High Precision Spectroscopy of Protoplanetary Disk and Exoplanet Atmospheres with Keck

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The spectra of protoplanetary disk and exoplanet atmospheres tell us not only about their current physical state and composition, but their histories. In disks, for example, the differential movement of dust/ice and gas leads to significant changes in the carbon-to-oxygen ratios (C/O) within the gas and solid reservoirs versus distance, height, and time. These changes can carry all the way through into giant planet formation, and high precision characterizations of exoplanet atmosphere are thus expected to provide crucial hints on their formation. While ALMA is pioneering new approaches to the study of gas and dust in disks, and the interactions of protoplanets and their natal environment, only infrared spectroscopy can provide access to key tracers, such as CH_4 and CO_2, in both the vapor and solid state, and to the innermost radii of disks that corresponds to the bulk of the discovered exoplanet population.

1.1 Current State-of-the-Art with NIRSPEC/KPIC

Even on 8-10m platforms for bright stars/close in planets, considerable telescope time is required for robust direct detections of exoplanet atmospheres and the high S/N recovery of key isotopic tracers of the major CNO species (such as ^{13}CO or $H_2^{(17,18)}O$. And, the modest instantaneous spectral grasp of even the upgraded NIRSPEC means that it is not possible to obtain simultaneous observations of key tracers of both Carbon and Oxygen chemistry, for example. This has serious consequences for the accurate retrieval of key constraints of disk evolution and exoplanet atmospheres. For example, even with simultaneous observations of CO and water in K-band data, the limited instantaneous spectral grasp means that there are strong correlations in the retrieved atmospheric lapse rate, for exoplanet for brown dwarf atmospheres, or the run of temperature with radius in disks, and the C/O ratio (versus semi-major axis for disks). Even with perfect brown dwarf or isolated exoplanet data, biases in excess of 0.5 dex are common from *known* inputs to existing pipelines and retrieval methods with current instruments. This arises because biases in the temperature structure are difficult to quantify given the limited wavelength coverage, and affect the different molecular tracers in different ways.

Instantaneous spectral grasp and spectral resolution also play key roles in the ability of observational approaches to recover accurate results. For example, the *timing* of disk and exoplanet observations is critical, especially in the limit of small numbers of observational epochs, as can often occur on the largest aperture ground-based observatories, and becomes quite challenging with gaps between echelle orders and limited broadband coverage of single detector instruments.

1.2 Enter HISPEC and IGNIS: The Power of Simultaneous Multi-Species Spectroscopy

Looking forward, then, an absolutely essential aspect of next generation instruments, such as HISPEC and IGNIS, is their instantaneous spectral grasp (please see the relevant instrument White Papers for details on these instruments). In addition to being able to study the atmospheres of protoplanetary disks and both hot and warm Jupiters/Neptunes, direct detection efforts with IGNIS and with HISPEC will enable a push outward in semi-major axis to begin to studying planets in habitable zones. Planets in habitable zones around M stars will likely be the first such targets for several reasons. First, as the most abundant stars, M stars would provide the most options for nearby planets to study. Second, with low temperatures ($T_{eff} \sim$ 3000 K), M dwarfs will have much closer in habitable zones than FG stars. Smaller periods within the habitable zone will allow for techniques like ours to obtain epochs around the planet's orbit without having to wait as long. The lower temperatures of M stars do present a major challenge to planetary detection via spectroscopic techniques, however, in that relative to FG stars, M stars can sustain a range of molecules in their photospheres that result in complex infrared spectra. The tasks associated with cross correlation approaches to exoplanet characterization or disk chemistry becomes increasingly difficult the more similar these two spectra appear, especially if the atmospheric L- and M-band are not covered. Therefore, the more complicated M star IR spectra could present a challenge that we have not yet encountered in detecting planets around FG stars. To be able to accurately detect the stellar features, we would then need to estimate starspot coverage and temperature for each stellar host to construct a good stellar spectral template.

By enabling simultaneous observations across the full H, K, L, M bands the high S/N spectra obtainable with IGNIS, or J-K bands with HISPRC, will permit a new era of exploration of exoplanet atmospheres and protoplanetary disks. When ultimately combined with tools such as High Dispersion Coronography, multi-spectrograph instruments such as IGNIS will permit the detection of super-Earth and Earth radius planets around Sun-like and low mass stars using ground based telescopes. Especially with an adaptive secondary and optimized AO system, the sensitivity at L- and M-band will be dramatically improved, and would enable spectro-astrometry to be routinely performed.

In disk observations, especially with a precise plate scale such as would be provided by a laser frequency comb, such S-A approaches will extend the ALMA-demonstrated recovery of protoplanet-disk deviations from Keplerian rotation into the inner few au. The ability to simultaneously detect the wide range of molecular species seen in comets, for example, would enable precise C/O ratios to be constrained, especially since the wide instantaneous grasp that would both recover accurate temperature structures and minimize the systemic errors that plague multi-grating setting measurements that are presently required. Since all relevant species would be recovered with each exposure, and the overall throughput and sensitivity compared to Keck-NIRSPEC2.0 would be dramatically enhanced, enabling robust programs in exoplanet and protoplanet science. High spectral resolution (R>40,000) nicely complements JWST, is key to both disk (velocity field) science and exoplanet atmospheres (recovery of rotational rates, emission scale heights, etc.) while enabling deep searches through the terrestrial atmosphere. A key further advance here will be much higher dynamic range correction approaches for tellurics, especially in short exposures on bright targets in the K, L and M atmospheric windows.