A New Window on Exoplanet Atmospheres: Observations and Instrumentation in the Near-Infrared

Emily K. Deibert

David A. Dunlap Department of Astronomy & Astrophysics, University of Toronto
Dunlap Institute for Astronomy & Astrophysics

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Abstract

Over four thousand exoplanets have been discovered, but relatively little is known about their atmospheric properties and compositions. Characterizing exoplanet atmospheres is the most promising avenue through which we can learn more about exoplanets themselves, and high-resolution spectroscopy is currently one of the best methods by which this can be accomplished. The goal of this thesis is to use state-of-the-art ground-based spectrographs in the near-infrared wavelength regime to detect, characterize, and understand the atmospheres of exoplanets, with a particular focus on super-Earths and hot Jupiters, for which there are no Solar System analogues and which remain poorly understood. This work will provide important insights on theories of planet formation and evolution, and shed light on the dynamics and chemical compositions of planetary atmospheres. In this brief report, I will summarize my progress to date, provide updates on previously-proposed projects, and propose new projects in line with these goals.

Thesis Committee

Suresh Sivanandam
Primary Advisor
Dunlap Institute for Astronomy & Astrophysics
sivanandam@dunlap.utoronto.ca

Ray Jayawardhana
Co-Advisor
Department of Astronomy, Cornell University
rayjay@cornell.edu

Diana Valencia
Committee Member
David A. Dunlap Department of Astronomy & Astrophysics
valencia@astro.utoronto.ca

Marten van Kerkwijk
Committee Member
David A. Dunlap Department of Astronomy & Astrophysics
mhvk@astro.utoronto.ca

Progress to Date

Paper 1: High-Resolution Transit Spectroscopy of Warm Saturns

- Published

In Deibert et al. (2019), I presented transmission spectroscopy of some of the smallest hot Jupiters to have had their atmospheres probed at high spectral resolution from ground-based facilities (namely, the GRACES instrument at Gemini-N and the HDS instrument at Subaru). I made use of a sophisticated Doppler cross-correlation technique which involves correlating highly-detailed model spectra with our observations, taking advantage of the large shifts in radial velocity of the exoplanets in question. While this method had been used in previous studies to make atmospheric detections around several hot Jupiters, the atmospheres of cooler, lower-mass planets remain elusive. My work in Deibert et al. (2019) focused on "warm Saturns", a smaller class of the massive hot Jupiter population, and served as a stepping-stone between the atmospheres of these giant hot Jupiters and detailed analyses of super-Earth atmospheres. I made the first detection of Na in the atmosphere of HAT-P-12b, and placed strong constraints on the presence of Na, K, and H_2O in the atmosphere of WASP-69b. This work will serve as a chapter in my thesis.

Paper 2: A Near-Infrared Chemical Inventory of the Atmosphere of 55 Cancri e

- To Be Submitted

In Deibert et al. (2020), I analyzed high-resolution NIR spectra during transits of the hot super-Earth 55 Cancri e from CARMENES/Calar Alto and SPIRou/CHFT. The analysis focused on absorption features due to CO, CO_2, H_2O, HCN, and NH_3, and took advantage of two facets of the observations: first, the wide combined wavelength coverage of both Calar Alto/CARMENES and CFHT/SPIRou, which together span thousands of absorption features of both water and various carbon-rich molecules; and second, the extremely high resolutions of both instruments used, which allowed us to individually resolve these thousands of absorption features.

While this analysis didn't result in a detection of the planet's atmosphere, we were able to place strong constraints on the presence of HCN and NH_3 in 55 Cnc e's atmosphere. Notably, while a previous study had used low-resolution data to tentatively suggest that HCN might be present in the atmosphere of 55 Cnc e (Tsiaras et al., 2016), our analysis rules out almost all HCN models consistent with the low-resolution analysis of Tsiaras et al. (2016). This indicates that either HCN is present at a high mean molecular weight and low volume mixing ratio (which has been ruled unlikely by Tsiaras et al. 2016), or that a different molecule was responsible for the absorption detected by Tsiaras et al. (2016).

This work will be submitted to AJ, and will serve as a chapter in my thesis.

Upcoming Projects

A Photonics Solution for the Doppler Cross-Correlation Method

This project involves exploratory work into a novel instrument concept that will make use of a photonics solution to carry out the Doppler cross-correlation technique optically, rather than after spectra have been obtained. The cross-correlation will be encoded in the optical output of the device, resulting in a simpler and less costly method of detecting molecular features in exoplanet atmospheres. Furthermore, since the light is not dispersed within this device, we may potentially be able to greatly increase the sensitivity for detection of exoplanet atmospheres. My role in this project will be to help determine what we can expect to achieve with such a device, and potentially test initial observations taken in this way.

We have recently obtained NIR observations of Saturn from IRD/Subaru, which will be used to carry out predictive measurements for this proposed photonics device. We also submitted an OPTICON proposal to observe Venus, Mars, and Jupiter with GIARPS/TNG, and while this proposal was successful, the observatory has closed due to the COVID-19 situation and we are currently not sure when it will reopen. If these data are obtained they will also be used to make predictive measurements for this device; until then, however, I will be focusing on the IRD data. I have to date carried out some basic reduction of this data, and will work towards finishing this data reduction shortly.

Characterizing the Atmospheres of Hot Jupiters in the WASP-94AB "Twin" Binary System

The process by which hot Jupiters form and migrate to their present-day orbits remains one of the key open questions in the field of exoplanets. One particularly promising method by which we can begin to constrain hot Jupiter formation/migration mechanisms is the characterization of their atmospheres. Various studies have shown that the C/O ratio of a hot Jupiters's atmosphere is a robust probe of its formation pathway, shedding light on the solid and volatile ratios available during formation and thus providing insight on where in the disk it may have formed. This project will focus on probing the atmospheres of two hot Jupiters orbiting "twin" stellar companions in the wide-orbit binary system WASP-94AB. Although the planets are comparable in size and period, their orbital architectures point to vastly different formation scenarios: WASP-94A b is misaligned with the host star spin axis and likely in a retrograde orbit, suggesting a dynamical formation, whereas WASP-94B b has a nearly circular orbit and does not appear to be misaligned.

I have submitted a proposal to IGRINS/Gemini-South to observe the transit of WASP-94A b and the phase-curve of WASP-94B b, which is non-transiting. If successful, these observations will target the thousands of strong absorption/emission lines from key molecular species that contribute to the C/O ratio in the NIR wavelength range of IGRINS, allowing us to compare the atmospheric compositions of hot Jupiters that formed under similar conditions but underwent distinct evolutionary pathways. The planets themselves are ideal targets for this technique: WASP-94A b is highly bloated, with an atmospheric scale-height more than 1% of its radius, while WASP-94B b has an extremely high equilibrium temperature due to its proximity to its host star.

Modifications from Thesis Proposal

Characterizing Atmospheres in the Young Planetary System V1298 Tau

Although my proposal to NEOSSAT for observing the V1298 Tau system was successful, the data were not of a high enough quality to successfully constrain the ephemerides of this system, and we ultimately did not pursue the project further. However, I feel that the WASP-94AB project proposed above addresses similar scientific questions: the goal of the V1298 Tau project was to study the atmospheres of different planets in the same system, thus learning more about their formation mechanisms; with the WASP-94AB project we will study the atmospheres of planets that likely formed in similar environments but underwent different formation pathways, allowing us to shed light on the formation histories of hot Jupiters.

The MMT Adaptive Optics Exoplanet Characterization System

Although I hope to be able to use the MMT Adaptive Optics Exoplanet Characterization System (MAPS) to observe exoplanet atmospheres in the future, the project has been delayed since my thesis qualifying exam and the timeline is currently uncertain, due in part to the COVID-19 situation. We will continue to monitor and assess the feasibility of using MAPS in my thesis, and are hopeful that it will be ready in early 2021.

Timeline

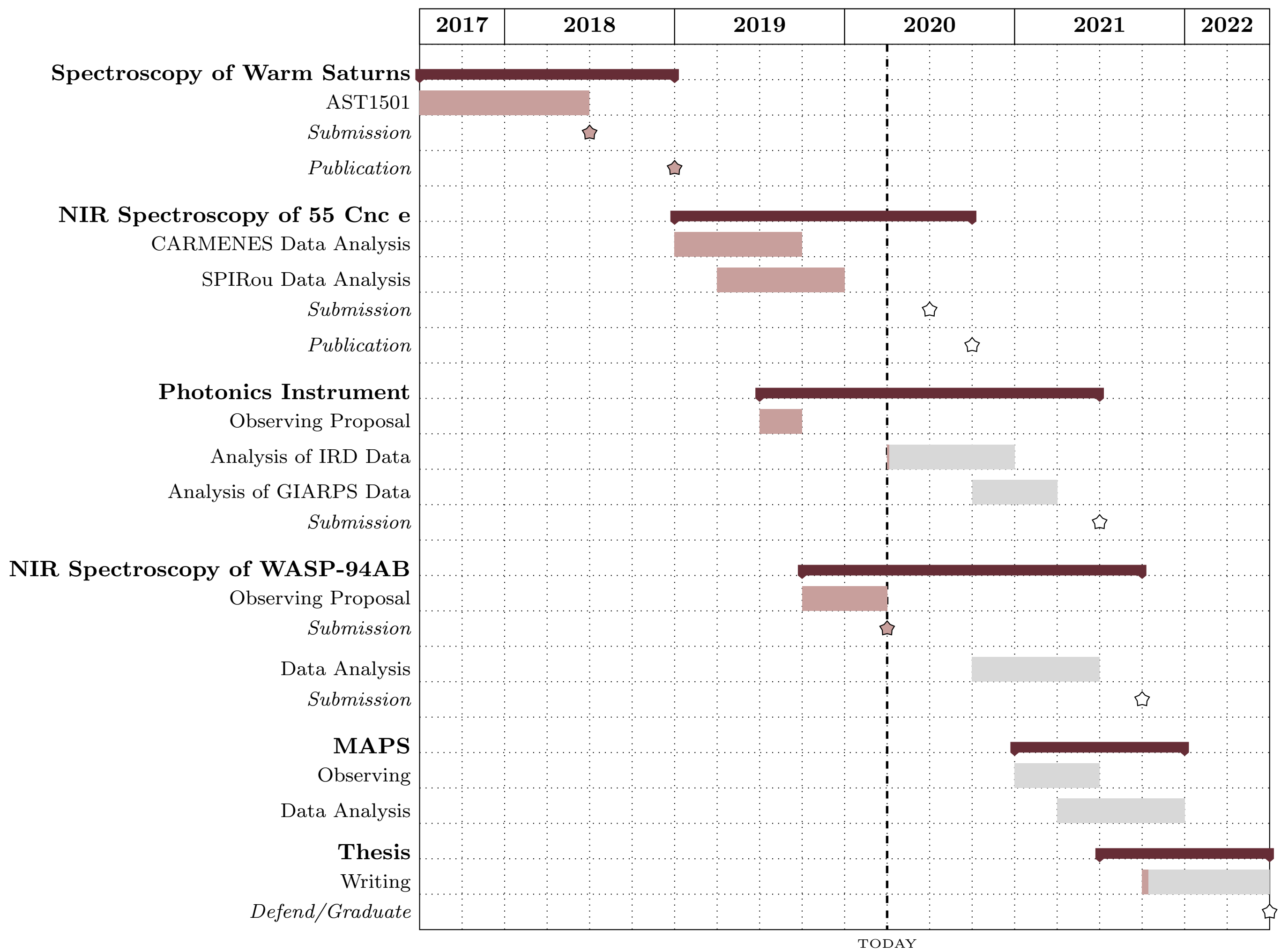

Figure 1: A visualization of the thesis timeline. Shaded regions correspond to the amount of each goal that has been completed, and stars correspond to various progress milestones, with coloured stars corresponding to completed milestones.

References

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