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An IRTF-iSHELL Survey of 4.52–5.25 μm CO Spectra in Protoplanetary Disks of Intermediate-mass Stars: Preliminary Sample and Analysis

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Abstract

We are conducting a survey of high-resolution near-infrared CO rovibrational spectra in protoplanetary disks around young intermediate-mass stars. We use IRTF-iSHELL with the 0.″375 and 0.″75 slits, providing 4 km s^{-1} and 6 km s^{-1} resolution and covering 4.52–5.25 μm in one single exposure. This includes part of the rovibrational R branch and most of the P branch of the CO fundamental band ($\Delta v = 1$), one of the best tracers of warm/hot gas in disks. The high quality of the spectra and the large sample covered in this survey will support multiple investigations to study the structure, kinematics, composition, and evolution of the inner 10 au in disks for years to come. The survey currently includes ~30 stars mostly within 200 pc, complementing extensive imaging campaigns that are observing their disks at optical, infrared, and millimeter wavelengths and revealing structures and planets.

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1. Introduction

While ALMA observations reveal protoplanetary disk structures at >10 au in great detail (Andrews 2020, for a review), a powerful probe of inner disks at <10 au is high-resolution spectroscopy of warm/hot molecular gas emission. Over the past two decades, infrared (IR) CO rovibrational spectra have been established as the most ubiquitous and easily observable probe of inner disk gas, tracing 300–1500 K gas in a few hundred disks (e.g., Najita et al. 2003; Brittain et al. 2007; Pontoppidan et al. 2011; Salyk et al. 2011; Brown et al. 2013; van der Plas et al. 2015). Recently, the analysis of CO spectra has focused on their potential in tracing the structure and evolution of dust and gas in inner disks, providing a complementary tool to ALMA to study disk evolution and planet formation in the innermost disk region (Banzatti & Pontoppidan 2015; Banzatti et al. 2017, 2018; Bosman et al. 2019; Antonellini et al. 2020). In disks around pre-main-sequence stars of masses ∼1.5–4 $M_{\odot}$, the combination of IR CO spectra and dust emission tracers shows that dust and gas in inner disks evolve together and that the excitation and kinematics of CO spectra trace different inner disk cavity structures (Banzatti et al. 2018; Bosman et al. 2019).

We are now conducting a new survey of *M* band CO spectra in disks using iSHELL (Rayner et al. 2016), the new near-infrared spectrograph on the NASA Infrared Telescope Facility (IRTF) on Maunakea. The survey leverages the unprecedented combination of a large spectral coverage and high spectral resolution of iSHELL, to collect a homogeneous atlas of high S/N (∼100) CO spectra to study the structure, kinematics, composition, and evolution of the inner 10 au in disks.

2. Sample and Data

The sample is focused on young intermediate-mass stars mostly within 200 pc that can be observed from Maunakea (see Figure 1). We are using IRTF-iSHELL with the $0\farcs375$ and $0\farcs75$ slits, providing 4 $\mathrm{km\,s^{-1}}$ and 6 $\mathrm{km\,s^{-1}}$ resolution, high sensitivity, and covering 4.52–5.25 μm in one single exposure (with small gaps between the orders, see Figure 1). This includes part of the rovibrational R branch (R0 to R20) and most of the P branch (P1 to P50) of the ^{12}CO fundamental band, as well as higher vibrational branches and other isotopologues emitting at these wavelengths. The data have been obtained in multiple semesters since 2016, and the survey is still ongoing. The sample currently includes: MWC 758, AB Aur, MWC 480, V892 Tau, LkHa 330, HD 141569, HD 179218, HD 169142, SR 21, HD 250550, HD 259431, 51 Oph, HD 142666, HD 150193, HD 163296, HD 190073, HD 36917, HD 35929, HD 37806, HD 58647, HD 144432, HD 149914, PDS 80, HD 35187, CQ Tau, PDS 201, RY Tau, SU Aur. A previous example of the high quality and richness of the iSHELL spectra can be found in Brittain et al. (2018), reporting on the analysis of rovibrational CO emission in HD 179218.

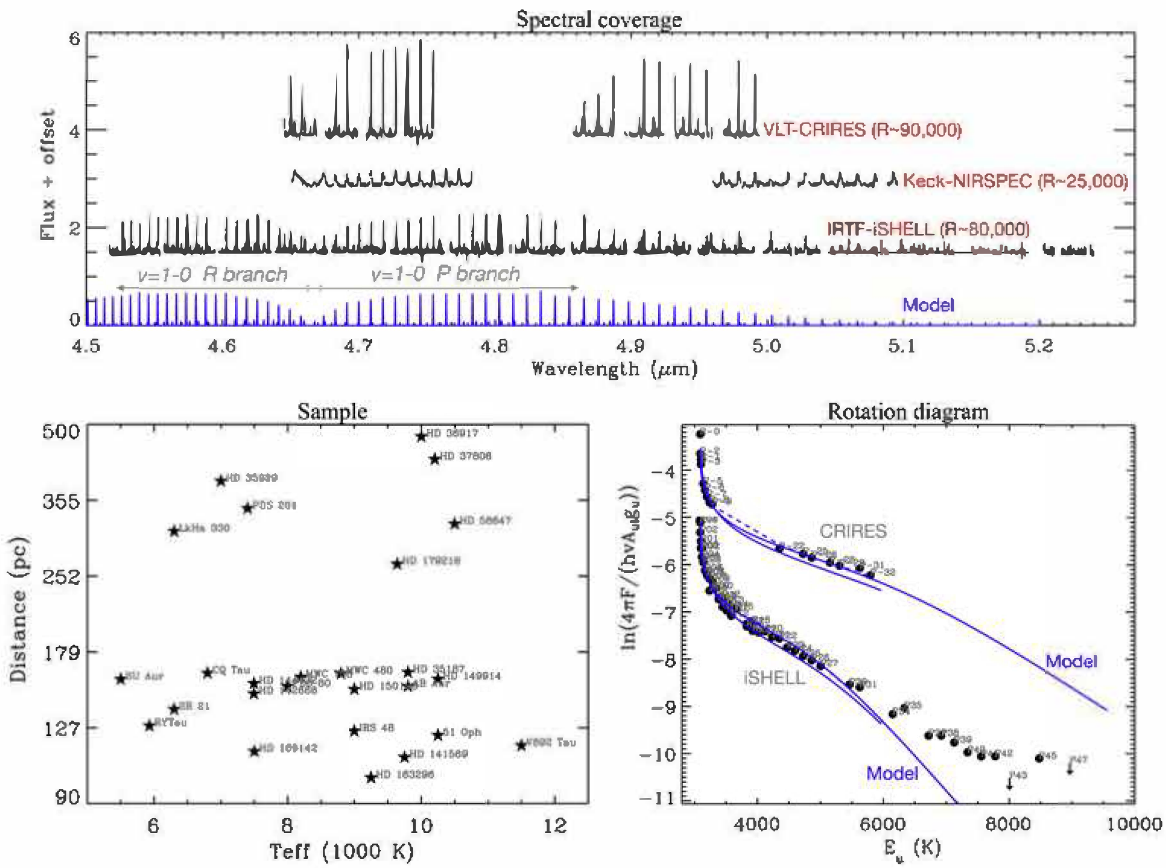

Figure 1. *Top*: example of an iSHELL spectrum in this survey as compared to spectra previously obtained with VLT-CRIRES and Keck-NIRSPEC. *Bottom left*: target sample included so far in this survey; the focus is on intermediate-mass stars within 200 pc, but some bright stars at >200 pc are included as well (three stars between 500 and 900 pc are excluded from this plot for better visualization of the sample). *Bottom right*: example of rotation diagrams for the CO $v = 1 - 0$ lines, illustrating the results from the different spectral coverage shown in the top panel. Slab models with a single temperature and column density are superimposed in blue for reference.

3. CO excitation Analysis

We measure CO line fluxes from the observed spectra, and fit them with a slab model of CO gas in LTE as described in Banzatti et al. (2012, 2015). The large spectral coverage of each spectrum provides ∼50 $v = 1 - 0$ lines and a similar number of $v = 2 - 1$ lines, totaling ∼100 line fluxes per disk spectrum. For comparison, the typical coverage of previous spectra taken with VLT-CRIRES or Keck-NIRSPEC provided ~15–20 line fluxes in one exposure (Figure 1). We explore here how the larger spectral coverage can improve our understanding of the gas properties.

The slab model includes 3 parameters: the excitation temperature T, the column density N, and the emitting area A. The approximation is that CO emission is dominated by a ring of gas at a certain distance from the star and described by one set of these parameters. We use the rotation diagram to visualize the data and best fit model, because this technique helps to visualize temperature and opacity effects, as well as deviations from LTE (Goldsmith & Langer 1999). The model includes the line optical depth, which can well reproduce the observed curvatures of rotation diagrams at low J levels (upper level energy E_u < 5500 K). The larger spectral coverage of iSHELL now shows that single slab models of gas in LTE cannot reproduce the entire spectra, especially at the high J levels (Figure 1). The CO spectra likely require either two emission components (Banzatti & Pontoppidan 2015) or non-LTE excitation (e.g., Bosman et al. 2019), or a combination of the two.

4. Data Availability

We are including the fully-reduced spectra and all line flux measurements into a new database for infrared spectra of exoplanet-forming disks, called *SpExoDisks* (Wheeler et al. in prep.), that we are building for the community and will be accessible through an online interface. The database currently includes the largest surveys of CO and H_2O spectra obtained with 5 spectrographs: IRTF-iSHELL, VLT-CRIRES, Keck-NIRSPEC, VLT-VISIR, Spitzer-IRS, and it is ready for JWST spectra. For questions, please contact us at spexodisks@gmail.com.

5. Conclusion and Future Outlook

Our preliminary analysis demonstrates the richness of the new iSHELL spectra of CO emission in planet-forming disks. The unprecedented spectral coverage, quality, and sample size of this survey (Figure 1) will support studies of the inner 10 au in disks for years to come, including to support the analysis of lower-resolution JWST spectra that lack kinematic information on the observed gas emission. The analysis and modeling of these spectra will be included in future papers, and we invite the community of disk observers and modelers to get involved in this effort.

This work includes data taken with iSHELL at the IRTF under multiple semesters between 2016 and 2021, with PI A. Banzatti or S. Brittain. We thank the IRTF staff for supporting iSHELL and this ongoing survey.

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