equatorial glow and do not have sufficient spatial resolution to spatially resolve Io's north-south hemispheric limb emission, so we cannot say whether an asymmetry is present in the 630.0 nm HIRES data.

Retherford et al. (2003) attributed a north-south asymmetry in Io's 135.6 nm O I] limb glow to the different electron column densities above and below each hemisphere, which vary with Io's position relative to the centrifugal equator. Auroral excitation would therefore come from electron bounce motion along the flux tubes above and below Io rather than impact of upstream torus electrons due to Jupiter's rotating magnetosphere. This would result in a change in the effective electron column density between the northern and southern hemispheres (and therefore a hemispheric brightness asymmetry), but it should not change the total disk-integrated brightness.

Consequently, we cannot constrain the plasma scale height with the limited sampling of System III magnetic latitudes available through our current set of observations. Additional observations would help to characterize both the random day-to-day variability in the brightnesses and the systematic variability with magnetic longitude.

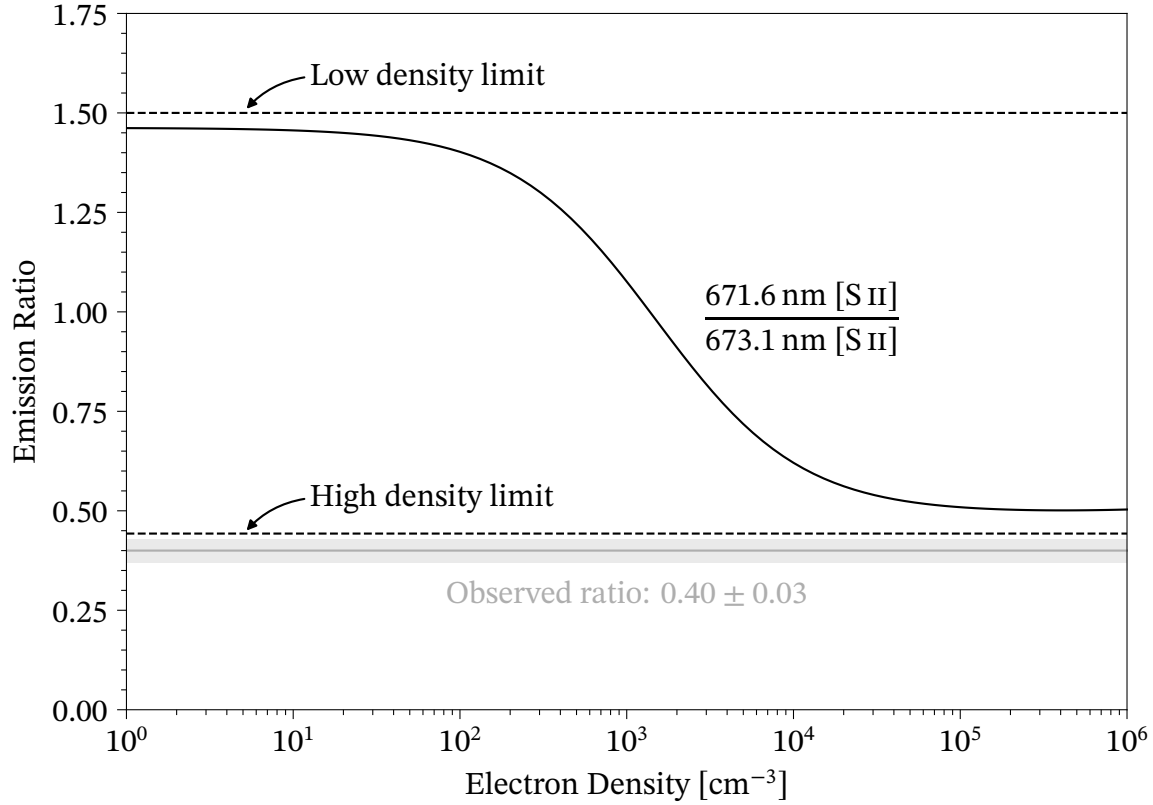


Figure 2.11: Dependence of the 671.6 nm/673.1 nm [S II] brightness ratio on electron number density assuming excitation by 5 eV electrons. The dashed lines show the low- and high-density limits defined in Equations (2.5) and (2.6). The solid gray line and shaded region show the observed ratio of 0.40 ± 0.03 which we calculated as the weighted average of the brightnesses in Table 2.2. Figure based on Osterbrock et al. (2006) Figure 5.8. Calculated using CHIANTI v10.1 (Dere et al., 1997; Dere et al., 2023).

2.4.6 Electron Number Density

Auroral photon emission rates are proportional to both the number density of the exciting electrons and the atmospheric column density, and consequently those two quantities are degenerate. Column densities for the major components of Io's atmosphere are not well constrained and likely variable on both short and long timescales (see Table 19.1 in McGrath et al., 2004), limiting the ability for our auroral emission model to accurately determine the required electron density necessary to produce the brightnesses we observe. Further, our model assumes only direct excitation of neutral atoms and dissociative excitation of neutral molecules and does not currently incorporate other processes that can lead to auroral emission like dissociative recombination of molecular ions.

However, the ratio between certain ion emission lines can be used to derive electron

density without the need to constrain the atmospheric column if those emission lines share the same ground level and have upper levels very close in energy. Two such lines frequently used to study Io's plasma torus are the forbidden 671.6 nm $S^+(^2D_{5/2}^0 \rightarrow ^4S_{3/2}^0)$ and 673.1 nm $S^+(^2D_{3/2}^0 \rightarrow ^4S_{3/2}^0)$ emissions (e.g., Brown et al., 1982; Küppers et al., 1997; Küppers et al., 2000; Nerney et al., 2024). Figure 2.11 shows how the ratio between these two emissions changes with electron densities between 1 and 10^6 cm^{-3} . At low electron densities (below around 100 cm^{-3}) the relative populations of the upper states are determined by their statistical weights $2J + 1$, so the emission line ratio limits to

$$\frac{2J_{671.6 \text{ nm}} + 1}{2J_{673.1 \text{ nm}} + 1} = \frac{2(5/2) + 1}{2(3/2) + 1} = 1.5. \quad (2.5)$$

At larger electron densities, electron collisions begin to de-excite the ions before they have a chance to radiate. Because the 671.6 nm state has a longer lifetime than the 673.1 nm state, collisions preferentially de-excite those ions, and the emission line ratio begins to decrease. Above an electron density of approximately 10^4 cm^{-3} , collisional de-excitation dominates for both states, and emission therefore comes only from the few atoms that survive long enough to radiate. In this case, the emission line ratio is modulated by the relative lifetimes τ of the states, equal to the inverse of the Einstein A coefficients for those emissions ($\tau = 1/A$):

$$\frac{(2J_{671.6 \text{ nm}} + 1)/\tau_{671.6 \text{ nm}}}{(2J_{673.1 \text{ nm}} + 1)/\tau_{673.1 \text{ nm}}} = 1.5 \left(\frac{2.02 \times 10^{-4} \text{ s}^{-1}}{6.84 \times 10^{-4} \text{ s}^{-1}} \right) = 0.44. \quad (2.6)$$

For the 671.6 nm [S II] transition, $A_{671.6 \text{ nm}}$ is the sum of the Einstein A coefficient for electric quadrupole emission $1.88 \times 10^{-4} \text{ s}^{-1}$ and magnetic dipole emission $1.39 \times 10^{-5} \text{ s}^{-1}$ (Podobedova et al., 2009). Similarly, for the 673.1 nm [S II] transition, $A_{673.1 \text{ nm}}$ is the sum of the Einstein A coefficient for electric quadrupole emission $1.21 \times 10^{-4} \text{ s}^{-1}$ and magnetic dipole emission $5.63 \times 10^{-5} \text{ s}^{-1}$ (Podobedova et al., 2009). Dashed gray lines in Figure 2.11 show these limits; the ratio (black line) does not exactly reach these limits due to additional processes modeled by CHIANTI that produce excited S^+ like recombination of S^{2+} .

The region where the emission line ratio is sensitive to changing electron densities (between 100 and $10,000 \text{ cm}^{-3}$) includes the range of electron densities expected in the upstream plasma torus (1200 to 3800 cm^{-3} ; Bagenal et al., 2020). However, the observed ratios (see Table 2.2 and Figure 2.11) are all below the high-density limit at any electron energy. While Io's Alfvén wings have much higher electron number densities (between 1.53×10^4 and $3.1 \times 10^4 \text{ cm}^{-3}$) compared to the surrounding plasma torus (Buccino et al., 2025), the observed ratio from our data is still well below the predicted ratio even for their higher electron number density estimates.

These results indicate that there must be either collisional quenching or additional sources of excited S^+ beyond electron impact on an existing ion column like charge exchange or dissociative recombination of SO^+ and/or SO_2^+ . We also looked at the modeled ratios of the other S^+ emissions at 406.9 and 407.6 nm and the O^+ emissions at 732.0 and 733.0 nm, but neither exhibited notable variability across the range of electron energies and densities plausible for Io's ionosphere and extended atmosphere; therefore, they were not useful diagnostics of either electron energy or density.

2.5 Conclusions

In this study, we analyzed visible and near-infrared auroral emissions from Io taken while it was in eclipse by Jupiter. From these spectra we isolated optical wavelength emissions from a variety of neutral and singly ionized atoms never before spectroscopically detected at Io. These included the O I lines at 777.4 and 844.6 nm, the Na I lines at 818.3 and 819.5 nm, the [S I] lines at 458.9 and 772.5 nm, the S I triplet at 922.3 nm, the [O II] lines at 732.0 and 733.0 nm and the [S II] lines at 406.9, 407.6, 671.6 and 673.1 nm. These new detections more than tripled the number of identified emission lines from Io at visible and near-infrared wavelengths.

We compared our spectral data with *Cassini*/ISS images of Io in eclipse to interpret the spatial distribution of the various emissions. We determined that the limb glow was consistent with electron impact on the atomic coroneae, while the equatorial spots were likely dominated by emission from dissociative impact on the molecular atmosphere. Volcanic plumes exhibited emissions from Na, K, O^+ and S^+ .

The detection of additional optical emission lines allowed us to use our auroral emission model to determine the atmospheric species producing the auroral oxygen emissions. We found that a three-species atmosphere composed of O, SO_2 and O_2 (which we interpreted as a proxy for SO) reproduced the observed emission brightnesses. The derived column densities for SO_2 were consistent with previous studies, but they did not show a clear, systematic decrease after eclipse ingress, suggesting that the molecular atmospheric columns producing auroral emission may be restricted to higher altitudes than the atomic columns. This could be interpreted as evidence for collisional quenching of O at lower altitudes, though the *Cassini*/ISS images isolating forbidden emissions with long lifetimes show emission all the way down to the surface. Alternatively, this could suggest an excitation process more complex than just electron impact on full neutral atomic and molecular columns. In particular, the fraction of the emission resulting from SO_2 may occur at high altitudes where the electron energy is still large enough to

produce dissociative excitation, while the low-altitude emission comes from electron impact on atomic O excited by the lower-energy electrons within Io's ionosphere.

We compared the connection between 630.0 nm [O I] auroral emission and ambient magnetospheric electron density but found only ambiguous evidence for a direct correlation. This could be explained by some combination of System III longitudinal variability in the plasma density or long-term secular variation in the atmospheric column density and/or magnetospheric electron number density. Alternatively, it could also indicate that the excitation came from electron bounce motion within Io's flux tube and therefore the disk-integrated brightness and particularly the equatorial glow were excited by the full electron column rather than the local electron number density. If so, the brightness would be insensitive to Io's vertical position within the torus. The small number of observations currently available prevented us from determining which effect dominates Io's auroral emission. A more comprehensive set of observations covering the full range of System III magnetic longitudes would help determine whether there is additional longitudinal variability in density.

Finally, we analyzed S^+ emission line ratios in order to determine the number density of the emission-exciting electrons, but we found that the observed ratios were incompatible with electron impact on a pure S^+ column, instead requiring additional sources of excited S^+ such as dissociation of ionospheric SO^+ and SO_2^+ . Consequently, the number density cannot be constrained from these data.

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Appendix: *Cassini*/ISS Image Files

Table 2.5 lists the filenames of *Cassini*/ISS Narrow Angle Camera images displayed in Figures 2.3 and 2.5. We accessed these images through the Planetary Data System Image Atlas at <https://pds-imaging.jpl.nasa.gov/search>.

Table 2.5: File names of *Cassini*/ISS images.

Filter	UTC Time ^a	File Name
CLR	12:44:23	N1357390564_1
BL1	11:41:15	N1357386776_1
GRN	11:37:02	N1357386523_1
RED+GRN	11:37:51	N1357386572_1
CB1	11:39:29	N1357386670_1
RED	11:42:04	N1357386825_1
RED+IR1	11:38:40	N1357386621_1
IR1	11:43:00	N1357386881_1
IR2	11:43:56	N1357386937_1
IR3	11:44:52	N1357386993_1

^a At the midpoint of the observation on 2001-01-05.

Chapter 3

EUROPA

Milby, Z., K. de Kleer, C. Schmidt, and M. Camarca (2026). “Variability of Europa’s Optical Aurora on Orbital and Multi-year Timescales”. *The Planetary Science Journal* 7, 3. DOI: 10.3847/PSJ/ae47f4.

Abstract

Europa’s auroras result from interactions between its tenuous atmosphere and the exogenous electron population trapped within Jupiter’s magnetosphere. In this study we analyzed spectra of Europa’s optical wavelength aurora taken during eclipse by Jupiter over ten nights between 2021 and 2025 using Keck I/HIRES. We found the bright 630.0 nm [O I] auroral emission correlated strongly with the expected change in ambient magnetospheric electron density owing to Europa’s changing distance from the centrifugal equator of Jupiter’s magnetic field, suggesting the optical aurora brightnesses can be used as a proxy for measuring electron density variations when assuming a stable atmosphere composition and density. We derived a typical azimuthal heterogeneity in electron densities with System III longitude of about $\pm 11\%$ and a long-term secular variability in the azimuthal average of about $\pm 20\%$ over the four years of observations, consistent with *in situ* measurements of plasma density at Europa’s orbit during the *Galileo* mission. Finally, we determined that any local sublimated water atmosphere present during daytime must collapse to below $2 \times 10^{18} \text{ m}^{-2}$ within the first few minutes of eclipse ingress.

3.1 Introduction

A combination of radiolysis, sputtering and solar-driven sublimation of surface ices produces and maintains Europa’s tenuous exosphere. Observations of its composition and the local plasma environment from within the Jovian system have been limited to intermittent spacecraft flybys (e.g., Wu et al., 1978; Gurnett et al., 1998; Paterson et al., 1999; Kurth et al., 2001; Hansen et al., 2005; Kurth et al., 2023; Allegrini et al., 2024; Ebert et al., 2025). However, the interaction of atmospheric atoms and molecules with electrons trapped in Jupiter’s magnetosphere generates auroral emissions that are also observable from Earth, providing a remote sensing window into both the composition of its atmosphere and local plasma conditions.

Infrared reflectivity measurements of Europa, Ganymede and Callisto led to the first detection of water ice (H₂O) on their surfaces (Pilcher et al., 1972). Wu et al. (1978) made the first detection of far-ultraviolet (FUV) atmospheric emission at Europa resulting from

electron impact excitation of oxygen (O). Subsequent laboratory experiments showed that the impact of hydrogen and helium ions on H₂O ice directly sputtered molecular oxygen (O₂; Brown et al., 1980). Further laboratory experiments showed radiolysis of ices common to the outer Solar System like H₂O, ammonia (NH₃) and methane (CH₄) preferentially liberates volatile diatomic molecules like H₂, O₂ and N₂, governing the composition of their atmospheres and altering surface composition and chemistry (Johnson, 1990, p. 153).

The atmosphere model of Smyth et al. (2006, see their Table 2) included sputtering rates where H₂ production occurred at twice the rate of O₂, while production of H₂O matched the O₂ rate and production of atomic H and O occurred at about half the O₂ rate. While this suggests that H₂O would be the dominant constituent of Europa's atmosphere, it readily freezes back onto the surface. In contrast, diatomic molecules like O₂ and H₂ do not freeze onto or react efficiently with surface ice under typical Europa surface conditions (McGrath et al., 2009; Johnson et al., 2009). The lighter H₂ escapes, generating Europa's neutral torus (Smyth et al., 2006; Johnson et al., 2009) (first observationally confirmed by Szalay et al., 2022) leaving O₂ as the dominant constituent in Europa's atmosphere. The more recent atmosphere model of Vorburger et al. (2018) considered a variety of sputtering processes in addition to sublimation for the source of atmospheric water group atoms and molecules and calculated total surface fluxes differing from each other by orders of magnitude. Johnson et al. (1982) made the first estimates of Europa's bound O₂ exosphere, which they calculated could be sustained at a column density in the range of 2×10^{19} and $3 \times 10^{19} \text{ m}^{-2}$.

Hall et al. (1995) made the first direct detection of Europa's atmosphere using the Goddard High Resolution Spectrograph (GHRS) on the *Hubble Space Telescope* (HST). They observed two ultraviolet (UV) auroral emissions emanating from Europa's trailing hemisphere: the optically allowed 130.4 nm O(3s ³S₁^o → ³P_{2,1,0}) triplet and the semi-forbidden 135.6 nm O(3s ⁵S₂^o → ³P_{2,1}) doublet. Though the observed emissions came from excited oxygen atoms, their analysis of the ratio of the two brightnesses indicated that the source was dissociative electron-impact excitation of O₂, not direct excitation of an atomic oxygen column. Hall et al. (1998) made a more detailed analysis of these observations in combination with the first UV detection of similar emission from Ganymede.

The auroras observed by Hall et al. (1995) and subsequent studies result from the interaction of exogenic charged particles with atmospheric atoms and/or molecules. To date, most auroral emissions detected at Europa come from atomic oxygen, though emissions from atomic sodium (Na) and potassium (K) excited by solar photons have

also been observed in its extended exosphere (Brown et al., 1996; Brown, 2001; Lovett et al., 2025).

The satellites are shielded from solar photons and photoelectrons during eclipse, so excitation results exclusively from collisions between magnetospheric electrons and oxygen-bearing atmospheric particles and therefore the emissions are auroral in nature. For atomic O, this can result in direct excitation to a higher energy state. For molecules like O₂, H₂O or CO₂, production of a higher energy oxygen atom requires dissociative excitation. As the higher energy O atom relaxes to a lower energy state, it emits an auroral photon. (The lower energy state is not necessarily the ground state O(³P₂), since many observed transitions are between other non-ground levels.)

Electron-impact excitation of O atoms and/or dissociative excitation of O-bearing molecules in Europa's atmosphere can result in oxygen fragments in both metastable and Rydberg states (for a comprehensive overview, see McConkey et al., 2008). Oxygen atoms in metastable states have long lifetimes from seconds to tens of minutes, and these states emit forbidden emission lines only if the excited state is not quenched by inter-particle collisions before the photon is radiated (Wiese et al., 1996). At optical wavelengths, these emissions include the forbidden 557.7 nm O(¹S₀ → ¹D₂) line (a forbidden electric quadrupole transition with a 0.8 s lifetime), the 630.0 and 636.4 nm O(¹D₂ → ³P_{2,1}) lines (forbidden magnetic dipole transitions with 3- and 9-minute lifetimes, respectively) and the optically allowed 777.4 nm O(3p ⁵P_{3,2,1} → 3s ⁵S₂⁰) and 844.6 nm O(3p ³P_{0,2,1} → 3s ³S₁⁰) triplets (allowed electric dipole transitions with 27 and 31 ns lifetimes, respectively; Wiese et al., 1996).

de Kleer et al. (2018) first studied Europa's optical wavelength aurora using a combination of data from the HST Space Telescope Imaging Spectrograph (STIS) and the High Resolution Imaging Spectrometer (HIRES; Vogt et al., 1994) on the Keck I telescope at the summit of Maunakea. Using the STIS spectra they made the first detections of the 630.0 and 636.4 nm [O I] emissions from Europa in eclipse and derived an O₂ column density between 1×10^{18} and $9 \times 10^{18} \text{ m}^{-2}$ assuming the median electron properties derived by Bagenal et al. (2015). Unfortunately, non-photometric observing conditions on Maunakea prevented them from assigning anything more than upper limits to the 630.0 and 636.4 nm [O I] brightnesses using their single night of HIRES data.

de Kleer et al. (2023) analyzed additional HIRES data taken over three nights in 2021 under photometric observing conditions and made the first detections of the 557.7 nm [O I] and 777.4 nm O I emissions from average spectra with total integration times between 40 and 60 minutes. They derived an average O₂ column density of $(4.1 \pm 0.1) \times 10^{18} \text{ m}^{-2}$ and calculated an H₂O/O₂ ratio of about 25%. They placed an

upper limit of 10^{17} m^{-2} on the atomic O column, consistent with the upper limit of $6 \times 10^{16} \text{ m}^{-2}$ derived from UV observations by Roth (2021).

While these observational studies have assumed optically thin, non-collisional atmospheres in order to simplify the derivation of column densities from auroral brightnesses, recent modeling work by Carberry Mogan et al. (2024) shows that non-thermal collisions between O_2 molecules and O atoms produced by electron-impact dissociation of O_2 have a non-negligible effect. These collisions produce a non-thermal O_2 component in the atmosphere at high altitudes and enhance the total O_2 escape rate. Because of the long lifetimes of the forbidden states of O atoms, this could reduce the total observed auroral brightness (especially reducing the observed 630.0 nm/557.7 nm emission ratio) and result in lower derived O_2 column densities.

Previous studies of Europa’s aurora have not examined its intra-eclipse variability over short timescales of 10 minutes or less. The comprehensive study by Roth et al. (2016) characterized Europa’s UV aurora, but they did not conduct high cadence analysis on timescales shorter than HST’s observing windows. The optical study by de Kleer et al. (2023) used average spectra for each individual eclipse in order to detect the faint 557.7 nm [O I] and 777.4 nm O I emissions, though they did use 630.0 and 636.4 nm [O I] emissions in individual spectra (each with five-minute integration times) to derive the plasma scale height at Europa’s orbit within the Jovian magnetosphere.

For this study, we analyzed the individual HIRES spectra taken during the three eclipses reported in de Kleer et al. (2023) along with spectra from six additional eclipses observed between 2022 and 2025 (described in Table 3.1). We used detections of the 557.7, 630.0 and 636.4 nm [O I] emissions in the individual spectra, each integrated for just a few minutes, to analyze the connection between the auroral brightness and the ambient electron density on both short, few-minute timescales and longer secular changes over the four years of the observations. Finally, we evaluated the expected contribution to the observed brightnesses from the H_2O atmosphere proposed by Roth (2021) to determine whether it would be detectable in the HIRES spectra and, if so, what limits could be placed on the timescale for water vapor to condense as Europa’s surface cools following its ingress into Jupiter’s shadow. (However, note that the H_2O atmosphere proposed by Roth (2021) was only for the Europa’s trailing hemisphere and may not be detectable in observations of the sub-Jovian hemisphere even if present.)

3.2 Observations and Data Reduction

We observed Europa in eclipse on 10 nights between 2021 and 2025 using Keck I/HIRES, summarized in Table 3.1. For the 2021 observations we used the D3 slit with a projected

Table 3.1: Overview of the Keck I/HIRES observations of Europa in eclipse.

Date ^a [UTC]	Program ID ^b	Used / Total ^c	λ_m^d [deg]	ϕ_m^e [deg]	r_I^f [R_J]	d^g [R_J]	v_{rel}^h [km s ⁻¹]
2021-05-20 [†]	C294	8 / 8	−0.200 to −5.799	69.1 to 33.3	9.403	0.003 to −0.683	−23.1 to −24.0
2021-06-21 [†]	C294	17 / 17	−8.743 to −0.616	312.4 to 250.9	9.439	−1.048 to −0.038	−19.8 to −21.4
2021-07-16 [†]	C294	9 / 10	−1.119 to 4.619	254.1 to 217.8	9.459	−0.106 to 0.612	−13.1 to −14.1
2022-08-18	N059	10 / 10	−2.289 to −7.748	58.2 to 19.5	9.428	−0.220 to −0.892	−14.4 to −15.4
2023-08-12	N018	15 / 16	−3.516 to −9.733	50.0 to 349.0	9.339	−0.378 to −1.139	−22.1 to −23.8
2024-10-08	N078	15 / 18	9.414 to 4.842	165.4 to 99.3	9.328	1.146 to 0.585	−20.0 to −21.9
2024-11-02	C377	0 / 8	4.151 to −0.143	94.8 to 67.8	9.357	0.506 to −0.024	−14.0 to −14.8
2025-02-06	C414	18 / 18	2.919 to −6.997	86.2 to 19.8	9.463	0.348 to −0.892	25.1 to 23.3
2025-03-03	C414	4 / 4	−9.259 to −8.829	333.8 to 321.2	9.475	−1.171 to −1.120	25.6 to 25.2
2025-11-10	N119	13 / 15	−8.965 to −7.037	350.0 to 300.5	9.303	−1.129 to −0.903	−20.3 to −21.7

Notes. Systematic detector issues caused problems retrieving the 630.0 nm [O I] brightness from all observations on 2024-11-02, so we eliminated all data from this date from our analysis. Additional issues with background subtraction caused us to remove the data with UTC time stamps 2021-07-16T11:19:43.000, 2023-08-12T13:11:09.000, 2024-10-08T13:17:10.000, 2024-10-08T13:24:11.000, 2024-10-08T13:31:30.000, 2025-11-10T13:00:04.000 and 2025-11-10T14:32:51.000.

^a UTC date on Maunakea at the start of the observations.

^b Keck Observatory Archive program ID.

^c Number of spectra used out of the total number of spectra taken; each spectrum had a five-minute integration time.

^d Magnetospheric latitude of Europa over the range of observations.

^e Magnetospheric longitude of Europa over the range of observations. This is the same as the System III west longitude, but converted here to east longitude.

^f Europa's orbital distance from Jupiter.

^g Distance between Europa and the plasma sheet centrifugal equator; positive when Europa is above the midplane and negative when Europa is below the midplane.

^h Velocity of Europa relative to an observer on Earth (the negative sign indicates motion toward the observer).

[†] Previously published by de Kleer et al. (2023).

angular size on the sky of $1.722'' \times 7''$, but for the subsequent nights we switched to using the longer $1.722'' \times 14''$ D4 slit to allow for a better background characterization and subtraction. We reverted to using the D3 slit for the 2024-10-08 observations as a test of our background subtraction algorithm, but we continued with the D4 slit for the remaining nights.

We used the same eclipse observing method as previous HIRES studies of Galilean satellite optical aurora (e.g., Bouchez et al., 2000; de Kleer et al., 2018; de Kleer et al., 2023; Schmidt et al., 2023; Milby et al., 2024; Milby et al., 2025). On two of the nights (the 2025 observations) we observed Europa during eclipse egress. On the remaining nights (2021 through 2024) we observed Europa during eclipse ingress. We used Io as the guide satellite during the 2021, 2022 and 2023 observations. For the 2024 and 2025 observations we used Ganymede as the guide satellite, with the exception of 2024-11-02 when we used Callisto.

We reduced and calibrated the data using the methodology and pipelines described in de Kleer et al. (2023), Milby et al. (2024) and Milby et al. (2025). Along with the science exposures of Europa in eclipse and the guide satellites listed above, we took flux calibration spectra of Jupiter’s sub-observer meridian (following Woodman et al., 1979), a trace spectrum of a standard star and a typical set of CCD preprocessing data including bias images, flat-lamp exposures and thorium-argon (ThAr) arc lamp spectra. All of these data are available from the Keck Observatory Archive under the program ID numbers listed in Table 3.1 (these ID numbers are not unique and must be queried in conjunction with the semester or UTC date). Across these 10 nights we collected a total of 124 spectra of Europa, each with an integration time of five minutes, but we eliminated 15 owing to systematic issues with either the HIRES detectors (affecting all spectra taken on 2024-11-02) or background subtraction artifacts, leaving a total of 109 individual spectra for this analysis.

3.2.1 Systematic Uncertainties

The forbidden 630.0 and 636.4 nm [O I] emission lines have a brightness ratio of 3.09 under optically thin conditions where de-excitation takes place only through spontaneous photon emission (Wiese et al., 1996). Under collisional de-excitation (quenching), the longer-lifetime 636.4 nm [O I] line would weaken, changing the apparent brightness ratio. When Milby et al. (2024) evaluated this ratio for eclipse spectra of Ganymede, they found that the ratio was lower than expected, so they added an additional 9% systematic uncertainty into all their retrieved brightnesses to account for it. However, when Milby et al. (2025) performed the same analysis on the much brighter emissions from Io, they

found the ratio consistent with expectations and did not add any additional systematic uncertainty.

We analyzed the 630.0 and 636.4 nm [O I] emission line brightnesses from Europa in eclipse and found that the ratio was lower than expected, similar to the results of Milby et al. (2024) for Ganymede. However, because the Europa emissions are brighter than those from Ganymede, we found that we only needed to add an additional 5% systematic error to the brightness measurements. Reported detectability thresholds (upper limits) do not have any additional systematic error added to them.

3.3 Analysis

3.3.1 Auroral Emission Line Detections

de Kleer et al. (2018) made the first eclipse detections of Europa’s forbidden 630.0 and 636.4 nm $O(^1D_2 \rightarrow ^3P_{2,1})$ emissions using HST/STIS. de Kleer et al. (2023) leveraged higher signal-to-noise Keck I/HIRES spectra to make the first eclipse detection of the spin-forbidden 557.7 nm $O(^1S_0 \rightarrow ^1D_2)$ emission and the optically allowed 777.4 nm $O(3p\ ^5P_{3,2,1} \rightarrow 3s\ ^5S_2^o)$ triplet emissions using averages of the 2021-05-20, 2021-06-21 and 2021-07-17 UTC spectra also used in this study. However, they reported a signal-to-noise ratio of just 2 for the 777.4 nm line, and they were only able to detect the emission in the average 2021-05-20 spectrum. Within individual spectra with five-minute integration times, we were able to detect (at a signal-to-noise ratio of 2 or greater) the three bright forbidden oxygen emissions at 557.7, 630.0 and 636.4 nm (see Figure 3.1 for example images of each of these three emission lines). For the 656.3 nm H α and the 777.4 and 844.6 nm O I emissions we have instead reported 1σ detectability thresholds. Figure 3.2 shows each of the individual brightnesses (or upper limits) sorted by time since umbral ingress. Lines connect individual observation sequences to better illustrate their individual variability. Overall, the brightnesses are fairly consistent over the course of a single night, but average magnitudes vary from night to night. The overall average brightness and standard deviation of the detected emission lines across all the nights are (44 ± 19) R for the 557.7 nm [O I] line, (720 ± 190) R for the 630.0 nm [O I] line and (240 ± 60) R for the 636.4 nm [O I] line.

3.3.2 Auroral Emission Model

We used the same version of the auroral emission model as Milby et al. (2025), built on the previous version developed by Milby et al. (2024), de Kleer et al. (2023) and de Kleer et al. (2018). This model includes cross sections for hydrogen and oxygen emissions within the HIRES wavelength sensitivity range, including the 557.7, 630.0

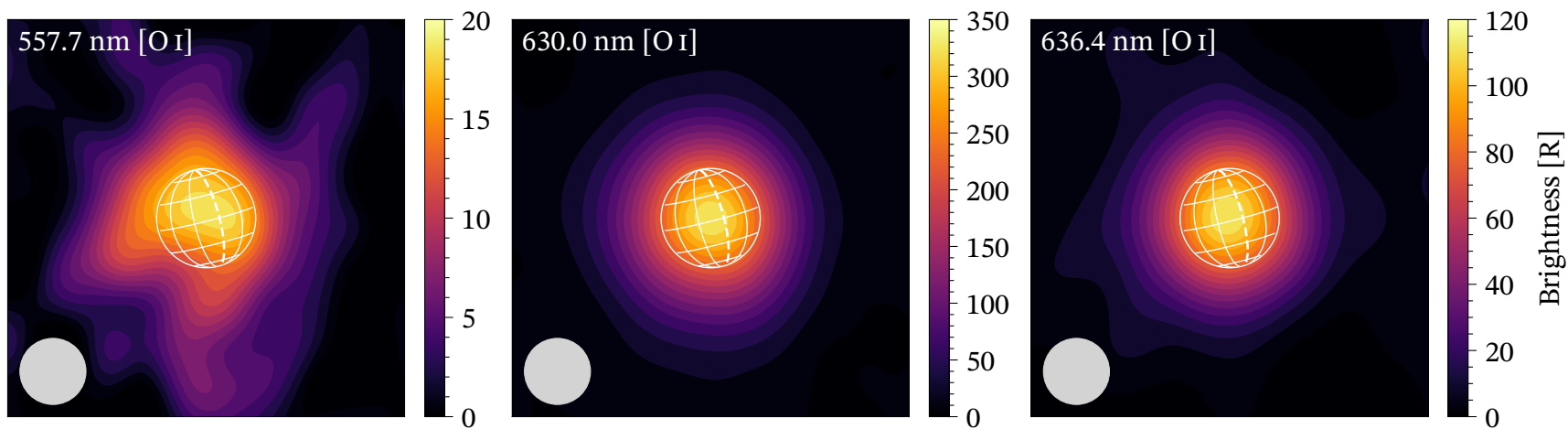


Figure 3.1: Example HIREs data showing the three oxygen emission lines identified in individual five-minute integrations. Calibrated brightnesses reported in this study assume emission from Europa's apparent solid angular disk; consequently, the brightness distribution in the images appears lower owing to blurring from atmospheric seeing and the presence of any extended coronal emission. White graticules show the physical size and orientation of Europa, with north oriented approximately upward. Dashed lines show the prime meridian. Telescope pointing accuracy was not sufficient to determine the position of the emission relative to Europa's apparent disk, so we centered the images and graticules on the brightness centroids to illustrate the relative extent of the emission. Gray circles in the lower left corner show the typical Maunakea seeing FWHM of around $0.6''$ (see statistics compiled at <http://mkwc.ifa.hawaii.edu/forecast/mko/stats/>).

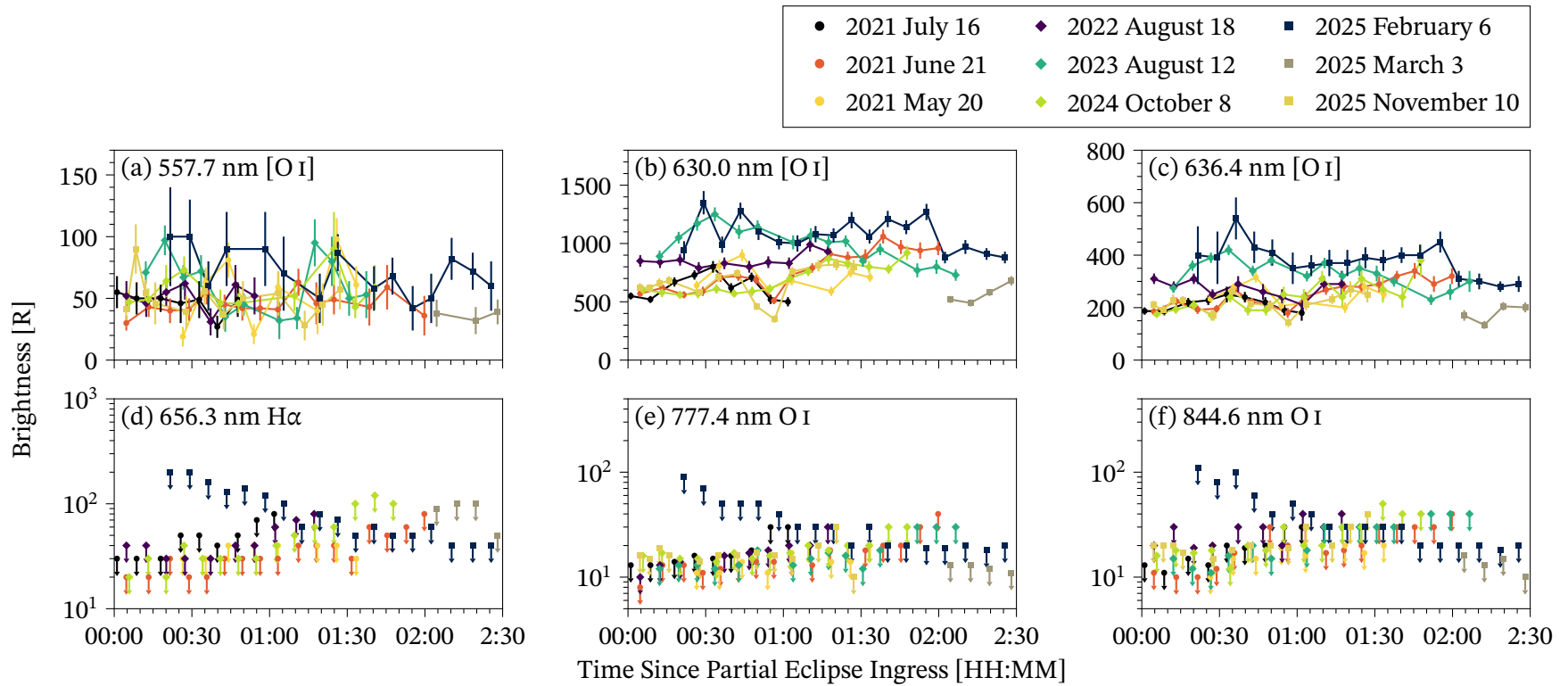


Figure 3.2: Calibrated auroral brightnesses for (a) 557.7 nm [O I], (b) 630.0 nm [O I], (c) 636.4 nm [O I] and 1σ detectability thresholds for (d) 656.3 nm H α , (e) 777.4 nm O I and (f) 844.6 nm O I sorted by time since partial eclipse ingress. Solid lines connect the time series of observations from a single night for detected emission lines (panels a to c). Larger detectability thresholds result from Europa's angular proximity to Jupiter: when Europa is close to Jupiter's limb, the scattered light is significantly larger which affects the fidelity of the background subtraction, resulting in larger upper limits (and uncertainties for detected lines) at either the beginning or end of a single night of observations. Perceptually uniform colors and symbols (circles, diamonds and squares) differentiate separate observing nights to allow the reader to evaluate the goodness of fit on a night-to-night basis, detailed in the legend in the upper right corner. (This legend also applies to Figures 3.6, 3.7, 3.8, 3.9 and 3.10.)

and 636.4 nm [O I] and 777.4 and 844.6 nm O I emissions resulting from electron impact on O, O₂, H₂O and CO₂ along with 656.3 nm H α emission from electron impact on H₂O. These cross sections combined with assumed electron energy distributions and number densities allowed us to calculate best-fit column densities for O, O₂ and H₂O and estimate brightnesses of both lines we did not detect and lines outside of the wavelength range of the HIRES instrument.

In this model, the emission rate coefficient γ_λ in [ph m³ electron⁻¹ particle⁻¹ s⁻¹] at wavelength λ for electron impact on atmospheric constituent s is

$$\gamma_\lambda = \int_0^\infty \sigma_{\lambda,s} v \, dE \quad (3.1)$$

where E is electron energy in [J], $\sigma_{\lambda,s}$ is the energy-dependent emission cross section at wavelength λ for electron impact on species s in [m² ph electron⁻¹ particle⁻¹] (though they are often reported just in area units) and v is the Maxwell-Boltzmann probability distribution of the electron energies in [s kg⁻¹ m⁻¹].

The total auroral brightness in [ph m⁻² s⁻¹] at a wavelength λ is the sum of all the emitting columns

$$B = n_{e^-} \sum_s \gamma_s N_s, \quad (3.2)$$

where n_{e^-} is the incident electron number density in [electrons m⁻³] and N_s is the atmospheric column density of constituent s in [particles m⁻²]. This can be converted to column emission rate in rayleighs (R) using the definition

$$1 \text{ R} \equiv 10^{10} \text{ ph m}^{-2} \text{ s}^{-1}, \quad (3.3)$$

the provenance and uses of which Baker et al. (1976) describe in detail.

For our analysis we assumed the upstream median electron density of 158 cm⁻³ derived by Bagenal et al. (2015) from *Galileo* flyby observations at Europa's orbit with 95% at 20 eV and 5% at 300 eV (see their Table 5), the same assumption used by de Kleer et al. (2018), Roth (2021) and de Kleer et al. (2023). Prior studies like Hall et al. (1995), Hall et al. (1998) and Roth et al. (2016) used a canonical density of 40 cm⁻³ and a slightly different energy partition of 95% at 20 eV and 5% at 250 eV derived from *Voyager 1* flyby data (Sittler et al., 1987; Bagenal et al., 2011).

Because the brightness (and consequently the derived column densities) are linearly proportional to the electron number density (Equation 3.2), deriving the expected column density for other electron density cases like the 10th- and 90th-percentile values

from Bagenal et al. (2015) and the 40 cm^{-3} measured during the *Voyager 1* flyby involves a simple multiplicative factor. For studies using the *Voyager*-era electron density like Hall et al. (1995), Hall et al. (1998) and Roth et al. (2016), the column densities reported must be multiplied by a factor of $1/4$ for comparison to those we report in this study and other more recent studies like Roth (2021). For studies that use the median density from Bagenal et al. (2015) like ours, column densities must be multiplied by a factor of $1/2.5$ for the 10th-percentile “low/hot” electron case and by a factor of 1.8 for the 90th-percentile “high/cold” case. Further, all of our derived column densities are disk-averaged quantities for the sub-Jovian hemisphere during eclipse. Consequently, the upper limits are not absolute because our analysis assumes that both the neutral atmosphere and electron fluxes are co-located and have uniform properties, which is not necessarily true if the atmosphere is patchy or the electron flux is non-uniform across the disk.

Recent *Juno* measurements have found electron densities consistent with both the *Voyager*-era and *Galileo*-era measurements. Kurth et al. (2023) analyzed observations obtained by *Juno*/Waves during the 2022-09-29 flyby of Europa and measured upstream electron densities varying between 50 cm^{-3} (comparable to the *Voyager*-era measurement) and 150 cm^{-3} (comparable to the median case of Bagenal et al., 2015). Kurth et al. (2023) also found an increase in electron density to approximately 330 cm^{-3} in the wake over Europa’s leading hemisphere. Allegrini et al. (2024) analyzed *Juno*/JADE observations during the same flyby and discovered field-aligned electron beams over the same hemisphere with energies ranging from 30 to 300 eV. While these localized increases in electron density modify the brightness of electron-impact-excited auroral emissions, their effect on emission observable over the sub-Jovian hemisphere has not been quantified, and we therefore do not account for plasma interactions that can change both the density and energy distribution of the electrons near Europa (see also Saur et al., 1998; Dols et al., 2016).

3.3.3 Determining Distance from the Centrifugal Equator

Coupling of the plasma to Jupiter’s magnetic field applies centrifugal forces due to corotation (Michel et al., 1974), resulting in the highest number densities occurring along the “centrifugal symmetry surface” or “centrifugal equator” (Gledhill, 1967; Hill et al., 1974). This surface (equator) is the point along any particular field line farthest from the rotation axis. Phipps et al. (2021) derived an analytical solution for calculating the planetographic latitude λ of the centrifugal equator as a function of distance from

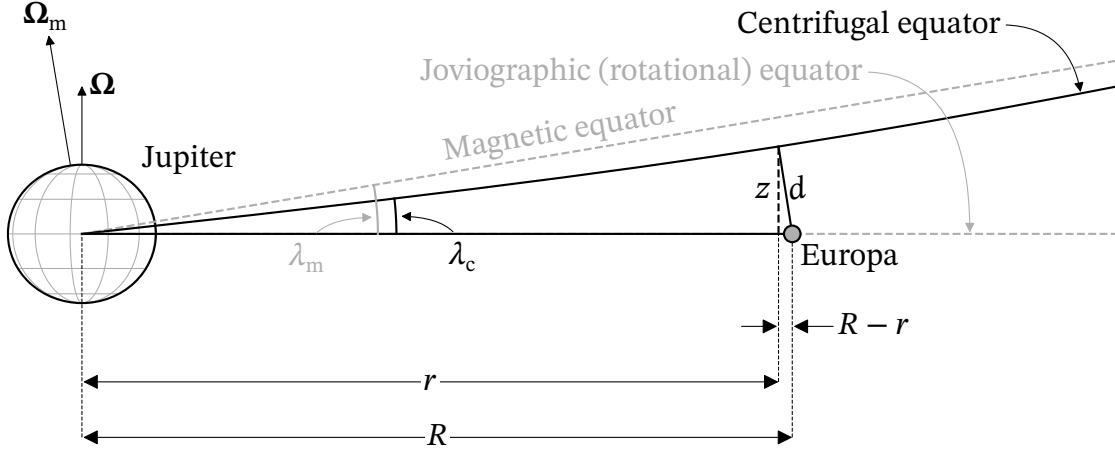


Figure 3.3: Geometric relationships between the centrifugal equator of the Jovian plasma sheet and Europa depicted at one of the maximum displacements between the magnetic and planetographic equators. Ω_m is the magnetic field north pole axis, offset by 9.5° from the planetographic rotation axis Ω toward 159.2° System III east longitude. R is Europa's instantaneous orbital distance from Jupiter. r is the distance along the planetographic equator that minimizes the length of the hypotenuse d of the right triangle with legs $z(r)$ and $(R - r)$. This corresponds to the ray perpendicular to the centrifugal equator that intersects Europa and minimizes the distance between Europa and the centrifugal equator. Based on Milby et al. (2024), Figure 3. Europa scaled up by a factor of 5.

Jupiter r and System III east longitude ϕ as

$$\lambda_c(r, \phi) = \left(1.66^\circ \tanh \left(0.131 \text{ rad} \frac{r}{R_J} - 1.62 \text{ rad} \right) + 7.76^\circ \right) \sin(\phi - 249.2^\circ), \quad (3.4)$$

where $R_J = 71\,492$ km is Jupiter's equatorial radius (Archinal et al., 2018).

Jupiter's magnetic field is primarily dipolar (Hill et al., 1974) and the first-order harmonic coefficients from the *Voyager*-era VIP4 model (Connerney et al., 1998) indicate that the magnetic field dipole axis Ω_m is offset from the magnetic field rotation axis Ω to a colatitude of 9.5° at 159.2° System III east longitude. The more up-to-date *Juno*-era JRM33 model (Connerney et al., 2022) moves Ω_m to a slightly lower colatitude of 10.25° and further to the east at 163.6° System III east longitude. Because Phipps et al. (2021) used the VIP4 model for their derivation of the centrifugal equator latitude, we also used the VIP4 dipole axis coordinates for our analysis. For the precision of our individual measurements the slight difference between the two models will not introduce noticeable systematic error.

Hill et al. (1976) showed that the plasma exhibits a Gaussian density profile perpendicular to the centrifugal equator of the form

$$n(r, d) = n_0(r) e^{-(d/H(r))^2}, \quad (3.5)$$

where n_0 is the plasma density at radial distance r from Jupiter's center, d is the distance from the centrifugal equator and $H(r)$ is the scale height (calculated using average ion mass and energy) at the same radial distance. However, because of the shape of the deviation of the centrifugal equator from the magnetic equator, the calculation of d for a particular observation is more complex than a simple trigonometric exercise. We calculated d by first determining the instantaneous planetographic latitude λ_c of the centrifugal equator (Equation 3.4). We then determined the distance between Europa and the centrifugal equator

$$d(r, \phi) = \sqrt{(R - r)^2 + z(r, \phi)^2} \quad (3.6)$$

where R is Europa's instantaneous orbital distance from Jupiter,

$$z(r, \phi) = r \tan(-\lambda_c(r, \phi)) \quad (3.7)$$

is the height of the centrifugal equator from the rotational equator and r is the solution to

$$\frac{\partial}{\partial r} d(r, \phi) = 0. \quad (3.8)$$

Figure 3.3 shows a graphical description of this geometry for a System III east longitude of 339.2° depicting one of the maximum offsets between the rotational and centrifugal equators (the other maximum occurs at 159.2°). At Europa's orbit, the offset between the magnetic and centrifugal equators is near its maximum, and while we used the carefully calculated distance value of d as depicted, the value of $R - r$ is never particularly large (at most about $0.19 R_J$, and therefore the difference between d and z is relatively small, typically less than $0.015 R_J$ or about $0.7 R_E$).

The plasma corotation velocity at Europa's orbit is about 118 km s^{-1} , but due to Europa's orbital velocity of around 14 km s^{-1} the actual incident plasma velocity is approximately 104 km s^{-1} (Archinal et al., 2018). This means that it takes about 11h 14m for Jupiter's magnetic field to complete one rotation relative to Europa. Further, due to the 9.5° offset of the magnetic field axis, there are two nodes where the centrifugal equator intersects with Europa's orbital plane (at System III east longitudes of 69.2° and 249.2°). Figure 3.4 shows a three-dimensional projection of Europa's orbit around Jupiter and the closest positions along the centrifugal equator, showing how Europa's distance changes with System III longitude.

3.3.4 Electron Density Modulation with Plasma Scale Height

To be consistent with recent studies like Roth et al. (2016) and de Kleer et al. (2023) we used the plasma scale height of $1.7 R_J$ derived by Bagenal et al. (2011) using a combination

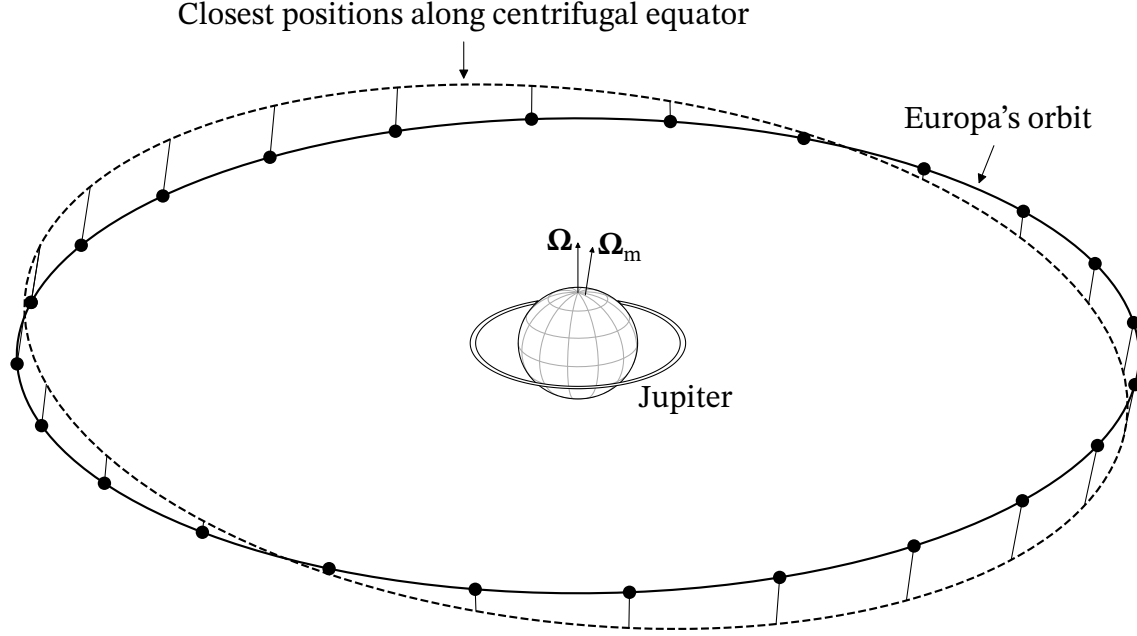


Figure 3.4: Three-dimensional projection of Europa's minimum distance from the centrifugal equator. The projection viewpoint is centered in System III coordinates above 25° latitude, 100° east longitude. Thin gray lines on Jupiter's spheroid show System III latitude and longitude with 30° spacing, and the ring shown is Jupiter's Main ring. Vectors show the planetographic rotation axis Ω and magnetic field north pole axis Ω_m . The solid black ring shows the location of Europa's orbit. The dashed black line shows the closest positions along the centrifugal equator as described in Figure 3.3. Small black circles show Europa's position every 15° in longitude, and thin black lines connect from the orbital position to the closest point along the centrifugal equator. Nodes at the intersection of Europa's orbit and the centrifugal equator are at 69.2° and 249.2° System III east longitude. Europa scaled up by a factor of 5.

of *Voyager 1* Plasma Science Experiment (PLS) and *Galileo* Plasma Subsystem (PLS) measurements. However, Bagenal et al. (2015) showed how variable measurements of plasma properties were at Europa's orbit during the *Galileo* era, and the parameters listed in their Table 5 allowed us to calculate the range of potential scale heights the plasma at Europa's orbit might exhibit. Assuming that the average ion energy is much larger than the electron energy, Equation (5) of Bagenal et al. (2011), describes the plasma scale height within Jupiter's magnetosphere as a function of average ion parameters

$$H = 0.64 R_J \sqrt{\xi \frac{\langle E_{\text{ion}} \rangle}{\langle m_{\text{ion}} \rangle}}, \quad (3.9)$$

where H is the scale height, $\langle E_{\text{ion}} \rangle$ is the average ion energy, $\langle m_{\text{ion}} \rangle$ is the average ion mass and ξ is the ratio of the atomic mass unit (u) to the electron volt (eV). For all percentiles

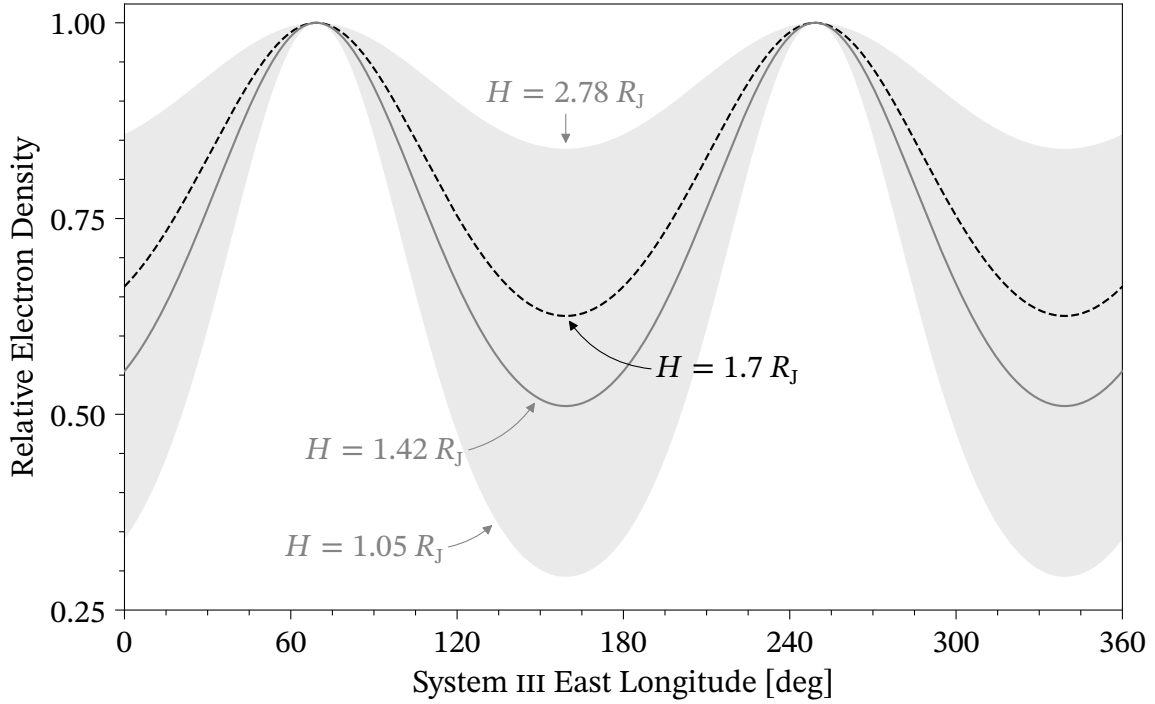


Figure 3.5: Relative ambient electron density as a function of System III east longitude for a plasma scale height of $1.7 R_J$ (Bagenal et al., 2011), calculated at Europa’s orbital distance from Jupiter ($9.4 R_J$) assuming azimuthal homogeneity in electron density along the centrifugal equator.

the average ion mass is 18 u. For the 10th-percentile “low/hot” case, the average ion energy is 340 eV and the scale height is $2.78 R_J$. For the median case, the average ion energy is 88 eV and the scale height is $1.42 R_J$. For the 90th-percentile “high/cold” case, the average ion energy is 48 eV and the scale height is $1.05 R_J$.

Figure 3.5 shows the relative electron density at Europa’s average semimajor axis of $9.4 R_J$ as a function of System III east longitude for this range of scale heights. The dashed black line shows a plasma scale height that decreases to $1/e$ at $1.7 R_J$ from the centrifugal equator (Bagenal et al., 2011). The solid gray line shows the same change for the median plasma scale height of $1.42 R_J$, while the shaded gray region shows the 10th- and 90th-percentile “low/hot” ($2.78 R_J$) and “high/cold” ($1.05 R_J$) boundaries based on a reanalysis of both *Galileo*/PLS and *Galileo* Plasma-Wave Subsystem (PWS) measurements as detailed in Bagenal et al. (2015, their Table 5). Though the relative densities appear sinusoidal with System III longitude, they are actually the superposition of two Gaussian profiles. The plausible ranges derived from the Bagenal et al. (2015) plasma properties show the substantial range in expected brightness that could occur for electron impact on a stable atmosphere: from around a 15% reduction in brightness for

the “low/hot” case with the large scale height to around a 70% reduction in brightness for the “high/cold” case.

3.4 Results and Discussion

3.4.1 Eclipse Atmosphere Composition

Figure 3.6 shows the column densities we derived using our auroral emission model with the median electron density of 158 cm^{-3} from Bagenal et al. (2015). The model results show that the only statistically significant atmospheric component is O_2 , while any O and/or H_2O components could not be detected from the observed emission brightnesses and corresponding uncertainties. This suggests that the observed 557.7, 630.0 and 636.4 nm [O I] brightnesses combined with the 1σ upper limits for the 656.3 nm $\text{H}\alpha$ and the 777.4 and 844.6 nm O I lines can be produced by an O_2 column with a disk-averaged density of $(4.6 \pm 0.2) \times 10^{18} \text{ m}^{-2}$ over the sub-Jovian hemisphere (see Figure 3.6) assuming excitation by the median upstream electron population. This column density is half of that derived by Roth et al. (2016) using an electron density of 40 cm^{-3} ; normalizing for the same electron density as our analysis would change their derived column to $2.3 \times 10^{18} \text{ m}^{-2}$, about half of our derived value. Roth (2021) derived an O_2 column density of about $2.5 \times 10^{18} \text{ m}^{-2}$ on Europa’s trailing hemisphere, again about half the magnitude of the column we derived using the optical auroral emissions. de Kleer et al. (2023) calculated an average O_2 column density of $(4.1 \pm 0.1) \times 10^{18} \text{ m}^{-2}$, though they used only three of the eight nights of data we used in our extended study.

The observed brightnesses and their uncertainties did not require any statistically significant contribution from either O or H_2O . We calculated average 1σ column density detectability thresholds for an individual five-minute integration of $1.1^{+1.1}_{-0.5} \times 10^{18} \text{ m}^{-2}$ for O and $1.9^{+1.0}_{-0.7} \times 10^{18} \text{ m}^{-2}$ for H_2O .

Table 3.2 lists the emission brightnesses predicted by our model for the average O_2 column and its standard deviation along with the brightnesses of the average 1σ upper limits of the O and H_2O columns. At these upper limits both O and H_2O contribute negligibly to the detected 557.7, 630.0 and 636.4 nm [O I] lines. Consequently, given the typical uncertainties on individual brightness measurements, the observed 557.7, 630.0 and 636.4 nm [O I] lines are not sensitive to either the O or H_2O column densities proposed by other observational or modeling studies, most of which are below our derived upper limits.

For atomic O, past derived column densities typically fall between 10^{16} and 10^{17} m^{-2} (e.g., Hansen et al., 2005; Smyth et al., 2006; Roth et al., 2016; Roth, 2021), at least an order of magnitude smaller than our upper limits. For H_2O , both observed and modeled

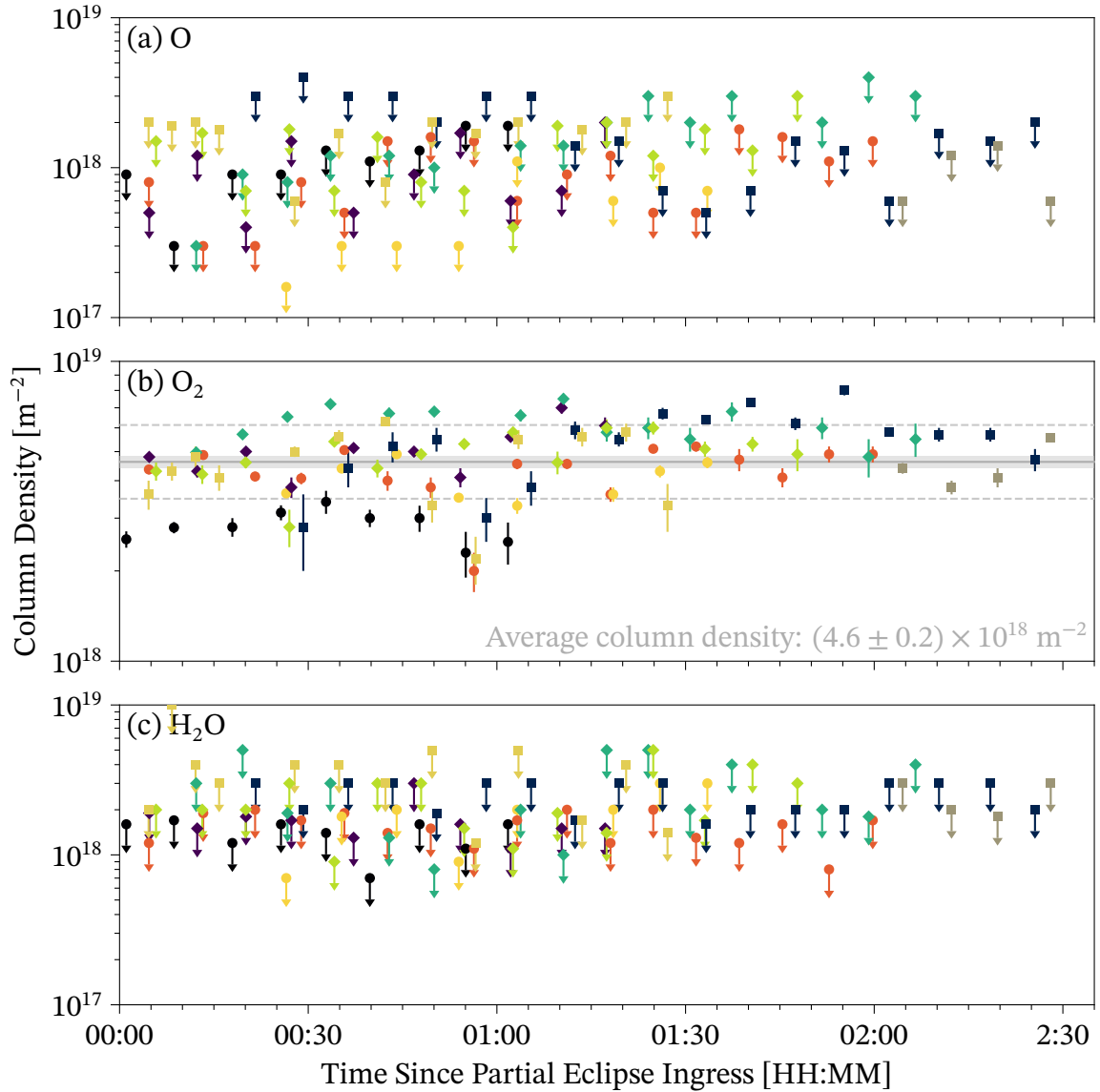


Figure 3.6: Best-fit component column densities for (b) molecular oxygen (O_2) and 1σ detectability thresholds for (a) atomic oxygen (O) and (c) water (H_2O). The model used the median density of 158 cm^{-3} (Bagenal et al., 2015), scaled according to the nominal System III longitude-dependent ambient electron density shown in Figure 3.8b. For O_2 , the solid gray horizontal line shows the geometric mean and the gray shaded region shows the uncertainty in the mean. The dashed lines show the standard deviation of the calculated column densities relative to the mean. To calculate the O_2 column density, we weighted the values by their inverse variance. Perceptually uniform colors and symbols (circles, diamonds and squares) differentiate separate observing nights to allow the reader to evaluate the goodness of fit on a night-to-night basis (see the legend in Figure 3.2).

Table 3.2: Emission model auroral brightness predictions.

Emission	Constituent Brightness		
	O ₂ [R]	O [R]	H ₂ O [R]
121.6 nm Ly α	—	—	29
130.4 nm O I	44	57	1.0
135.6 nm O I]	95	8.7	0.23
297.2 nm [O I]	1.8	0.46	0.43
486.1 nm H β	—	—	2.6
557.7 nm [O I]	30	7.7	7.1
630.0 nm [O I]	820	34	6.7
636.4 nm [O I]	270	11	2.2
656.3 nm H α	—	—	15
777.4 nm O I	51	3.3	0.61
844.6 nm O I	27	17	1.2

Note. Assumes excitation by a two-component Maxwell-Boltzmann electron population (95% at 20 eV and 5% at 300 eV) with a number density of 158 cm^{-3} (the median case of Bagenal et al., 2015, their Table 5). Calculated using an O₂ column density of $4.6 \times 10^{18} \text{ m}^{-2}$ and detection thresholds of $1.1 \times 10^{18} \text{ m}^{-2}$ for O and $1.9 \times 10^{18} \text{ m}^{-2}$ for H₂O discussed in Section 3.4.1 and shown in Figure 3.6.

column densities vary fairly substantially. Smyth et al. (2006) modeled an H₂O column density of $2.3 \times 10^{16} \text{ m}^{-2}$, about twice that of their modeled O column density but still two orders of magnitude below our detectability threshold. In contrast, we estimated a disk-integrated H₂O column of approximately $7 \times 10^{18} \text{ m}^{-2}$ from the results of Roth (2021), though they derived the H₂O atmosphere only on the sunlit trailing hemisphere and their observations of the sub-Jovian hemisphere did not indicate the presence of a sublimation-supported H₂O atmosphere. However, for completeness we evaluated the detectability of their trailing hemisphere H₂O atmosphere as an upper limit for the sub-Jovian hemisphere.

While the contribution from electron impact on H₂O to the 557.7, 630.0 and 636.4 nm [O I] brightnesses typically falls below the uncertainties of individual observations, the lack of clear 656.3 nm H α emission provides the strongest constraint on the H₂O

column density upper limit from our emission model. Assuming an electron density of 158 cm^{-3} our model predicts a $656.3 \text{ nm H}\alpha$ brightness of 58 R for the disk-integrated trailing hemisphere column density of Roth (2021). Though some early observations taken on 2025-02-06 have upper limits of around 200 R, the uncertainties are driven by scattered continuum emission from Jupiter, and careful inspection of the spectra shows no evidence of isolated $\text{H}\alpha$ emission. Our typical observed upper limits are below this brightness, as demonstrated in Figure 3.2 (d). However, it is possible that a sublimation-driven H_2O atmosphere had frozen back onto the surface by the time we began our observations (see Section 3.4.2).

3.4.2 Minimum Timescale for H_2O Atmosphere Collapse

The high cadence of the HIRES observations allowed us to estimate a timescale for the collapse of an H_2O atmosphere of the magnitude proposed by Roth (2021) if one were present over the sub-Jovian hemisphere prior to eclipse ingress. In addition to the 58 R $\text{H}\alpha$ brightness, our model predicted an H_2O contribution of 28 R for the 557.7 nm [O I] line, 26 R for the 630.0 nm [O I] line and 8 R for the 636.4 nm [O I] line using the median electron properties of Bagenal et al. (2015) and the H_2O disk-integrated column density of $7 \times 10^{18} \text{ m}^{-2}$ we derived from Roth (2021). Combined with their O_2 column of about 2.5 m^{-2} , our model predicted a brightness at eclipse ingress of about 44 R in the 557.7 nm [O I] line, of which 16 R comes from the O_2 component. Our observations have a typical Poisson noise for the 557.7 nm [O I] line between 10 and 20 R, suggesting that we should have detected the presence of an H_2O column of the magnitude proposed by Roth (2021) in the 557.7 nm [O I] line brightness at a signal-to-noise ratio between 2 and 4 and should see it decrease to a signal-to-noise ratio of 1 if the column freezes onto the surface. If instead we use our best-fit O_2 column density, which contributes 31 R to the observed 557.7 nm [O I] line brightness, the brightness should change from 59 R to 31 R if the Roth (2021) H_2O column freezes onto the surface during the initial eclipse.

The lack of 557.7 nm [O I] and $656.3 \text{ nm H}\alpha$ detections provides the best constraint on the timescale for the collapse of an H_2O sublimation atmosphere (if present). The duration of Europa's partial eclipses varies between 4 and 5 minutes. The earliest observation in our dataset (taken on 2025-11-10) began about 4 minutes after partial eclipse ingress and had a 3-minute integration time. The brightness of the 557.7 nm [O I] line derived from this spectrum showed no statistical change when compared with subsequent observations on the same date. The other dates with observations close to eclipse ingress (2021-06-21, 2021-07-16, 2022-08-18 and 2024-10-08) also show a similar stability in the time-series brightness of the 557.7 nm [O I] line. This stability, coupled

with the lack of any measurable 656.3 nm H α emission, indicates that an H₂O column of the magnitude proposed by Roth (2021) present over the sub-Jovian hemisphere must collapse to approximately $2 \times 10^{18} \text{ m}^{-2}$ or less (consistent with our derived detectability threshold) within the first few minutes of the eclipse.

3.4.3 Long-Term Electron Density Variability

Figure 3.7 shows the variation in the average 630.0 nm [O I] brightness over the five years of observations we analyzed in this study, with the largest magnitude change of a factor of two occurring between July 2021 and August 2023. Figure 3.8 shows the individual 630.0 nm [O I] brightnesses sorted by System III east longitude. These brightnesses show two local maxima as expected from two crossings of the centrifugal equator. However, there is considerable night-to-night variance in absolute brightness. Bagenal et al. (2015, Figure 10) showed a comparable variability in observations of electron densities between 1996 and 2001 measured by *Galileo*/PWS. The similar distributions between the aggregated electron density measurements and observed in Europa's 630.0 nm [O I] brightnesses suggest that variations in electron density may explain most of the night-to-night variability without requiring significant changes in atmospheric column densities. (Note that Bagenal et al. (2015) use conventional System III west longitudes, so a reader must invert their horizontal axis when comparing to our data.) This would further suggest both short- and long-term stability of the O₂ column density, a finding supported by UV observations that show similar brightnesses in daylight and eclipse (Roth et al., 2016). However, auroral emissions are proxy (rather than direct) measurements for both atmosphere and electron density and therefore do not unambiguously indicate a lack of variability in either parameter.

While the azimuthal brightness variation explanation is the most plausible given the variability seen in the combined observations, our data cannot rule out long-term secular variability in the average electron density as the cause. The observable duration of the eclipses is at most about two hours, meaning that for any one night of HIRES observations we could only observe about 20% of System III longitudes. Consequently, we have no single night of observations demonstrating a systematic longitudinal asymmetry in the brightnesses that could be attributed to a large-scale azimuthal asymmetry in electron density.

However, the overall variations in electron densities measured by *Galileo*/PWS appear to be in good agreement with the aggregated variations in the 630.0 nm [O I] brightnesses we derived. The similar spread in their variability reinforces our conclusion that 630.0 nm [O I] is a good probe of the local plasma density variability at Europa

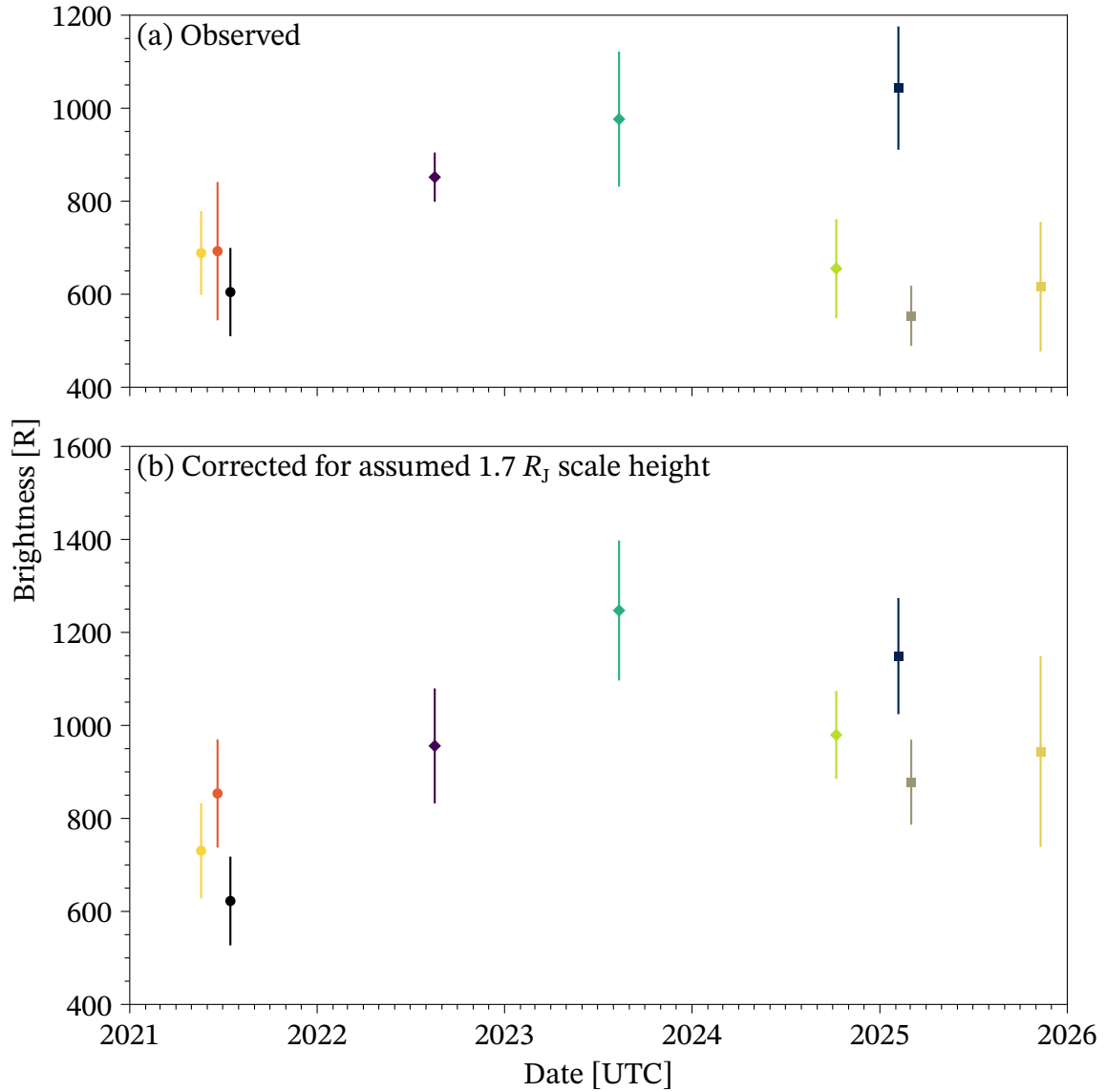


Figure 3.7: Weighted average nightly 630.0 nm [O I] brightness over the five years of observations (a) as observed and (b) after correcting for ambient plasma density with a scale height of $1.7 R_J$ (Bagenal et al., 2011). Error bars show the standard deviation in the weighted averages. Perceptually uniform colors and symbols (circles, diamonds and squares) differentiate separate observing nights to allow the reader to evaluate the goodness of fit on a night-to-night basis (see the legend in Figure 3.2).

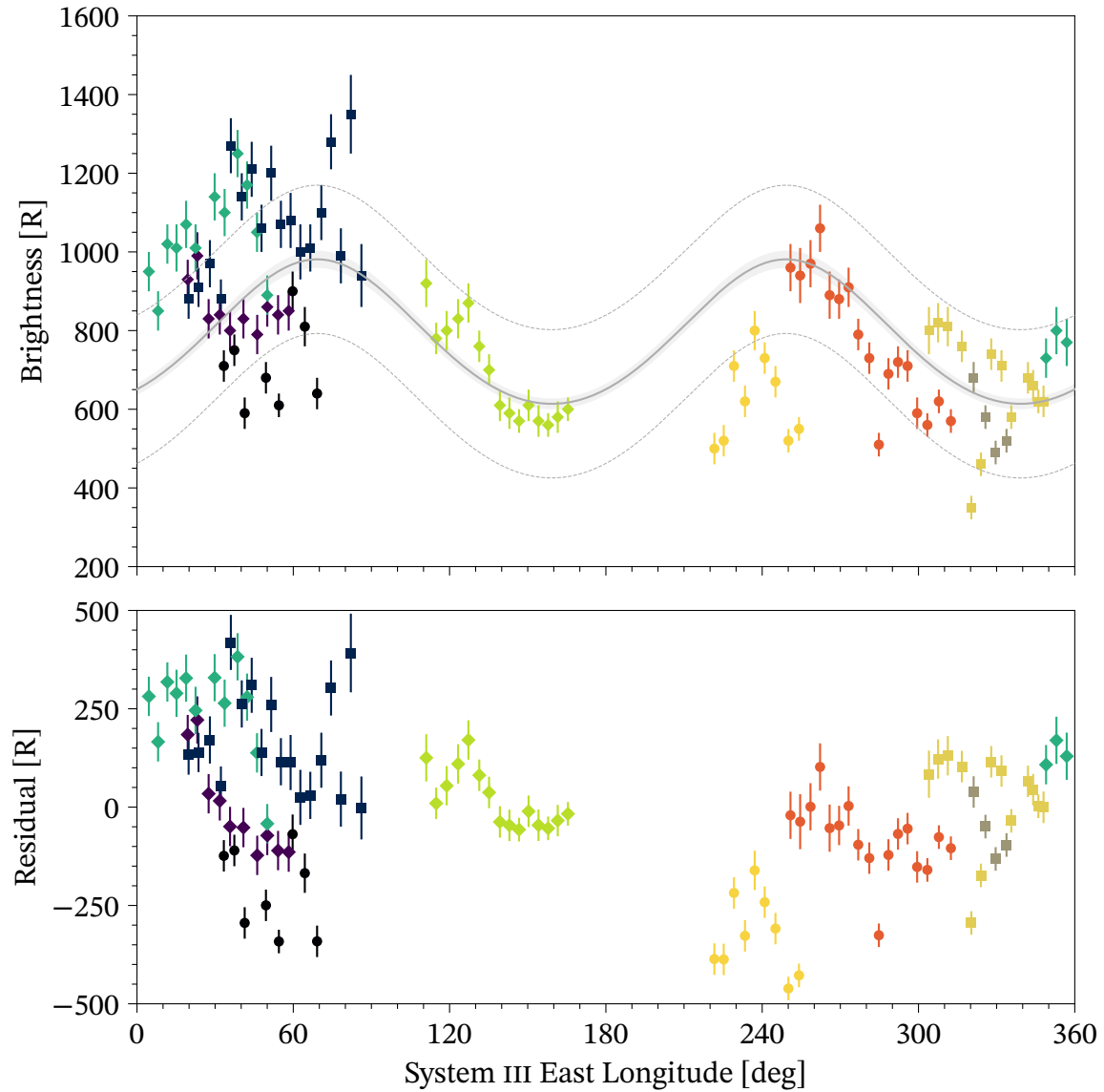


Figure 3.8: Fit of the nominal ambient electron density (Figure 3.5) to Europa's 630.0 nm [O I] brightnesses assuming equal covariance between electron density and emission brightness (Equation 3.2). The solid gray line shows the best fit, the shaded gray region shows the uncertainty in the fit and the dashed gray lines show the standard deviation of the observations relative to the best fit. Perceptually uniform colors and symbols (circles, diamonds and squares) differentiate separate observing nights to allow the reader to evaluate the goodness of fit on a night-to-night basis (see the legend in Figure 3.2).

(an analogous conclusion at Io was made by Oliverson et al., 2001). The long-term standard deviation in the brightnesses is 200 R, corresponding to a $\pm 20\%$ long-term secular variability in electron densities. For the derived plasma conditions of Bagenal et al. (2015, their Table 5), this amounts to a fluctuation of $\pm 32 \text{ cm}^{-3}$ for the median case of 158 cm^{-3} , $\pm 13 \text{ cm}^{-3}$ for the 10th-percentile case of 63 cm^{-3} and $\pm 58 \text{ cm}^{-3}$ for the 90th-percentile case of 290 cm^{-3} . For the *Voyager*-era density of 40 cm^{-3} this amounts to a fluctuation of $\pm 8 \text{ cm}^{-3}$.

3.4.4 Plasma Scale Height

The high cadence and signal-to-noise ratio afforded by the HIRES observations allowed us to compare the correlation between ambient electron density and auroral brightness across multiple nights. Observations during three of the nights (2021-06-21, 2023-08-12 and 2024-10-08) sampled a large range of distances from the centrifugal equator. For each of these nights we fit two forms of Equation (3.5) as expressed in Figure 3.5 assuming direct proportionality between electron density and auroral brightness (Equation 3.2): for one fit we kept H constant at $1.7 R_J$ (Bagenal et al., 2011), allowing only the amplitude n_0 to vary, and for the other fit we allowed both to vary.

Figure 3.9 shows the results of these fits. Note that the reported uncertainties in the fits are dependent only on the random measurement uncertainties for the individual data points and do not include any additional systematic uncertainty. Consequently, the uncertainties in the scale height parameters are likely larger than those calculated for the best fits.

On two of the nights, the magnitude of the brightness changed more than expected for an electron scale height of $1.7 R_J$. On 2021-06-21 the observations sampled System III east longitudes between approximately 240° and 315° . The observations exhibited a change in brightness consistent with an electron scale height of $(1.32 \pm 0.09) R_J$. On 2024-10-08 the observations sampled System III east longitudes between approximately 90° and 170° . The observations exhibited a change in brightness consistent with an electron scale height of $(1.24 \pm 0.05) R_J$. However, on 2023-08-12 the observations exhibited a change in brightness consistent with an electron scale height of $(1.70 \pm 0.15) R_J$, exactly the modeled value of Bagenal et al. (2011).

Nevertheless, the correlation between electron scale height and observed optical wavelength auroral brightness is much stronger at Europa than at Io (Milby et al., 2025) or Ganymede (Milby et al., 2024). Unfortunately, we have not acquired sufficient observations to conclude whether or not the electron scale height truly varies substantially or whether there are other effects contributing to the observed brightness trend. A

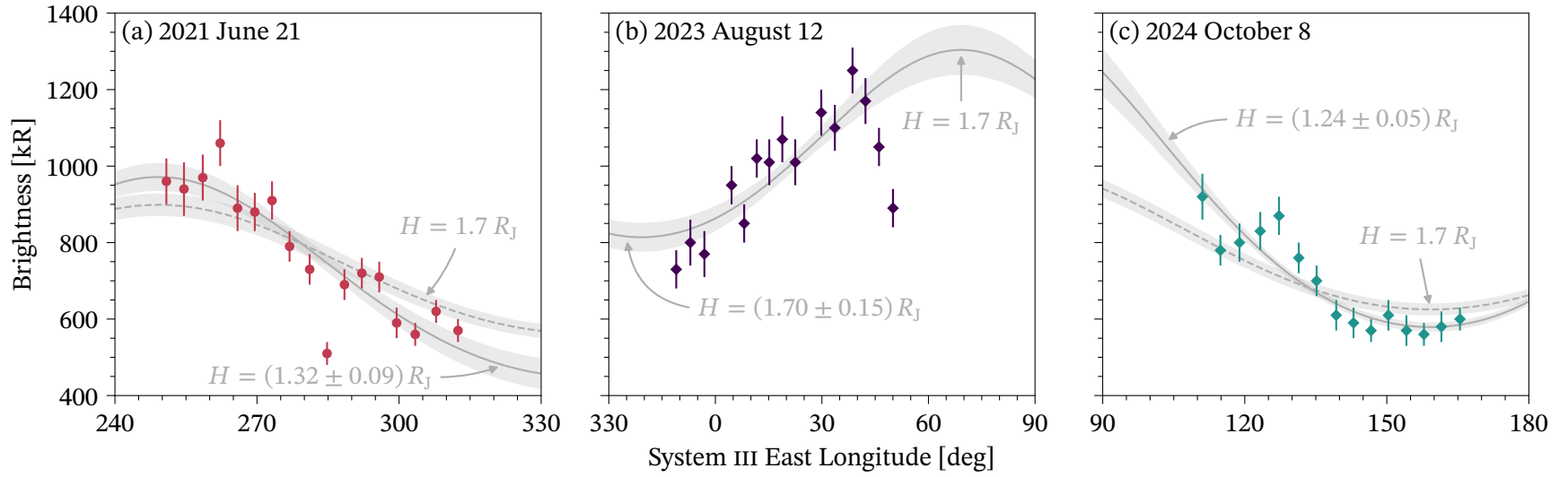


Figure 3.9: Electron density scale height fits to observations of Europa’s 630.0 nm [O I] auroral brightnesses assuming direct proportionality between electron density and emission brightness (Equation 3.2). The points with error bars are the observed brightnesses and their individual random uncertainties. The solid gray line shows a fit of the expected change in brightness (density) at an orbital distance of $9.4 R_J$ as a function of System III east longitude allowing the scale height and amplitude to vary. The dashed gray line shows the same type of fit but with the scale height fixed to $1.7 R_J$ (Bagenal et al., 2011). In panel (b) these are the same, so we have only displayed the variable scale height fit. The shaded gray regions show the uncertainties in the fits and are affected only by random uncertainties in the individual measurements; therefore, they likely underestimate the total uncertainty on the scale height parameter.

similar scale height analysis of the 130.4 nm O I and 135.6 nm O I] emissions by Roth et al. (2016) found scale heights consistent with the modeled value of $1.7 R_J$ calculated by Bagenal et al. (2011), supporting interpretation of this value as the long-term average.

Assuming that the O₂ column remains stable during the eclipse phase of Europa's orbit and other plausible constituents like O and H₂O contribute negligibly to the observed brightnesses (see Section 3.4.3), another plausible explanation for the inconsistent derived scale height are larger-scale azimuthal heterogeneities in electron density along the centrifugal equator, consistent with the variability measured by Bagenal et al. (2011). Analyses of *in situ* measurements beginning during the *Galileo* era have revealed interchange at Europa's orbit between outwardly moving flux tubes containing cold, dense plasma and inwardly moving flux tubes containing hot, rarefied plasma (e.g., Daly et al., 2024). These interchange events would manifest as localized changes in plasma density. Further, as *Voyager 1* flew by Jupiter in March of 1979, its Plasma Spectrometer instrument (PLS) detected a plasma heterogeneity manifesting as "cold blobs" (lower-energy electrons) embedded within the larger, warmer plasma sheet (McNutt et al., 1981), likely the result of the same type of interchange phenomenon. Dougherty et al. (2017) calculated the physical parameters of these blobs and found that they had a diameter of approximately $0.5 R_J$ at a distance of $20 R_J$ from Jupiter. If these blobs do not change in size as they propagate outward from Jupiter, Europa would transit through one of these blobs over the course of approximately half an hour. This would result in a systematic change in brightness with a characteristic width of approximately 23° in System III longitude (see Section 3.3.3) and would manifest as additional variability in the brightnesses above the Poisson noise. This phenomenon could explain the several high electron density measurements made during the *Galileo* E12 Europa flyby (Bagenal et al., 2015, Figure 10).

3.4.5 Azimuthal Electron Density Heterogeneity

After accounting for the expected change in brightness with scale height, the observed 630.0 nm [O I] brightnesses exhibit residual variability that exceeds the typical uncertainties (as shown by the individual error bars) regardless of the scale height chosen (Figure 3.9). Assuming that the electron energy distribution does not vary substantially over the range of the observations (i.e., γ in Equation (3.2) remains constant), this variability must result from some combination of changes in absolute electron number density or atmospheric column density (Equation 3.2). However, if the atmosphere column densities N_s remain relatively constant (at least in terms of their measurable contribution to the 630.0 nm [O I] brightness) and the brightness error bars accurately capture

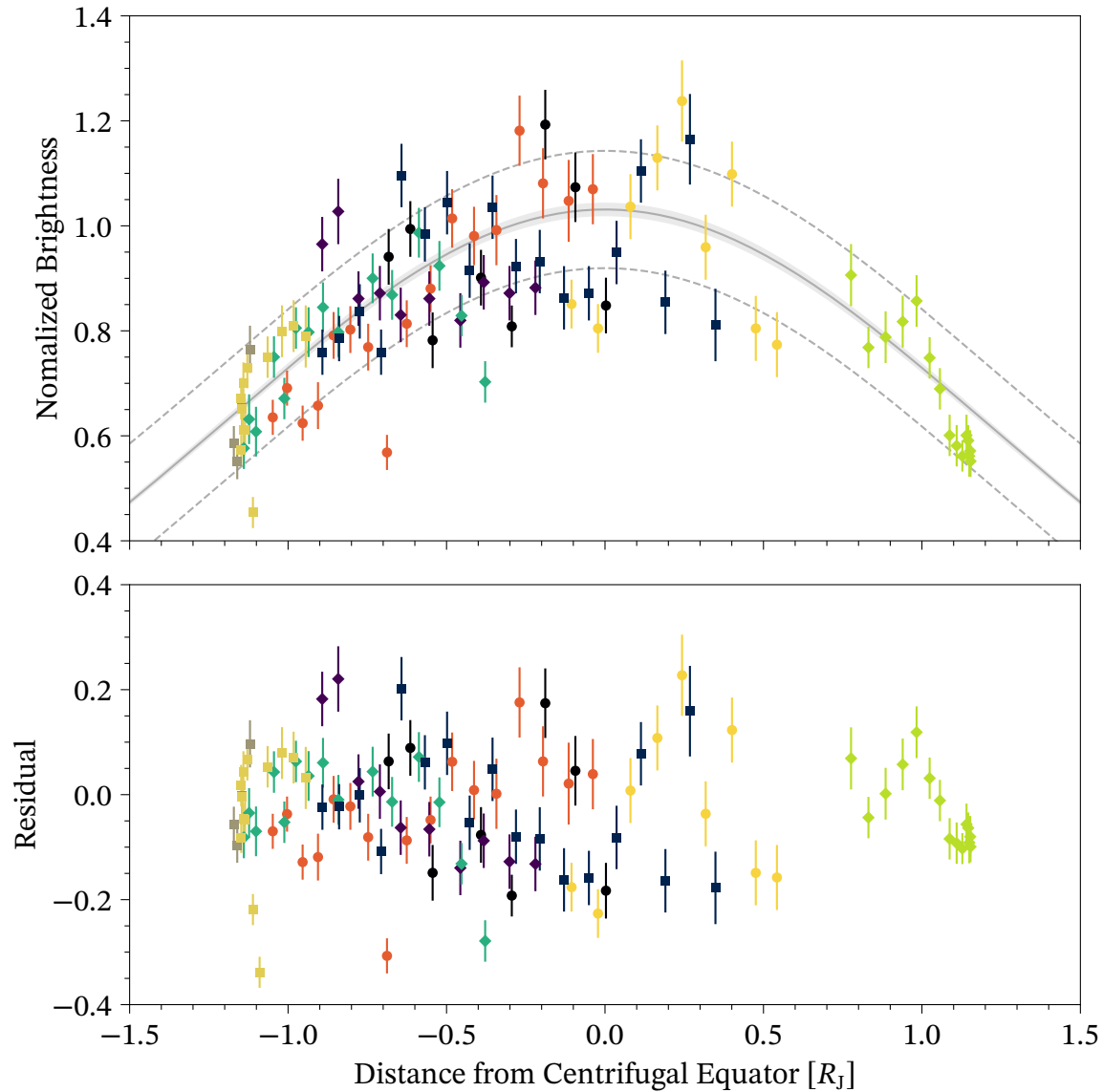


Figure 3.10: Correlation between Europa’s normalized 630.0 nm [O I] brightness and distance from the plasma sheet centrifugal equator for an electron scale height of $1.7 R_J$ (Bagenal et al., 2011). See Section 3.4.4 for a description of the normalization process. Negative distances occur when Europa is “below” the centrifugal equator, with “up” defined toward north. The solid gray line shows the best fit of Equation (3.5) to the complete set of normalized brightnesses with the scale height fixed. The shaded gray region shows the uncertainty in the amplitude from the fit and the dashed gray lines show the standard deviation of the observations relative to the fit (11% at the centrifugal equator). Perceptually uniform colors and symbols (circles, diamonds and squares) differentiate separate observing nights to allow the reader to evaluate the goodness of fit on a night-to-night basis (see the legend in Figure 3.2).

the random statistical noise of an individual observation, this apparent variability must reflect random azimuthal fluctuations in electron density within the plasma sheet.

To quantify the magnitude of the random heterogeneity observed in the 630.0 nm [O I] brightnesses, we normalized them by first fitting Equation (3.5) to an individual night of observations with the scale height fixed to $1.7 R_J$ (Bagenal et al., 2011, the same procedure demonstrated in Figure 3.9) and then dividing the observed brightnesses (and their uncertainties) by the best-fit amplitude n_0 . We then fit Equation (3.5) to the ensemble of normalized brightnesses, as shown by the solid gray line in Figure 3.10. The resulting standard deviation of the normalized brightnesses relative to the fit is about $\pm 11\%$ at the centrifugal equator, shown by the dashed lines in Figure 3.10. For the derived plasma conditions of Bagenal et al. (2015, their Table 5), this constitutes a standard deviation in electron densities with azimuth of $\pm 17 \text{ cm}^{-3}$ for the median case of 158 cm^{-3} , $\pm 7 \text{ cm}^{-3}$ for the 10th-percentile case of 63 cm^{-3} and $\pm 32 \text{ cm}^{-3}$ for the 90th-percentile case of 290 cm^{-3} . For the *Voyager*-era electron density of 40 cm^{-3} this constitutes a standard deviation of $\pm 4 \text{ cm}^{-3}$. A similar analysis of electron densities measured near Europa's orbit found an upper limit in the variability of approximately 10% over length scales of just a few Jupiter radii (Richardson et al., 1987), which agrees with our observational evidence, further supporting our conclusion that the random variability between spectra on any given night results from changes in local plasma density.

3.5 Conclusions

We observed Europa's optical aurora in eclipse across 10 nights between 2021 and 2025 with Keck I/HIRES. Our analysis of the aurora yielded the following results:

1. Our auroral emission model showed that dissociative electron impact on O_2 can explain almost all of the observed 557.7, 630.0 and 636.4 nm [O I] auroral emissions. Assuming the median electron properties of Bagenal et al. (2015), we derived a disk-averaged O_2 column of $(4.6 \pm 0.2) \times 10^{18} \text{ m}^{-2}$ which, because O_2 does not freeze onto or react with the surface ice, remains stable during the eclipse phase of Europa's orbit.
2. The non-detection of $\text{H}\alpha$ emission on each observation date (even after co-adding spectra) along with the relative stability of the 557.7 nm [O I] emission line with time after eclipse ingress places upper limits on the column density of Europa's H_2O atmosphere. Our analysis suggested that if a sublimation-driven H_2O atmo-

sphere is present in daylight, it must collapse to below $2 \times 10^{18} \text{ m}^{-2}$ within the first few minutes of eclipse ingress.

3. The long-term systematic variability in Europa's 630.0 nm [O I] brightnesses shows a strong correlation with the observed long-term variability in electron densities measured by *Galileo*/PWS, suggesting that long-timescale secular changes in electron density (rather than changes in atmospheric column density) can explain the systematic auroral brightness variability. We calculated a standard deviation of about 20% in the average electron density at the centrifugal equator, which corresponds to a variability of $\pm 32 \text{ cm}^{-3}$ for the median density case of 158 cm^{-3} from Bagenal et al. (2015) assumed by most recent studies to model auroral emission at Europa.
4. After removing the systematic effect of long-term variability, observations of Europa's 630.0 nm [O I] brightnesses exhibited residual random variability above the Poisson noise. Assuming that electron density variability, not variability in the density of the neutral atmosphere, dominates the observed scatter in the brightnesses over the short timescales of a single eclipse observation, the ensemble of normalized 630.0 nm [O I] brightnesses revealed that the azimuthal standard deviation of the electron density with System III longitude is about 11%, agreeing with upper limits calculated from PLS data taken near Europa's orbit. The most recent estimate of absolute electron density at Europa's orbit is 158 cm^{-3} (Bagenal et al., 2015), so this amounts to a $\pm 17 \text{ cm}^{-3}$ standard deviation in density with System III longitude.
5. Europa's 630.0 nm [O I] auroral brightnesses exhibited a strong correlation with distance from the plasma sheet centrifugal equator, suggesting that the ambient plasma density drives the auroral brightnesses in contrast to similar optical aurora analyses of Io (Milby et al., 2025) and Ganymede (Milby et al., 2024). We analyzed three dates that sampled a large range of the expected density variation due to the plasma scale height and found that one date matched the modeled scale height of Bagenal et al. (2011) while the other two were consistent with smaller scale heights, indicating that the observations sampled a range of electron properties similar to the *Galileo*-era measurements of Bagenal et al. (2011).

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Chapter 4

GANYMEDE

Milby, Z., K. de Kleer, C. Schmidt, and F. Leblanc (2024). “Short-timescale Spatial Variability of Ganymede’s Optical Aurora”. *The Planetary Science Journal* 5, 7. DOI: 10.3847/PSJ/ad49a2.

Abstract

Ganymede’s auroras are the product of complex interactions between its intrinsic magnetosphere and the surrounding Jovian plasma environment and can be used to derive both atmospheric composition and density. In this study, we analyzed a time series of Ganymede’s optical auroras taken with Keck I/HIRES during eclipse by Jupiter on 2021-06-08 UTC, one day after the Juno flyby of Ganymede. The data had sufficient signal-to-noise ratio in individual 5-minute observations to allow for the first high-cadence analysis of the spatial distribution of the aurora brightness and the ratio between the 630.0 and 557.7 nm disk-integrated auroral brightnesses—a quantity diagnostic of the relative abundances of O, O₂ and H₂O in Ganymede’s atmosphere. We found that the hemisphere closer to the centrifugal equator of Jupiter’s magnetosphere (where electron number density is highest) was up to twice as bright as the opposing hemisphere. The dusk (trailing) hemisphere, subjected to the highest flux of charged particles from Jupiter’s magnetosphere, was also consistently almost twice as bright as the dawn (leading) hemisphere. We modeled emission from simulated O₂ and H₂O atmospheres during eclipse and found that if Ganymede hosts an H₂O sublimation atmosphere in sunlight, it must collapse on a faster timescale than expected to explain its absence in our data given our current understanding of Ganymede’s surface properties.

4.1 Introduction

The first detection of the presence of a tenuous atmosphere around Ganymede was made using stellar occultation measurements over half a century ago (Carlson et al., 1973). The initial occultation measurements suggested a surface pressure of 0.1 Pa, and follow-up photochemical modeling showed that photolysis of H₂O and preferential escape of H would produce an O₂-dominated atmosphere (Yung et al., 1977). Kumar et al. (1982) showed there was an additional stable equilibrium in the Yung et al. (1977) model at a much lower surface pressure of 10^{−7} Pa, consistent with the upper limit of 10^{−6} Pa found using data taken during the *Voyager 1* flyby (Broadfoot et al., 1979).

Ganymede’s atmosphere is influenced by the presence of an internally generated dipolar magnetic field offset by about 10° from its rotation axis (Kivelson et al., 1996).

This field redirects charged particles from Jupiter’s magnetosphere toward Ganymede’s planetographic poles, producing auroral ovals similar to those on Earth. The interaction between Ganymede’s magnetic field and the Jovian magnetosphere in which it resides modifies its structure, in particular the planetographic latitudes on Ganymede at which the boundaries between open and closed field lines occur. Because Jupiter’s magnetic field rotates with a sidereal period of around 10 hours—much faster than Ganymede’s 172-hour orbital period—pressure from Jupiter’s magnetosphere forces the boundary to higher latitudes on Ganymede’s ram-facing trailing hemisphere (Kivelson et al., 2004; Jia et al., 2009; Duling et al., 2022).

Hall et al. (1998) reported the first detection of emission from Ganymede’s atmosphere. They observed two atomic oxygen emission lines in the far-ultraviolet at 130.4 and 135.6 nm, and concluded that the brightness ratio of the lines meant they were produced from dissociative electron impact on O₂. They also found that the emission was spatially confined near the satellite’s poles, matching the magnetic field model of Kivelson et al. (1996).

Feldman et al. (2000a) observed the far-ultraviolet aurora on Ganymede with the Space Telescope Imaging Spectrograph (STIS) on the *Hubble Space Telescope* (HST). They used a slit wider than Ganymede’s angular diameter, giving them the ability to image the spatial distribution of any monochromatic emission. They detected emission at both 130.4 and 135.6 nm, narrowly confined at latitudes above $\pm 40^\circ$ which was consistent with the expected location of the boundary between the open and closed field lines. They found the brightness both spatially and temporally variable, which led them to conclude that the emission was auroral and driven by interactions between Ganymede’s magnetosphere and plasma trapped in Jupiter’s rotating magnetic field.

Ganymede’s auroras are produced from the dissociation of atmospheric molecules by electrons trapped in Jupiter’s magnetosphere, where rotational forces dominate the distribution of plasma. The best constraints on magnetospheric plasma properties currently available come from *Galileo* and *Voyager 1* data. Bagenal et al. (2011) used these data to model the space environment around Jupiter and calculate densities, energies and scale heights of electrons in the plasma sheet as a function of distance from Jupiter. Eviatar et al. (2001) analyzed the intensity of the ultraviolet observations of Feldman et al. (2000a) and found that direct impact from electrons in Jupiter’s rotating magnetosphere could not excite the observed aurora brightnesses given the *Galileo* measurements of electron number density. They concluded that the electrons must be accelerated to higher energies by magnetospheric interactions at the open/closed field

line boundary where Ganymede's magnetic field reconnects with Jupiter's magnetic field.

McGrath et al. (2013) observed differences in the morphology of the ultraviolet aurora for the leading, trailing and sub-Jovian hemispheres. These observations showed the emission at higher latitudes on the trailing/upstream hemisphere, consistent with the magnetohydrodynamic simulations of Jia et al. (2009). Later observations exhibit this same hemispheric morphology, demonstrating the intrinsic shape of Ganymede's auroral ovals and their spatial correlation with the open/closed field line boundary of Ganymede's magnetosphere (Musacchio et al., 2017; Molyneux et al., 2018; Roth et al., 2021; Greathouse et al., 2022; Marzok et al., 2022; Saur et al., 2022).

A major outstanding question is the composition of Ganymede's atmosphere. Most previous far-ultraviolet aurora observations (Hall et al., 1998; Feldman et al., 2000a; McGrath et al., 2013) concluded that the ratio of the 130.4 nm O I and 135.6 nm O I] auroral brightnesses was indicative of an O₂ atmosphere with a column density between 10^{18} and 10^{19} m⁻². However, Roth et al. (2021) found a difference in the ratio of the two emissions between the disk center and limb using high spatial resolution spectra from HST/STIS. They attributed this variability to the presence of a localized H₂O atmosphere around the subsolar point (near the disk center) with a peak column density of around 6×10^{19} m⁻² in sunlight, existing in addition to the global O₂ atmosphere.

Though ground-based optical observations have lower spatial resolution, there are four independent optical oxygen emissions (the 557.7 nm [O I] line, the 630.0/636.4 nm [O I] doublet, the 777.4 nm O I triplet and the 844.6 nm O I triplet) compared to just two detected in the ultraviolet (the 130.4 nm O I triplet and the 135.6 nm O I] doublet). Because optical wavelengths can be observed from the ground, large telescopes provide the ability for observing cadences with shorter integration times and better signal-to-noise ratio. de Kleer et al. (2023) published the first optical wavelength observations of Ganymede's aurora, where they found evidence for an O₂ atmosphere with a column density of $(4.7 \pm 0.1) \times 10^{18}$ m⁻². They found an upper limit on the H₂O column density of 3×10^{17} m⁻², giving a maximum hemisphere-averaged H₂O/O₂ column density ratio of just 0.06 in eclipse. The H₂O distribution and density in the sunlit atmosphere proposed by Roth et al. (2021) would produce 46 R of H α emission, whereas de Kleer et al. (2023) did not detect any H α (in eclipse) and placed a 2σ upper limit of 1.8 R. This major disagreement in H₂O abundance between observations is suggestive of day/night difference, which could be investigated by observing any atmospheric changes on short timescales during eclipse ingress as the satellite passes into the shadow.

To evaluate potential variability in Ganymede's atmosphere, we conducted a time-

series analysis of its optical auroras using data taken on 2021-06-08 UTC. The spatially- and temporally-averaged auroral brightnesses from this observation were published as a part of the broader data set in de Kleer et al. (2023). For this study, we examined the spatial and temporal variability between the individual observations. In order to provide additional confidence in conclusions about H_2O column densities from the optical aurora, we also quantitatively evaluated whether the H_2O atmosphere modeled by Leblanc et al. (2023) to explain the Roth et al. (2021) observations would be detectable under our optical observational constraints. We took our optical spectra one day after the Juno flyby of Ganymede on 2021-06-07 UTC, which included ultraviolet observations from the onboard Ultraviolet Spectrograph (UVS) instrument (Greathouse et al., 2022) and complementary HST/STIS observations just before and just after the flyby (Saur et al., 2022).

4.2 Observations and Data Reduction

We analyzed 17 spectra of Ganymede in eclipse (see Table 4.1), taken on 2021-06-08 UTC using the High Resolution Echelle Spectrometer (HIRES; Vogt et al., 1994) on the Keck I telescope at the summit of Maunakea. Average seeing over the course of the eclipse observations was about $0.55''$.¹ Ganymede’s average velocity relative to Earth was about -24 km s^{-1} (the negative sign indicating motion toward Earth), a velocity sufficient to Doppler shift Ganymede’s monochromatic auroral emission from telluric emission line counterparts. Between 12:48 and 16:15 UTC, Ganymede passed through Jupiter’s umbra, allowing observation of the faint auroral emissions from its atmosphere without the overwhelming presence of reflected solar continuum. Though the full set of eclipse observations includes 17 spectra, we analyzed only 15; we eliminated the last two spectra (taken during nautical twilight) due to large systematic contamination by scattered light from Earth’s atmosphere as the Sun rose. The partial umbral eclipse lasted for about 8 minutes at the beginning and end of the umbral eclipse. The positions of Earth and Jupiter relative to the Sun allowed the telescope’s line of sight to see Ganymede enter Jupiter’s umbra just beyond Jupiter’s eastern limb (see Figure 4.1 for a graphical depiction of this viewing geometry). We used the JPL Horizons Ephemeris Service² (hereafter called JPL Horizons) to determine when Ganymede would be eclipsed by Jupiter and observable from Maunakea.

¹Historical seeing conditions for Maunakea are available at <http://mkwc.ifa.hawaii.edu/current/seeing/>.

²Web interface available at <https://ssd.jpl.nasa.gov/horizons/app.html>. We used the Python interface provided through Astroquery (<https://astroquery.readthedocs.io/en/latest/jplhorizons/jplhorizons.html>).

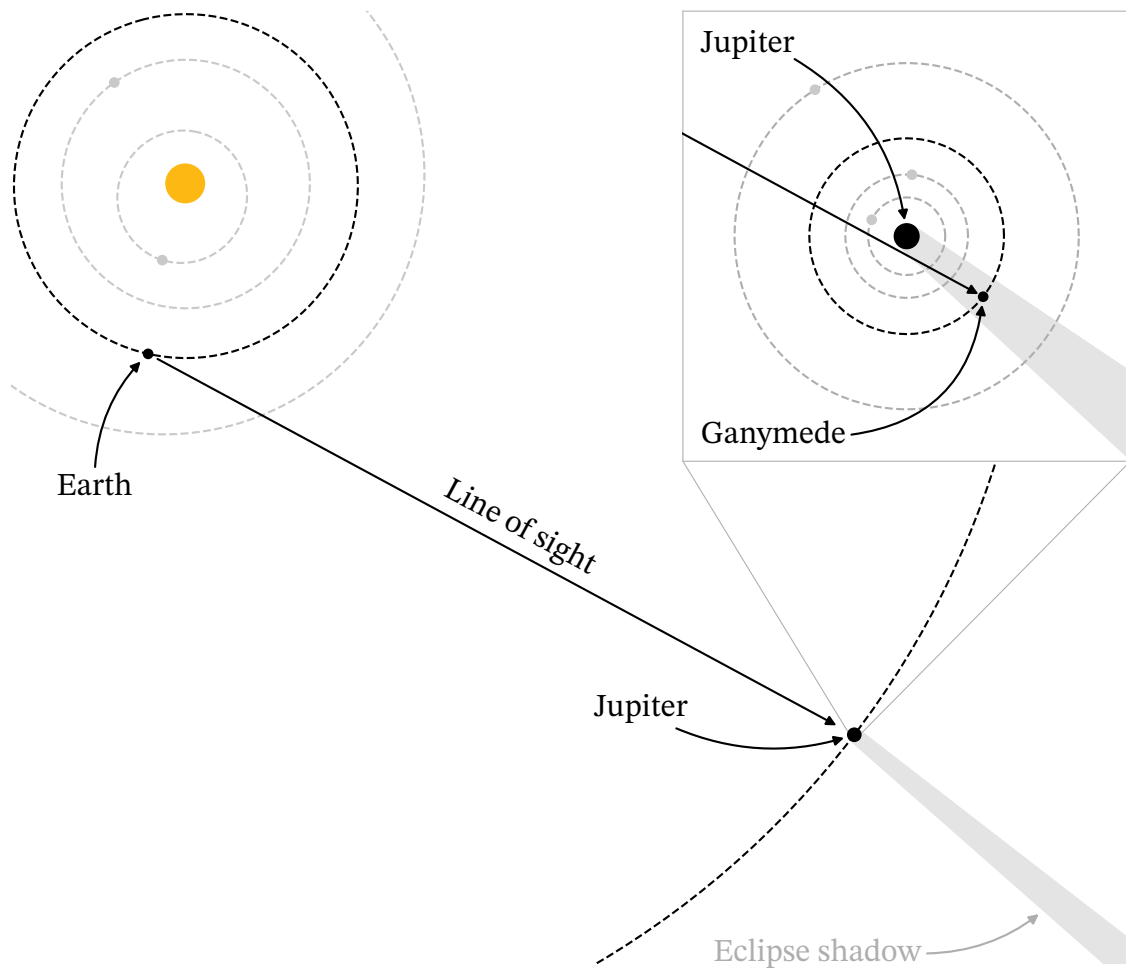


Figure 4.1: Line-of-sight observing geometry of Ganymede during eclipse by Jupiter on 2021-06-08 UTC. The inset axis shows a zoom-in on the Jovian system with the positions and orbits of the other Galilean satellites. Earth's position relative to Jupiter allowed us to observe Ganymede as it passed into Jupiter's umbra. We retrieved the positions of planets and their orbital elements using JPL Horizons, and we have exaggerated the physical sizes of the planets and Jupiter's umbra (but not the relative spacing of the orbits) for illustrative purposes.

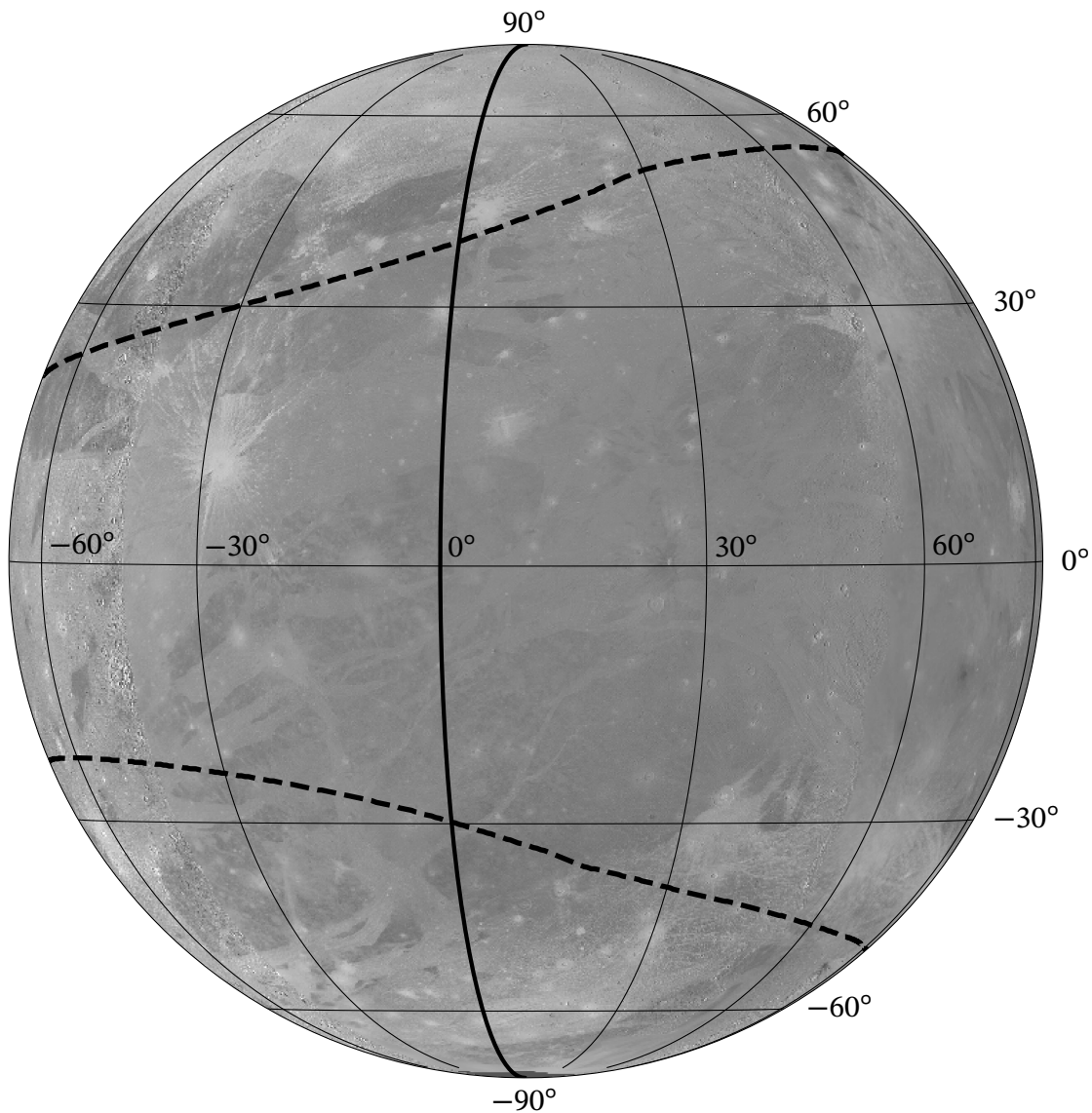


Figure 4.2: Hemispheric observing geometry of Ganymede on 2021-06-08 between 12:58 and 15:08 UTC. Due to the geometry of eclipse observations, the line of sight intersected near the center of the sub-Jovian hemisphere. The sub-observer longitude changed over the duration of the observations by $\pm 2.3^\circ$ from the central longitude in this projection. Labels mark latitude and planetocentric east longitude; the thicker black line shows the prime meridian. The dashed black lines show the locations of the auroral ovals (Duling et al., 2022), marking the boundary between the open and closed field lines of Ganymede's magnetic field. In this view the leading hemisphere is on the left and the trailing hemisphere is on the right. Ganymede surface map courtesy of the United States Geological Survey (USGS 2020).

Observations of Ganymede as it passes through Jupiter’s shadow exclusively measure the sub-Jovian hemisphere. The observations in this data set had a sub-observer east longitude between 8.7° and 13.3° . Figure 4.2 shows an average view of Ganymede as observed on 2021-06-08 UTC. (The sub-observer longitude only varied from this projection by $\pm 2.3^\circ$ over the duration of the observations.)

Twilight on the summit of Maunakea began at 14:18 UTC and astronomical twilight ended at 14:49 UTC. Consequently, the last two observations exhibit greater uncertainty due to higher background from scattered sunlight. Sunrise occurred at 15:46 UTC, preventing any observations of the end of the eclipse.

The HIRES instrument allows an observer to change the angles of the echelle and cross-disperser gratings in order to optimize wavelength coverage on the detectors. The setup chosen for these observations includes emission for atomic oxygen at 557.7, 630.0, 636.4, 777.4 and 844.6 nm along with $H\alpha$ at 656.3 nm. de Kleer et al. (2023) reported the first analysis of these data, evaluating disk-integrated auroral brightnesses retrieved from spectra averaged over all individual observations. The brighter oxygen aurora emissions at 557.7 and 630.0 nm have a sufficient signal-to-noise ratio in the individual five-minute exposures to allow for an analysis of both spatial and temporal variability, which we will present in this study.

In addition to the eclipse spectra of Ganymede, our data included 10 bias exposures, 4 flat-lamp exposures and 5 thorium-argon (ThAr) arc lamp exposures taken a few hours prior to the eclipse. For flux calibration, we took a spectrum of Jupiter’s central meridian with the slit oriented north-south in the center of the disk. Because Ganymede was eclipsed by Jupiter and not visible for guiding, we used JPL Horizons to calculate offsets from another nearby Galilean satellite (the “guide” satellite) and manual telescope tracking rates for Ganymede’s apparent angular velocity in right ascension and declination. We then slewed the telescope manually from the guide satellite to the expected position of Ganymede and took five-minute exposures using the manual tracking rates. After each exposure, we offset back to the expected position of another nearby Galilean satellite and took a fiducial exposure to record the expected position of Ganymede within the slit. The guide satellite was initially Io, but after two exposures we switched to Europa because Io began transiting Jupiter’s disk.

4.2.1 HIRES Data Reduction Pipeline

We reduced the data using an improved version of the pipeline described in de Kleer et al. (2023). The pipeline exists in two parts: the data reduction pipeline (Milby, 2024b) is a generic HIRES pipeline, while the data calibration/brightness retrieval pipeline (Milby,

2024a) is specific to the aurora observations. We used version 2.1.0 of the data reduction pipeline and version 2.15.0 of the data calibration/brightness retrieval pipeline.

4.2.1.1 Reduction

We designed our data reduction pipeline to work with data taken both before the 2004 detector upgrade (the single 2048×2048 pixel detector, hereafter called “legacy” data) and after the detector upgrade (the current three-detector mosaic setup, hereafter called “mosaic” data). The data reduction pipeline first combines the mosaic images into a single image with proper physical separation so that orders crossing between the detectors can still be partially used (this step is skipped for the legacy data). It uses a standard star observation (or similar bright point source) to find traces along the spectral dimension for each echelle order. Using the pixel positions of the traces, it constructs an order mask image using the slit length and pixel dimensions, both in units of arcseconds. This mask is an array of zeros everywhere except half of the length of the slit above and below the traces, which are set to ones. To find the edges of the orders, it cross-correlates the mask image with the master flatfield along the spatial axis, which is able to account for the effect of overlapping orders, orders crossing between detectors and a reference trace which isn’t precisely centered in the slit along the spatial axis. It extracts and rectifies individual orders by taking each pixel along the spatial dimension that fell within the boundaries of the mask order at the maximum offset of the cross-correlation.

To produce a wavelength solution, the pipeline takes the rectified ThAr arc lamp spectra, averages them along the spatial axis (to produce a one-dimensional spectrum) and normalizes them. It then produces a two-dimensional “image” of each one-dimensional spectrum stacked together. The HIRES data reduction pipeline MAKEE³ includes templates taken at a variety of echelle and cross-disperser angles that identify order numbers, wavelengths and central pixel positions of lines in the ThAr arc lamp spectra. Our pipeline finds the template closest to the echelle and cross-disperser angles used in the observations, then constructs a similar two-dimensional template of stacked one-dimensional spectra. It simulates individual lines within the one-dimensional spectra by using a Gaussian line profile at the central pixel position with a full width at half maximum (FWHM) equal to the slit width. It then cross-correlates the template reference spectrum with the observed arc lamp spectrum along both the spatial and spectral axes. It uses the maximum cross-correlation to construct an initial wavelength solution. It then fits a Gaussian function to the observed spectrum at the initial pixel position and assigns the center of the best fit as the fractional pixel position corresponding to

³<https://sites.astro.caltech.edu/~tb/makee/>

the wavelength guess. After assigning refined pixel positions to every identified wavelength, the pipeline fits a two-dimensional polynomial surface to construct a complete wavelength solution for each spectral-dimension pixel in each order. The use of lines identified in adjacent orders allows for a better wavelength solution in orders with fewer identified lines. Finally, it reduces the data by subtracting a median bias and flat-fielding using a normalized median flatfield, then corrects for wavelength-dependent airmass extinction based on the median curve from Buton et al. (2013), removing the diluting effects of Earth’s atmosphere from all science images, including flux calibration images of Jupiter’s central meridian (described in the following section).

4.2.1.2 Flux Calibration

The calibration pipeline uses a spectrum of Jupiter’s central meridian taken on the same night as the eclipse observations, a solar radiance reference spectrum F_E at 1 au (Coddington et al., 2023) and Jupiter’s spectral reflectivity (I/F) from Woodman et al. (1979) to calibrate the data from [counts s⁻¹] to rayleighs [R], a unit of photon column emission commonly used for aurora and airglow, defined as $1 \text{ R} \equiv (10^{10}/4\pi) \text{ ph s}^{-1} \text{ m}^{-2} \text{ sr}^{-1}$.

For Ganymede (and the other icy satellites Europa and Callisto), the pipeline retrieves aurora brightnesses for atomic oxygen emission at 557.7, 630.0, 636.4, 777.4 and 844.6 nm and for atomic hydrogen emission at 656.3 nm. To calculate the expected spectral brightness B_J of Jupiter, it scales the solar reference spectrum with units of [R nm⁻¹] by the square of the distance between the Sun and Jupiter a_J at the time of the observation and applies Jupiter’s wavelength-dependent spectral reflectivity:

$$B_J = F_E \left(\frac{1 \text{ au}}{a_J} \right)^2 \left(\frac{I}{F} \right). \quad (4.1)$$

Jupiter fills the slit, so to determine the observed flux rate $\dot{N}_J$ from Jupiter at a particular wavelength λ , the pipeline calculates the median value for the column in the two-dimensional Jupiter meridian spectrum containing the desired wavelength, then multiplies that median value by the number of pixels subtended by the slit on the detector, thereby estimating the total count rate at a given wavelength λ from the slit.

Individual HIRES mosaic detector pixels have angular dimensions of $0.119'' \times 0.179''$ along the spatial and spectral dimensions. The data in this study have 3×1 spatial/spectral binning, so each bin has a projected size of $0.358'' \times 0.179''$ on the sky, or an angular area of about 0.0641 arcsec^2 ($1.51 \times 10^{-12} \text{ sr}$). HIRES users can choose from a series of slit length and width combinations by means of a series of deckers (movable metal plates containing the slits). The D3 decker used for these observations

has a projected angular size of $1.722'' \times 7''$, so the entrance area corresponds to 188 bins on the detector.

For each individual observation of Ganymede, the pipeline takes the section of the two-dimensional spectrum within ± 0.25 nm for targeted auroral wavelength (Doppler shifted by Ganymede's velocity relative to the observer), then produces calibrated two-dimensional images by multiplying the ratio between the observed count rate per bin from Ganymede to the observed count rate from Jupiter by the physical unit conversion factor B_J described above,

$$B_G = B_J \left(\frac{\dot{N}_G}{\Omega_{\text{bin}}} \right) \left(\frac{\Omega_{\text{slit}}}{\dot{N}_J} \right) w_{\text{slit}} \Delta\lambda, \quad (4.2)$$

where $\dot{N}_G$ is the observed flux rate from Ganymede in $[\text{counts s}^{-1} \text{ bin}^{-1}]$, Ω_{bin} is the solid angular size of one detector bin in $[\text{sr bin}^{-1}]$, $\dot{N}_J$ is the observed flux rate from Jupiter in $[\text{counts s}^{-1}]$ calculated as described above and Ω_{slit} is the solid angular size of the slit in $[\text{sr}]$. To account for the spectral resolution of the slit, it multiplies by the width of the slit w_{slit} in [bins] and the wavelength dispersion $\Delta\lambda$ in $[\text{nm bin}^{-1}]$ at the targeted wavelength.

To calculate disk-integrated brightnesses for the science target satellite, it averages the emission over a user-defined circular aperture Ω_a which is larger than the apparent angular size of the target. Because it assumes emission from a disk with the angular area of Ganymede Ω_G , it scales the average by the ratio $(\Omega_a/\Omega_G)^2$.

4.3 Analysis

Our analysis makes use of the right-handed equivalent of the System III coordinate system (with longitudes measured positively to the east rather than to the west). In this frame, the Joviographic rotation axis $\mathbf{\Omega}$ defines latitude λ_{III} and the rotation of Jupiter's magnetic field defines longitude $\phi_{\text{III,RH}}$ such that the magnetic field's rotation axis is offset from the Joviographic rotation axis by 9.5° toward 159° longitude (Connerney et al., 1998). We also calculated magnetic latitudes λ_{m} defined by the magnetic rotation axis $\mathbf{\Omega}_{\text{m}}$ by converting System III Joviographic latitude λ_{III} to the magnetospheric reference frame using $\lambda_{\text{m}} = 9.5^\circ \cos(\phi_{\text{III,RH}} - 159^\circ) - \lambda_{\text{III}}$. Longitudes in the magnetospheric coordinate system are the same as the right-handed System III Joviographic coordinate system ($\phi_{\text{m}} = \phi_{\text{III,RH}}$).

4.3.1 Retrieval of Disk-Integrated Brightnesses

Table 4.1 lists the observation parameters and retrieved brightnesses for each of the 17 eclipse spectra in the time series. The apparent emission covers an area on the

Table 4.1: Overview of the Keck/HIRES observations of Ganymede in eclipse on 2021-06-08 UTC.

t_E^a [UTC]	t_{LT}^b [UTC]	Right Ascension [HMS]	Declination [DMS]	Airmass	λ_{obs}^c [deg]	ϕ_{obs}^d [deg]	λ_m^e [deg]	ϕ_m^f [deg]	r_G^g [R_J]	θ^h [arcsec]	d^i [R_J]	v_{rel}^j [km s^{-1}]
12:58:16	12:19:22	22 ^h 15 ^m 54 ^s 230	-11°44'25"152	1.519	0.564	11.9	7.014	115.3	14.936	78.4	1.555	-23.7
13:05:29	12:26:35	22 ^h 15 ^m 54 ^s 358	-11°44'24"432	1.479	:	11.7	6.525	111.2	:	77.0	1.446	-23.8
13:22:12	12:43:18	22 ^h 15 ^m 54 ^s 650	-11°44'22"812	1.401	:	11.1	5.273	101.7	:	73.9	1.164	-23.8
13:29:41	12:50:47	22 ^h 15 ^m 54 ^s 782	-11°44'22"092	1.371	:	10.8	4.664	97.4	:	72.5	1.027	-23.9
13:36:46	12:57:52	22 ^h 15 ^m 54 ^s 907	-11°44'21"408	1.346	:	10.6	4.065	93.4	:	71.2	0.892	-23.9
13:44:33	13:05:39	22 ^h 15 ^m 55 ^s 046	-11°44'20"652	1.320	:	10.3	3.385	89.0	:	69.7	0.738	-24.0
13:51:41	13:12:47	22 ^h 15 ^m 55 ^s 171	-11°44'19"932	1.299	:	10.0	2.744	84.9	:	68.4	0.592	-24.0
13:58:52	13:19:58	22 ^h 15 ^m 55 ^s 298	-11°44'19"248	1.280	:	9.8	2.085	80.8	:	67.0	0.443	-24.0
14:08:09	13:29:15	22 ^h 15 ^m 55 ^s 462	-11°44'18"348	1.257	:	9.5	1.219	75.5	:	65.3	0.246	-24.1
14:15:28	13:36:34	22 ^h 15 ^m 55 ^s 591	-11°44'17"628	1.242	:	9.2	0.530	71.4	:	63.9	0.089	-24.1
14:22:45	13:43:51	22 ^h 15 ^m 55 ^s 718	-11°44'16"908	1.228	:	9.0	-0.158	67.2	:	62.5	-0.068	-24.1
14:29:56	13:51:02	22 ^h 15 ^m 55 ^s 846	-11°44'16"188	1.216	:	8.7	-0.835	63.1	:	61.2	-0.222	-24.2
14:37:35	13:58:41	22 ^h 15 ^m 55 ^s 980	-11°44'15"468	1.205	:	8.4	-1.550	58.8	:	59.7	-0.384	-24.2
14:44:47	14:05:53	22 ^h 15 ^m 56 ^s 107	-11°44'14"748	1.197	:	8.2	-2.214	54.7	:	58.4	-0.535	-24.2
14:52:33	14:13:39	22 ^h 15 ^m 56 ^s 246	-11°44'13"992	1.189	:	7.9	-2.917	50.2	:	56.9	-0.695	-24.3
15:01:18	14:22:24	22 ^h 15 ^m 56 ^s 400	-11°44'13"128	1.181	:	7.6	-3.688	45.3	:	55.2	-0.869	-24.3
15:08:29	14:29:35	22 ^h 15 ^m 56 ^s 527	-11°44'12"408	1.177	:	7.4	-4.299	41.2	:	53.9	-1.007	-24.3
Average		22 ^h 15 ^m 55 ^s 355	-11°44'18"780	1.289	0.564	9.8	1.989	81.0	14.936	65.6	0.419	-24.0

Notes: The average values and analyses in this paper do not include the last two observations at 15:01:18 and 15:08:29 which were taken during nautical twilight and exhibited significant scattered light contribution from Earth's atmosphere, affecting retrieved brightnesses and background subtraction.

^a UTC time on Earth at the start of the observation.

^b UTC time on Earth corrected for light travel time between Ganymede and Maunakea.

^c Sub-observer latitude on Ganymede as observed from Maunakea.

^d Sub-observer east longitude on Ganymede as observed from Maunakea.

^e Magnetospheric latitude of Ganymede.

^f Magnetospheric longitude of Ganymede (the same as the System III west longitude, converted here to east longitude).

^g Ganymede's orbital distance from Jupiter.

^h Disk-center-to-disk-center angular separation between the Jupiter and Ganymede. Jupiter's angular radius was 21.11" on 2021-06-08 UTC, so the effective separation from Jupiter's limb is smaller than the listed value.

ⁱ Distance between Ganymede and the plasma sheet centrifugal equator; positive when Ganymede is above the mid-plane and negative when Ganymede is below the mid-plane.

^j Velocity of Ganymede relative to an observer on Earth (the negative sign indicates motion toward the observer).

detector larger than the size of Ganymede's apparent disk because of the blurring effect of atmospheric seeing and telescope pointing variability between observations. To determine an appropriate aperture size, we used the two-dimensional spectra containing the bright 630.0 nm [O I] emission. We found that an aperture with a radius of 1.75" fully enclosed the apparent flux, so we used this aperture size for all of the different spectral lines. This was about 2.25-times the size of Ganymede's apparent angular radius.

Table 4.2: Retrieved optical aurora brightnesses for emission from atomic oxygen and atomic hydrogen.

Observation Start Time [UTC]	Disk-Integrated Brightness					
	557.7 nm [O I] [R]	630.0 nm [O I] [R]	636.4 nm [O I] [R]	656.3 nm H α [R]	777.4 nm O I [R]	844.6 nm O I [R]
12:58:16	13 $\pm$ 2	125 $\pm$ 12	51 $\pm$ 5	9 $\pm$ 9	47 $\pm$ 6	14 $\pm$ 5
13:05:29	16 $\pm$ 2	102 $\pm$ 10	42 $\pm$ 4	-15 $\pm$ 9	15 $\pm$ 5	-4 $\pm$ 4
13:22:12	12 $\pm$ 2	124 $\pm$ 12	50 $\pm$ 5	34 $\pm$ 9	25 $\pm$ 5	13 $\pm$ 4
13:29:41	8 $\pm$ 2	132 $\pm$ 12	49 $\pm$ 5	-2 $\pm$ 9	32 $\pm$ 5	25 $\pm$ 5
13:36:46	11 $\pm$ 2	121 $\pm$ 11	44 $\pm$ 5	-23 $\pm$ 9	33 $\pm$ 5	14 $\pm$ 4
13:44:33	8 $\pm$ 2	151 $\pm$ 14	48 $\pm$ 5	-2 $\pm$ 9	47 $\pm$ 6	15 $\pm$ 4
13:51:41	14 $\pm$ 2	143 $\pm$ 13	47 $\pm$ 5	9 $\pm$ 9	13 $\pm$ 4	36 $\pm$ 5
13:58:52	10 $\pm$ 2	113 $\pm$ 11	35 $\pm$ 4	11 $\pm$ 9	24 $\pm$ 5	11 $\pm$ 4
14:08:09	12 $\pm$ 2	122 $\pm$ 11	43 $\pm$ 4	-5 $\pm$ 9	14 $\pm$ 5	17 $\pm$ 5
14:15:28	2 $\pm$ 2	118 $\pm$ 11	33 $\pm$ 4	0 $\pm$ 10	6 $\pm$ 4	6 $\pm$ 7
14:22:45	19 $\pm$ 3	131 $\pm$ 12	41 $\pm$ 4	21 $\pm$ 10	31 $\pm$ 5	36 $\pm$ 6
14:29:56	16 $\pm$ 3	150 $\pm$ 14	43 $\pm$ 4	-14 $\pm$ 9	20 $\pm$ 5	23 $\pm$ 6
14:37:35	18 $\pm$ 3	156 $\pm$ 14	47 $\pm$ 5	7 $\pm$ 10	35 $\pm$ 6	4 $\pm$ 6
14:44:47	9 $\pm$ 2	143 $\pm$ 13	49 $\pm$ 5	-16 $\pm$ 10	10 $\pm$ 5	-12 $\pm$ 5
14:52:33	20 $\pm$ 3	121 $\pm$ 11	39 $\pm$ 4	-18 $\pm$ 11	9 $\pm$ 6	-25 $\pm$ 8
Average ^a	11.5 $\pm$ 0.6	127 $\pm$ 3	43.0 $\pm$ 1.2	0 $\pm$ 2	22.0 $\pm$ 1.3	12.5 $\pm$ 1.3

Notes: We retrieved each brightness from a circular aperture with a radius of 1.75". Assuming emission from a disk with the solid angular size of Ganymede (it had an apparent angular radius of 0.775" on 2021-06-08 UTC), we scaled the brightness by the ratio (1.75"/0.775")². Listed errors include 9% systematic uncertainty.

^a Calculated using weighted averages as $\langle B \rangle = \sum_{i=1}^{15} (B_i w_i) / \sum_{i=1}^{15} w_i$ with average uncertainty $\langle \sigma \rangle = 1 / \sqrt{\sum_{i=1}^{15} w_i}$, where $w_i = 1/\sigma_i^2$ is the inverse variance.

We used the standard deviation of the spectrum near the emission to estimate the random error from instrumental effects and photon counting. To estimate systematic error, we compared the ratio of the 630.0 nm [O I] brightness to the 636.4 nm [O I] brightness to see how many of the observed ratios deviated from the expected value. The lifetime for O(¹D₂ → ³P₂) 630.0 nm emission is 178 s while the lifetime for O(¹D₂ → ³P₁) 636.4 nm emission is 549 s (Wiese et al., 1996), so if there is collisional quenching, the observed 636.4 nm emission should be suppressed more than the 630.0 nm emission and the 630.0 nm/636.4 nm emission ratio should be larger. However, the value cannot be any lower than the expected ratio of 3.09 for a collisionless atmosphere (Wiese et al., 1996). We found that including a 9% systematic error in addition to the random error derived from the standard deviation of the spectrum resulted in approximately two-thirds of the observed ratios being within 1 σ of the expected value. All uncertainties listed in this paper are the quadrature sum of these two errors.

4.3.2 Calculation of Incident Electron Densities

The distribution of plasma in Jupiter's magnetosphere is affected by both rotational forces and particle energies. Phipps et al. (2021) showed that the plasma density reaches its maximum along a centrifugal equator that exhibits a variable latitudinal offset from the magnetic field equator depending on distance from Jupiter. Bagenal et al. (2011) modeled the plasma distribution and derived how the vertical scale height of the electrons varies with radial distance from Jupiter due to competition between centrifugal forces and thermal pressure. The combination of these two effects with Jupiter's rotating magnetosphere affects the incident plasma density exciting the aurora.

To evaluate this effect quantitatively, we calculated the location of the plasma sheet mid-plane using the methodology outlined in Phipps et al. (2021). Assuming symmetry along the azimuth axis, they derived an empirical fit to a dipole magnetic field which gives the Joviographic latitude λ_{ceq} of the plasma density maxima as a function of distance from Jupiter r and sub-Jovian east longitude ϕ

$$\lambda_{\text{ceq}}(r, \phi) = \left(a \tanh \left(b \frac{r}{R_J} - c \right) + d \right) \sin(\phi - e), \quad (4.3)$$

where the empirically derived best-fit constants are $a = 1.66^\circ$, $b = 0.131 \text{ rad}$, $c = 1.62 \text{ rad}$, $d = 7.76^\circ$ and $e = 249^\circ$.

We retrieved the distance between Jupiter and Ganymede r_G and the sub-Jovian west longitude $\phi_{\text{III,LH}}$ and latitude $\lambda_{\text{III,RH}}$ in Jupiter's System III Joviographic reference frame using JPL Horizons. We first made an initial query targeting Ganymede as observed from Maunakea and retrieved the light travel time between Ganymede and Earth. We then subtracted that travel time from the observation start time and made a second query targeting Jupiter as observed from Ganymede at the new time, retrieving ephemeris information within the Jupiter system at the time of the observation. We converted all System III coordinates to the right-handed Joviographic coordinate system.

Figure 4.3 shows the geometric relationships relevant to the calculation of the plasma density. Ganymede orbits Jupiter at a distance r_G , but because of the relative tilt of the magnetic field axis, the height of Ganymede above the highest-density mid-plane of the plasma sheet d , which falls along the centrifugal equator, varies with the approximately 10-hour rotation period of Jupiter's magnetosphere. To calculate the effective plasma density n incident at Ganymede, we used a mid-plane density of $n_0 = 20 \text{ cm}^{-3}$ measured during the *Voyager* flyby (Scudder et al., 1981) scaled with a Gaussian vertical distribution of the form

$$n = n_0 e^{-(d/H)^2}, \quad (4.4)$$

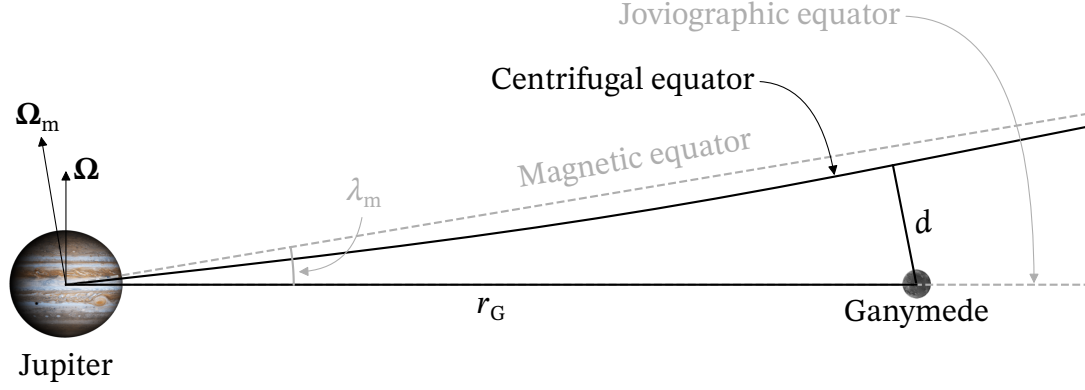


Figure 4.3: Geometric relationships relevant to the retrieval of electron properties. Ganymede orbits Jupiter at a distance of r_G . However, because of the tilt of the magnetic field rotation axis Ω_m relative to the Joviographic rotation axis Ω , Ganymede's distance d from the centrifugal equator varies over the approximately 10-hour magnetospheric rotation period of Jupiter. See Phipps et al. (2021) for a detailed description of this geometry. Image credits: Jupiter (JPL 2001), Ganymede (USGS 2020).

where H is the scale height of the plasma at Ganymede's orbital distance from Jupiter r_G and d is the minimum distance between Ganymede and the centrifugal equator, equivalent to the distance to the tangent to the centrifugal equator from which a normal line intersects Ganymede's orbit (Gledhill, 1967). We used a fixed scale height value of $2.78 R_J$ and orbital distance of $14.936 R_J$ (Bagenal et al., 2011). Because the auroral brightness is directly proportional to the density of the exciting electrons in the case of a thin, non-collisional atmosphere (de Kleer et al., 2018), this equation also describes the expected change in brightness B with distance from the centrifugal equator (see Figure 4.4), such that it can be rewritten as

$$B = B_0 e^{-(d/H)^2} \quad (4.5)$$

where B_0 is the peak brightness when Ganymede is at the high-density plasma sheet mid-plane.

4.4 Results and Discussion

4.4.1 Disk-Integrated Brightness Variability

The disk-integrated brightnesses of Ganymede's aurora do not correlate solely with its location relative to the plasma sheet (see Figure 4.4). Instead, the brightness appears to exhibit a bimodal distribution, reaching local maxima when Ganymede is both above and below the mid-plane of the plasma sheet (the peaks near $0.7 R_J$ and $-0.3 R_J$, respectively). There are not enough high-cadence observations of Ganymede's aurora as

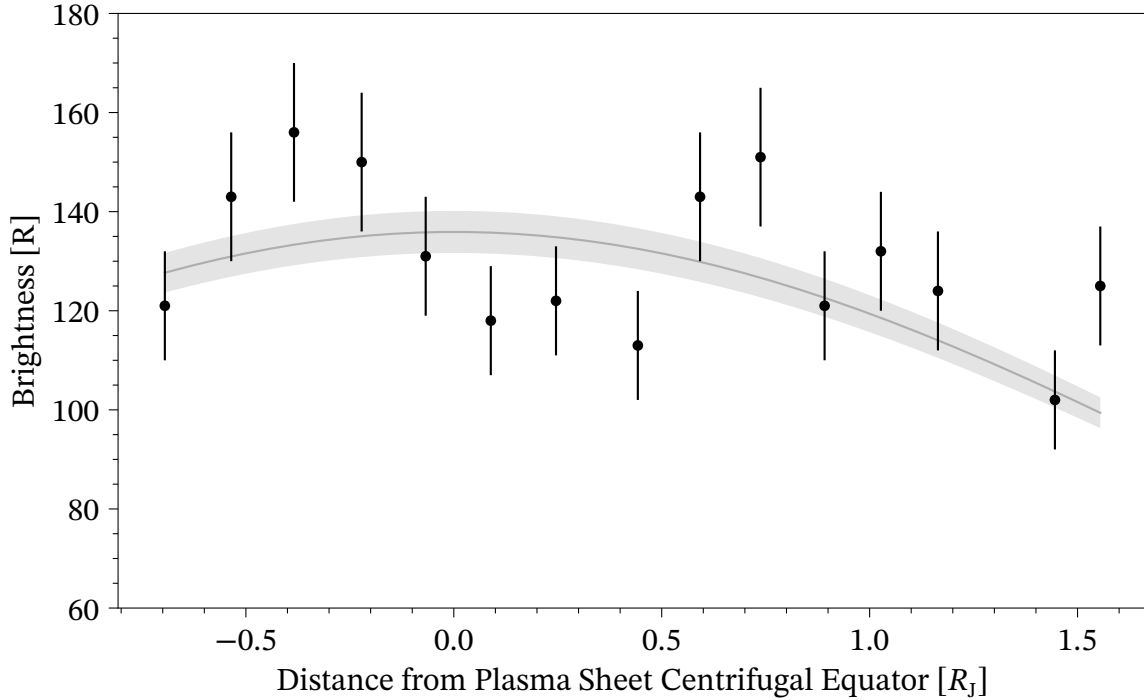


Figure 4.4: Disk-integrated brightness of Ganymede’s 630.0 nm [O I] aurora as a function of distance from the plasma sheet mid-plane. The black points are the observations with error bars showing the combined random and systematic uncertainties. The gray line is a fit of Equation (4.5) with $B_0 = (130 \pm 5) \text{ R}$ and the scale height H fixed to $2.78 R_J$ (Bagenal et al., 2011). The shaded gray region shows the uncertainty in the peak brightness (B_0) of the fit. The fit shows that the brightness exhibits a moderate correlation with distance from the plasma sheet mid-plane, and has an expected peak brightness of about 130 R if the oscillation is due to localized variations in plasma density. In this Figure, the timing of the observations moves from right to left: Ganymede was above the plasma sheet mid-plane at the start of the observations and moved through the center to below the sheet by the end of the night.

it passes through the plasma sheet mid-plane to determine whether the dimming of the brightness between $0.5 R_J$ and the mid-plane is physically meaningful rather than either stochastic variability in local electron number density or an observational effect such as Ganymede drifting in and out of the slit. Therefore, we cannot know if this apparent bi-modality about the plasma sheet centrifugal equator is a persistent feature. However, the brightness varies smoothly in time, suggesting it isn’t due to random noise. Additionally, the variability exceeds the statistical error in the individual observations. Note that time moves from right to left in this image; the first observations were taken when Ganymede was above the plasma sheet, and the last were taken when it was below.

These results are less clear than similar analyses of Europa, which showed a di-

rect correlation between distance from the plasma sheet and disk-integrated aurora brightness (Roth et al., 2016; de Kleer et al., 2023). Europa’s lack of a magnetic field simplifies the excitation process in comparison to Ganymede, since incident electrons at Europa are neither locally accelerated nor restricted to particular geographic locations like they are for Ganymede. However, de Kleer et al. (2023) did find a potentially similar decrease in brightness when Europa was near the plasma sheet mid-plane in two sets of observations taken on 2021-06-21 UTC and 2021-07-16 UTC, though neither data sub-set observed Europa both above and below the mid-plane. Musacchio et al. (2017) analyzed UV observations taken by HST/STIS and found an increase in brightness on the leading hemisphere and a decrease in brightness on the trailing hemisphere when Ganymede was near the plasma sheet mid-plane. In contrast, the optical observations view the sub-Jovian hemisphere, and we did not observe a change in the brightness ratio between the dusk-dawn (leading-trailing) hemispheres as Ganymede crossed through the mid-plane (see Section 4.4.2 and Figure 4.7).

Io’s 135.6 nm O I] auroral limb glow exhibits a comparable decrease in brightness with distance from the plasma sheet centrifugal equator (Retherford et al., 2003). Oliverson et al. (2001) and Schmidt et al. (2023) observed the same effect in Io’s 630.0 nm [O I] auroral emission, but the higher cadence of the optical observations revealed additional variability, which Schmidt et al. (2023) attributed to heterogeneity in the local plasma density that sweeps past the satellite. Analysis of *Cassini* data taken during its flyby of Jupiter showed variations in electron number density with magnetic longitude (Steffl et al., 2006; Steffl et al., 2008). This suggests that the bi-modal brightness modulation apparent in Figure 4.4 may have simply reflected local upstream plasma conditions changing over the course of the observations. Simulations of interactions between Ganymede’s magnetosphere and Jupiter’s also suggest that magnetic reconnection rates vary on the order of tens of seconds, affecting the supply of electrons into Ganymede’s atmosphere and subsequently the number of electron impact excitations leading to auroral emission (Jia et al., 2009).

Figure 4.4 shows a fit of Equation (4.5) with the scale height H fixed to a value of $2.78 R_J$ as calculated by Bagenal et al. (2011) for Ganymede’s orbital distance from Jupiter. The resulting fit has a Pearson correlation coefficient of 0.415 and a p -value of 0.124 (not achieving statistical significance for a 95% confidence threshold). Though we expect there to be a correlation with plasma sheet distance, the poor correlation suggests two simultaneous phenomena may be affecting Ganymede’s auroral brightness: first-order brightness variation from scale-height-induced density variation as its position changes relative to the plasma sheet mid-plane and second-order brightness bi-modality from

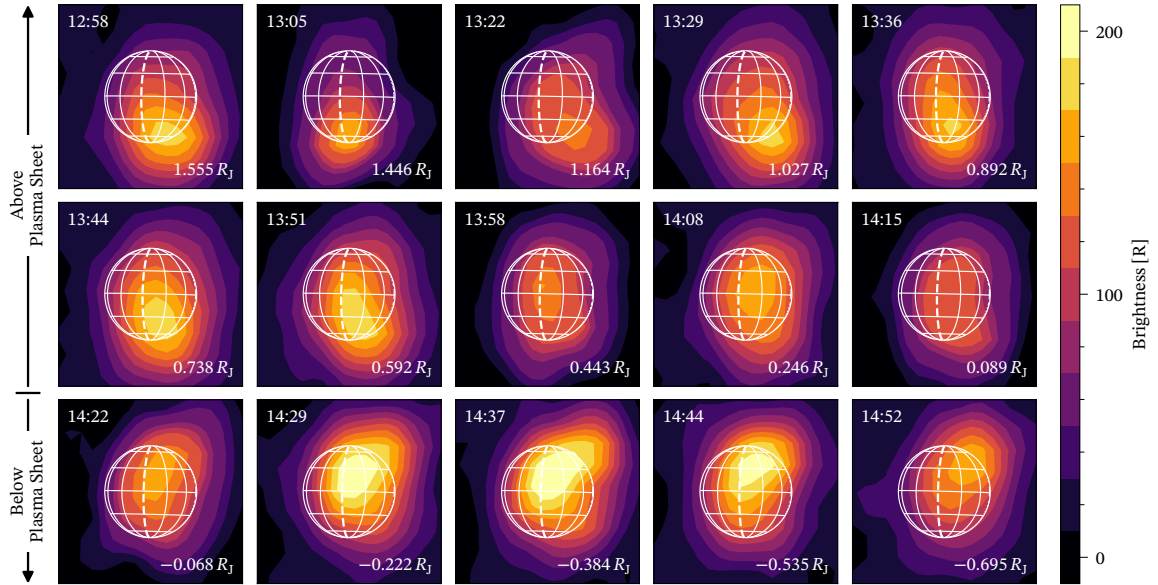


Figure 4.5: Calibrated images of Ganymede’s 630.0 nm [O I] auroral emission displayed in 20 R contours. To better reveal the spatial variability, we smoothed the data using a Gaussian kernel with a FWHM of $0.5''$ approximating typical seeing conditions for the morning of 2021-06-08 UTC. The time in the upper left of each image is the UTC time at the start of the observation; the annotation in the lower right is the distance to the plasma sheet centrifugal equator and is positive when Ganymede is above the mid-plane and negative when it is below. As Ganymede moved vertically through the plasma sheet, the hemisphere closest to the mid-plane exhibited the brightest aurora. From approximately 14:00 to 14:45 UTC, Ganymede is within $\pm 0.5 R_J$ and the brightness is more evenly-distributed across the disk. Ganymede passed through the highest-density plasma mid-plane at 14:20 UTC, so the top two rows display data when Ganymede was above the mid-plane (with enhanced brightness at southern latitudes) and the bottom row displays data when Ganymede was below the mid-plane (with enhanced brightness at northern latitudes). Because of the blurring effect of atmospheric seeing, the calibrated brightness distribution of the individual pixels is lower than the disk-averaged value reported in de Kleer et al. (2023) and Table 4.1, which assume all emission originates from a disk with Ganymede’s solid angular size. The white grid shows the physical size and orientation of Ganymede, with north pointing upward (for more details on this observing geometry, see Figure 4.2).

localized density variations in the plasma as it sweeps past. These observations suggest that the longitudinal density heterogeneity overwhelms the scale height dependence, but further observations will be needed to confirm this conclusion statistically.

4.4.2 Hemispheric Brightness Asymmetries

The 630.0 nm [O I] emission data show both north-south and dusk-dawn (equivalent to trailing-leading in optical observations of the sub-Jovian hemisphere) hemispheric asymmetries (Figure 4.5).

4.4.2.1 North-South Asymmetry

When Ganymede is above the plasma sheet mid-plane (the first two rows in Figure 4.5), the southern mid-plane-facing hemisphere is brighter. As the high-density center of the plasma sheet moves past Ganymede, the brightness is more evenly spread across the disk. Once Ganymede is below the mid-plane, the northern hemisphere is brighter. In all of the images, the peak brightness appears shifted toward dusk (trailing) hemisphere longitudes.

In order to quantify these asymmetries, we calculated the hemisphere-integrated brightnesses from semi-circular apertures with radii of $2.25 R_G$. For pixels that fell in both hemispheres we allocated the brightness based on the relative pixel area in each hemisphere. Table 4.3 lists the brightnesses of each relevant hemisphere.

Retherford et al. (2003) showed that electrons in the Jovian magnetosphere impact Io's atmosphere along two different pathways: the bulk rotation of the plasma sheet, which produces a flux directed at the trailing hemisphere, and bounce motion along flux tubes constrained by the morphology of Jupiter's magnetic field lines and how they connect with Io's magnetic field. They analyzed a similar north-south brightness asymmetry observed in Io's UV aurora and showed that modeled field-aligned electron motion along a flux tube accurately reproduced the brightness ratio they observed. Assuming the symmetric Gaussian profile around the centrifugal equator with a scale height of $H = 2.78 R_J$ (Equation 4.4), we numerically integrated the ratio $R_{N/S}$ of the flux tube electron column densities for a distance d from the plasma sheet centrifugal equator,

$$R_{N/S} = \frac{\int_0^{\infty} e^{-(x/H)^2} dx}{\int_{-\infty}^0 e^{-(x/H)^2} dx}. \quad (4.6)$$

Figure 4.6 shows the ratio of the northern hemisphere brightness to the southern hemisphere brightness with a logarithmic vertical axis so that the apparent spacing of the ratios is meaningful. The diagonal gray line shows the result of the integral ratio in

Table 4.3: 630.0 nm [O I] brightnesses calculated for the northern, southern, dawn (leading) and dusk (trailing) hemispheres.

Observation Start Time [UTC]	Hemisphere-Integrated Brightness			
	North [R]	South [R]	Dawn [R]	Dusk [R]
12:58:16	76 ± 8	175 ± 16	88 ± 9	175 ± 16
13:05:29	68 ± 8	136 ± 13	111 ± 11	103 ± 10
13:22:12	83 ± 9	163 ± 15	71 ± 8	186 ± 17
13:29:41	98 ± 10	167 ± 16	88 ± 9	187 ± 17
13:36:46	105 ± 11	145 ± 14	106 ± 11	149 ± 14
13:44:33	121 ± 12	183 ± 17	120 ± 12	192 ± 18
13:51:41	116 ± 11	178 ± 17	112 ± 11	189 ± 18
13:58:52	105 ± 11	131 ± 13	97 ± 10	142 ± 14
14:08:09	120 ± 12	146 ± 14	87 ± 9	183 ± 17
14:15:28	108 ± 11	135 ± 13	94 ± 10	154 ± 15
14:22:45	149 ± 14	130 ± 13	92 ± 10	185 ± 17
14:29:56	192 ± 18	140 ± 13	110 ± 11	220 ± 20
14:37:35	195 ± 19	148 ± 14	105 ± 11	230 ± 20
14:44:47	180 ± 17	128 ± 12	113 ± 11	188 ± 18
14:52:33	152 ± 15	111 ± 11	80 ± 9	178 ± 17
Average	106 ± 3	143 ± 4	95 ± 3	165 ± 4

Equation (4.6) evaluated for the range of plasma sheet distances across the Ganymede observations. This line is not a fit to the data; the correlation coefficient between the expected ratio and the observations is 0.952 with $p \ll 0.001$, clearly demonstrating that the asymmetric column densities along the flux tubes intersecting each hemisphere quantitatively match the observed north-south brightness asymmetry of Ganymede's aurora.

Saur et al. (2022) looked at this same hemispheric brightness ratio in 135.6 nm [O I] UV data taken on 2021-06-07 UTC (the day before these HIREs observations), but the low signal-to-noise ratio at ultraviolet wavelengths required them to integrate for longer, reducing the cadence of their time-series observations. Regardless, they found a similarly-variable hemispheric brightness ratio in the ultraviolet data, and their north-south ratio varied between 1.6 and 0.4 (see Saur et al., 2022, Figure 5) which matches the extremes in the 630.0 nm [O I] HIREs observations. At an orbital distance of $14.936 R_J$ we calculated that Ganymede reaches a maximum height above or below the plasma sheet centrifugal equator of $2.44 R_J$, so from Equation (4.6), the peak north-south hemispheric brightness ratio should be about 4.35 at $-2.44 R_J$ and 0.230 at $2.44 R_J$.

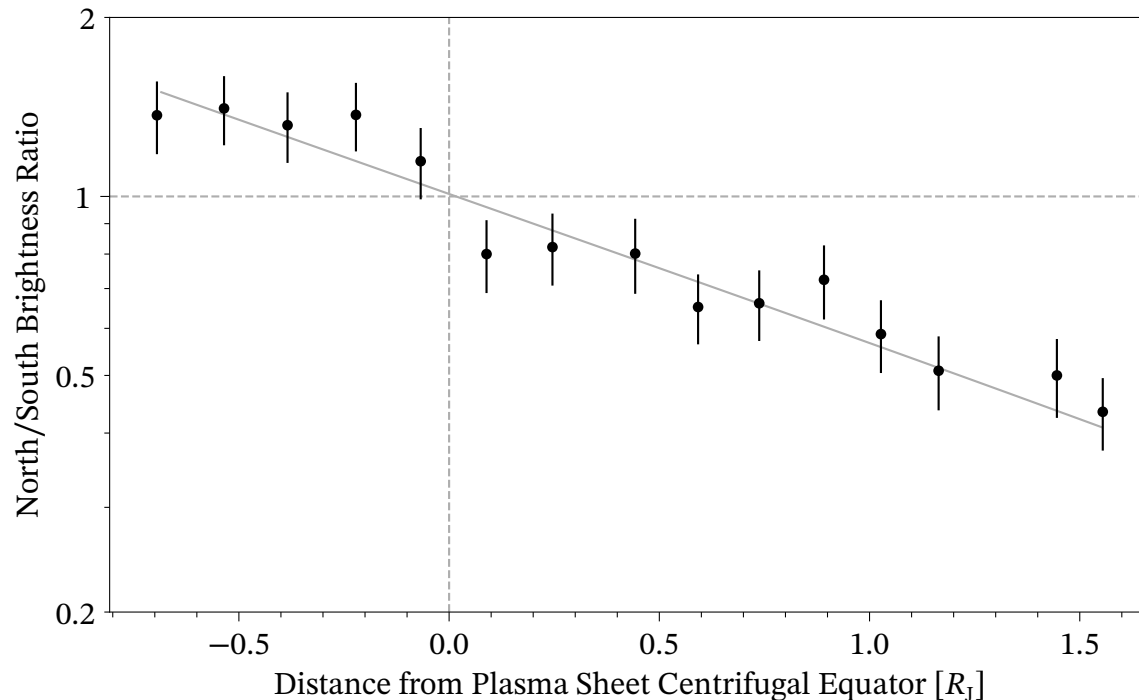


Figure 4.6: Ratio of Ganymede’s 630.0 nm [O I] auroral emission between its northern and southern hemispheres out to an angular distance of $2.25 R_G$. The horizontal dashed gray line indicates a ratio of 1 (equal average brightness between hemispheres), and the vertical dashed gray line shows where Ganymede passed through the center of the plasma sheet. The diagonal line shows the expected brightness ratio due to asymmetric flux tube electron column densities (Equation 4.6).

4.4.2.2 Dusk-Dawn Asymmetry

Figure 4.7 shows the ratio of the dusk hemisphere brightness to the dawn hemisphere brightness. We found that the dusk (trailing) hemisphere was almost always twice as bright as the dawn (leading) hemisphere. McGrath et al. (2013) observed a similar brightness asymmetry in HST observations of Ganymede’s 135.6 nm O I] emission. Musacchio et al. (2017) and Molyneux et al. (2018) did not observe the same relative enhancement of the leading hemisphere, but they observed just the leading or trailing hemisphere (rather than the simultaneous leading-trailing geometry of the sub-Jovian optical observations), so they would not be able to see the same kind of inter-hemisphere enhancement that we did.

Leblanc et al. (2017) simulated Ganymede’s atmosphere and showed an enhancement in O_2 column density toward the dusk hemisphere in eclipse (see their Figure 5). Because O_2 does not readily condense on the Ganymede’s surface, they suggested the asymmetry is due to a combination of the thermal inertia of the surface ice, the morphology of

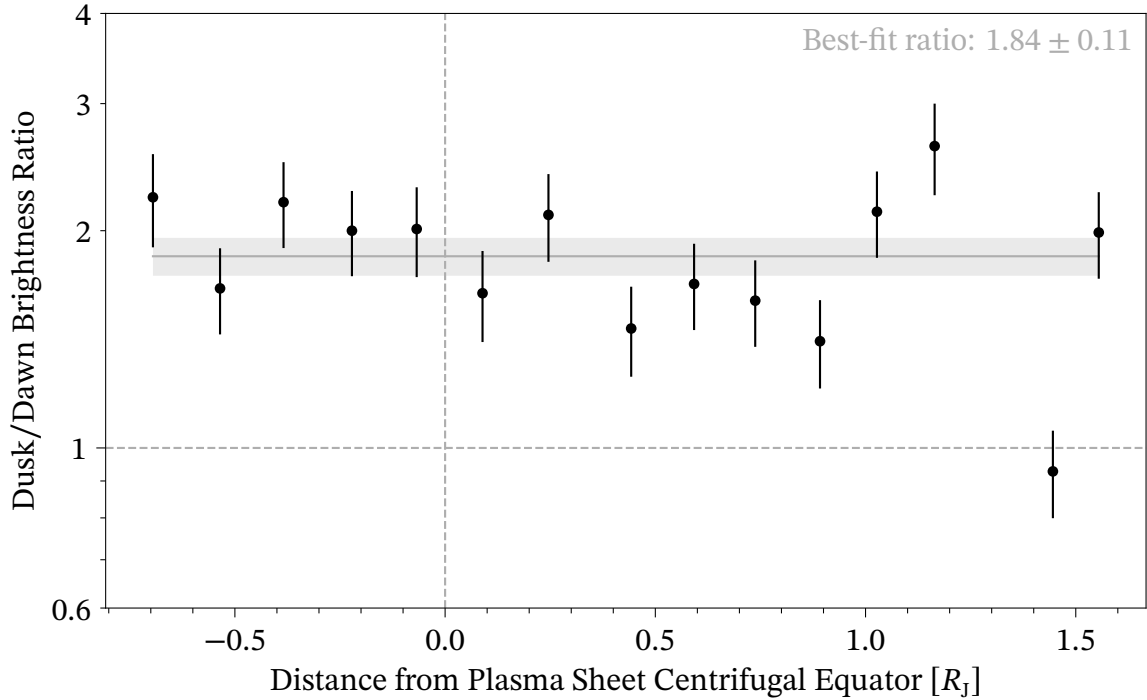


Figure 4.7: Ratio of Ganymede’s 630.0 nm [O I] auroral emission between its dusk and dawn hemispheres out to an angular distance of $2.25 R_G$. The horizontal dashed gray line indicates a ratio of 1 (equal average brightness between hemispheres), and the vertical dashed gray line shows where Ganymede passed through the center of the plasma sheet. The horizontal line is a best-fit constant and the shaded gray area shows the uncertainty in the fit.

the magnetic field and the incident sputtering particles originating from the direction of the trailing hemisphere. In particular, thermal lag in the surface ice causes the surface to be warmer toward dusk compared to dawn. A higher temperature on the hemisphere subjected to sputtering particle flux allows for a larger sputtering rate (Cassidy et al., 2013). Oza et al. (2018) estimated latitude-averaged O_2 column densities on several tidally-locked Solar System moons, including Ganymede and Europa, and estimated a hemispherically averaged dusk-dawn ratio of 1.22, far below our minimum estimated ratio of 1.84 ± 0.11 . The higher asymmetry found in the aurora brightnesses is likely the product of both the larger column density and a larger electron flux on the trailing hemisphere; however, the optical aurora data cannot decouple their relative contributions.

Though we assumed that an increased electron flux on the trailing hemisphere contributes to the dusk-dawn asymmetry, the physical structure of Ganymede’s magnetosphere and the way it connects with Jupiter’s almost certainly complicates the

electron flux path. Kivelson et al. (2004) showed how the interaction between Jupiter's magnetosphere and a magnetized moon like Ganymede results in field line reconnection which restricts plasma flow and redirects it toward a narrow range of magnetic latitudes near the magnetic poles, allowing for electron flux on both the leading and trailing hemispheres (rather than concentrating the bulk of the flux on the trailing hemisphere). Our analysis of the north-south hemispheric brightness ratio provides evidence for flow along the field lines connecting to Jupiter and therefore access to the full vertical extent of the plasma split between the hemispheres. In contrast, simple impact on the trailing hemisphere from the rotation of Jupiter's magnetosphere would produce a much smaller ratio between the northern and southern hemispheres since the relative difference in electron flux could only come from the vertical extent of Ganymede's physical cross section. Eviatar et al. (2001) assumed an increased electron energy to account for the effects of Ganymede's magnetic field, while Saur et al. (2022) increased both the number density and the peak of the electron energy distribution (to double that of Eviatar et al., 2001). Though we used the electron densities derived from *Voyager* data (Scudder et al., 1981) and the energy distribution given by Eviatar et al. (2001), we also evaluated the effect of the electron properties given by Saur et al. (2022) on observed optical aurora brightnesses as detailed in Section 4.4.5.

4.4.3 Constraints on Atmospheric Composition Variability over Eclipse

The ratio of the 630.0 nm [O I] brightness to the 557.7 nm [O I] brightness is particularly sensitive to the presence of H₂O as a parent molecule (Table 4.4; see also de Kleer et al., 2023, Table 5). Since the publication of de Kleer et al. (2023) we have expanded the aurora model to include cross sections for electron impact on CO₂ producing emission at 630.0 nm and 636.4 nm (Strickland et al., 1969) and 777.4 and 844.6 nm (Zipf, 1984). Using the same cross sections for O, O₂ and H₂O listed in de Kleer et al. (2023), we have calculated a 630.0 nm to 557.7 nm emission ratio of 13.5 for electron impact on O₂, 2.72 for for electron impact on O, 0.943 for for electron impact on H₂O and 0.892 for electron impact on CO₂. The H₂O ratio is nearly 1, so we should observe approximately equal brightnesses at 557.7 and 630.0 nm if the primary source of the auroral emission was electron impact on water molecules.

Figure 4.8 shows a time series of the 630.0 nm [O I] to 557.7 nm [O I] emission ratio retrieved from the individual Ganymede observations. The ratio appears relatively constant over the duration of the eclipse, though on average lower than expected for a pure O₂ atmosphere, indicative of the presence of an atmospheric species beyond O₂. If Ganymede's atmosphere is collisional, quenching of the longer-lived O(¹D₂) atoms

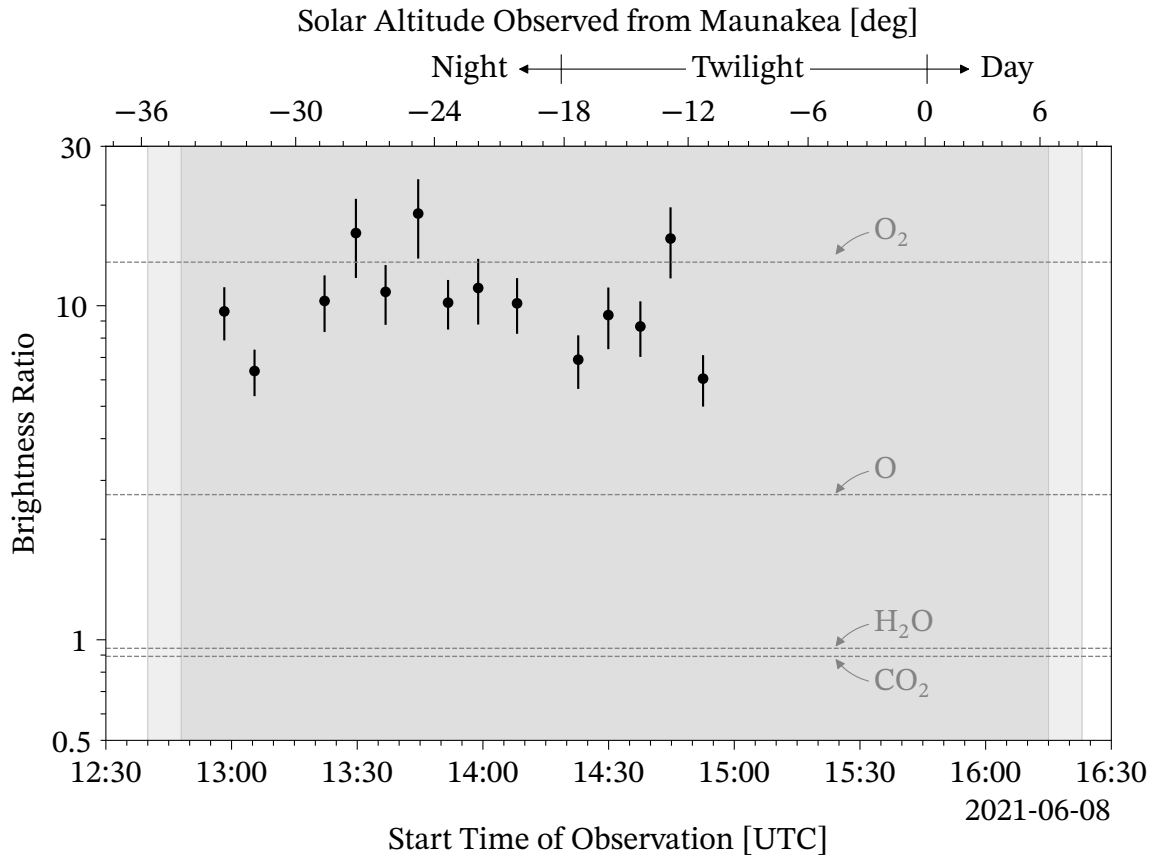


Figure 4.8: Time series of the ratio of the [O I] aurora brightness at 630.0 nm to the brightness at 557.7 nm. We have selected only data points for which the ratio signal-to-noise ratio was greater than 2, which eliminated the observation at 14:15:28. Dashed horizontal lines show the modeled ratios for atmospheres of pure O, O₂, H₂O and CO₂. The ratios remain relatively constant over the duration of the observed eclipse and do not show evidence for the presence of significant H₂O or CO₂. The dark gray background region spanning most of the time range shows the 3-hour and 47-minute duration of the umbral eclipse. The light gray regions on either side are the approximately 8-minute duration of the partial umbral eclipse. The top axis shows the altitude of the Sun as observed from the summit of Maunakea. Sunrise on Maunakea occurred at 15:46 UTC, preventing observations of the end of the eclipse.

Table 4.4: Modeled emission ratios relative to 557.7 nm [O I] for Ganymede’s optical aurora, assuming an electron population with a Maxwell-Boltzmann distribution centered at 100 eV and a number density of 20 cm^{-3} .

	Parent Species			
	O	O ₂	H ₂ O	CO ₂
121.6 nm Ly α	—	—	4.58	—
130.4 nm O I	18.7	1.38	0.178	0.0471
135.6 nm O I]	0.661	3.11	0.0416	0.0480
297.2 nm [O I]	0.0598	0.0598	0.0598	0.0598
486.1 nm H β	—	—	0.409	—
557.7 nm [O I]	1	1	1	1
630.0 nm [O I]	2.72	13.5	0.943	0.892
636.4 nm [O I]	0.880	4.38	0.305	0.288
656.3 nm H α	—	—	2.27	—
777.4 nm O I	0.241	2.06	0.0716	0.0282
844.6 nm O I	3.24	0.972	0.186	0.0205

(Wiese et al., 1996) could also lower the ratio of 630.0 nm to 557.7 nm [O I] emission. (Transitions from O(¹D₂) emit both the 630.0 and 636.4 nm photons when relaxing to the O(³P₂) and O(³P₁) ground states, respectively.) However, we did not find any evidence of collisional quenching in our analysis of the 630.0 nm/636.4 nm emission ratio when estimating systematic error (see Section 4.3.1).

The relatively constant ratio suggests that atmospheric composition was not changing over the course of the observations; if there was an H₂O atmosphere, it either collapsed within the first 10 minutes of umbral eclipse (an effect we analyzed in Section 4.4.4) or the emissions we observed included only a minor contribution from H₂O.

We used the same Markov chain Monte Carlo (MCMC) method described in de Kleer et al. (2023) to estimate the relative column densities of a four-species atmosphere consisting of O, O₂, H₂O and CO₂ using an electron number density of 20 cm^{-3} (Scudder et al., 1981) and a Maxwell-Boltzmann velocity distribution centered at 100 eV (Eviatar et al., 2001). Table 4.5 lists the median atmospheres for each observation along with the median atmosphere to the average brightnesses listed in Table 4.1.

For each individual observation, the median atmospheres tended toward a primarily O₂ composition, but included minor contributions from both O and H₂O to account for the brightness ratio of less than 13.5 expected for a pure O₂ atmosphere. CO₂ is a trace component of Ganymede’s surface ice (McCord et al., 1998), and our model found a

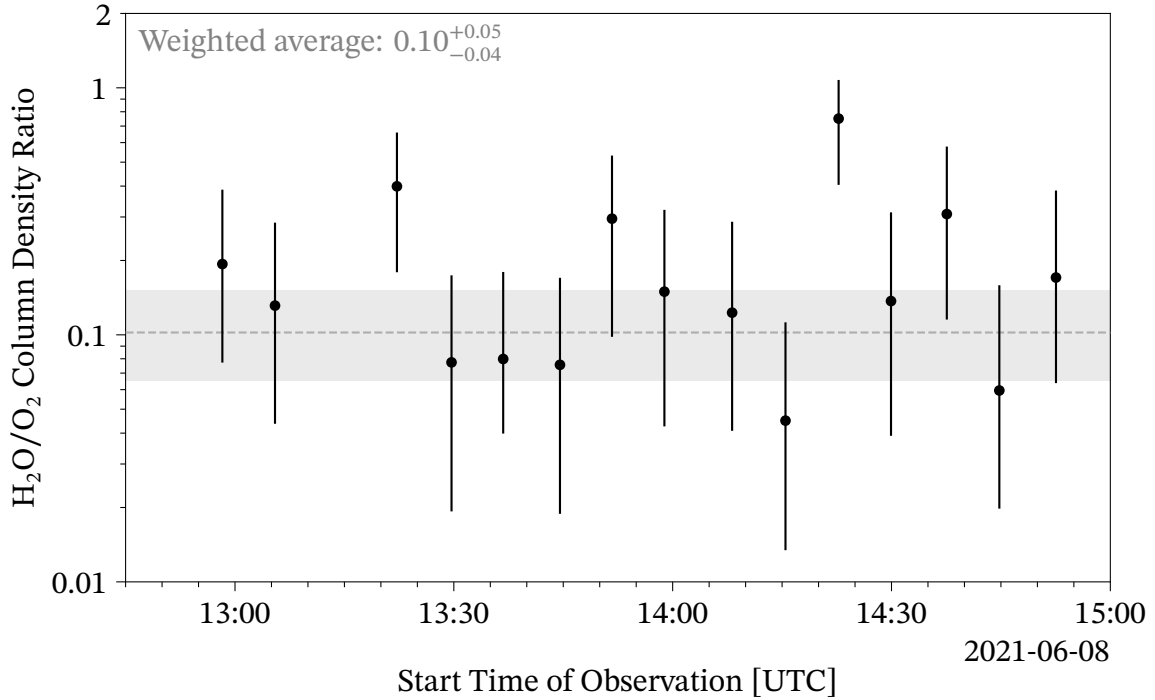


Figure 4.9: $\text{H}_2\text{O}/\text{O}_2$ column density ratio derived from MCMC fits to retrieved aurora brightnesses. The dashed gray line shows the weighted average of the individual points and the shaded gray region shows the asymmetric uncertainty of the weighted average. This average column density ratio of $0.10^{+0.05}_{-0.04}$ matches the upper limit found by de Kleer et al. (2023) for the same date.

correspondingly minor CO_2 component about 1 order of magnitude lower than H_2O for each observation. The brightness contribution from a CO_2 column of this magnitude is less than the measurement uncertainties of the auroral brightnesses, so we treat this result as an upper limit on a potential CO_2 component in Ganymede’s atmospheric composition.

Figure 4.9 shows the modeled $\text{H}_2\text{O}/\text{O}_2$ column density ratio for each observation. The weighted average (shown in gray) is $0.10^{+0.05}_{-0.04}$. This ratio matches the 2σ upper limit of 0.10 found by de Kleer et al. (2023) for the 2021-06-08 UTC observations using averages of the spectra and still suggests an O_2 -dominated atmosphere. (Though de Kleer et al. (2023) report an upper limit of 0.06 for the $\text{H}_2\text{O}/\text{O}_2$ column ratio, they calculated this value using averages over multiple nights of Ganymede observations; their best-fit atmosphere for the 2021-06-08 UTC data had an upper limit ratio of 0.10.)

Table 4.5: MCMC median atmosphere column densities using retrieved brightnesses listed in Table 4.1.

Observation Start Time [UTC]	Column Density [$\times 10^{18}$]			
	O [m^{-2}]	O ₂ [m^{-2}]	H ₂ O [m^{-2}]	CO ₂ [m^{-2}]
12:58:16	0.08 ^{+0.08} _{-0.06}	5.17 ^{+0.17} _{-0.17}	1.0 ^{+1.0} _{-0.6}	0.08 ^{+0.09} _{-0.05}
13:05:29	0.19 ^{+0.12} _{-0.11}	4.57 ^{+0.17} _{-0.16}	0.6 ^{+0.7} _{-0.4}	0.24 ^{+0.14} _{-0.13}
13:22:12	0.09 ^{+0.09} _{-0.06}	5.01 ^{+0.17} _{-0.17}	2.0 ^{+1.3} _{-1.1}	0.06 ^{+0.08} _{-0.04}
13:29:41	0.09 ^{+0.09} _{-0.06}	5.17 ^{+0.17} _{-0.17}	0.4 ^{+0.5} _{-0.3}	0.04 ^{+0.05} _{-0.03}
13:36:46	0.11 ^{+0.10} _{-0.07}	5.01 ^{+0.16} _{-0.16}	0.4 ^{+0.5} _{-0.2}	0.06 ^{+0.07} _{-0.04}
13:44:33	0.07 ^{+0.08} _{-0.05}	5.29 ^{+0.16} _{-0.16}	0.4 ^{+0.5} _{-0.3}	0.04 ^{+0.05} _{-0.03}
13:51:41	0.09 ^{+0.09} _{-0.06}	5.08 ^{+0.17} _{-0.17}	1.5 ^{+1.2} _{-1.0}	0.12 ^{+0.12} _{-0.08}
13:58:52	0.18 ^{+0.12} _{-0.10}	4.68 ^{+0.16} _{-0.17}	0.7 ^{+0.8} _{-0.5}	0.05 ^{+0.07} _{-0.04}
14:08:09	0.14 ^{+0.11} _{-0.08}	4.88 ^{+0.16} _{-0.17}	0.6 ^{+0.8} _{-0.4}	0.09 ^{+0.10} _{-0.06}
14:15:28	0.27 ^{+0.13} _{-0.12}	4.45 ^{+0.16} _{-0.17}	0.20 ^{+0.30} _{-0.14}	0.019 ^{+0.030} _{-0.013}
14:22:45	0.09 ^{+0.09} _{-0.06}	4.93 ^{+0.17} _{-0.17}	3.7 ^{+1.6} _{-1.7}	0.17 ^{+0.16} _{-0.12}
14:29:56	0.09 ^{+0.09} _{-0.06}	5.11 ^{+0.17} _{-0.18}	0.7 ^{+0.9} _{-0.5}	0.23 ^{+0.14} _{-0.13}
14:37:35	0.07 ^{+0.08} _{-0.04}	5.19 ^{+0.17} _{-0.18}	1.6 ^{+1.4} _{-1.0}	0.27 ^{+0.17} _{-0.15}
14:44:47	0.10 ^{+0.10} _{-0.07}	5.04 ^{+0.17} _{-0.17}	0.3 ^{+0.5} _{-0.2}	0.06 ^{+0.07} _{-0.04}
14:52:33	0.15 ^{+0.12} _{-0.09}	4.69 ^{+0.18} _{-0.18}	0.8 ^{+1.0} _{-0.5}	0.45 ^{+0.16} _{-0.17}
Average	0.11 ^{+0.09} _{-0.07}	5.13 ^{+0.15} _{-0.15}	0.4 ^{+0.4} _{-0.3}	0.07 ^{+0.06} _{-0.05}

Note. The listed uncertainties are the 16th and 84th-percentile quantiles.

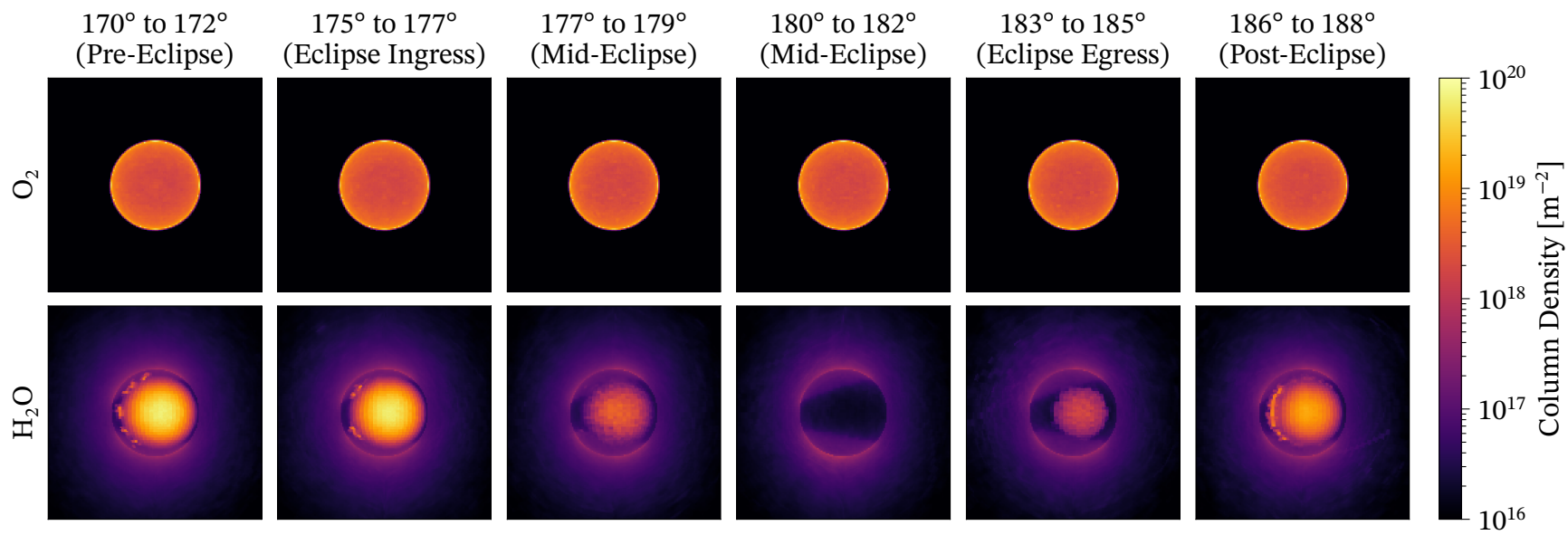


Figure 4.10: Simulation of Ganymede's O_2 (top row) and H_2O (bottom row) atmospheric column densities before, during and after eclipse by Jupiter as observed from Earth. Each time step was averaged over 2° (57 minutes) of Ganymede's orbit. The coordinate system is right-handed, measured counter-clockwise along Ganymede's orbit with 0° pointing toward the Sun and 180° at the mid-point of the eclipse. Small-scale structures prominent in the H_2O column densities are artifacts from the Monte Carlo simulation method. These simulations suggest that the H_2O atmosphere, if present, collapses rapidly after the onset of the eclipse and recovers quickly after Ganymede emerges back into sunlight.

4.4.4 Detectability of an H₂O Atmosphere with Keck I/HIRES

de Kleer et al. (2023) found that the column density of H₂O derived by Roth et al. (2021) would have produced more [O I] emission at 557.7 and 656.3 nm than they detected in the average disk-integrated optical observations. However, because O₂ and H₂O may have different spatial distributions (Roth et al., 2021; Leblanc et al., 2017; Leblanc et al., 2023), the observing geometry during eclipse could reduce observed emission from electron impact on H₂O due to the physical separation between the open/closed field line boundary and the higher-density H₂O column near the disk center. In order to explore this spatial effect on the aurora emission, we simulated optical observations assuming the modeled atmosphere from Leblanc et al. (2023), which was tuned to reproduce the Roth et al. (2021) UV observations.

We evaluated simulations of both O₂ and H₂O atmospheres (Figure 4.10). Each time step was averaged over 2° of Ganymede’s orbit around Jupiter (a duration of 57 minutes). To simulate eclipse conditions, the effects of solar photon ionization and dissociation were disabled between orbital angles of 176.26° and 183.74°, measured in a right-handed coordinate system from a reference position of 0° pointing toward the Sun. These angles correspond approximately to the midpoint of the partial umbral eclipses. In our analysis of the simulations (Figures 4.11 and 4.12), we converted this angular coordinate system to time relative to the eclipse midpoint.

The simulated O₂ atmospheres have a disk-integrated column density between 4.45×10^{18} and $4.5 \times 10^{18} \text{ m}^{-2}$, which is between 5% and 13% lower than the average column density from our best-fit model atmosphere and that of de Kleer et al. (2023). The simulated H₂O disk-integrated column densities vary between about 10^{19} m^{-2} before eclipse ingress and a minimum of about $7 \times 10^{16} \text{ m}^{-2}$ just before eclipse egress. The peak simulated H₂O column density decreases from $6 \times 10^{19} \text{ m}^{-2}$ to $2 \times 10^{16} \text{ m}^{-2}$.

We used the same Maxwell-Boltzmann electron population centered at 100 eV as described in Leblanc et al. (2023), with the density modified spatially to account for acceleration near the open/closed field line boundaries. We set the background number density to 20 cm^{-3} , increasing to a peak of 70 cm^{-3} at the latitudes of the ovals from Duling et al. (2022) following a Gaussian shape with a FWHM of 20°, chosen by Leblanc et al. (2023) to match simulations of Ganymede’s magnetosphere (Jia et al., 2009).

We calculated the auroral emission at the native resolution of the simulations, then rebinned the results to the detector resolution of HIRES. Finally, we smoothed the data using a two-dimensional Gaussian kernel with a FWHM of 0.5'', representative of the typical seeing conditions on the night of 2021-06-08 UTC. We then calculated

the disk-integrated brightnesses with the same aperture size we used for the HIRES observations.

Figure 4.11 shows a comparison between the simulated and observed brightnesses for 557.7 nm [O I] and 656.3 nm H α auroral emission. The six time steps in the simulated brightnesses shown in each plot in red correspond to the total emission from both the H₂O and O₂ simulations. The simulated column density of O₂ does not change substantially over the course of the eclipse, maintaining a steady simulated disk-integrated 557.7 nm brightness of about 13 R. The simulated steady-state H₂O atmosphere in full sunlight has a disk-integrated column density ratio with the O₂ atmosphere of about 3, and our aurora model produces a simulated 20 R of emission at 557.7 nm and 45 R of emission at 656.3 nm from the model H₂O atmosphere alone. Combining the model H₂O and O₂ atmospheres, the simulated 557.7 nm brightness reaches 33 R, almost triple the average observed value of (11.5 ± 0.6) R. de Kleer et al. (2023) showed that Ganymede's disk-integrated auroras were extremely consistent across three different nights of observation spanning more than 20 years, so random variability in the incident electron densities alone likely cannot account for the difference between the modeled sunlit H₂O and O₂ brightness and the observed brightness.

A possible explanation for the apparent lack of emission from electron impact on H₂O is the rapid condensation of the H₂O atmosphere onto the surface at the onset of eclipse, an effect seen in the simulated H₂O atmosphere. The simulated column density of H₂O decreases substantially between the second simulation time step (which includes the onset of eclipse) and the third simulation time step (fully in eclipse). The modeled sunlit 557.7 nm [O I] and 656.3 nm H α emissions from electron impact on H₂O are well above our detection threshold, whereas the modeled in-eclipse emissions are near or below our detection threshold. (The plotted detection thresholds are the average of the combined random and systematic uncertainties and represent the typical noise level at a given wavelength.) This suggests that we would be able to detect the presence of an actively condensing H₂O atmosphere as modeled by Leblanc et al. (2023) with observations taken sufficiently early during the eclipse. Instead, the observed emissions show no temporal changes in either the 557.7 nm [O I] and 656.3 nm H α brightnesses over the first 10 to 15 minutes of eclipse (Figure 4.11). If there was a localized sublimation H₂O atmosphere present in sunlight that froze out in eclipse, the deposition process must occur within the first ten to fifteen minutes of Ganymede entering the full umbral eclipse.

Figure 4.12 shows the simulated surface temperature of Ganymede's sub-solar point before, during and after eclipse (Leblanc et al., 2017) along with the number of H₂O

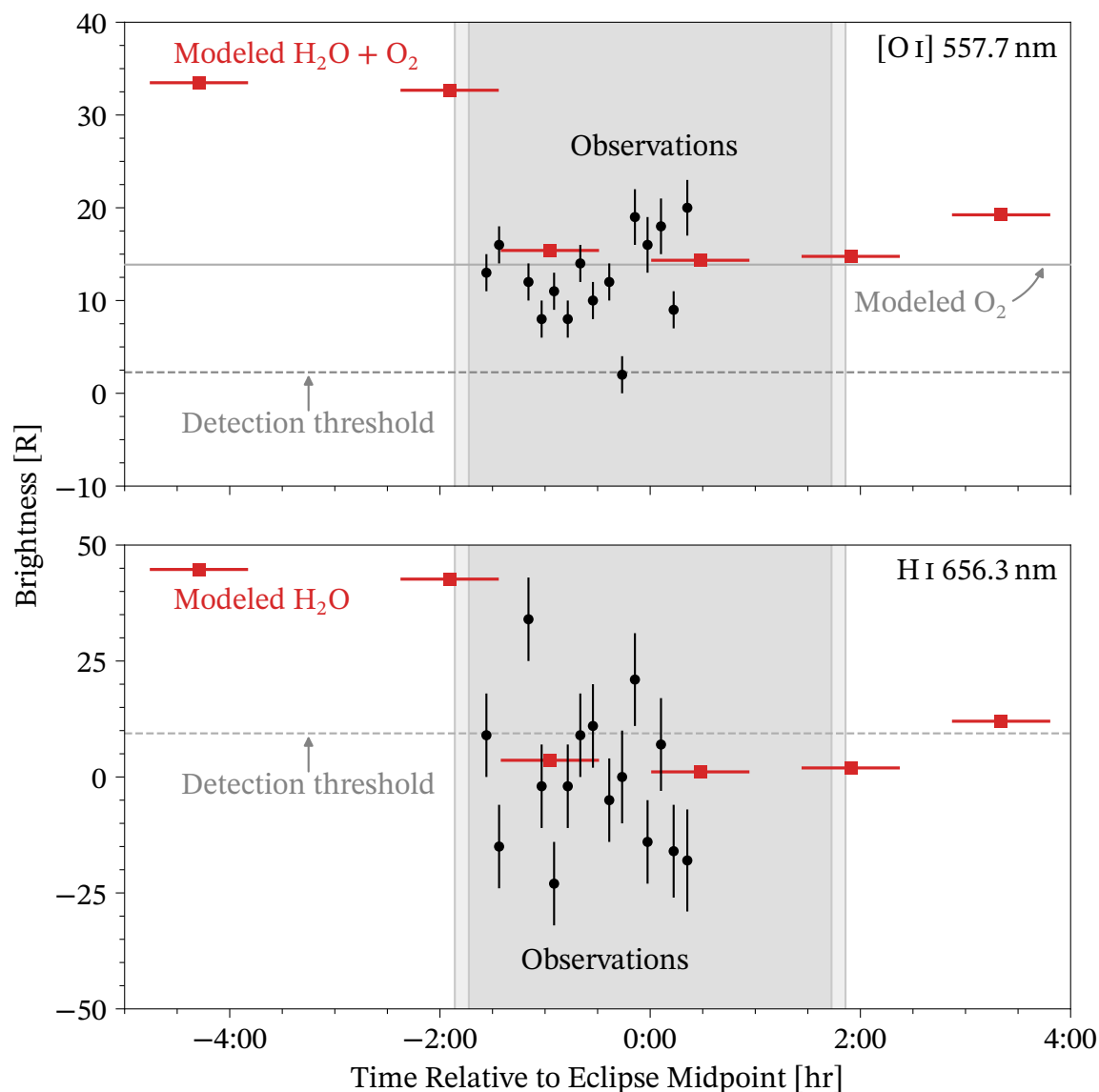


Figure 4.11: Comparison between 557.7 nm [O I] and 656.3 nm H α disk-integrated brightness observations and predicted brightnesses from modeled column densities. Black circles with vertical error bars show observations and their associated uncertainties. Red squares show predicted brightnesses from column densities averaged over 57 minutes (2°) of Ganymede's orbit (the horizontal bars show the extent of the averaging window). The dashed gray horizontal line in each plot shows the detection threshold (the typical standard deviation of the observations). The 557.7 nm [O I] modeled brightness from the O₂ atmosphere does not substantially change over the course of the eclipse, so we have shown its value as a solid horizontal dark gray line. The shaded gray regions in the background are the same eclipse boundaries shown in Figure 4.8. For both the 557.7 nm [O I] and 656.3 nm H α observed brightnesses, the H₂O contribution quickly drops below the detection threshold.

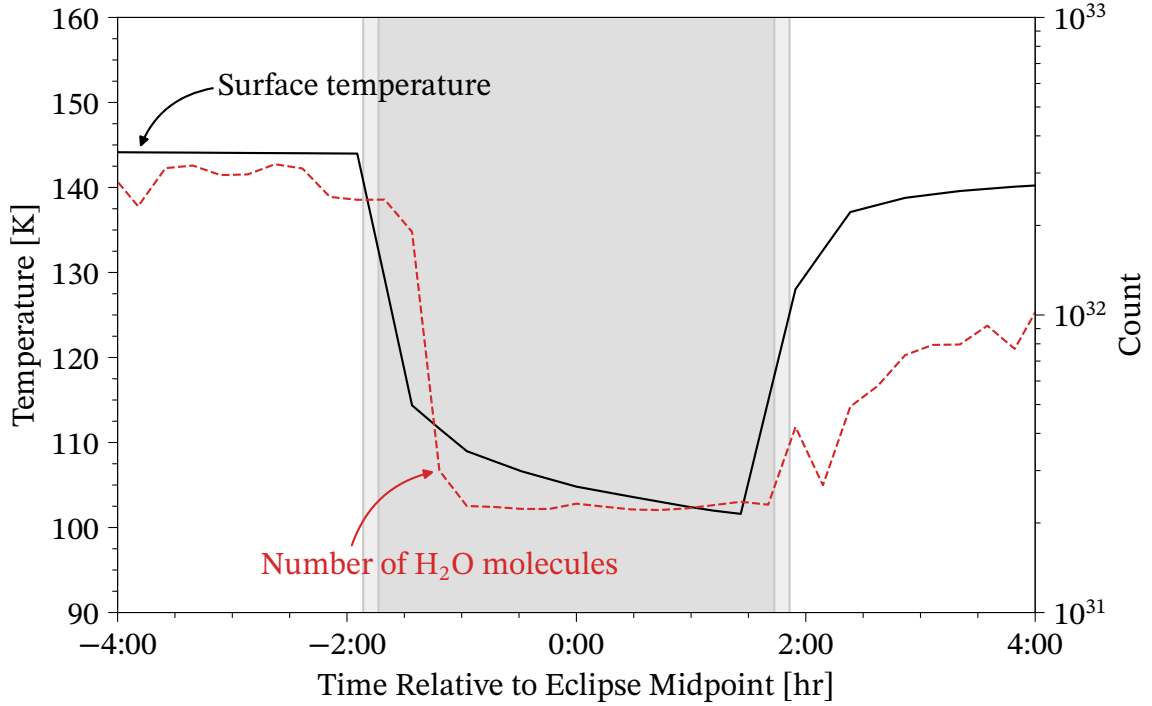


Figure 4.12: Simulated sub-solar surface temperature (Leblanc et al., 2017) and number of simulated H_2O molecules before, during and after eclipse. Ganymede’s surface temperature dropped rapidly at the onset of eclipse, decreasing by 30 K in the first half hour and a further 5 K by the end of the first hour. The number of simulated H_2O molecules in the simulation (proportional to the H_2O number density) decreased by an order of magnitude within the first hour, and remained relatively constant for the rest of the eclipse even though the temperature continued to decrease by an additional 7 K before the end of the eclipse.

molecules in the Monte Carlo simulation. The model only tracks molecules in the gas phase, so as the H_2O molecules freeze onto the surface, the number of simulated particles proportionally decreases. The simulated surface temperature of Ganymede decreased from 143 K to 113 K at a rate of -1 K min^{-1} during the first 30 minutes of the eclipse. By the end of the eclipse the surface temperature had decreased by a further 12 K to a minimum of 101 K. Within the first hour, the number of simulated H_2O molecules (a quantity proportional to H_2O density) decreased by an order of magnitude.

We evaluated the change in H_2O column density over the duration of the first three observations to see what emission we could expect to detect from the collapsing H_2O atmosphere in the simulation. During the time interval that corresponds to the first HIRES observation (integrated from 10 to 15 minutes after the start of the full umbral eclipse), the model temperature fell from 122 K to 117 K and the column density decreased from 73% to 66% of the pre-eclipse maximum. Auroral brightness is directly proportional

to column density, so at 557.7 nm we would expect to measure the 13.5 R of constant emission from electron impact on O₂ and an equivalent brightness from electron impact on H₂O, for a total of about 27 R, almost 8σ above the observed brightness of (12 ± 2) R. At 656.3 nm we would expect to measure 27.6 R of emission from electron impact on H₂O, about 2σ above the observed brightness of (9 ± 9) R.

By the start of the time interval covered by the second observation (integrated from 17 to 22 minutes after the start of the full umbral eclipse), the simulated temperature decrease has slowed and the surface temperature only changed by 1 K from 114 K to 113 K. The column density decreased from 63% to 45% of the pre-eclipse maximum, so from electron impact on H₂O we would expect 10.5 R of emission at 557.7 nm for a total of 24 R (5σ above the observed brightness) and 21.6 R of emission at 656.3 nm (2.4σ above the noise threshold).

At the start of the time interval covered by the third observation (integrated from 34 minutes to 39 minutes after the start of the full umbral eclipse), the surface temperature has dropped to about 111 K and the column density has decreased to 9% of the pre-eclipse maximum. The contribution to the brightnesses for both 557.7 nm [O I] and 656.3 nm H α from electron impact on H₂O are below the noise level of the individual observations.

These simulations suggest that we should detect a contribution from electron impact on H₂O to the observed brightnesses at 557.7 and 656.3 nm in the first two observations. However, for both observations the observed brightnesses are consistent with the presence of at most a minor H₂O atmospheric column.

4.4.5 Potential Impact of New Juno-Derived Electron Properties on Aurora Interpretation

Saur et al. (2022) provide an important caveat to the interpretation of modeled aurora brightnesses for Ganymede. Because of local electron acceleration within Ganymede's magnetic field, the upstream electron distribution used in most models (including ours) does not accurately represent the electron distribution that produces the aurora, and the 70 cm^{-3} density enhancement near the auroral ovals may not be physically accurate. Greathouse et al. (2022) reported Juno observations of the 130.4 nm O I and 135.6 nm O I] UV auroras at very high spatial resolution. They showed that the emission was narrowly confined in latitude near the open/closed field line boundary, with combined brightnesses peaking around 1000 R. Saur et al. (2022) evaluated the electron distribution necessary to excite auroras of these combined brightnesses and found that the electrons must have a Maxwell-Boltzmann distribution centered at 200 eV (twice the

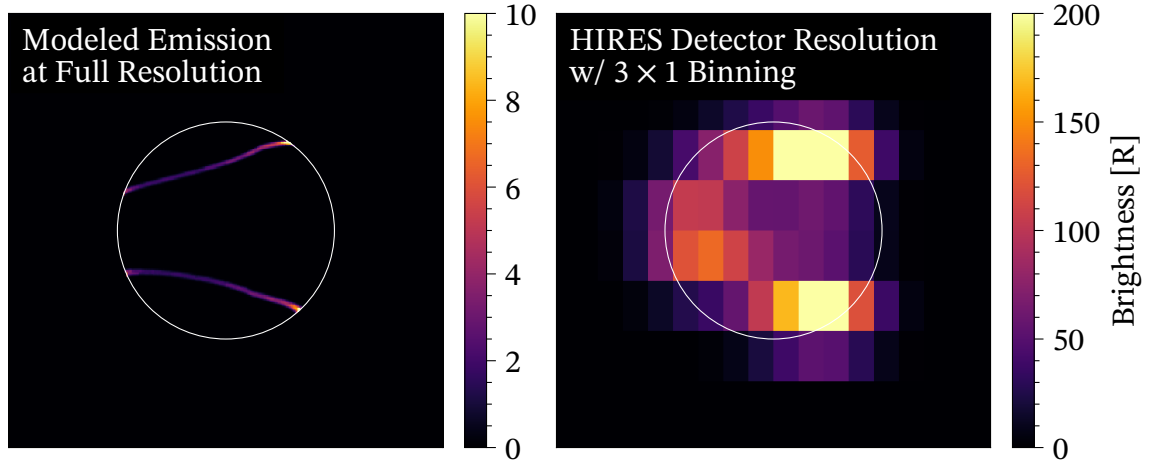


Figure 4.13: Simulation of Ganymede’s 630.0 nm [O I] auroral emission from electron impact on O_2 incorporating an updated electron energy distribution and emitting region. We used a Maxwell-Boltzmann electron energy distribution centered at 200 eV with a number density of 950 cm^{-3} (Saur et al., 2022), a typical O_2 column density during eclipse and we restricted the aurora emission to a Gaussian shape along the open/closed field line boundaries with a FWHM of 5° (Greathouse et al., 2022). The left high-resolution image shows the spatially-confined emission from discrete elements $0.01''$ wide, with brightnesses peaking above 10 kR at the limb. The right image shows this same image scaled down to the detector resolution and binning used in the Ganymede eclipse observations on 2021-06-08 UTC. We convolved this image with a two-dimensional Gaussian kernel with a FWHM of $0.5''$, approximating typical seeing conditions on the summit of Maunakea. The white circle shows the size of the apparent disk of Ganymede. This simulation has equal electron flux for the northern and southern hemispheres, and is therefore representative of the plasma conditions encountered by Ganymede at the plasma sheet mid-plane.

assumed energy of the upstream electrons) and a density of 950 cm^{-3} (about 50 times higher than the assumed upstream electron number density). The significantly smaller brightnesses found by our work and previous UV studies are due to coarse spatial resolution spreading the brightness over resolution elements much larger than the emitting region.

To explore the manifestation of this effect in the HIRES observations, we evaluated the 630.0 nm [O I] emission using these electron properties and the simulated O_2 column density from 177° to 179° (see Figure 4.10). We restricted the emission to the latitudes of the open/closed field line boundaries (Duling et al., 2022) using a Gaussian profile with a FWHM of 5° (Greathouse et al., 2022). To account for the leading-trailing brightness asymmetries apparent in the HIRES observations, we applied a sinusoidal scaling to the electron densities with longitude, decreasing from 950 cm^{-3} at the trailing hemisphere

limb longitude to 26% of this value (244 cm^{-3}) at the leading hemisphere limb longitude. This produces an electron flux with a dusk-dawn asymmetry matching the value of 1.84 we found in our analysis of the HIRES observations. Though we assume that this brightness gradient is due exclusively to spatially varying electron number density, it could also incorporate a higher O_2 column density on the trailing hemisphere (Oza et al., 2018).

Figure 4.13 shows the simulated physical emission from Ganymede with these parameters at full resolution in the left image and at HIRES detector resolution in the right image. The total simulated disk-integrated brightness is 149 R, which we retrieved from the simulation using the same aperture size as the data. This result is extremely close to the best-fit value of $(136 \pm 4) \text{ R}$ for 630.0 nm [O I] retrieved from the HIRES observations for the center of the plasma sheet (Figure 4.4), especially considering the simplistic assumptions of this simulation; small changes in the electron gradient could easily produce a result matching the observed brightnesses. As a result, we concluded that the observations are therefore consistent with the electron properties derived by Saur et al. (2022) when coupled with the emission spatial distribution and hemispheric brightness asymmetry from Greathouse et al. (2022) and the pixel scale of the HIRES detectors.

This further demonstrates that either choice of electron energy distribution, number density and spatial distribution is consistent with the derived column densities of this and other works. Table 4.6 lists the expected emission ratios for this higher-energy and higher-number-density *Juno*-derived electron distribution. The 200 eV electron energy distribution from Saur et al. (2022) is consistent with the *in situ* measurements of the low-energy electron distribution reported by Allegrini et al. (2022), which were made from within Ganymede’s magnetosphere by the Jovian Auroral Distributions Experiment (JADE) during the *Juno* flyby of Ganymede on 2021-06-07 UTC. They did not report any corresponding measurements of electron number density from within Ganymede’s magnetosphere, but outside of it, they found densities that were typically between 5 and 20 cm^{-3} , more consistent with the *Voyager* flyby results (Scudder et al., 1981). Similarly, Kurth et al. (2022) used measurements of total electron densities made by the Juno/Waves instrument during the same Ganymede flyby and found they varied between 15 and 30 cm^{-3} . However, when we simulated auroral emission like that shown in Figure 4.13 assuming the same column densities but using with a Maxwell-Boltzmann electron energy distribution centered at 200 eV and a number density of 20 cm^{-3} , we found a predicted [O I] emission of only 3 R at 630.0 nm, suggesting more complex acceleration processes must be occurring within Ganymede’s magnetic field.

Table 4.6: Modeled emission ratios relative to 557.7 nm [O I] for Ganymede’s optical aurora, assuming the Juno-derived electron population with a Maxwell-Boltzmann distribution at 200 eV and a number density of 950 cm^{-3} .

	Parent Species			
	O	O ₂	H ₂ O	CO ₂
121.6 nm Ly α	—	—	4.53	—
130.4 nm O I	33.1	1.29	0.177	0.0481
135.6 nm O I]	0.539	2.96	0.0414	0.0458
297.2 nm [O I]	0.0598	0.0598	0.0598	0.0598
486.1 nm H β	—	—	0.402	—
557.7 nm [O I]	1	1	1	1
630.0 nm [O I]	2.40	11.3	0.943	0.872
636.4 nm [O I]	0.775	3.64	0.305	0.282
656.3 nm H α	—	—	2.24	—
777.4 nm O I	0.194	2.06	0.0609	0.0288
844.6 nm O I	4.43	0.963	0.181	0.0209

4.5 Conclusions

In this study, we presented a time-series analysis of 17 high-resolution spectra of Ganymede’s auroral emission at optical wavelengths taken with Keck I/HIRES on 2021-06-08 UTC. This study was the first to resolve and analyze the spatial variability of Ganymede’s aurora at optical wavelengths and the first at any wavelength to evaluate these changes on a cadence of just a few minutes. We observed Ganymede during eclipse by Jupiter, which allowed us to capture the aurora without the overwhelming presence of reflected solar continuum. The timing of the eclipse also allowed us to observe Ganymede as it passed through the mid-plane of the Jovian plasma sheet where it was subjected to the highest incident electron number density. The high cadence of the observations also let us evaluate the potential for the rapid collapse of a localized H₂O atmosphere near the sub-solar point as Ganymede passed into Jupiter’s shadow.

We observed Ganymede’s plasma sheet mid-plane-facing hemisphere brightening relative to the opposite hemisphere, reaching a peak hemispheric brightness ratio of nearly 2 when it was about $1 R_J$ from the centrifugal equator of the plasma sheet. We did not observe the same exponential drop-off of brightness with distance from the plasma sheet mid-plane that has been seen at Europa (Roth et al., 2016; de Kleer et al., 2023), though there was additional variability in the brightness that we attributed to longitudinal density heterogeneities in the Jovian plasma sheet. Additional observations

could help to provide a better understanding of the nature of the variability seen in the brightness.

In addition to evaluating the north-south hemispheric brightness ratio, we also compared the dusk-dawn (trailing-leading) hemispheric brightness ratio. This ratio did not change with plasma sheet distance like the north-south ratio, but we did find that the dusk hemisphere was almost always nearly 2 times brighter than the dawn hemisphere. This effect is likely a combination of both higher incident electron number density on the ram-facing trailing hemisphere and a higher O₂ column density toward dusk due to higher afternoon surface temperatures predicted by models (e.g., Leblanc et al., 2017; Oza et al., 2018). Unfortunately, we cannot decouple these effects with eclipse observations because of the viewing geometry limitations.

Our MCMC model found a median atmospheric H₂O/O₂ column density ratio of $0.10^{+0.05}_{-0.04}$, matching the upper limit of 0.10 found by de Kleer et al. (2023) for 2021-06-08 UTC but well below the H₂O abundance found by Roth et al. (2021) from sunlit UV observations. The 630.0 nm/557.7 nm [O I] brightness ratio is well suited to differentiating between electron impact on O₂ and H₂O as the source of the excited O atoms producing the auroral emission. We quantitatively tested our ability to detect an H₂O atmosphere localized to near the sub-solar point by using the Monte Carlo simulations of Leblanc et al. (2023) for Ganymede's O₂ and H₂O atmospheres in eclipse. We combined these simulations with our aurora model to simulate emission components proposed by Roth et al. (2021) and evaluate their detectability with HIRES.

The modeled emission from the simulated sunlit H₂O and O₂ atmospheres produced brightnesses of 33 R at 557.7 nm and 45 R at 656.3 nm, well above our typical observed brightnesses of 11.5 ± 0.6 and 0 ± 2 R, respectively. Our results are therefore inconsistent with the presence of a localized high-density H₂O atmosphere near the disk center proposed by Roth et al. (2021) based on sunlit observations.

Even though the simulations of the eclipse atmospheres suggest that the H₂O column density decreases rapidly during eclipse ingress, emission from electron impact on the actively condensing H₂O atmosphere should still be a significant component of the observed 557.7 and 656.3 nm [O I] brightnesses for the first two observations in our data set. We did not detect any variability in the brightness that would suggest an actively condensing H₂O atmosphere during eclipse ingress, implying that if a sublimation H₂O atmosphere exists in sunlight and freezes back onto the surface during eclipse, the timescale for condensation must be around 10 minutes or less.

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Chapter 5

CALLISTO

Milby, Z., K. de Kleer, and C. Schmidt (2026). “Variability of Callisto’s Optical Aurora in Eclipse”. *The Planetary Science Journal* 7, 5. DOI: 10.3847/PSJ/ae650c.

Abstract

Detections of auroral emission from Callisto have been difficult due to the low density of electrons that excite the aurora at its large orbital distance from Jupiter. However, large ground-based telescopes with sensitive spectrographs can detect the faint emissions at optical wavelengths when Callisto is eclipsed by Jupiter. In this study, we analyzed two sets of optical wavelength spectra observed with Keck I/HIRES. We detected the 630.0 nm [O I] emission line in individual five-minute integrations and found its disk-averaged brightness decreased with distance from the centrifugal equator of Jupiter’s plasma sheet. The average brightness matched simulations of emission from an atmosphere composed of O, O₂, H₂O and CO₂ using the most up-to-date estimates or upper limits for their individual column densities, supporting the prevailing paradigm that Callisto’s atmosphere may be the densest of the icy Galilean satellites and is composed primarily of O₂. We also modeled the emission from the same atmosphere if an ionosphere inhibited excitation by the thermal electron population but found the resulting brightness was an order of magnitude below observations.

5.1 Introduction

Callisto’s atmosphere and plasma environment are the least well constrained of the Galilean satellites. *In situ* measurements come primarily from the flybys of the *Galileo* spacecraft in the late 1990s (Gurnett et al., 1997; Gurnett et al., 2000; Kliore et al., 2002), while limited remote sensing observations have been made from spacecraft orbiting within the Jovian system (Scudder et al., 1981; Belcher, 1983; Carlson, 1999; Le Liboux et al., 2025) and from ground- and space-based telescopes at Earth (Strobel et al., 2002; Cunningham et al., 2015; de Kleer et al., 2023).

Gurnett et al. (1997) analyzed *Galileo* Plasma Wave Subsystem (PWS) observations during a flyby of Callisto and found that, despite its nearly comparable size, Callisto showed no evidence of an internally generated magnetic field like the one previously discovered at Ganymede (Kivelson et al., 1996). However, they did derive electron densities that were much higher than the ambient upstream densities in Jupiter’s magnetosphere. They posited these electrons therefore had to originate from Callisto, implying the pres-

ence of a neutral atmosphere which could be ionized to produce the electrons. Gurnett et al. (2000) expanded the analysis to seven close flybys of Callisto. In one, they measured an electron density of about 400 cm^{-3} , further hinting at the presence of an ionosphere.

The atmospheres of Callisto's companion satellites Europa and Ganymede were first detected via electron-excited auroral emission from oxygen using the *Hubble Space Telescope* (HST; Hall et al., 1995; Hall et al., 1998). The first emission detected from Callisto's atmosphere was the near-infrared $\text{CO}_2 \nu_3$ band system airglow, observed in a single limb scan by the *Galileo* Near-Infrared Mapping Spectrometer (NIMS; Carlson, 1999). The observed emissions were near the equator around noon local time and extended from the surface to an altitude of around 100 km before becoming indistinguishable from background noise. Assuming an isothermal atmosphere at 150 K, they calculated a scale height of 23 km and a corresponding CO_2 column density of $(8 \pm 5) \times 10^{18} \text{ m}^{-2}$.

Kliore et al. (2002) analyzed *Galileo* radio occultations and found a measurable ionosphere over Callisto's trailing (plasma ram-facing) hemisphere. They argued for O_2^+ as the principle ion, and thereby inferred an O_2 -dominated atmosphere. Peak plasma densities of 10^4 cm^{-3} at altitudes between 30 and 50 km above Callisto's surface suggested an atmosphere dense enough to absorb nearly all ionizing radiation. They inferred a neutral O_2 column density between 3×10^{20} and $4 \times 10^{20} \text{ m}^{-2}$, more than an order of magnitude larger than the CO_2 density inferred by Carlson (1999).

Strobel et al. (2002) searched for UV emissions from atomic oxygen similar to those observed at Europa (Hall et al., 1995; Hall et al., 1998) and Ganymede (Hall et al., 1998) but failed to detect any. They calculated upper limits of 15 R for the UV emissions (including from atomic carbon), which resulted in upper limits of 10^{21} m^{-2} for O_2 , CO_2 and CO, 10^{17} m^{-2} for C and $2.5 \times 10^{17} \text{ m}^{-2}$ for O. They suggested the lack of detectable emission was due to the ionosphere diverting plasma flow around the satellite, shielding much of the atmosphere from electron-impact excitation. They calculated the ionosphere detected by Kliore et al. (2002) would allow only 0.07% of the cold thermal plasma to reach Callisto's surface. However, Kliore et al. (2002) only detected the ionosphere when the trailing hemisphere was illuminated by sunlight; they did not observe increased electron densities during their leading hemisphere occultation. In contrast, Gurnett et al. (2000) observed substantial electron densities over Callisto's nightside leading hemisphere. Consequently, while the ionosphere may only be present under specific orbital geometries, the processes responsible for generating it remain unclear.

Cunningham et al. (2015) reported the first detection of UV aurora at Callisto using the Cosmic Origins Spectrograph (COS) on HST. They observed the 130.4 nm O I triplet with an average brightness of $(4.7 \pm 0.7) \text{ R}$ and the 135.6 nm O I] doublet with an average

on-disk brightness of (3.2 ± 1.6) R and concluded that the brightness ratio was indicative of a collisional O₂ atmosphere with a column density of $4 \times 10^{19} \text{ m}^{-2}$. They also concluded the CO₂ atmosphere from Carlson (1999) had too small of a column density to produce detectable UV emission given the noise levels in their observations, and suggested the trailing hemisphere O₂ column density could be an order of magnitude larger than the leading hemisphere column density. They compared excitation via photoelectrons and magnetospheric electrons and concluded that the impact of photoelectrons was the likely excitation mechanism.

An analysis of archival HST/STIS data revealed the presence of an atomic hydrogen corona with a column density between 6×10^{15} and $1.2 \times 10^{16} \text{ m}^{-2}$ (Roth et al., 2017). To explore its origin, Carberry Mogan et al. (2022) simulated the production of atomic H at Callisto through the interaction of magnetospheric electrons and solar photons with H₂ and H₂O. They determined that sublimated H₂O was too localized to be the origin of the atomic H, suggesting the more radially extended H₂ corona is the likely source. This agreed with the conclusions of Gurnett et al. (1997), who suggested the electron densities observed near Callisto indicated the presence of an extended neutral atmosphere. Carberry Mogan et al. (2022) also placed an upper limit on the H₂O column density of 10^{19} m^{-2} .

de Kleer et al. (2023) made the first detection of the 630.0 and 636.4 nm [O I] emissions from Callisto in eclipse, which could not result from photoelectron excitation. These emissions originate from the same upper state and therefore do not have a brightness ratio that varies with parent species and cannot be used to constrain the source of the atomic oxygen.

Recent spatially resolved observations with the Near Infrared Spectrograph (NIR-Spec) on the *James Webb Space Telescope* (JWST) revealed a patchy CO₂ atmosphere over the trailing hemisphere with a typical disk-averaged column density around $5 \times 10^{18} \text{ m}^{-2}$ (Cartwright et al., 2024, see also Table 5.1). The distribution of the CO₂ gas was offset from the subsolar point, suggesting it was produced either through sputtering/radiolysis or possibly through some unknown geological process. Camarca et al. (2026) expanded this analysis to Callisto's leading hemisphere and found even larger column densities that were also offset from the subsolar point. They showed a correlation with Callisto's position relative to the centrifugal equator of Jupiter's plasma sheet and suggested that, if the correlation was confirmed through additional time series measurements, this would resolve the question of geological processes versus sputtering as the source of the CO₂ gas. Table 5.1 summarizes the column densities measured or inferred from observations.

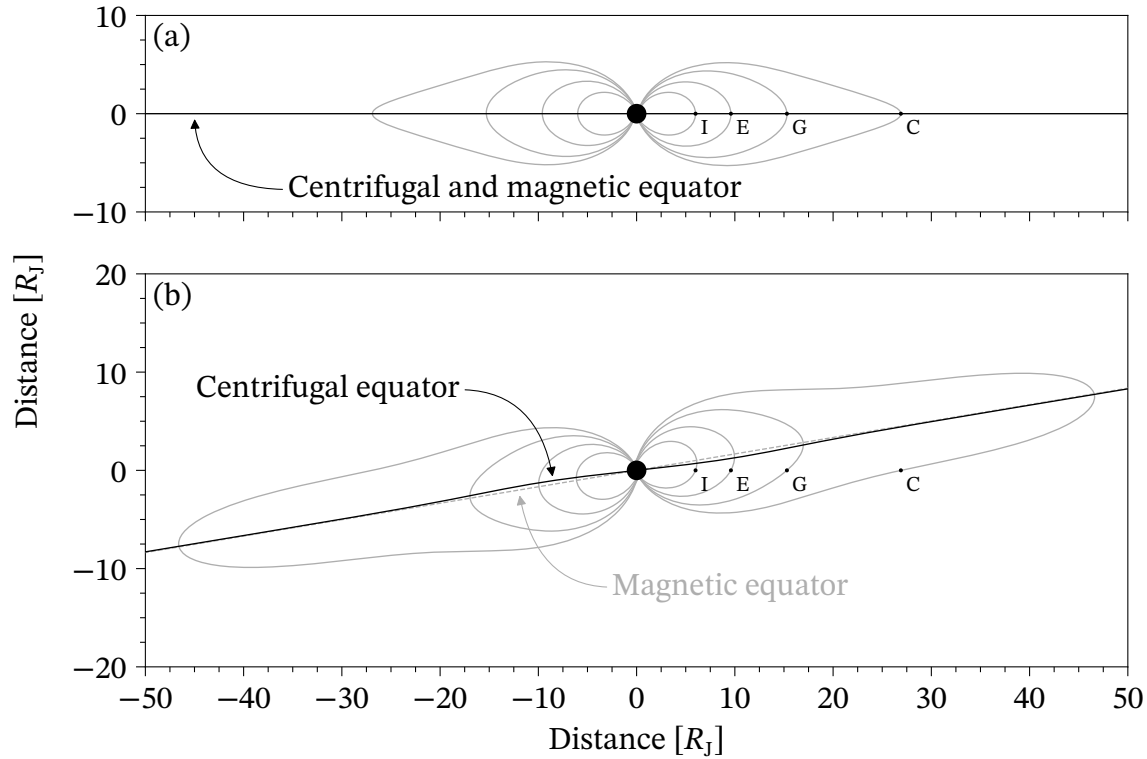


Figure 5.1: Jovian magnetic field lines (M-shells) intersecting the Galilean satellites (a) when the rotational and magnetic equators align at 69° or 249° System III east longitude and (b) when they have their maximum offset of 9.5° (shown here with the satellites south of the centrifugal equator at 339° System III east longitude). The large black circle at the center represents Jupiter, and the four smaller black circles are each of the Galilean satellites at their nominal orbital distances, labeled “I” for Io, “E” for Europa, “G” for Ganymede and “C” for Callisto. Callisto experiences this full range of M-shells within a 2.5 hour quarter rotation of Jupiter. Generated using the “JRM33” magnetic field model (Connerney et al., 2022) with the “CON2020” current sheet model (Connerney et al., 2020) as implemented in the Python package *JupiterMag* (Wilson et al., 2023).

Ionospheric shielding alone cannot explain the dimness of Callisto’s aurora, nor we do not fully understand the processes generating Callisto’s possibly transient ionosphere. Further, plasma properties may also vary significantly due to Callisto’s large semimajor axis. The M-shell (the radial distance at which a magnetic field line crosses the Jovian magnetic field equator) intersecting Callisto varies from 26.3 to around $69 R_J$ (Paranicas et al., 2018). Interaction with the solar wind further modifies the geometry of the Jovian magnetic field, and so a broad range of M-shells in the Jovian magnetotail could potentially intersect Callisto when it is in the eclipse phase of its orbit (see Figure 24.1 in Khurana et al., 2004). Analysis of *Juno* observations from October 2024 showed that the impact of a coronal mass ejection can enhance this effect even further, potentially

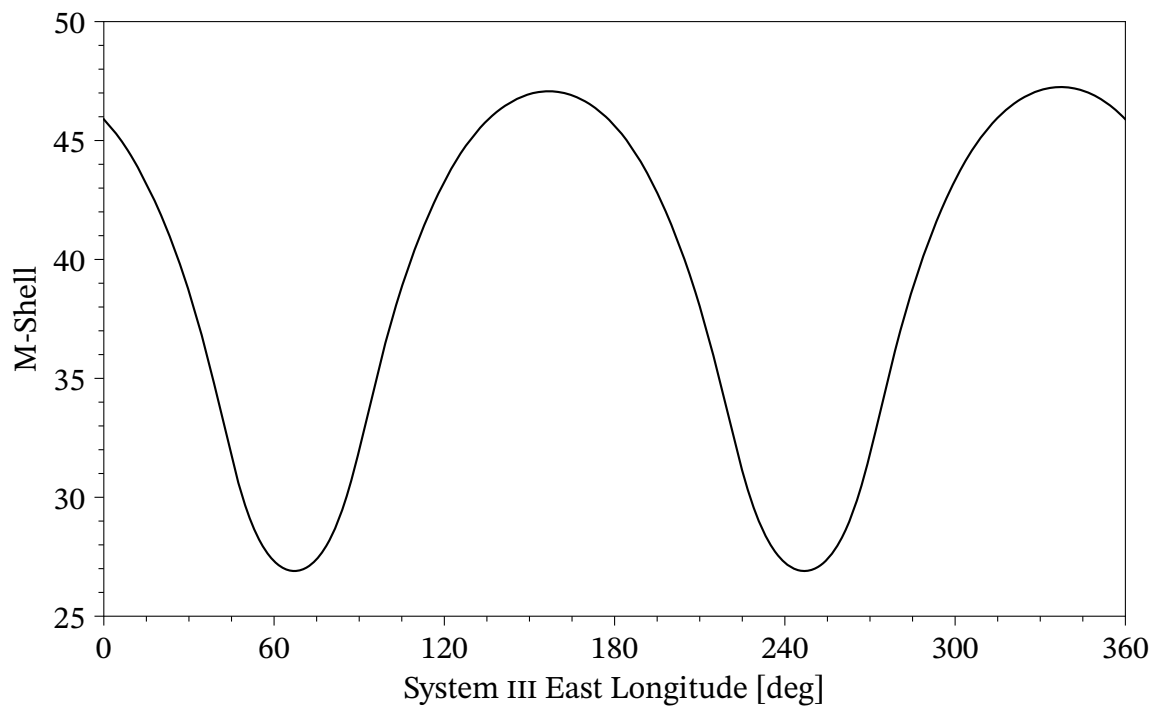


Figure 5.2: M-shells intersecting Callisto over one full rotation of Jupiter’s magnetic field. Generated using the “JRM33” magnetic field model (Connerney et al., 2022) with the “CON2020” current sheet model (Connerney et al., 2020) as implemented in the Python package `JupiterMag` (Wilson et al., 2023).

Table 5.1: Summary of measured and inferred atmospheric column densities for oxygen-bearing constituents.

Reference	Column Density [$\times 10^{18} \text{ m}^{-2}$]					Hemisphere
	O	O ₂	H ₂ O	CO ₂	CO	
Carlson (1999)	—	—	—	8 ± 5	—	Subsolar (limb line-of-sight)
Kliore et al. (2002)	—	350 ± 50	—	—	—	Trailing (implied)
Strobel et al. (2002)	<0.25	<1000	—	<1000	<1000	Leading and trailing
Cunningham et al. (2015)	—	40	—	—	—	Sub-Jovian, leading
	—	400	—	—	—	Trailing
Hartkorn et al. (2017)	—	21 ± 11	—	—	—	Subsolar
Carberry Mogan et al. (2022)	—	—	<10	—	—	
de Kleer et al. (2023)	—	40 ± 9	—	—	—	Sub-Jovian
Cartwright et al. (2024)	—	—	—	4 to 10	—	Leading and trailing
Camarca et al. (2026)	—	—	—	5 ± 2	—	Trailing
	—	—	—	5 ± 2	—	Asgard (223° E)
	—	—	—	6 ± 3	—	Valhalla (304° E)

pushing the magnetopause to a distance inside of Callisto's semimajor axis (Wilson et al., 2026). However, Callisto will remain within the magnetosphere during eclipse observations, which are taken when Callisto's sub-Jovian longitude is near Jupiter's local midnight.

Measurements taken at Callisto's orbit during the two *Voyager* flybys revealed a two-component electron population (Scudder et al., 1981; Belcher, 1983). The thermal “core” population, often referred to as the “cold” electrons, had energies varying between 50 and 300 eV, with a typical energy of around 100 eV and a number density of approximately 1 cm^{-3} . The suprathermal “hot” population had energies varying between 2 and 3 keV with a number density around 0.01 cm^{-3} . Plasma density measurements taken during the *Galileo* mission varied between 0.01 and 0.7 cm^{-3} , with an average of 0.15 cm^{-3} (Gurnett et al., 2000; Kivelson et al., 2004) and potential variability at Callisto's orbit of up to a factor of 10 (Kivelson et al., 2004). Bagenal et al. (2011) combined *Voyager 1* and *Galileo* measurements to derive a density profile which predicts a density of 0.14 cm^{-3} at $26.9 R_J$. A more recent combination of *Galileo* and *Juno* measurements shows Callisto experiences a maximum density of 0.22 cm^{-3} at M-shells between 22.5 and $27.5 R_J$ and a minimum density of 0.0088 cm^{-3} at M-shells between 47.5 and $52.5 R_J$ (Le Liboux et al., 2025).

Figure 5.1 shows the magnetic field geometry leading to the large range of M-shells intersecting Callisto which results due to its orbital distance from Jupiter and the modification of the dipole field due to the current sheet. Figure 5.2 shows the M-shell intersecting Callisto as a function of System III east longitude, from a minimum of $26.9 R_J$ at 69° and 159° east longitude to a maximum of approximately $47.2 R_J$ at 159° and 339° east longitude. These models do not include the effect of other currents external to the Jupiter system which modify the structure of the field lines (see Figure 24.1 in Khurana et al., 2004); consequently the maximum M-shell could be as far as $69 R_J$ (Paranicas et al., 2018).

Unsurprisingly, modeling studies have varied somewhat in their electron population assumptions. Kliore et al. (2002) used a two-component thermal population comprised of a “cold” population between 0.2 and 0.5 cm^{-3} at 100 eV and a 0.02 cm^{-3} “hot” population at 2 keV. Cunningham et al. (2015) also used a two-component electron distribution with a cold Maxwellian core component of 0.11 cm^{-3} at 35 eV based on Belcher (1983) and a hot, suprathermal component of 0.04 cm^{-3} at 1.5 keV. de Kleer et al. (2023) found the inclusion of a suprathermal population did not significantly affect optical aurora excitation due to the low-energy peaks of the emission cross sections, and therefore chose to use a single Maxwellian population at 35 eV similar to the core population of

Cunningham et al. (2015) but with the larger total number density of 0.15 cm^{-3} . Carberry Mogan et al. (2022) used a Maxwellian population of 1.1 cm^{-3} at 100 eV following the recommendation of Neubauer (1998, Table 1), which was based on Belcher (1983), Sittler et al. (1987) and Khurana et al. (1997).

In this study, we combine new eclipse observations of Callisto’s optical aurora with spectra previously published by de Kleer et al. (2023) to evaluate whether the observed auroral brightnesses are consistent with emission from atmospheres measured and inferred from other studies, whether the emission indicates the presence of an ionosphere like that proposed by Kliore et al. (2002), and if the emission changes linearly with the ambient upstream electron density of Jupiter’s magnetospheric plasma.

5.2 Observations and Data Reduction

We observed Callisto in eclipse by Jupiter with the High Resolution Echelle Spectrometer (HIRES) on the Keck I telescope on 2021-07-04 and 2025-11-29 using the same Galilean satellite optical aurora methodology employed by previous studies (Bouchez et al., 2000; de Kleer et al., 2018; de Kleer et al., 2019a; de Kleer et al., 2023; Schmidt et al., 2023; Milby et al., 2024; Milby et al., 2025; Milby et al., 2026b). (Jupiter did not eclipse Callisto from mid-2022 through mid-2025, preventing us from acquiring additional optical aurora observations until recently.) For both of these observations, we used the D4 slit which has a projected angular size on the sky of $1.722'' \times 14''$. On each date, Callisto had an apparent angular diameter of approximately $1.5''$, so the wider slit and monochromatic auroral emissions allowed for HIRES to operate as an imaging spectrograph with two axes of spatial information. For the 2021-07-04 observations, we used Europa as the guide satellite; for the 2025-11-29 observations, we used Io as the guide satellite. The 2025 observations add an additional 70 minutes of integration time to the 25 minutes from 2021. Each set of science exposures also includes standard processing data including bias and flat-lamp images, ThAr arc lamp spectra for wavelength calibration, a trace spectrum of a standard star, and a spectrum of Jupiter’s subobserver meridian for flux calibration (following the methodology described by Woodman et al., 1979).

de Kleer et al. (2023) originally published the 2021-07-04 observations, which we re-processed and re-analyzed for this study. We reduced and flux-calibrated the data using the most up-to-date versions of the same data reduction and calibration pipelines employed by previous Galilean satellite optical aurora studies (de Kleer et al., 2023; Milby et al., 2024), but made use of the improved background subtraction algorithm employed by Milby et al. (2025) and Milby et al. (2026b) in order to carefully remove

Table 5.2: Individual 630.0 nm [O I] brightness measurements.

Observation Time [UTC]	Distance ^a [R_J]	Brightness [R]
2021-07-04		
14:36:22	2.52	12 ± 3
14:43:37	2.25	8 ± 4
14:51:27	1.93	11 ± 3
15:00:34	1.55	12 ± 3
15:07:33	1.25	10 ± 4
2025-11-29		
09:40:14	4.23	9 ± 6
09:48:29	4.07	9 ± 4
09:56:25	3.89	-3 ± 4
10:05:19	3.66	-3 ± 3
10:13:25	3.43	9 ± 5
10:21:04	3.18	-6 ± 4
10:28:58	2.91	7 ± 6
10:36:45	2.63	12 ± 4
10:45:01	2.31	13 ± 5
10:52:34	2.00	-6 ± 4
11:00:58	1.64	11 ± 4
11:08:30	1.31	25 ± 4
11:16:18	0.97	19 ± 5
11:23:55	0.62	26 ± 6

^a Distance d from the centrifugal equator (which we assumed to be the same as the magnetic equator at Callisto's orbital distance from Jupiter), calculated as $d = 26.9 R_J \sin \lambda_m$, where λ_m is the magnetic latitude of Callisto at System III east longitude $\phi_{\text{III,RH}}$.

scattered light from Jupiter and reveal the faint auroral signals (compare the 2021-07-04 data in our Figure 5.3 to the same data in de Kleer et al., 2023, Figure 4).

5.3 Analysis and Discussion

5.3.1 Auroral Emission Line Detections

Despite both measured and inferred atmospheric column densities an order of magnitude or more larger than those of either Europa or Ganymede, Callisto's optical auroras are very dim in comparison due to much lower electron densities at its orbital distance

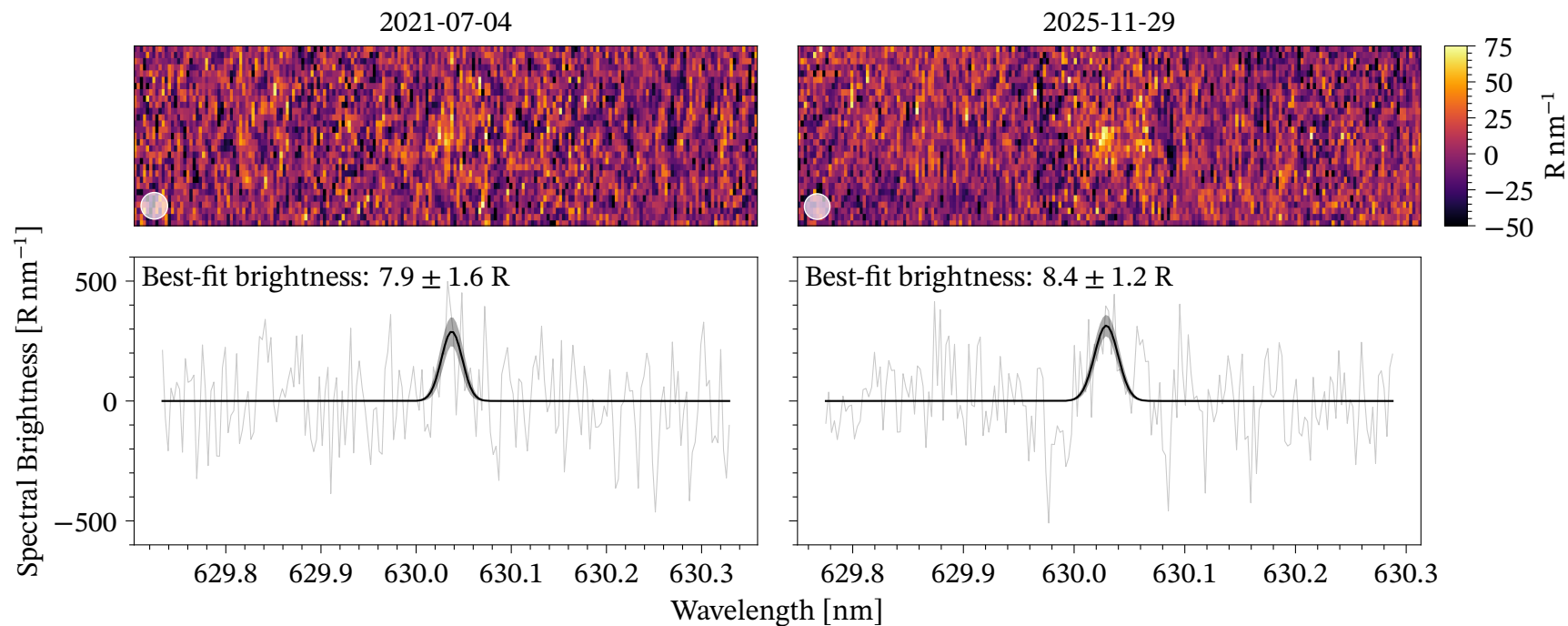


Figure 5.3: Callisto's 630.0 nm [O I] emission on 2021-07-04 (left column) and 2025-11-29 (right column). The two plots in the top row show the two-dimensional calibrated average spectra over the 14'' slit length with scattered light from Jupiter and the 630.0 nm [O I] telluric emission line subtracted. The two plots in the bottom row show one-dimensional spectra summed over a 2'' aperture (light gray lines) along with best-fit Gaussian functions (solid black lines) and their corresponding uncertainties (gray shaded regions). White circles in the lower left of the top panels show the relative size of Callisto's disk. Larger residuals occur where we have subtracted telluric emission lines, which is especially evident to the left of the Callisto emission in the top plot of 2025-11-29. The annotation in the upper left of the bottom panels is the total brightness (assuming emission from Callisto's disk).

Table 5.3: Average Measured Optical Auroral Brightnesses

Observation Date [UTC]	Brightness					
	557.7 nm [O I] [R]	630.0 nm [O I] [R]	636.4 nm [O I] [R]	656.3 nm H α [R]	777.4 nm O I [R]	844.6 nm O I [R]
2021-07-04	<1.7	7.9 ± 1.6	2.8 ± 1.2	<4	<2	<1.9
2025-11-29	<1.6	8.4 ± 1.2	3.5 ± 0.9	—	<1.5	<1.5
Average	—	8.2 ± 1.0	3.2 ± 0.8	—	—	—

Notes. 1σ upper limits indicated with the less than (“<”) symbol. Echelle and cross-disperser angles chosen for 2025-11-29 excluded coverage of H α . de Kleer et al. (2023) first published the 2021-07-04 brightnesses and upper limits; the 630.0 nm brightnesses we calculated are brighter than theirs but agree within the uncertainties.

from Jupiter. We found convincing detections in average two-dimensional spectra for the 630.0 and 636.4 nm [O I] lines, shown in Figure 5.3. For the other oxygen lines within the wavelength range of the HIRES spectra, we could only calculate upper limits estimated from the surrounding spectral noise. Table 5.3 lists the brightnesses and upper limits derived from the averaged spectra. For the 630.0 nm [O I] line, we were able to calculate individual brightnesses, listed in Table 5.2.

5.3.2 Emission Modeling and Comparison with Measured and Inferred Atmospheres

We modeled Callisto’s optical auroral emission using the most up-to-date version of the model employed by previous optical studies including de Kleer et al. (2023), with the addition of cross sections for 557.7, 630.0 and 636.4 nm [O I] emission from electron impact on CO₂ (see Milby et al., 2024, Section 4.3). We did not consider any CO atmospheric column due to a lack of available electron-impact cross sections. We could not fit for individual atmospheric components because we detected only two transitions, both of which share the same upper level; consequently, their emission ratio does not change depending on the source atom or molecule.

We instead compared the derived auroral brightnesses and upper limits from the observations to model predictions of Callisto’s optical auroral emission from electron impact on a neutral atmosphere composed of the most recent estimates for constituent column densities: we used the upper limit column density of $2.5 \times 10^{17} \text{ m}^{-2}$ for O (Strobel et al., 2002), the inferred sub-Jovian column density of $4 \times 10^{19} \text{ m}^{-2}$ for O₂ (Cunningham et al., 2015), an average column density of $5 \times 10^{18} \text{ m}^{-2}$ for CO₂ (Cartwright et al., 2024; Camarca et al., 2026) and the upper limit column density of 10^{19} m^{-2} for H₂O (Carberry Mogan et al., 2022). Note that this H₂O upper limit applies to a sublimated atmosphere in daylight; in eclipse, much of the H₂O column likely freezes onto the surface, though the timescale remains unconstrained.

We considered emission resulting from the impact of a two-component Maxwellian electron distribution of “cold” 35 eV electrons at 0.11 cm^{-3} and “hot” 1.5 keV electrons at 0.04 cm^{-3} following Cunningham et al. (2015). Emission resulting from the impact of the hot population alone, was well below the noise level for each emission and contributed less than 10% to the total brightness of the detected 630.0 nm [O I] line, indicating the observed optical auroral emissions are consistent with excitation primarily from the low-energy population. This suggests an electron flux consistent with non-ionospheric conditions; however, an electron population capable of dissociative excitation of O₂,

H₂O and CO₂ is also capable of ionizing those molecules, and therefore, the optical aurora alone cannot indicate the presence or absence of an ionosphere.

Table 5.4 shows the results of the model simulations, with columns listing the relative brightnesses from each atmospheric component and the total expected brightness. Note that due to uncertainties in the laboratory cross-section measurements, atmosphere column densities and electron population parameters, we chose to report just one or two significant figures for each brightness.

Auroral brightness measurements across both the UV and optical, interpreted with these simulations, support the conclusion that Callisto has an atmosphere at least an order of magnitude larger than its icy companion satellites Europa and Ganymede. The predicted UV emission brightnesses are smaller than those reported by Cunningham et al. (2015) by a factor of about 6 for the 130.4 nm O I line and 3 for the 135.6 nm O I line, though their uncertainties are large and are less than 2σ from the simulated brightnesses. The optical wavelength brightnesses match well for the forbidden 630.0 and 636.4 nm [O I] lines, and none of the others exceed the calculated upper limits.

These results suggest that the forbidden 630.0 and 636.4 nm [O I] emission primarily comes from electron impact on Callisto's O₂ atmosphere, with the contribution from CO₂ a factor of 20 smaller. The results also support O₂ as the primary constituent of Callisto's eclipse atmosphere. The upper limit sublimated H₂O atmosphere from Carberry Mogan et al. (2022) contributes negligibly to the brightness, and if the H₂O atmosphere collapses in eclipse similar to Europa (Roth, 2021; Milby et al., 2026b) and Ganymede (Roth et al., 2021; Milby et al., 2024), its contribution to the observed brightnesses would decrease even further. The next brightest optical emission should be the forbidden 557.7 nm [O I] line, which would appear in our observations at a signal-to-noise of about 1 with about 2 hours of co-added data, and a signal-to-noise of 2 after about 4 hours of co-added data. Callisto's observable eclipses from Maunakea can be up to 4 hours long, so a 2σ detection of the 557.7 nm [O I] line should be achievable from just a single night of observing. Additionally, with the same echelle and cross-disperser angles, multiple nights of data could be easily co-added.

We focused our analysis on the 630.0 nm [O I] emission line because it had the highest signal-to-noise in the HIRES spectra. The predicted brightness from our emission model of 7 R (see Table 5.4) is too low by a factor of 1.17 ± 0.14 , or between 3% and 31%. An increase in O₂ column density by a factor of between approximately 1.05 to 1.25 would be sufficient to bring the modeled brightness to within the uncertainties of the average of the observed 630.0 nm [O I] emission line. Considering the expectation that the trailing hemisphere column density could be up to 10 times larger than the leading

Table 5.4: Modeled auroral emission brightnesses.

Emission	Brightness [R]				
	O	O ₂	H ₂ O	CO ₂	Total
121.6 nm Ly α	—	—	0.2	—	0.2
130.4 nm O I	0.012	0.5	0.009	0.014	0.5
135.6 nm O I]	0.0011	1.0	0.002	0.013	1.1
297.2 nm [O I]	0.00007	0.020	0.003	0.02	0.04
486.1 nm H β	—	—	0.02	—	0.02
557.7 nm [O I]	0.0011	0.3	0.05	0.4	0.7
630.0 nm [O I]	0.004	6	0.05	0.3	7
636.4 nm [O I]	0.0013	2	0.016	0.10	2
656.3 nm H α	—	—	0.12	—	0.12
777.4 nm O I	0.0004	0.6	0.004	0.008	0.6
844.6 nm O I	0.003	0.3	0.01	0.006	0.3

Notes. Assumes a two-component Maxwellian electron distribution of “cold” 35 eV electrons at 0.11 cm^{-3} and “hot” 1.5 keV electrons at 0.04 cm^{-3} . Assumes the upper limit column density of $2.5 \times 10^{17} \text{ m}^{-2}$ for O (Strobel et al., 2002), the inferred sub-Jovian column density of $4 \times 10^{19} \text{ m}^{-2}$ for O₂ (Cunningham et al., 2015), the upper limit column density of 10^{19} m^{-2} for H₂O (Carberry Mogan et al., 2022) and the average column density of $5 \times 10^{18} \text{ m}^{-2}$ for CO₂ (Cartwright et al., 2024; Camarca et al., 2026).

hemisphere (Cunningham et al., 2015) and that the geometry of observing the sub-Jovian hemisphere includes half of both the leading and trailing hemispheres, these small factors are not unreasonable. The CO₂ column would have to increase by a factor of between approximately 2 to 9, which would still be consistent with the Carlson (1999) measurement. The H₂O column would have to increase by a factor between 10 and 30 and the O column by a factor of between 100 and 350 to achieve the same brightness increase.

5.3.3 Brightness Modulation with Plasma Sheet Distance

Emission brightness should in principle scale linearly with electron precipitation rates. Assuming the same relative partitioning of cold and hot electrons, the density only needs to increase between 0.01 and 0.05 cm^{-3} to produce the observed 630.0 nm [O I] brightnesses. This is well within the range of plausible electron densities used by previous analytical studies (Kliore et al., 2002; Cunningham et al., 2015; Carberry Mogan

et al., 2022; de Kleer et al., 2023) and *in situ* measurements from spacecraft missions like *Voyager* (Scudder et al., 1981; Belcher, 1983), *Galileo* (Gurnett et al., 2000; Kivelson et al., 2004) and *Juno* (Le Liboux et al., 2025). However, note that these observations sample a range of magnetic latitudes (and consequently distances from the centrifugal equator; see Figure 5.4), and therefore, these electron density ranges represent lower limits on the density at the centrifugal equator. Further, the large range of expected electron densities given the range of M-shells intersecting Callisto for different magnetic latitudes (see Figures 5.1 and 5.2) suggests the average centrifugal equator electron density between M-shells of 26 and 50 R_J could be larger than even the 0.2 cm^{-3} implied by the upper limit of our measurements of the 630.0 nm [O I] line brightness.

Hill et al. (1976) showed how plasma trapped in Jupiter’s magnetic field exhibits a Gaussian-like profile perpendicular to the centrifugal equator of the form

$$n(r, d) = n_0(r) e^{-(d/H(r))^2}, \quad (5.1)$$

where n_0 is the plasma density along the centrifugal equator at a radial distance r from Jupiter, d is the distance from the centrifugal equator and $H(r)$ is the scale height, approximately $3.7 R_J$ at Callisto’s semimajor axis of $26.9 R_J$ (Bagenal et al., 2011), though *Galileo* measurements show the scale height increasing to $4 R_J$ or higher beyond $20 R_J$ (Bagenal et al., 2016). Other measurements of auroral emission from the Galilean satellites, including allowed and semi-forbidden transitions in the UV (Roth et al., 2014; Roth et al., 2016) and the forbidden 630.0 nm [O I] emission in the optical (de Kleer et al., 2023; Milby et al., 2026b) show a correlation between the upstream ambient plasma density and the auroral brightness, such that the observed auroral brightness follows the same Gaussian profile as the electron density.

The previously published optical aurora observations of Callisto by de Kleer et al., 2023 had only marginal signal-to-noise in the co-added spectra, and they were unable to evaluate any brightness modulation with System III longitude. We have improved upon the background subtraction utilized in their study and added a new set of observations covering nearly a full range of positive magnetic latitudes (and therefore distances from the centrifugal equator; see Figure 5.4). In 10 of the 14 individual spectra, we were able to calculate a 630.0 nm [O I] brightness. Figure 5.5 shows a scatterplot of these brightnesses along with a best fit following the functional form of Equation (5.1) to the 2025-11-29 data assuming that auroral brightness varies linearly with electron number density n . While we did not include the 2021-07-04 data in the fit (in case the electron properties changed significantly between the two sets of observations), we included

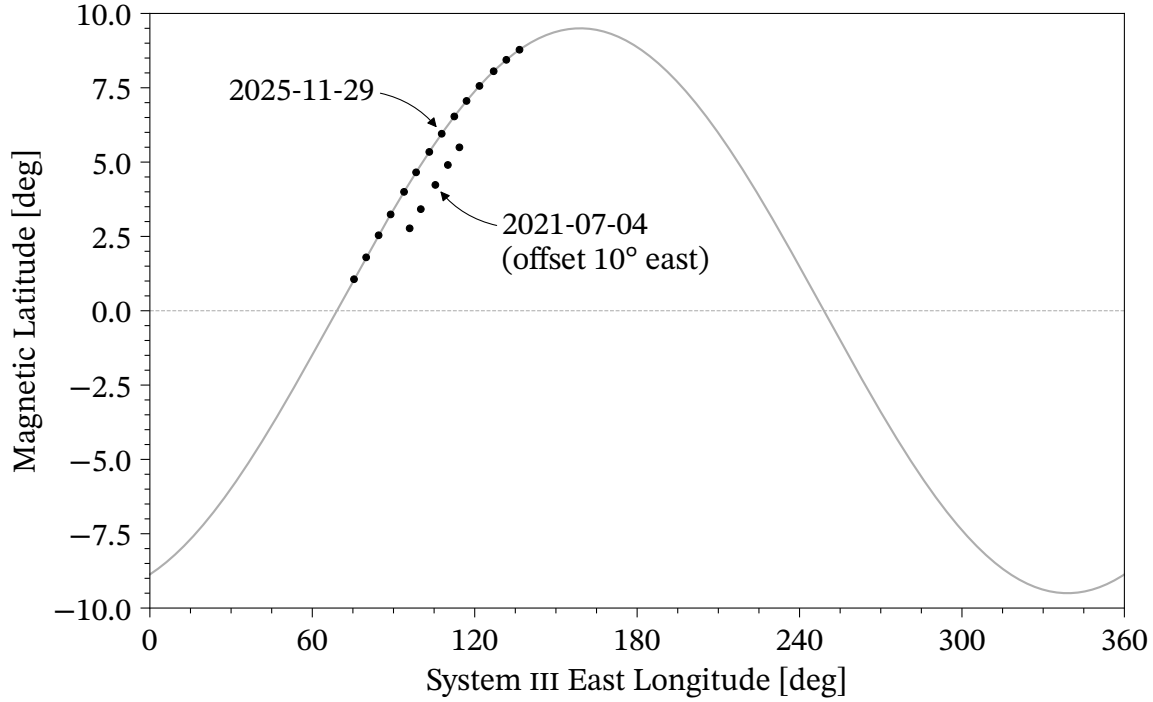


Figure 5.4: Observational sampling of Jovian magnetic latitudes. The solid gray line shows Callisto's magnetic latitude as a function of System III east longitude. The dashed horizontal gray line shows the location of the magnetic equator (effectively equal to the location of the centrifugal equator at Callisto's orbital distance from Jupiter). Scatter points show the magnetic latitude at the start of each of the five minute integrations, with the five points on 2021-07-04 offset east by 10° for clarity.

them on the plot to show their consistency with later brightnesses measured at similar distances from the centrifugal equator.

The best fit has a scale height of $(3.6 \pm 0.7) R_J$, almost exactly that calculated by Bagenal et al. (2011), and a peak 630.0 nm [O I] brightness at the centrifugal equator of $(19 \pm 2) R$. For the atmosphere model we evaluated in Section 5.3.2, this corresponds to a centrifugal equator electron density of $(0.42 \pm 0.04) \text{ cm}^{-3}$ at $26.9 R_J$. This is nearly twice that measured during the *Juno* mission (Le Liboux et al., 2025) but within the range measured during the *Galileo* mission (Gurnett et al., 2000; Kivelson et al., 2004) and still less than the approximately 1 cm^{-3} measured during the *Voyager* missions (Scudder et al., 1981; Belcher, 1983).

The larger increase in brightness of the three data points closest to the centrifugal equator (which occurred later in the eclipse) could also indicate the collapse of the ionosphere during the eclipse and subsequently an increase in electron precipitation. Consequently, while the brightness modulates with distance approximately following the

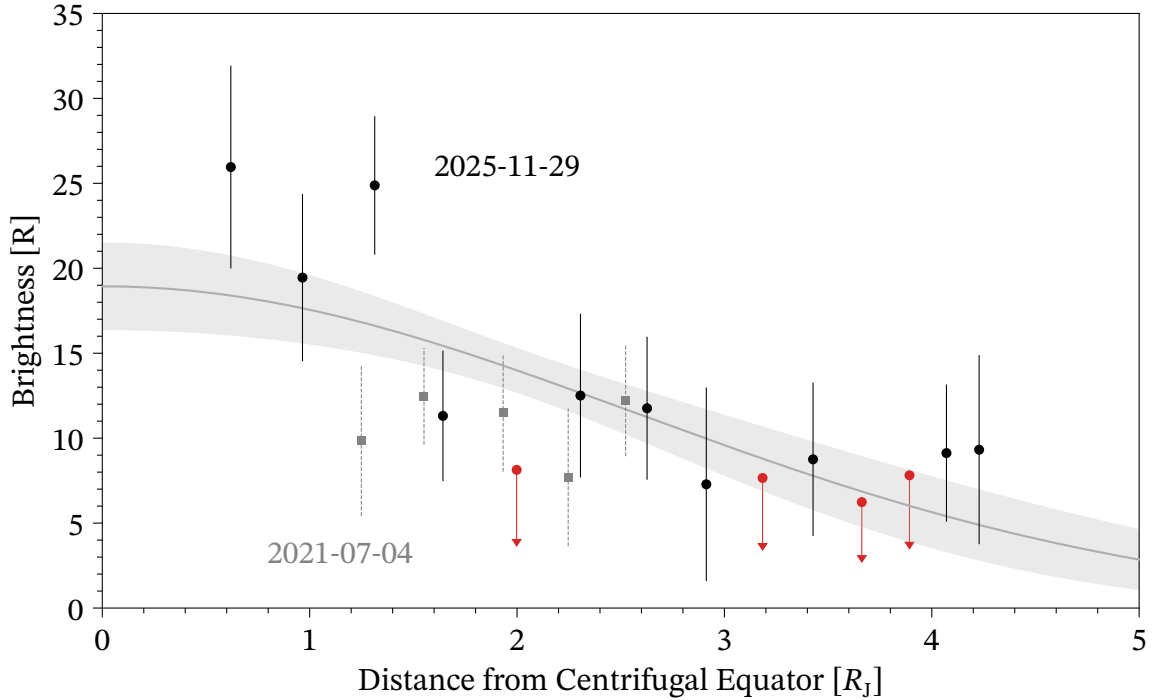


Figure 5.5: Change in Callisto’s 630.0 nm [O I] emission with distance from the plasma sheet centrifugal equator. Scatter points with error bars show the brightness and uncertainty calculated from individual five minute integrations on 2021-07-04 (gray) and 2025-11-29 (black). Scatter points with downward-pointing arrows (red) are the 2σ upper limits for non-detections. The solid gray line and shaded light gray region shows the best fit of Equation (5.1) to the 2025-11-29 data.

ambient upstream electron density, we cannot say definitively whether the change in the 630.0 nm [O I] auroral brightnesses indicates the presence or absence of an ionosphere. However, it does suggest the ram flux of the upstream electron population is responsible for the excitation of Callisto’s optical aurora.

5.4 Conclusions

We combined two spectral data sets of Callisto’s optical aurora emission in eclipse by Jupiter taken over four years apart with Keck I/HIRES. Using an improved background subtraction algorithm, we were able to detect the 630.0 nm [O I] emission line in both averaged data and individual 5-minute integrations. Our analysis of these data yielded the following results:

1. We simulated emission from an atmosphere composed of O, O₂, H₂O and CO₂ using the most recent available estimates (or upper limits) for their column densities. We considered two different electron populations: one composed of just

a high-energy suprathermal population capable of penetrating the ionosphere detected over the trailing hemisphere by Kliore et al. (2002), and another composed of both a low-energy thermal population and a high-energy suprathermal population. The high-energy electrons alone were insufficient to reproduce the observed 630.0 nm [O I] brightnesses, indicating the absence of an ionosphere of the magnitude proposed by Kliore et al. (2002).

2. Simulated auroral brightnesses from the same assumed atmosphere with the two-component electron population were consistent with observed brightnesses and upper limits derived from the HIRES spectra, supporting the proposition that Callisto's eclipse atmosphere is between 10 and 100 times denser than either Europa's or Ganymede's and is primarily O₂ (Cunningham et al., 2015).
3. Our data reduction and background subtraction process produced 630.0 nm [O I] brightness estimates that were greater than zero for 10 out of the 14 individual spectra taken on 2025-11-29. The decrease in brightness with distance from the centrifugal equator of Jupiter's plasma sheet matches the expected decrease in electron density derived by Bagenal et al. (2011), suggesting the impact of the ambient upstream electron population produces Callisto's optical aurora emission.

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Chapter 6

CONCLUSION

To conclude my thesis, rather than summarize takeaways from the four science chapters, I'd like to instead briefly discuss some of the potential scientific frontiers of Galilean satellite aurora observations and analysis.

Joint observations across different wavelength regimes. As of the submission of this thesis, we have not observed simultaneously across multiple wavelength regimes, e.g., acquiring *Hubble Space Telescope* ultraviolet spectra or *James Webb Space Telescope* infrared spectra at the same time as HIRES optical wavelength spectra. When we incorporated UV brightnesses for the 130.4 nm O I and 135.6 nm O I] lines, we used averages reported by other observers. Though they tend to be consistent with expected brightnesses based solely on the optical wavelength emissions, it would be interesting to know how these brightnesses change over the same short timescales as the HIRES observations and how they vary in comparison to the longer-lifetime forbidden transitions since they could conceivably be excited by different electron populations.

Updated cross sections from either laboratory measurements or theoretical calculations. A quick glance at Table 1.7 yields two pretty obvious shortcomings: most of the cross sections are excitation, not emission, and many were measured decades ago. It seems almost certain that technology has improved enough to get better laboratory measurements of these cross sections, especially measurements of emission cross sections from longer-lived states. Further, for the difficult-to-measure emissions for which laboratory measurements are still not possible (or for some other practicality reasons), surely our ability to mathematically model the quantum mechanics of excitation and emission has improved enough that theoretical emission cross section calculations would be feasible. Ideally, I would like to see a comprehensive set of theoretical emission cross sections for analysis of auroral emissions from the Galilean satellites from electron impact on H, O, S, Na, K, H₂O, O₂, CO₂, SO and SO₂ producing atomic emissions from H, C, O, Na, O⁺, S and S⁺ and K, validated with calibrated laboratory measurements wherever possible. This would allow for a more comprehensive analysis of the emissions and better constraints on their sources; for example, are we seeing the S⁺ emission from direct excitation of ionospheric atoms or from dissociative recombination of molecules?

How do the auroral brightnesses change with altitude as particles precipitate into the satellite atmospheres?

We almost always assumed the “upstream” magnetospheric electron properties when modeling the auroral emission brightnesses. However, we know that both the electron number densities and velocity distributions change as they precipitate into the satellite atmospheres, especially when they encounter induced ionospheres. There are also flanks and wakes in the plasma, so the properties change not only with radial distance from the satellite but also depend on position around the satellite. And don’t get me started on Ganymede and its “mini magnetosphere.” How does this affect the aurora we observe? Are the assumptions we make reasonable, or are our results significantly affected by not accounting for the changes in the electron properties? What about the effect of secondary electrons produced from ionization? This could be reasonably answered by comparing observed brightnesses to forward modeling with tunable-parameter chemistry models.

I’m especially curious to know whether or not the UV and optical emissions come from the same atmospheric columns, since the longer lifetime forbidden emissions could be quenched at lower altitudes. So, another reason to try to get simultaneous measurements across different wavelength regimes. This could help reveal how electrons precipitate into the atmospheres and whether different populations could be responsible for different emissions, e.g., the UV emissions come from the full column because they are excited by higher energy electrons which can penetrate all the way to the surface, while the forbidden visible wavelength emissions are restricted to higher altitudes because the electrons exciting them have lower energy and cannot penetrate as deeply.

Europa Clipper and Juice. The arrival of two new spacecraft to the Jupiter system at the beginning of the next decade will provide a wealth of knowledge about the satellites’ atmospheres and their plasma environment. Both missions include UV/visible/near-IR spectroscopic imagers and plasma instruments. *Juice* will even end up in orbit of Ganymede, potentially providing the most scientifically useful data ever gathered about the satellite. Its orbit will evolve from eccentric to circular at an altitude of about 500 km, then eventually down to a circular orbit only 200 km from the surface, meaning it will sample Ganymede’s exosphere across a huge range of altitudes. The opportunity for coordinated observing with ground-based telescopes on Earth could provide useful simultaneous constraints on several variables like atmospheric composition, column density, and upstream plasma properties, which would help us to understand how the optical aurora map to plasma precipitation into the atmospheres and whether or not their emissions are patchy and localized or diffuse and globally distributed.

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A p p e n d i x A

TECHNICAL DRAWINGS

This appendix contains technical reference drawings that I found either interesting or useful.

Figure A.1 shows a topographical map of the summit of Maunakea using conventional imperial units modified from a map originally published by the University of Hawai‘i Institute for Astronomy (2015). Annotated on the map is the Maunakea Access Road, the eight currently operating telescopes, the location of the United Kingdom Infrared Telescope currently being decommissioned, and the proposed site of the Thirty Meter Telescope. Curiously, sources seem to disagree about the height of the summit. Some say 13 796 ft, some 13 796 ft, others 14 803 ft. I’ve kept the measurement used by the University of Hawai‘i, but it could be too short by 7 ft.

Figures A.2 and A.3 show plan (overhead) and section (side) schematics of HIRES and its relative position to the Keck I telescope, based on several sheets from Osborne et al. (1993). I became particularly interested in the physical instrument itself after I learned it was the size of a small room! These diagrams give an idea of its size relative to the primary mirror and right Nasmyth platform, and an overview of the size and placement of the optical components within. In Figure A.3, dashed orange lines trace the boundaries of the light beam from incidence on the primary mirror to the CCD mosaic; after the collimators we’ve only drawn the center line of the beam.

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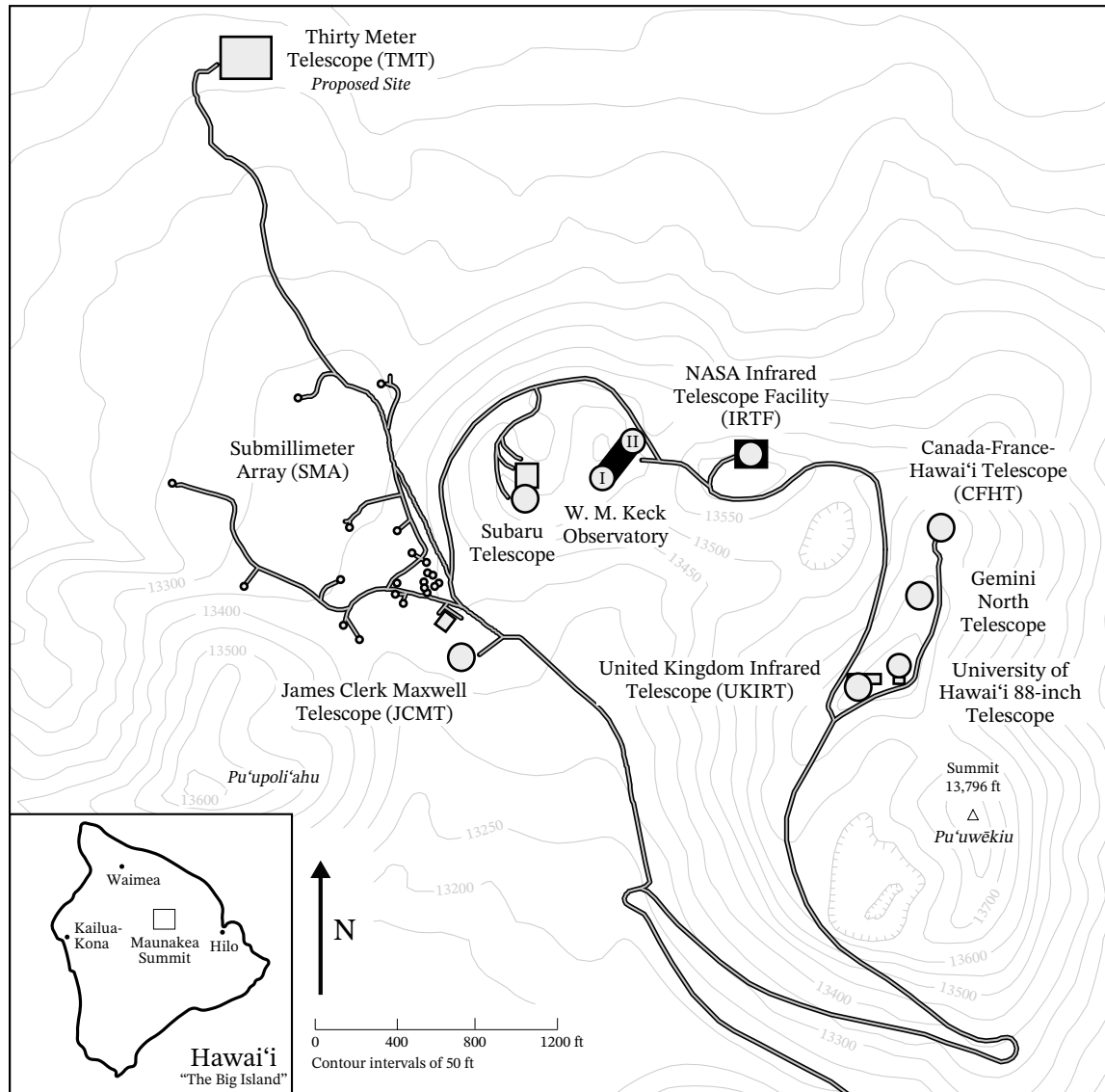


Figure A.1: Topographic map of the summit of Maunakea with annotated observatory locations. Current as of April 2026; decommissioning of UKIRT underway as of July 2025. Modified from a map originally published by the University of Hawai'i Institute for Astronomy (2015).

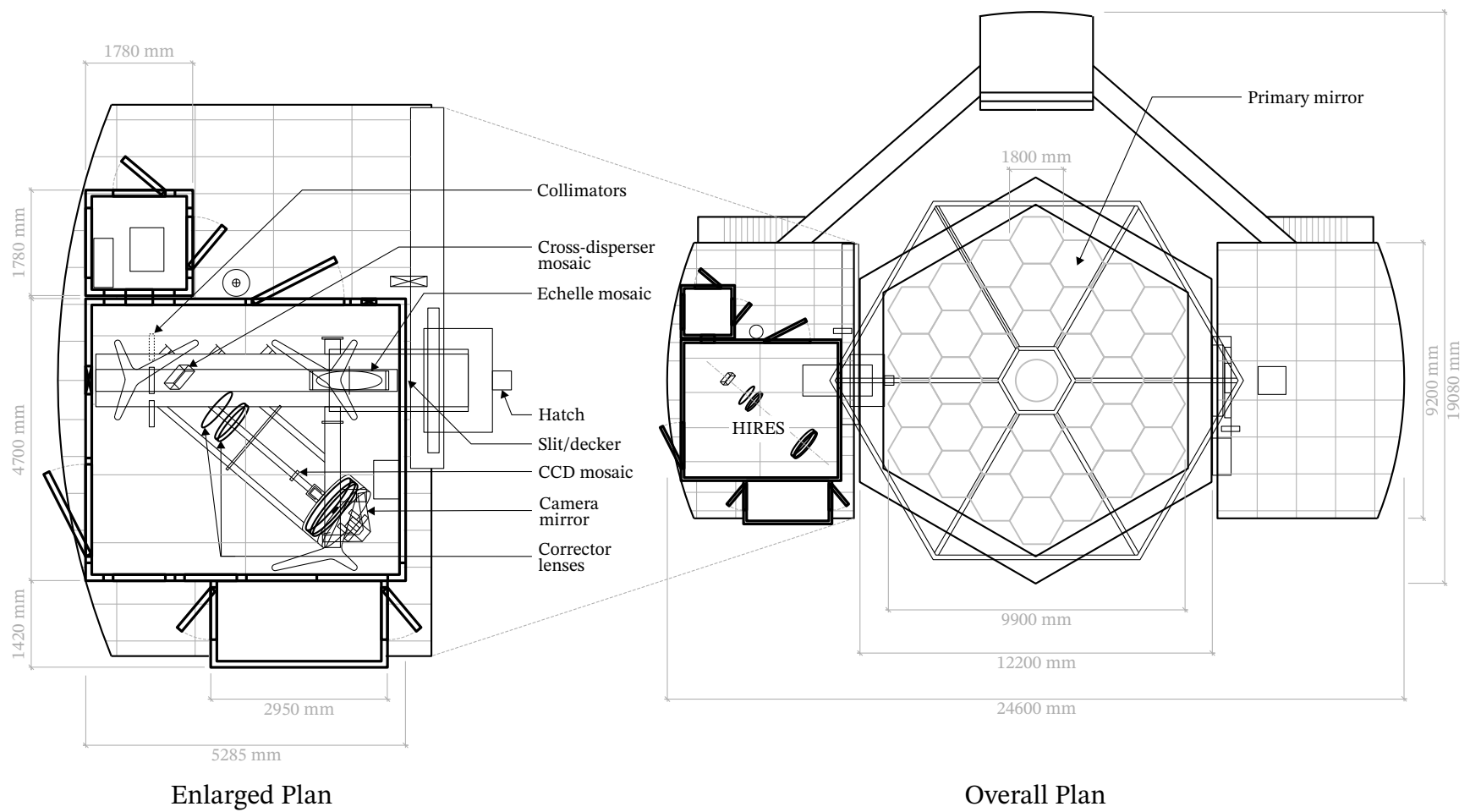


Figure A.2: Schematic plan diagram of the Keck I telescope and the HIRES instrument on the right Nasmyth platform. All measurements approximate. Drawn by Mitchell Deans based on Osborne et al. (1993).

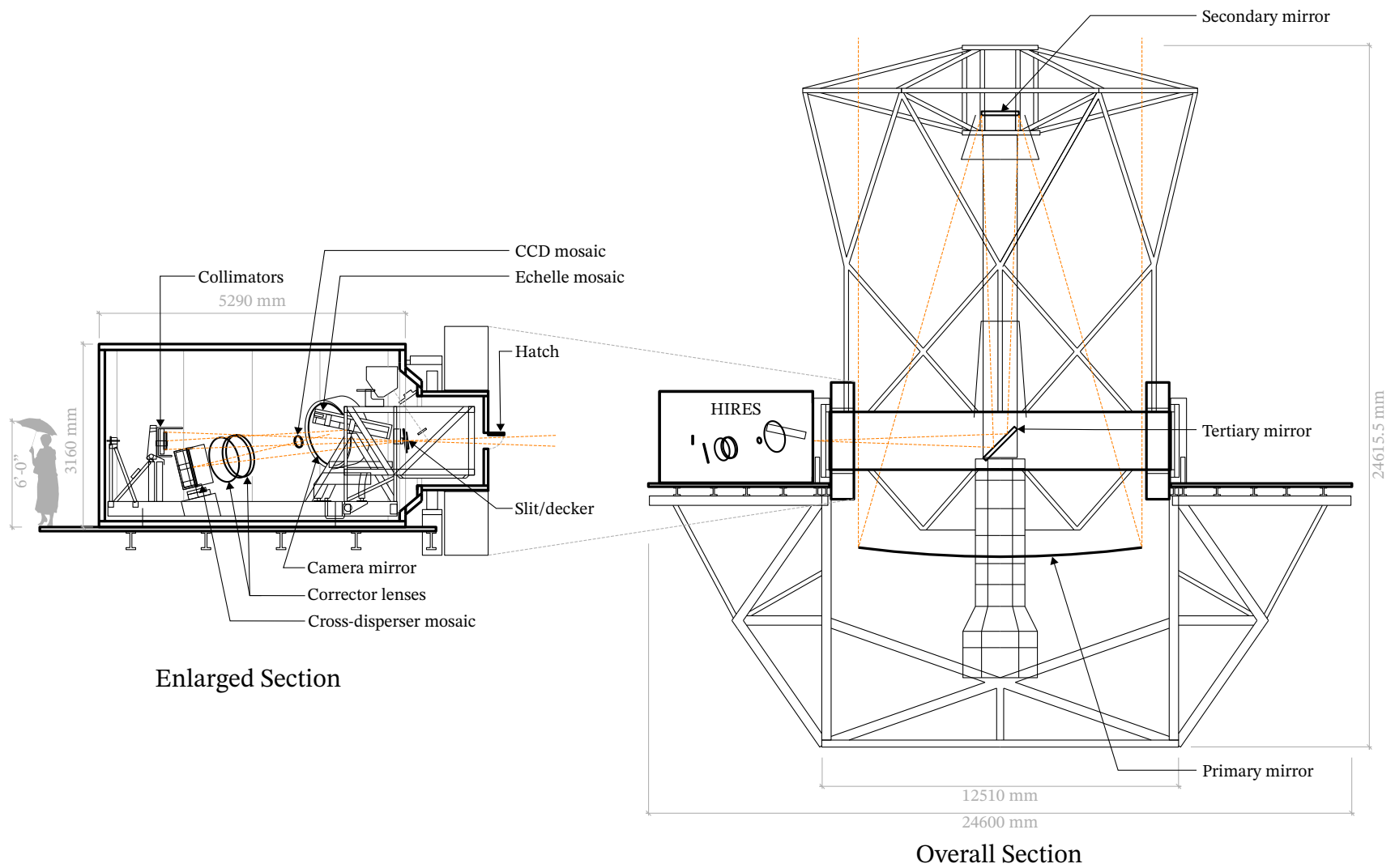


Figure A.3: Schematic section diagram of the Keck I telescope and the HIRES instrument on the right Nasmyth platform. Dashed orange lines show the light beam path. All measurements approximate. Drawn by Mitchell Deans based on Osborne et al. (1993).

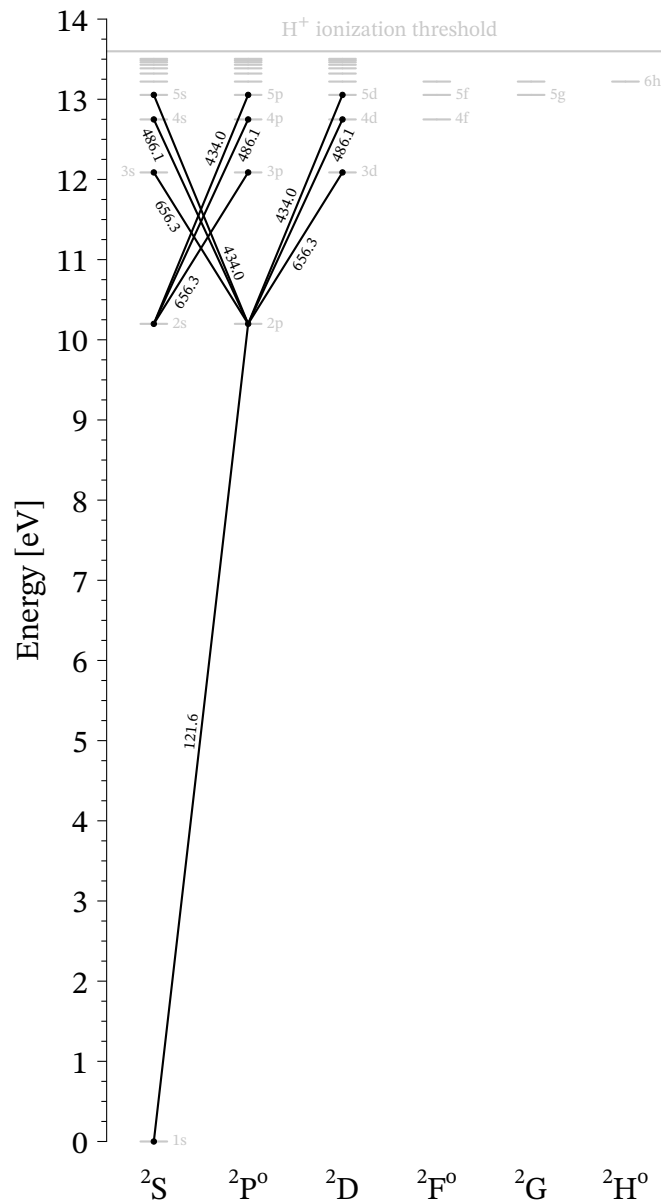
Appendix B

ADDITIONAL ATOMIC ENERGY LEVEL DIAGRAMS

This appendix contains additional “Grotrian” energy level diagrams for some of the other ultraviolet, visible and (very) near-infrared transitions observed (or hypothetically present) in the Galilean satellite aurora, mostly from Io. These include atomic hydrogen (H; Table B.1), singly ionized oxygen (O^+ ; B.2), neutral sodium (Na; Table B.3), neutral sulfur (S; Table B.4), singly ionized sulfur (S^+ ; B.5) and neutral potassium (K; Table B.6). The diagram for neutral oxygen (O) can be found in Figure 1.22. Levels, energies and wavelengths come from the NIST Atomic Spectra Database (Kramida et al., 2024). Further information about each transition like that contained in Table 1.6 can also be found using the NIST Atomic Spectra Database.

References

Kramida, A., Y. Ralchenko, J. Reader, and the NIST ASD Team (2024). *NIST Atomic Spectra Database*. URL: <https://physics.nist.gov/asd>.



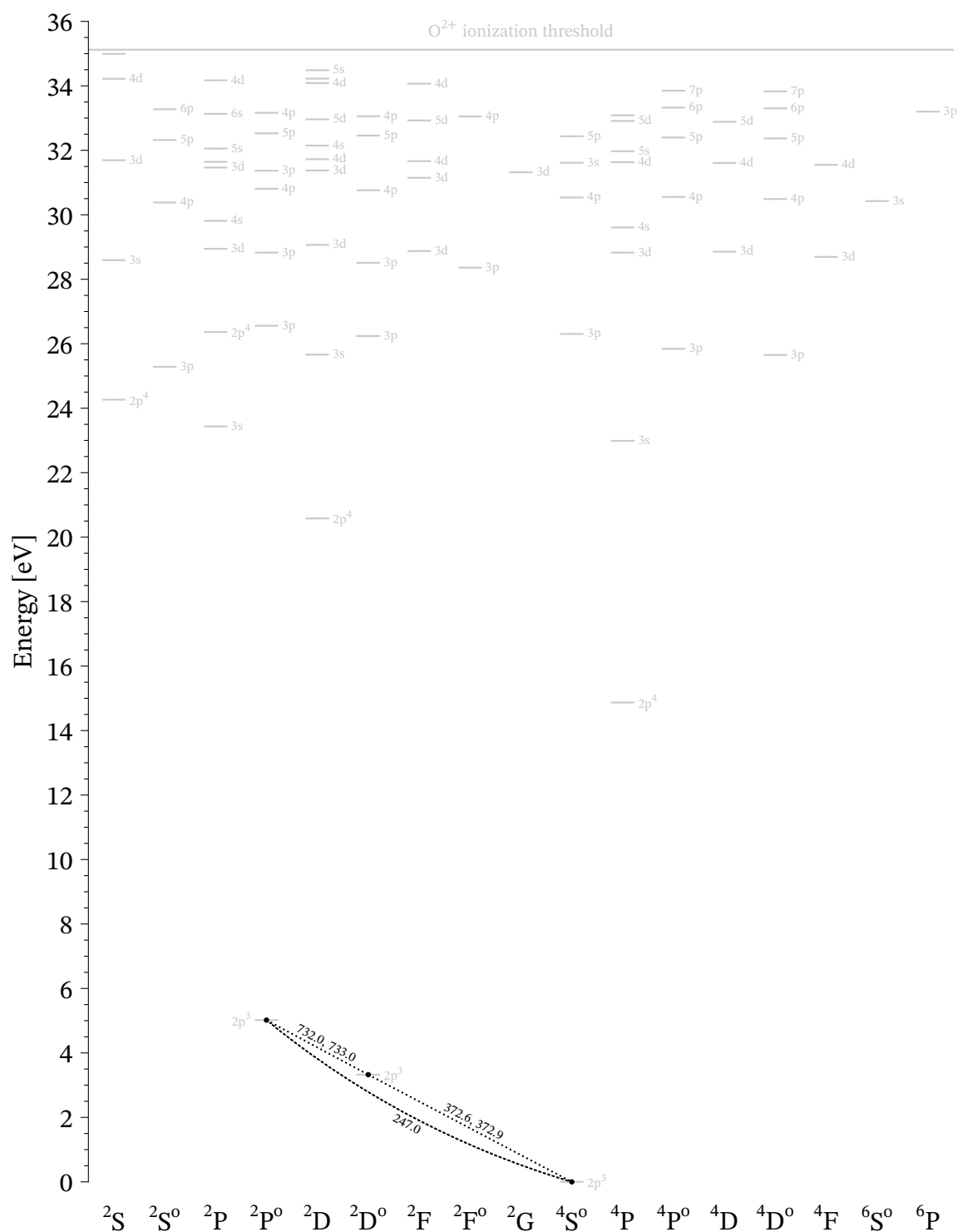


Figure B.2: Partial energy level diagram for singly ionized oxygen (O^+). Wavelengths have units of nanometers (in air). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions.

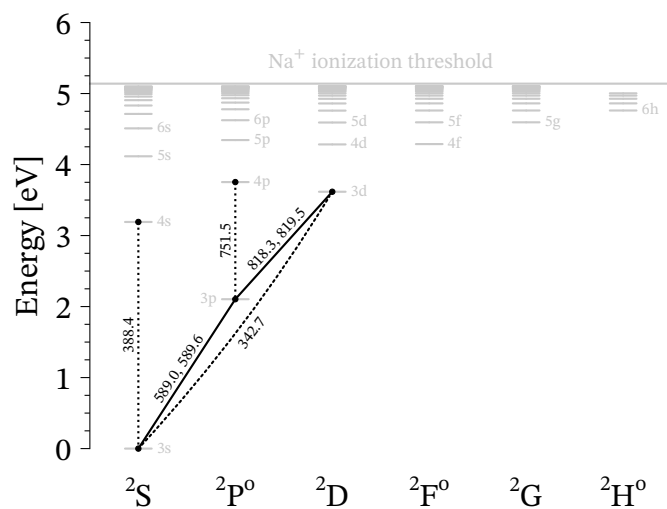


Figure B.3: Partial energy level diagram for neutral sodium (Na). Wavelengths have units of nanometers (in air). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions.

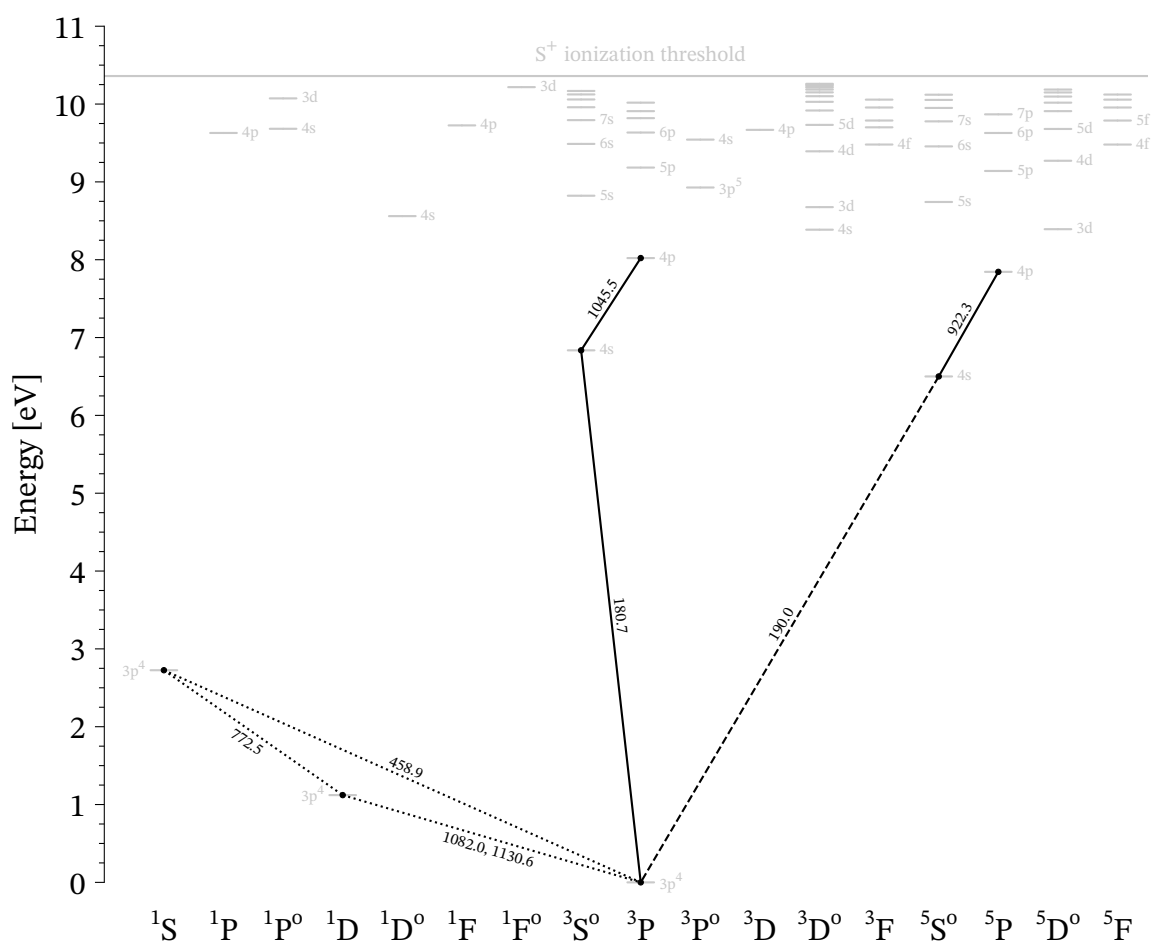


Figure B.4: Partial energy level diagram for neutral sulfur (S). Wavelengths have units of nanometers (in air above 200 nm and in vacuum at and below 200 nm). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions.

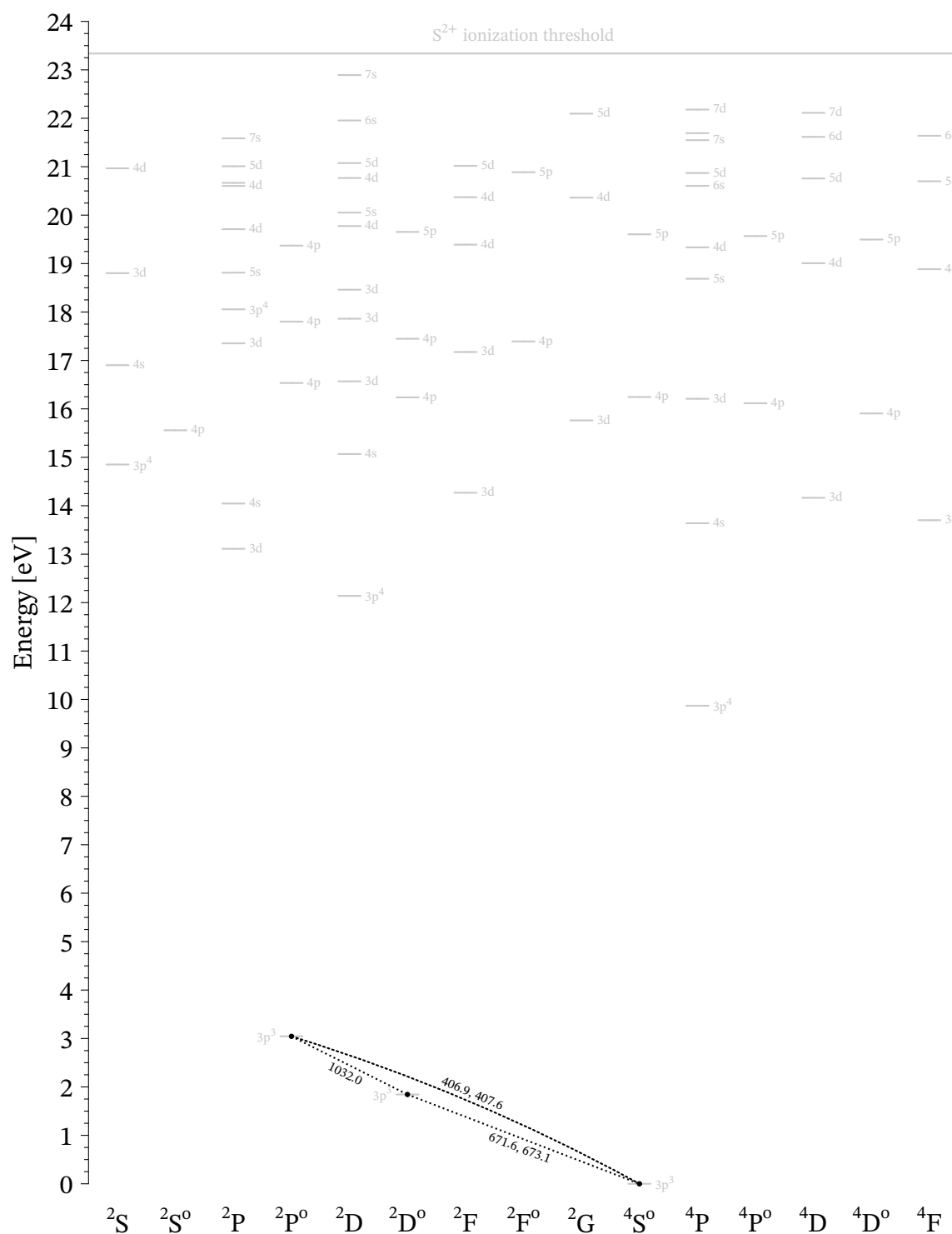


Figure B.5: Partial energy level diagram for singly ionized sulfur (S^+). Wavelengths have units of nanometers (in air). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions.

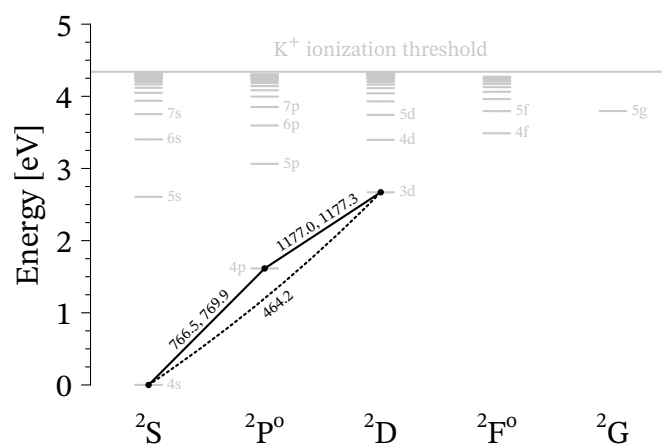


Figure B.6: Partial energy level diagram for neutral potassium (K). Wavelengths have units of nanometers (in air). Solid lines indicate allowed transitions, dashed lines indicate semi-forbidden transitions and dotted lines indicate forbidden transitions.