High-resolution Spectroscopy of Directly Imaged Exoplanets and Brown Dwarfs

In the previous few decades, indirect exoplanet detection techniques such as the radial velocity method and transit method have detected thousands of exoplanets, revealing an unexpected diversity of planetary systems. From hot-Jupiters to super-Earths, discoveries continually challenge our understanding of planetary formation, migration, and evolution. However, indirect detection methods are currently limited by instrumentation and observation baselines to close-in, short-period planets, leaving key aspects of planetary formation unexplored. Massive gas giants, orbiting at tens to thousands of astronomical units (au) from their host stars, are only observable through direct imaging (DI).

Although far fewer exoplanets have been directly imaged, all these planets, as well as brown dwarf-mass companions, are accessible to characterization through direct spectroscopy, enabling researchers to examine their atmospheres. My research focuses on using high-resolution spectroscopy (HRS, Resolution = R $\geq$25,000) to study exoplanet atmospheres and understand exoplanet formation and evolution. HRS resolves individual molecular absorption features in an exoplanet's atmosphere. Based on our understanding of how exoplanets form, the composition of the atmosphere can imply mechanisms of formation and the composition of the protoplanetary disk. Using techniques like cross-correlation (CC) with molecular templates, HRS facilitates the detection of key constituents (e.g., CO and H_2O in K-band) of giant planet atmospheres, atmospheric parameters like effective temperature, surface gravity, the presence or absence of clouds and hazes, along with dynamical quantities like the companion's radial velocity and projected rotation rate, v$sin(i)$. By studying near-infrared (NIR) absorbing species such as carbon monoxide, water, methane, and oxygen, we gain insight into the formation history of DI companions.

The Keck Planet Imager and Characterizer (KPIC) is a high-resolution single-mode fiber-fed spectrograph that leverages both the Keck-II 10m-class telescope and its adaptive optics (AO) system, as well as the inherent stability of a single-mode fiber-fed spectrograph. Using KPIC, I led an atmospheric characterization and orbital analysis of HD 206893 B, a 26 Jupiter-mass (M_{Jup}) companion in a multi-companion system, presenting an interesting test to the planetary formation theories of gravitational instability and pebble accretion. Using a forward-model framework, we detected HD 206893 B at $>8\sigma$ significance via cross-correlation in two epochs. We determined an effective temperature, surface gravity, and near-solar C/O ratio for the companion. The C/O ratio we measure fits the tentative trend of >4 M_{Jup} companions having near-solar C/O ratios, while less massive companions have greater-than-solar C/O ratios. The measured C/O ratio, coupled with the current architecture of the system, cannot rule out a core accretion scenario, nor a disk fragmentation scenario regarding the formation pathway of HD 206893 B. I continue my research with KPIC, now looking at the brown dwarf HR 7672 B. This time, we aim to measure the carbon and oxygen isotopes in the atmosphere of HR 7672 B. For example, carbon-12 (^{12}C) is the most common isotope at 98.93% while carbon-13 (^{13}C, 6 protons, 7 neutrons) makes up just 1.08%. We do not yet know, for most exoplanets, what the ratio of isotopes is, but the ratio is thought to change based on where the exoplanet formed in its disk, which in turn can predict how that planet formed.

The final portion of my dissertation involves the design, construction, and testing of the calibration system and data reduction pipeline for the upcoming High-resolution Infrared Spectrograph for Exoplanet Characterization (HISPEC). HISPEC is a collaboration between UCSD, UCLA, Caltech, JPL, Northwestern, the Astrobiology Center, and Keck Observatory, and takes many lessons from KPIC design, but increases the spectral resolution even further, turning HISPEC into a different class of instrument capable of making precise radial velocity measurements. The HISPEC calibration system and data reduction pipeline are being built at UCSD. I will validate the CAL subsystem to achieve the necessary absolute calibration of the spectrograph and overall stability of the instrument, which is critical to its long-term operation and ability to study exoplanets in the future.