EVERT NASEDKIN

SIMULATED INSTRUMENTAL CONSTRAINTS ON SUB-STELLAR ATMOSPHERIC RETRIEVALS FOR THE JAMES WEBB SPACE TELESCOPE'S MID-INFRARED INSTRUMENT.

Evert Nasedkin

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ABSTRACT

Following its launch in 2021, the James Webb Telescope will provide the best infrared observations of exoplanets and brown dwarfs to date. In particular, the Mid-Infrared Instrument (MIRI), will allow for medium resolution spectroscopy across a wide wavelength band, from 4.9-28.8μm. This will allow us to derive atmospheric properties of objects at lower temperatures than currently possible. MIRI's medium resolution spectrometer (MRS) is an integrated field unit that will perform these observations, providing both spatial and spectral information about targets. Understanding the instrumental effects is critical to analyzing data from MIRI. With that in mind, the MIRISIM instrumental simulator was developed to provide observational simulations of the various sub instruments of MIRI.

This thesis improves the implementation of a thin-film fringing model for point sources to MIRISIM, considering how the fringing effect from the detector layers varies with position. Fringing is a periodic, wavelength dependent effect, and thus has a strong impact on any spectroscopic observations. A comparison to the existing model was made, demonstrating the necessity of considering this effect when analyzing data. We will improve the fringing removal by identifying the point source location from the constructed data cube, and select the correct fringe flat for removal.

Understanding the instrumental effects is key to quantifying the ability of MIRI to derive atmospheric properties. Existing literature has considered the NIRCAM instrument and the MIRI Low-Resolution Spectrometer, but to date no retrieval studies have been performed using MIRISIM, or for the MIRI MRS, though it is critical to extend wavelength coverage to improve the results of an atmospheric retrieval. Model atmospheres will be generated using PetitRadTrans, and processed using MIRISIM and the JWST pipeline to produce a mock observation. An atmospheric retrieval will be performed, demonstrating to what extent MIRI will be able to retrieve atmospheric parameters such as temperature, pressure and composition. The posterior distributions of these parameters are compared with and without the fringing removal, again demonstrating the importance of correcting for this effect.

CONTENTS

1 INTRODUCTION

Since the first detection of a planet around a sun-like star (Mayor and Queloz) the field of exoplanets has evolved rapidly. Thousands of companions have been identified using the radial velocity and transit detection methods, and a handful have been imaged directly using both ground and space based observatories. In the last decade, many advances have been made that allow us to begin to characterize the properties of a few of these planets using spectroscopy. With the launch of the James Webb Space Telescope (JWST) in 2021, and the dawn of the era of extremely large telescopes, we will be able to peer deeper into these planets and further constrain atmospheric or geological properties, allowing us to answer questions about their formation history, climate, and even the prospects for habitability and life.

JWST will operate in near to mid infrared wavelengths, which will provide a new window into studying the atmospheres of exoplanets and brown dwarfs. The Mid Infrared Instrument (MIRI) will provide unprecedented spectral resolution in the mid infrared, allowing for the measurement of composition, pressure and temperature. Novel instrumentation does not come without challenges. Optical and instrumental effects will constrain the ability to which we can measure spectral features, which will ultimately limit the science that can be accomplished.

In this thesis, we will measure the impact of thin-film fringing in the layers of the detectors in the MIRI Medium-Resolution Spectrometer on measurements of atmospheric parameters of brown dwarfs and exoplanets. This will provide a baseline for determining the level of correction necessary to minimize the impact of fringing, as well as providing a first look into the ability of the MRS to characterize atmospheres.

1.1 EXOPLANETS

The last quarter century of observations has revealed the diversity of exoplanets and extra-solar systems. Both the architecture and individual planetary characteristics vary greatly when compared to each other, as well as to our own solar system. From the hot Jupiters initially found by Mayor and Queloz (Mayor and Queloz) to the thousands of planets discovered by the Kepler mission, the variety in exoplanets has raised questions about their formation and development, as well as their present day structure, climate, and even prospects for life. Improvements to observational techniques have allowed us to improve our understanding of these planets. Secondary eclipse and transmission spectroscopy has opened the door to the study of planets in close orbits to their host stars, while emission spectroscopy of young planet has allowed for constraints on models of planet formation. Over the next decades, new instruments will be developed that improve sensitivity,

allowing us to study smaller, colder and fainter planets: with the ultimate goal of studying atmospheric and surface features of an earth-like planet.

Of particular interest are observable features that allow us to measure physical properties of exoplanets. The radial velocity (RV) method provides a measure of the planet mass, while a transit can constrain the radius. Already these properties tell us something about the overall structure of the planet. Spectroscopy can provide insight into the composition of the planet's atmosphere, as well as its temperature and pressure. These properties are linked to its age and location of formation in the circumstellar disk. The atmosphere, combined with the distance between the planet and its star determine the climate of the planet.

Direct Imaging

While the majority of exoplanet detections have been made using the radial velocity or transit techniques, direct imaging opens up the possibility of collecting light from the planet itself. This provides a window into the planet's atmosphere and surface. Most direct imaging to date has used near-to-mid infrared wavelengths, where the contrast between the thermal emission from the planet and the star is at a minimum. This has its drawbacks: we are so far only able to image young planets that have retained some of the heat from their formation.

Direct imaging can make use of both ground and space based observatories. However, the high spatial resolution required drives the need for a large primary mirror, limiting the possibilities of space-based telescopes. On the other hand, atmospheric turbulence necessitates the use of an adaptive optics equipped facility to observe from the ground. Atmospheric absorption due to telluric lines (absorption lines of Earth's atmosphere) also restrict infrared observations to narrow bands.

In addition to the requiring high spatial resolution, it is also challenging to separate the light emitted by the planet from that of the star. Imaging techniques such as Angular Differential Imaging (ADI) (**Marois2007**) and Reference Differential Imaging (RDI) (**Lefreniere2009**; **Soummer2012**) provide methods for reducing the stellar point-spread-function (PSF). Coronagraphs are optical elements which suppress the stellar PSF through self-destructive interference or physical occultation, depending on the position in the optical path. The difference in spectra between the planet and the star can also be used to separate the two sources.

Presently, 10m class telescopes such as the Very Large Telescope (VLT) in Paranal, Chile or the Gemini Observatory split between Hawaii and Chile provide the best combination of resolution and instrumentation to perform direct imaging of exoplanets. The NACO instrument at the VLT provided the first image of an exoplanet in 2004 (**Chauvin2004**). These observatories are among those equipped with an adaptive optics system, corongraphic instrumentation and near to mid infrared imaging and spectroscopic capabilities to directly image exoplanets, with several exemplar systems becoming standard objects of interest. The parameters of some directly imaged exoplanets are summarized in table 1

Name
2M1207b
β Pic b
HR8799b
HR8799c
HR8799d
HR8799e
Fomalhaut b
2M J044144b
LkCa 15b
HD 95086b
Gliese 504b
51 Eridani b
PDS 70b
PDS 70c

Table 1: Summary of directly imaged planet parameters Bowler and references therin.

(Beichman et al., "Direct Imaging and Spectroscopy of Exoplanets with the James Webb Space Telescope") (**Lagage2015**) (Macintosh et al.) (Macintosh et al.)

Beta Pictoris b

Discovered in 2008 (Lagrange et al.), β Pic b is one of the most well-studied exoplanet systems (**Hoeihmakers2018**; Quanz et al. Chilcote et al. Chilcote et al.). Due to its young age of 23±3 Myr (**Mamajek2014**) and high mass of 12.9 M_j(Chilcote et al.) it remains hot, between 1590K and 1847K (**Nowak2019**). Combined with its typically wide separation on it's 9.2AU orbit (**Chauvin2012**), this allows for relatively easy imaging and spectroscopy in the near infrared. Recent RV observations indicate the possibility of an additional planet at 2.3 AU (**Lagrange2019**).

The quantity and quality of spectral data for β Pic b has allowed for the study and characterization of it's atmosphere: measurements of its metallicity and C/O ratio can trace the formation history of the planet (**Nowak2019**; Chilcote et al.). It also provides insight into its current atmospheric structure and composition, which can in turn inform models of exoplanet atmospheres.

HR 8799 System

PDS 70 b,c

1.2 BROWN DWARFS

(Oliveira) (Helling and Casewell)(**Cooper2014**) (Madhusudhan and Seager) (Burrows, Sudarsky, and Lunine) (**Marley2014**) (Manjavacas) (B. Biller) (Faherty et al.) (Morley et al.)

1.2.1 Physics

1.2.2 Observational Properties

T-Type

L-Type

Y-Type

1.3 MOTIVATION

1.3.1 Current Status of Atmospheric Characterization

(Kreidberg)(B. A. Biller and Bonnefoy, "Exoplanet Atmosphere Measurements from Direct Imaging") (Bozza, Mancini, and Sozzetti) (Danielski et al.) (Madhusudhan et al.)

Transmission Spectroscopy

(Lee, Fletcher, and P. G. Irwin) (MacDonald and Madhusudhan) (Madhusudhan et al.)

Emission Spectroscopy

1.3.2 JWST Studies

(Beichman et al., "Direct Imaging and Spectroscopy of Exoplanets with the James Webb Space Telescope")

1.3.3 Biosignatures and Future Missions

1.4 THESIS OVERVIEW

2 | MIRI: THE MID-INFRARED INSTRUMENT

MIRI is an imaging and spectroscopic instrument on board the James Webb Space Telescope (JWST). It will operate at a temperature of 6.7K to reduce instrumental backgrounds over its wavelength range of 4.8-28.8μm. Rieke et al., " The Mid-Infrared Instrument for the James Webb Space Telescope , I: Introduction " **Kendrew2015**

2.1 JWST

JWST is a 6.5m space based observatory that will be located at the L2 Earth-Sun Lagrange point. As the successor to the Hubble Space Telescope and the Spitzer Space Telescope, it will provide a new perspective for infrared astronomy. It is currently scheduled to launch in March 2021.

2.2 MRS

Wells et al.

2.2.1 Integrated Field Spectroscopy

2.2.2 Optical Systems

Channels, bands, etc Chen et al., "Habitability and Spectroscopic Observability of Warm M-dwarf Exoplanets Evaluated with a 3D Chemistry-Climate Model"

2.2.3 Detectors

2.3 COORDINATES

2.4 OBSERVATIONS

2.4.1 Dithering

2.4.2 Readout Modes

2.4.3 Exposure time calculations

3 | FRINGING EFFECTS IN MIRISIM

3.1 FRINGING

- FRINGING REQUIREMENTS FOR MIRI - context - sub percent residuals - is this true and if so how much does it impact real spectral features? - What has been done so far - fitting, optical modelling - only for some channels - Might remove actual spectral features as well - justification for this work (especially re posn dependence) - need to reproduce plots from fringing white paper - explain why point sources are harder (angle => optical thickness => large phase shift) - **Lahuis2018**

3.2 MIRISIM

Consortium, "MIRISim Documentation" **Cossou2019** The MIRI instrument has been modeled in python as a program known as MIRISM. This program takes in an astronomical 'scene' along with some configuration parameters to output a detector data product, similar to what will be produced by the actual instrument. This is relatively full-featured simulator, modelling the instrumental PSF, various noise sources and distortion maps, among other effects. While MIRISIM is functional for all of the MIRI sub-instruments, this report will only deal with the Medium-Resolution Spectrometer (MRS) sub instrument, described in section 2.2. The goal of this section is to describe the implementation and testing of an updated optical model of the 'fringing' effect - an optical effect caused by thin film interference from the multiple layers of the detector.

3.2.1 Architecture

SCENE - SEDs SIMULATOR PYSPECSIM

3.2.2 Data Products

3.2.3 Instrumental effects

3.2.4 Fringing

Lahuis and Boogert VanderPlas A key effect on spectral data is fringing, described in **ref:Argyriou2018**. MIRI uses a total of three Si:As impurity band conduction detector arrays, two of which are used by the MRS. These detectors consist of 7 layers, listed in table 2 and illustrated in Fig. 1.

Thin film interference occurs when light is coherently reflected at the boundary between two layers and interferes with the incident light. This

Figure 1

Table 2

is the principle on which Fabry-Pérot interferometers function. As we wish to determine the effect of fringing on the amplitude of the signal received by the detector, we are effectively interested in the transmittance of a series of Fabry–Pérot interferometers. Assuming an ideal plane-parallel optical cavity with a reflectance R at both boundaries, thickness D, and an angle θ at which the light travels within the cavity, we can compute the transmittance as:

$$T_c = \frac{1}{1 + \frac{4R}{(1-R)^2} \sin^2\left(\frac{\delta}{2}\right)}$$ (1)

Where the phase δ at half a wavelength ($\phi = \pi$), with wavenumber σ is:

$$\delta = 4\pi\sigma D \cos\theta - (\phi - \pi)$$ (2)

If all of the parameters were known, this would be sufficient to numerically solve for the fringing pattern within MIRI. Unfortunately, uncertainties in the thickness in the detector layers, variations in the layer deposition thickness, and the uncertainty of transmittance and reflectance of the materials used at cryogenic temperatures prevents the implementation of such a numerical model.

Instead, we turn to calibration data taken to characterize the fringing pattern.

DESCRIBE CURRENT MODEL - GENERIC FRINGING

However, due to the dependance of fringing on the incident angle of the light, a single model of fringing is insufficient to describe the full effect. Therefore, we use data taken in XXXXXXXXX at various points across the detector and quantify how this changes the extracted spectra after processing in the JWST pipeline.

DESCRIBE HOW THE DATA WAS TAKEN HERE. - Problems with point vs extended sources - multiple collection runs

Ultimately this data collection produced a series of 'fringe-flats' of an almost point like at various position across the detector and in each channel. We implemented a new routine into the pySpecSim portion of MIRISIM to read in the location of point sources within a scene, and apply the correct position dependent fringe flat. This implementation comes with several caveats: namely that the fringing model is not yet fully developed, so it can only be considered accurate for point sources located at the same (α, β) location as the source used to produce the fringe flat. Additionally, the source used to generate the data is not a true point source, nor are there fringe flats produced for the full MRS wavelength range. We stress that the goal of this testing is to demonstrate the significance of this effect to justify the need for

Figure 2

a more complete model along with additional calibration data to constrain the detector layer parameters.

FM Data

CV Data

3.2.5 Implementation

3.2.6 JWST Pipeline

Bushouse, Droettboom, and Greenfield Labiano-Ortega et al., "The MIRI Medium Resolution Spectrometer calibration pipeline"

Stage 1 Processing

Stage 2 Processing

Fringing correction

Carnall

Aperture Photometry

3.2.7 Cross–Correlation

I. Snellen et al.**Simkin1974 Tonry1979** Petermann **Bodis2007** To quantify the similarity of the spectrum output by the JWST pipeline to the input into MIRISIM, we rely on the technique of cross correlation. For two arbitrary, complex-valued functions $f(t)$ and $g(t)$, we can compute the cross correlation as as function of the shift τ between the functions (typically in time or velocity space):

$$(f \star g)(\tau) \equiv \int_{-\infty}^{\infty} f^*(t)g(t+\tau)dt \tag{3}$$

Our signals of interest are astrophysical spectra, measured in a finite number of discrete wavelength bins. For such a signal with M bins:

$$(f \star g)[n] \equiv \sum_{m=0}^{M} f^*[m]g[m+n] \tag{4}$$

Care must be taken when cross-correlating signals, as differences in normalization can result in changes in the correlation coefficient. Our procedure takes in two spectra. The first is an emission spectrum produced by the petitRadTrans program Mollière et al., which provides our forward model with which we compare our data spectrum. Our data is the result of passing the template spectrum through MIRISIM, and extracting it from the resulting detector image using the JWST pipeline. We then rebin the high-resolution input spectrum to the same wavelength bins as the data spectrum, using the `spectres` package. Prior to normalization, we remove any outliers from the spectrum (due to binning errors or instrumental effects) by setting any data points separater by more than 15 standard deviations from the mean to the median value of the spectrum. For each spectrum, we subtract the minimum

value to remove any offset in the spectrum, and divide by the maximum value to restrict the range to [0,1]. We then use apply a Savitzky-Golay filter with a window of 1/4 the length of the spectrum and a polynomial order of 3, which we then subtract from the unfiltered spectrum. This removes the continuum emission from the spectrum, and centers it around 0. We then renormalize the spectrum by dividing by the maximum absolute value such that the range is in [-1,1]. The cross correlation between the forward model and itself is computed, excluding the region of interest around 0 offset. This 'autocorrelation' is subtracted from the cross correlation between the forward model and the data spectrum in order to remove secondary peaks. Finally, we normalize the cross correlation by the standard deviation of the cross correlation (excluding the central peak), giving an output measured as a signal to noise ratio.

3.2.8 Residual Statistics

In addition to computing the cross correlation between the forward model and the data spectrum, we also examine the residuals between the two spectra. Here we can see any unexpected variations between the two (periodic signals, offsets or other features). We can also examine a histogram of the residuals, normalized by the standard deviation of the data spectrum. This provides us with a distribution which should have a mean of 0 and unit width if the data are unbiased and share a distribution with the true input spectrum.

3.3 FRINGING RESULTS

1. A stronger input signal results in a stronger correlation. 2. Fringing does NOT necessarily degrade the cross correlation SNR, but rather increases it. The scale of this increase seems to depend on the absolute magnitude of the correlation (ie, a larger increase at higher SNR) 3. The residuals from subtracting the template from the data has structure. 4. If the residuals are histogrammed (and normalized by the standard deviation of the data), the width of the distribution may correspond to the cross correlation SNR (wider distribution = lower SNR) 5. Only when strongly increasing the fringing effect does the SNR decrease. 6. Correcting for fringing using the standard JWST fringe map decreases the SNR when compared to the case of fringing with no correction, but is typically still above the no-fringing case. 7. The JWST correction performs worse in the off axis case, as the fringe pattern begins to vary more when compared to the CV fringing model.

3.3.1 Effects of fringing on spectral extraction

4 | ATMOSPHERIC RETRIVALS

Schlawin et al. Madhusudhan, "Atmospheric Retrieval of Exoplanets" Fisher et al. **Oreshenko2019**Barman et al. Benneke and Seager Benneke and Seager **Blanco-Cuaresma2018** Konopacky et al. **Morley2018** Lupu et al. Gandhi and Madhusudhan Baudino et al. Line et al. **Madhusudhan2018b** P. G. Irwin et al. Robinson, Stapelfeldt, and Marley Waldmann et al. Waldmann et al. Line et al. "Uniform Atmospheric Retrieval Analysis of Ultracool Dwarfs. II. Properties of 11 T dwarfs" Zalesky et al.

4.1 INTRODUCTION

Batalha et al.Feng et al. Mollière et al.

4.2 ATMOSPHERIC MODELING

Behmard, Petigura, and HowardGuillot, "On the radiative equilibrium of irradiated planetary atmospheres" Chen et al., "Habitability and Spectroscopic Observability of Warm M-dwarf Exoplanets Evaluated with a 3D Chemistry-Climate Model" Mollière et al.

M. Zhang et al.

4.2.1 petitRadTrans

Mollière et al.

Radiative Transfer

Line-by-line

Correlated K

Goody et al. Lacis and Oinas

Clouds

Line and Parmentier Faherty et al. Morley et al.

4.3 BAYESIAN METHODS

Lavie et al.

4.3.1 MCMC

Foreman-Mackey et al. Speagle **MacKay2003**

4.3.2 Nested Sampling

Skilling **Feroz2007** Feroz and Hobson **Feroz2014** Feroz et al.

4.3.3 multinest

Hyperparameters

4.3.4 Prior choice

4.3.5 Bayesian Model Selection

4.4 TARGETS

4.4.1 Atmospheric Parameters

Madhusudhan, "C/O ratio as a dimension for characterizing exoplanetary atmospheres"**Moses2012**Garland and P. G. J. Irwin Bowler **Fegley1994** Tokunaga

4.4.2 petitRadTrans

4.5 RESULTS

4.5.1 Posterior Distributions

5 | CONCLUSIONS

A | APPENDICES

A.1 PACKAGE REQUIREMENTS

```
numpy=1.4.0
scipy=1.5
```

WORKS CITED

"1194 - Characterization of the HR 8799 planetary system and planet search".
 1194 (2019): 1–36. Print.

Argyriou, Ioannis, Ruymán Azzollini, and Bart Vandenbussche. "Spectrum
 extraction from detector plane images for the medium-resolution spec-
 trometer of the mid-Infrared Instrument on-board the James Webb Space
 Telescope." July 2018 (2018): 124. Print.

——."Spectrum extraction from detector plane images for the medium-resolution
 spectrometer of the mid-Infrared Instrument on-board the James Webb
 Space Telescope." July 2018 (2018): 124. Print.

Argyriou, Ioannis, Bart Vandenbussche, and Martyn Wells. "Fringing solu-
 tion for the mid-infrared instrument on-board the James Webb Space Tele-
 scope". July 2018 (2018): 127. Print.

——."Fringing solution for the mid-infrared instrument on-board the James
 Webb Space Telescope". July 2018 (2018): 127. Print.

Argyriou, Ioannis, et al. "Nature of point source fringes in mid-infrared spec-
 tra acquired with the James Webb Space Telescope" (2020): 1–13. Print.

Avenue, North Cherry, et al. "Accreting Protoplanets in the LkCa 15 Transi-
 tion Disc" (2006). arXiv: arXiv:1511.07456v1.

Barman, Travis S., et al. "Simultaneous detection of water, methane, and
 carbon monoxide in the atmosphere of Exoplanet hr 8799 b". *Astrophysical
 Journal* 804.1 (2015): 1–10. arXiv: 1503.03539. Web.

Batalha, Natasha E., et al. " Strategies for Constraining the Atmospheres of
 Temperate Terrestrial Planets with JWST ". *The Astrophysical Journal* 856.2
 (2018): L34. arXiv: 1803.07983. Web.

Baudino, Jean-loup, et al. "Toward the Analysis of JWST Exoplanet Spectra
 : Identifying Troublesome Model Parameters". *The Astrophysical Journal*
 850.2 (2017): 150. Web.

Behmard, Aida, Erik A. Petigura, and Andrew W. Howard. "Data-driven
 Spectroscopy of Cool Stars at High Spectral Resolution". *The Astrophysical
 Journal* 876.1 (2019): 68. arXiv: arXiv:1904.00094v1.

Beichman, Charles A. and Thomas P. Greene. "Observing Exoplanets with
 the James Webb Space Telescope". *Handbook of Exoplanets* 2009 (2018): 1283–
 1308. Print.

——."Observing Exoplanets with the James Webb Space Telescope". *Handbook
 of Exoplanets* 2009 (2018): 1283–1308. Print.

Beichman, Charles A, et al. "Astro2020 Science White Paper: Direct Imaging
 and Spectroscopy of Exoplanets with the James Webb Space Telescope"
 (2019). Web.

——."Direct Imaging and Spectroscopy of Exoplanets with the James Webb
 Space Telescope". *Astro2020 Science White Paper* (2019). Web.

Benneke, Bjoern and Sara Seager. "Atmospheric retrieval for super-earths:
 Uniquely constraining the atmospheric composition with transmission spec-
 troscopy". *Astrophysical Journal* 753.2 (2012). arXiv: 1203.4018.

Benneke, Björn and Sara Seager. "How to distinguish between cloudy mini-neptunes and water/volatile- dominated super-earths". *Astrophysical Journal* 778.2 (2013). arXiv: 1306.6325.

Biller, Beth. "The time domain for brown dwarfs and directly imaged giant exoplanets: the power of variability monitoring". *Astronomical Review* 13.1 (2017): 1–27. Web.

Biller, Beth A. and Mickaël Bonnefoy. "Exoplanet Atmosphere Measurements from Direct Imaging". *Handbook of Exoplanets* (2018): 2107–2135. arXiv: arXiv:1807.05136v1.

——."Exoplanet Atmosphere Measurements from Direct Imaging". *Handbook of Exoplanets* (2018): 2107–2135. arXiv: arXiv:1807.05136v1.

Blanco-cuaresma, Sergi. "Modern stellar spectroscopy caveats". 22.April (2019): 1–22. arXiv: arXiv:1902.09558v2.

Bonse, Markus J, Sascha P Quanz, and Adam Amara. "Application of a de-noising technique in the time domain" (2018): 1–10. arXiv: arXiv:1804.05063v1.

Bowler, Brendan P. "Imaging Extrasolar Giant Planets". *Publications of the Astronomical Society of the Pacific* 128.968 (2016): 1–38. Web.

Bozza, Valerio, Luigi Mancini, and Alessandro Sozzetti. *Astrophysics of Exoplanetary Atmospheres*. Print.

Burrows, Adam, David Sudarsky, and Jonathan I. Lunine. "Beyond the T Dwarfs: Theoretical Spectra, Colors, and Detectability of the Coolest Brown Dwarfs". *The Astrophysical Journal* 596.1 (2003): 587–596. arXiv: 0304226 [astro-ph].

Bushouse, Howard, Michael Droettboom, and Perry Greenfield. "The James Webb Space Telescope Data Calibration Pipeline". *Python in Science*. 2015. 43–47. Print.

Carnall, A. C. "SpectRes: A Fast Spectral Resampling Tool in Python". 2 (2017): 1–4. arXiv: 1705.05165. Web.

Chen, Howard, et al. "Habitability and Spectroscopic Observability of Warm M-dwarf Exoplanets Evaluated with a 3D Chemistry-Climate Model" (2019). arXiv: 1907.10048. Web.

——."Habitability and Spectroscopic Observability of Warm M-dwarf Exoplanets Evaluated with a 3D Chemistry-Climate Model" (2019). arXiv: 1907.10048. Web.

Chilcote, Jeffrey, et al. " 1–2.4 μ m Near-IR Spectrum of the Giant Planet β Pictoris b Obtained with the Gemini Planet Imager ". *The Astronomical Journal* 153.4 (2017): 182. arXiv: 1703.00011. Web.

Chilcote, Jeffrey, et al. "The first H-band spectrum of the giant planet β Pictoris b". *Astrophysical Journal Letters* 798.1 (2015): 1–5. Print.

Christiaens, Valentin, et al. "Evidence for a Circumplanetary Disk around Protoplanet PDS 70 b". *The Astrophysical Journal* 877.2 (2019): L33. arXiv: 1905.06370. Web.

Citation, Suggested. *Exoplanet science strategy*. 2019. 1–172. Print.

Coi, Charles A Beichman. "1188 - Spectroscopy of Young , Widely Separated Exoplanets". 1188.4 (2019). Print.

Collaboration, Gravity, et al. "First direct detection of an exoplanet by optical interferometry". *Astronomy & Astrophysics* 623 (2019): L11. Print.

Consortium, Miri European. "MIRISim Documentation" (2018). Print.

——."MIRISim Documentation" (2018). Print.

Cooper, Curtis S, et al. "Modeling the Formation of Clouds in Brown Dwarf Atmospheres" (2001). arXiv: `0205192v3 [arXiv:astro-ph]`.

Cossou, Christophe. "MIRISim Spreadsheet and Quick examples" (2018): 1–12. Print.

Danielski, Camilla, et al. " Atmospheric Characterization of Directly Imaged Exoplanets with JWST /MIRI ". *The Astronomical Journal* 156.6 (2018): 276. arXiv: 1810.00894.

Davis, Tonry. "Early Cross Correlation" (). Print.

Faherty, Jacqueline K, et al. "Indications of water clouds in the coldest known brown dwarf". 2014 (2018). arXiv: arXiv:1408.4671v2.

Feng, Y. Katherina, et al. "Characterizing Earth Analogs in Reflected Light: Atmospheric Retrieval Studies for Future Space Telescopes". *The Astronomical Journal* 155.5 (2018): 200. Web.

Ferguson, Henry, Perry Greenfield, and Alberto Conti. "JWST Astronomy Data Analysis Tools Roadmap Documentation" (2016). Print.

Feroz, F. and M. P. Hobson. "Multimodal nested sampling: An efficient and robust alternative to Markov Chain Monte Carlo methods for astronomical data analyses". *Monthly Notices of the Royal Astronomical Society* 384.2 (2008): 449–463. arXiv: 0704.3704.

Feroz, F., M. P. Hobson, and M. Bridges. "MultiNest: An efficient and robust Bayesian inference tool for cosmology and particle physics". *Monthly Notices of the Royal Astronomical Society* 398.4 (2009): 1601–1614. arXiv: 0809.3437.

——."MultiNest: An efficient and robust Bayesian inference tool for cosmology and particle physics". *Monthly Notices of the Royal Astronomical Society* 398.4 (2009): 1601–1614. arXiv: 0809.3437.

Feroz, F., et al. "Importance Nested Sampling and the MultiNest Algorithm" (2013): 1–28. arXiv: 1306.2144. Web.

Feroz, Farhan, et al. "Importance Nested Sampling and the MultiNest Algorithm". *The Open Journal of Astrophysics* 2.1 (2019): 1–17. arXiv: 1306.2144.

Fisher, Chloe, et al. "Interpreting High-Resolution Spectroscopy of Exoplanets Using Cross-Correlations and Supervised Machine Learning" (2019): 1–15. arXiv: 1910.11627. Web.

Foreman-Mackey, Daniel, et al. "emcee : The MCMC Hammer ". *Publications of the Astronomical Society of the Pacific* 125.925 (2013): 306–312. arXiv: 1202.3665.

Gandhi, Siddharth and Nikku Madhusudhan. "Retrieval of exoplanet emission spectra with HyDRA". *Monthly Notices of the Royal Astronomical Society* 474.1 (2018): 271–278. arXiv: 1710.06433.

Garland, R. and P. G. J. Irwin. "Effectively Calculating Gaseous Absorption in Radiative Transfer Models of Exoplanetary and Brown Dwarf Atmospheres". March (2019). arXiv: 1903.03997. Web.

Goody, Richard, et al. "The correlated-k method for radiation calculations in nonhomogeneous atmospheres". *Journal of Quantitative Spectroscopy and Radiative Transfer* 42.6 (1989): 539–550. Print.

GRAVITY Collaboration, et al. "Peering into the formation history of beta Pictoris b with VLTI/GRAVITY long baseline interferometry". 2011 (2019): 1–21. arXiv: 1912.04651. Web.

Greenbaum, Alexandra Z., et al. " GPI Spectra of HR 8799 c, d, and e from 1.5 to 2.4 μ m with KLIP Forward Modeling ". *The Astronomical Journal* 155.6 (2018): 226. arXiv: 1804.07774.

Guillot, T. "On the radiative equilibrium of irradiated planetary atmospheres". *Astronomy and Astrophysics* 520.18 (2010): 1–13. arXiv: 1006.4702.

——."On the radiative equilibrium of irradiated planetary atmospheres". *Astronomy and Astrophysics* 520.18 (2010): 1–13. arXiv: 1006.4702.

Haffert, S. Y., et al. "Two accreting protoplanets around the young star PDS 70". *Nature Astronomy* 3.8 (2019): 749–754. Web.

Helling, Christiane and Sarah Casewell. "Atmospheres of Brown Dwarfs". *The Astronomy and Astrophysics Review* 22 (2014): 1–53. arXiv: arXiv:1410.6029v2.

Hoeijmakers, H. J., et al. "Medium-resolution integral-field spectroscopy for high-contrast exoplanet imaging: Molecule maps of the β Pictoris system with SINFONI". *Astronomy and Astrophysics* 617 (2018): 1–11. arXiv: 1802.09721.

Irwin, P. G.J., et al. "The NEMESIS planetary atmosphere radiative transfer and retrieval tool". *Journal of Quantitative Spectroscopy and Radiative Transfer* 109.6 (2008): 1136–1150. Print.

"JWST Pipeline Documentation" (2018). Print.

Keppler, M., et al. "Discovery of a planetary-mass companion within the gap of the transition disk around PDS 70". *Astronomy and Astrophysics* 617 (2018): 1–21. arXiv: 1806.11568.

Konopacky, Quinn M., et al. "Detection of carbon monoxide and water absorption lines in an exoplanet atmosphere". *Science* 339.6126 (2013): 1398–1401. Print.

Kreidberg, Laura. "Exoplanet Atmosphere Measurements from Transmission Spectroscopy and Other Planet Star Combined Light Observations". *Handbook of Exoplanets* (2018): 2083–2105. arXiv: arXiv:1709.05941v2.

Labiano-Ortega, Alvaro, et al. "The MIRI Medium Resolution Spectrometer calibration pipeline". exposure 1 (2016): 117. Print.

——."The MIRI Medium Resolution Spectrometer calibration pipeline". exposure 1 (2016): 117. Print.

Lacis, A. A. and V. Oinas. "A description of the correlated k distribution method for modeling nongray gaseous absorption, thermal emission, and multiple scattering in vertically inhomogeneous atmospheres". *Journal of Geophysical Research* 96.D5 (1991): 9027–9063. Print.

Lagage, P, et al. "The Mid-Infrared Instrument for the James Webb Space Telescope , IV : The Low Resolution Spectrometer" (): 1–23. Print.

——."The Mid-Infrared Instrument for the James Webb Space Telescope , IV : The Low Resolution Spectrometer" (): 1–23. Print.

Lagrange, A. M., et al. "A probable giant planet imaged in the β Pictoris disk* VLT/NaCo deep L'-band imaging". *Astronomy and Astrophysics* 493.2 (2009): 21–25. Print.

Lahuis, F and A Boogert. "How to Get Rid of Fringes in SIRTF/{IR}S Data". *SFChem 2002: Chemistry as a Diagnostic of Star Formation* January 2003 (2003): 335. Print.

Lavie, Baptiste, et al. " HELIOS–RETRIEVAL: An Open-source, Nested Sampling Atmospheric Retrieval Code; Application to the HR 8799 Exoplanets and Inferred Constraints for Planet Formation ". *The Astronomical Journal* 154.3 (2017): 91. arXiv: 1610.03216.

Lee, J. M., L. N. Fletcher, and P. G.J. Irwin. "Optimal estimation retrievals of the atmospheric structure and composition of HD189733b from secondary eclipse spectroscopy". *Monthly Notices of the Royal Astronomical Society* 420.1 (2012): 170–182. arXiv: 1110.2934.

Li, Jianfeng, et al. "A comparative study of point-to-point algorithms for matching spectra". *Chemometrics and Intelligent Laboratory Systems* 82.1-2 SPEC. ISS (2006): 50–58. Print.

Line, Michael R. and Vivien Parmentier. "the Influence of Nonuniform Cloud Cover on Transit Transmission Spectra". *The Astrophysical Journal* 820.1 (2016): 78. arXiv: 1511.09443. Web.

Line, Michael R., et al. "A systematic retrieval analysis of secondary eclipse spectra. I. A comparison of atmospheric retrieval techniques". *Astrophysical Journal* 775.2 (2013). arXiv: 1304.5561.

Line, Michael R., et al. "UNIFORM ATMOSPHERIC RETRIEVAL ANALYSIS of ULTRACOOL DWARFS. I. CHARACTERIZING BENCHMARKS, Gl 570D and HD 3651B". *Astrophysical Journal* 807.2 (2015): 183. arXiv: 1504.06670. Web.

Line, Michael R., et al. "Uniform Atmospheric Retrieval Analysis of Ultracool Dwarfs. II. Properties of 11 T dwarfs". *The Astrophysical Journal* 848.2 (2017): 83. arXiv: 1612.02809. Web.

——."Uniform Atmospheric Retrieval Analysis of Ultracool Dwarfs. II. Properties of 11 T dwarfs". *The Astrophysical Journal* 848.2 (2017): 83. arXiv: 1612.02809.

Line, Michael R, et al. "A systematic retrieval analysis of secondary eclipse spectra i: a comparison of atmospheric retrieval techniques" (). arXiv: arXiv: 1304.5561v2.

Lupu, Roxana E., et al. "Developing Atmospheric Retrieval Methods for Direct Imaging Spectroscopy of Gas Giants in Reflected Light. I. Methane Abundances and Basic Cloud Properties". *The Astronomical Journal* 152.6 (2016): 217. arXiv: 1604.05370. Web.

Lupu, Roxana E, et al. "DEVELOPING ATMOSPHERIC RETRIEVAL METHODS FOR DIRECT IMAGING SPECTROSCOPY OF GAS GIANTS IN REFLECTED LIGHT . I . METHANE ABUNDANCES AND BASIC CLOUD PROPERTIES". *The Astronomical Journal* 10.October (2018): 1–29. arXiv: arXiv: 1306.2144v2. Web.

MacDonald, Ryan J. and Nikku Madhusudhan. "HD 209458b in new light: evidence of nitrogen chemistry, patchy clouds and sub-solar water". *Monthly Notices of the Royal Astronomical Society* 469.2 (2017): 1979–1996. arXiv: 1701.01113.

Macintosh, B., et al. "Discovery and spectroscopy of the young jovian planet 51 Eri b with the Gemini Planet Imager". *Science* 350.6256 (2015): 64–67. Print.

Macintosh, Bruce, et al. "ANGULAR DIFFERENTIAL IMAGING : A POWERFUL HIGH-CONTRAST IMAGING TECHNIQUE 1" (2006): 556–564. Print.

Madhusudhan, N and S Seager. "A TEMPERATURE AND ABUNDANCE RETRIEVAL METHOD FOR EXOPLANET ATMOSPHERES" (2018). arXiv: arXiv:0910.1347v2.

Madhusudhan, Nikku. "Atmospheric Retrieval of Exoplanets". *Handbook of Exoplanets* (2018): 2153–2182. arXiv: 1808.04824.

——."C/O ratio as a dimension for characterizing exoplanetary atmospheres". *Astrophysical Journal* 758.1 (2012). arXiv: 1209.2412.

Madhusudhan, Nikku, et al. "Exoplanetary Atmospheres—Chemistry, Formation Conditions, and Habitability". *Space Science Reviews* 205.1-4 (2016): 285–348. arXiv: arXiv:1604.06092v1.

Madhusudhan, Nikku, et al. "High C / O Ratio and Weak Thermal Inversion in the Very Hot Atmosphere of Exoplanet WASP-12b". 54 (). Print.

Malik, Matej, et al. "Supervised Machine Learning for Inter-comparision of Model Grids of Brown Dwarfs: Application to GJ 570D and the Epsilon Indi B Binary System" (2019). arXiv: arXiv:1910.11795v1.

Manjavacas, Elena. "Physical characterization of brown dwarfs" (2014). Print.

Marley, M S and T D Robinson. "On the Cool Side : Modeling the Atmospheres of Brown Dwarfs and Giant Planets arXiv : 1410 . 6512v1 [astro-ph . EP] 23 Oct 2014" (): 1–57. arXiv: arXiv:1410.6512v1.

Marois, Christian, et al. "Direct imaging of multiple planets orbiting the star HR 8799". *Science* 322.5906 (2008): 1348–1352. arXiv: 0811.2606.

Mather, John. "The James Webb Space Telescope". *Adaptive Optics: Analysis, Methods and Systems, AO 2015* Scipy (2015): 289. arXiv: 0606175 [astro-ph].

Mayor, M and D Queloz. "A Jupiter-mass companion to a solar-type star". *Nature* 378 (1995): 667–668. Print.

Mesa, D., et al. "VLT/SPHERE exploration of the young multiplanetary system PDS70". *Astronomy and Astrophysics* 632 (2019): 1–12. arXiv: 1910.11169.

Meunier, N., et al. "Activity time series of old stars from late F to early K. I. Simulating radial velocity, astrometry, photometry, and chromospheric emission". 2015 (2019): 1–20. arXiv: 1904.01437. Web.

Milli, J, et al. "Speckle lifetime in XAO coronagraphic images : temporal evolution of SPHERE coronagraphic images" (): 3–7. arXiv: arXiv:1608.02149v3.

Molliere, P. and I. A.G. Snellen. "Detecting isotopologues in exoplanet atmospheres using ground-based high-dispersion spectroscopy". *Astronomy and Astrophysics* 622 (2019). arXiv: 1809.01156.

Mollière, P., et al. "petitRADTRANS: a Python radiative transfer package for exoplanet characterization and retrieval". 67 (2019): 1–17. arXiv: 1904.11504. Web.

Mollière, P, et al. "MODEL ATMOSPHERES OF IRRADIATED EXOPLANETS : THE INFLUENCE OF STELLAR PARAMETERS , METALLICITY , AND THE C / O RATIO". *The Astrophysical Journal* 813.1 (2015): 47. Web.

Morley, Caroline V., et al. "Measuring the D/H Ratios of Exoplanets and Brown Dwarfs". *The Astrophysical Journal* 882.2 (2019): L29. arXiv: 1810.04241.

Morley, Caroline V., et al. "Water clouds in y dwarfs and exoplanets". *Astrophysical Journal* 787.1 (2014). arXiv: 1404.0005.

Moses, J. I., et al. "Chemical consequences of the C/O ratio on hot jupiters: Examples from WASP-12b, CoRoT-2b, XO-1b, and HD 189733b". *Astrophysical Journal* 763.1 (2013). arXiv: 1211.2996.

"No Title" (). Print.

Observation, Folder, Observing Template, and Science Target. "1275 - Spectroscopic characterization of PSO J318". 1275 (2019): 1–6. Print.

Observation, Folder, et al. "1278 - MIRI Spectroscopic Observations of Brown Dwarfs". 1278.2 (2019): 1–5. Print.

Oliveira, Catarina Alves De. "Peering into the physics of brown dwarfs : spectroscopy with JWST / NIRSpec" (). Print.

Petermann, R. "Atmospheric characterization of terrestrial planets using high-resolution spectroscopy with ELT / METIS A study of Proxima Cen b" (2019): 1–28. Print.

Planetary, European and Science Congress. "Exoplanets characterisation with the JWST and particularly MIRI". 10.October (2018): 6–7. Print.

Quanz, Sascha P., et al. "First results from very large telescope NACO apodizing phase plate: 4 μm images of the exoplanet β Pictoris b". *Astrophysical Journal Letters* 722.1 PART 2 (2010): 49–53. Print.

Rieke, G H, et al. " The Mid-Infrared Instrument for the James Webb Space Telescope , I: Introduction ". *Publications of the Astronomical Society of the Pacific* 127.953 (2015): 584–594. Print.

——." The Mid-Infrared Instrument for the James Webb Space Telescope , I: Introduction ". *Publications of the Astronomical Society of the Pacific* 127.953 (2015): 584–594. Print.

——." The Mid-Infrared Instrument for the James Webb Space Telescope , I: Introduction ". *Publications of the Astronomical Society of the Pacific* 127.953 (2015): 584–594. Print.

Robinson, Tyler D., Karl R. Stapelfeldt, and Mark S. Marley. "Characterizing rocky and gaseous exoplanets with 2m class space-based coronagraphs". *Publications of the Astronomical Society of the Pacific* 128.960 (2016): 1–22. Web.

Roellig, Thomas L, et al. "Studies of the Coldest Brown Dwarfs with the James Webb Space Telescope" (2014): 2014. Print.

Ruane, Garreth, et al. "Reference Star Differential Imaging of Close-in Companions and Circumstellar Disks with the NIRC2 Vortex Coronagraph at the W. M. Keck Observatory". *The Astronomical Journal* 157.3 (2019): 118. arXiv: arXiv:1901.04090v2.

Schlawin, Everett, et al. " Clear and Cloudy Exoplanet Forecasts for JWST : Maps, Retrieved Composition, and Constraints on Formation with MIRI and NIRCam ". *The Astronomical Journal* 156.1 (2018): 40. arXiv: 1803.08173.

Seager, Sara. "Bayesian Atmospheric Retrieval for Exoplanets" (2013). Print.

Skilling, John. "Nested Sampling". 395.November 2004 (2004): 395–405. Print.

Snellen, I., et al. "Combining high-dispersion spectroscopy with high contrast imaging: Probing rocky planets around our nearest neighbors". *Astronomy and Astrophysics* 576.3 (2015). arXiv: 1503.01136.

Snellen, Ignas, et al. "The fast spin-rotation of a young extrasolar planet". *Nature* 509.7498 (2014): 63–65. arXiv: 1404.7506 [astro-ph.EP]. Web.

Speagle, Joshua S. "A Conceptual Introduction to Markov Chain Monte Carlo Methods" (2019). arXiv: 1909.12313. Web.

Teague, Richard, et al. "A Kinematical Detection of Two Embedded Jupiter-mass Planets in HD 163296". *The Astrophysical Journal* 860.1 (2018): L12. arXiv: arXiv:1805.10290v2.

Template, Observing and Science Target. "1276 - Spectroscopic Observations of WD 0806-661B". 1276 (2019): 1–7. Print.

Thiébaut, Éric, et al. "Image Reconstruction in Optical Interferometry Éric Thiébaut To cite this version : HAL Id : hal-00715974 Image Reconstruction in Optical Interferometry" (2012). Print.

Tokunaga, Alan T. "No Title". October (1983): 691–699. Print.

Tsiaras, A., et al. "A Population Study of Gaseous Exoplanets". *The Astronomical Journal* 155.4 (2018): 156. Web.

VanderPlas, Jacob T. "Understanding the Lomb–Scargle Periodogram". *The Astrophysical Journal Supplement Series* 236.1 (2018): 16. arXiv: 1703.09824. Web.

Version, Raft. "ATMOSPHERIC COMPOSITIONS OF THREE BROWN DWARFS AND IMPLICATIONS FOR THEIR FORMATION" (2018). arXiv: arXiv: 1612.03174v1.

Vicum, Lars. "Research Collection: Theses". *PhD thesis* (2005). Print.

Waldmann, I. P., et al. "T-REx. II. RETRIEVAL of EMISSION SPECTRA". *Astrophysical Journal* 813.1 (2015): 13. arXiv: 1508.07591. Web.

Waldmann, I. P., et al. "Tau-REx I: A next generation retrieval code for exoplanetary atmospheres". *Astrophysical Journal* 802.2 (2015): 107. arXiv: 1409.2312. Web.

Webb, James and Space Telescope. "MIRI MRS FM Fringing Analysis" (2018). Print.

Wells, Martyn, et al. " The Mid-Infrared Instrument for the James Webb Space Telescope , VI: The Medium Resolution Spectrometer ". *Publications of the Astronomical Society of the Pacific* 127.953 (2015): 646–664. arXiv: 1508.03070.

Zalesky, Joseph A., et al. "A Uniform Retrieval Analysis of Ultra-cool Dwarfs. III. Properties of Y Dwarfs". *The Astrophysical Journal* 877.1 (2019): 24. arXiv: 1903.11658.

Zhang, Le and Raja R.A. Issa. *Development of IFC-based construction industry ontology for information retrieval from IFC models*. 2014. Print.

Zhang, Michael, et al. "Forward modeling and retrievals with PLATON, a fast open-source tool". *Publications of the Astronomical Society of the Pacific* 131.997 (2019). arXiv: 1811.11761.

Zucker, S. "Cross-correlation and maximum-likelihood analysis : a new approach to combining cross-correlation functions 2 F RO M M A X I M U M L I K E L I H O O D T O C R O S S - C O R R E L AT I O N 1292". 1298 (2003): 1291–1298. Print.

Zurlo, A., et al. "First light of the VLT planet finder SPHERE: III. New spectrophotometry and astrometry of the HR 8799 exoplanetary system". *Astronomy and Astrophysics* 587 (2016): 1–13. arXiv: 1511.04083.