Chapter 7

Final Thoughts and Future Work

Molecular emission is a common, and nearly ubiquitous, feature of the spectra of circumstellar disks. We now know that, as expected, the planet-forming regions of circumstellar disks are gas-rich, with upper atmospheres sufficiently heated to produce infrared emission from a variety of molecules, including CO, H_2O, OH, HCN, C_2H_2, and CO_2. Transitional disks, in which the inner disks have been partially depleted of small dust grains, are also gas-rich, although they do not show evidence for molecules besides CO, and, perhaps, H_2, in the 4.5–30 μm range. Preliminary results show that the strength of emission lines in classical circumstellar disks depends on such factors as disk structure, dust settling, and spectral type. Disk structure and dust settling have an effect on the total column of gas visible to the observer, while all three can determine the type and strength of radiation to which the gas is exposed.

The results presented here have inspired many new projects, and several are already underway. L-band (3 μm) surveys for H_2O in disks are being pursued with NIRSPEC, on the Keck telescope, as well as with CRIRES—a high-resolution spectrograph on the Very Large Telescope. The advantage of these ground-based studies is that the lines are spectrally resolved, and so can better constrain the emitting location. The shorter wavelength spectra also complement the Spitzer-IRS results, as they probe vibrational transitions with higher excitation energies than the purely rotational lines observed with the IRS (for water and OH). In Figure 7.1, we plot H_2O and OH emission from a few circumstellar disks (as well as a photospheric template star) that have been observed with NIRSPEC. Note that line:continuum ratios are significantly higher for CO than for H_2O (and were adjusted to display on the same scale), but appear correlated for any given source. Additional emission lines are also being investigated, including HCN, which has been identified in one source thus far (Figure 7.2). If several molecules are detected, it may be possible to detect differences in line shapes due to the different locations of each molecule's condensation radius, and hence test various disk models (e.g., Dodson-Robinson et al., 2009). Very high spectral resolution data are required to be sensitive to Keplerian velocities at several AU, where the molecules condense, so such a project would best be pursued with instruments such as TEXES or CRIRES.

M-band veiling measurements of transitional disks have produced some curious results (see Figure 3.7) that are not yet understood—the continuum emission seems to be too high at 5 μm. Is this a statistical fluke, or is infrared continuum emission not well-fit by a single blackbody? And if not, what are the emission components? Does this discrepancy hold for classical disks, as well as transitional? This mystery will be pursued by measuring J, H and K-band veiling for a larger sample of transitional disks with TripleSpec on the Palomar 200" telescope, or SpeX on the IRTF, and combining these with veiling measurements derived from our M- and L-band surveys.

The Pfβ (4.6538 μm, n=7→5) hydrogen recombination line was serendipitously covered in our survey for CO rovibrational emission from circumstellar disks (see, for example, Figure 7.1). By relating the Pfβ line luminosity to accretion luminosity, accretion rates can be estimated for our entire sample of over 100 circumstellar disks. Because Pfβ is a high-energy transition, it is likely to be optically thin, and thus a good tracer of the total accretion column. Since the emission is at a significantly longer wavelength than some of the more commonly used tracers, it may provide accretion rates for disks obscured by a significant amount of extinction. Additionally, these data provide contemporaneous measures of CO emission and accretion rate, the latter of which is known to be highly variable in some disks. Preliminary results (shown in Figure 7.3) show that Pfβ luminosities are well-correlated with accretion luminosity, albeit with the $\sim$ 1 order of magnitude scatter typical for these types of correlations (e.g., Herczeg and Hillenbrand, 2008).

The true nature of transitional disks is still not known, but several images (Hughes et al., 2007; Brown et al., 2008; Dutrey et al., 2008) have already confirmed that SED-based interpretations are correct—the inner disks really are depleted of small dust grains. Observations are now being pushed a step further with CARMA, which has implemented a new antenna 'buddy-system' that uses small antennas alongside the main array to correct for atmospheric phase fluctuations (Perez-Muñoz et al., in prep). This system allows CARMA to produce sharper images in its longest baseline configurations, and has already resulted in images of transitional disk clearings with sub-arcsecond resolution and much improved image fidelity.

One of the most exciting elements of this work is that the rich Spitzer-IRS high S/N dataset (discussed in Chapter 6) has only begun to be explored. Radiative transfer models are currently being created to model the disk emission in more detail than the slab models presented here (Meijerink et al., in prep). Preliminary results for H_2O suggest that creation of emission lines may depend crucially on having a gas kinetic temperature in excess of the local dust temperature. Also, non-LTE excitation is important, especially for the strongest emission lines, so these effects need to be included to properly compute gas column densities. An interesting dichotomy between transitional disks and classical disks was unearthed, but is still not understood. Why is CO prevalent in transitional disks, but not H_2O? An investigation into the effects of photodissociation on both molecules, in both kinds of disks, might provide the answer, as CO is expected to self-shield, while many other molecules do not. Evidence for CO self-shielding could lend support to its possible role in the creation of the varying oxygen isotope ratios found in solar-system materials. Finally, the IRS dataset can also be used to measure the ortho-para ratio of disk atmosperic water vapor. This ratio equilibrates to 3 at high temperatures, but would be lower than 3 if the observed vapor derived from sublimated icy grains or planetesimals.

In the coming years, the 3.5 meter Herschel space telescope promises to provide a new window into circumstellar disks and planet formation, and hopefully some exciting new results. Launched successfully on 14 May 2009, it consists of a high-resolution heterodyne spectrometer (HIFI), and two photometer/mid-resolution spectrometers (PACS and SPIRE). It will observe dust and gas from circumstellar disks at wavelengths from 55–672 μm over its 3.5 year lifetime—covering a region in-between the wavelengths covered by Spitzer and most ground-based instruments, both infrared observatories such as Keck or the VLT and (sub-)millimeter wavelength facilities such as SMA, CARMA, and IRAM. Most importantly, like Spitzer, Herschel is not subject to the absorption and blurring of light caused by the Earth's atmosphere.

On a longer timescale, the Stratospheric Observatory For Infrared Astronomy (SOFIA), the James Webb Space Telescope (JWST), the Atacama Large Millimeter Array (ALMA) and a new generation of 30-meter-class telescopes promise to create breakthroughs in the study of disks and planet formation. SOFIA, a 2.5 meter telescope set to begin science observations in Fall 2009, has a suite of infrared imagers and spectrometers covering the near- to far-infrared, and will reside above the bulk of the Earth's atmosphere. The instrument most relevant to the work presented here is EXES—the first high-resolution (up to R $\sim$ 100,000) infrared spectrometer to be situated above the Earth's atmosphere. JWST, a 6.5 meter space telescope scheduled for launch in 2013, includes a mid-infrared imager/spectrograph (MIRI). Covering 5–27μm, it will overlap with the wavelengths observed by Spitzer, but provide higher resolution (R $\sim$ 3000) and greater sensitivity.

ALMA, set to be fully constructed by 2012, is perhaps the most ambitious astronomical project in history—an array of 80 antennas located in the Atacama desert, created by an international collaboration between scientific partners in Asia, Europe, and North America. Its 80 antennas provide a large collecting area, and excellent uv-coverage, and the stable, dry Atacama air allows for baselines as large as 10 km. Thus, this array should produce phenomenal images of circumstellar disks, and, potentially, of actively forming young planets, with a continuum resolution down to $\sim$ 1 AU for nearby star-forming regions. Finally, 30-meter-class telescopes, such as the Thirty Meter Telescope (TMT) and the European Extremely Large Telescope (E-ELT), are planned for $\sim$ 2018. These facilities will offer unprecedented spatial resolution and collecting areas for infrared observations.

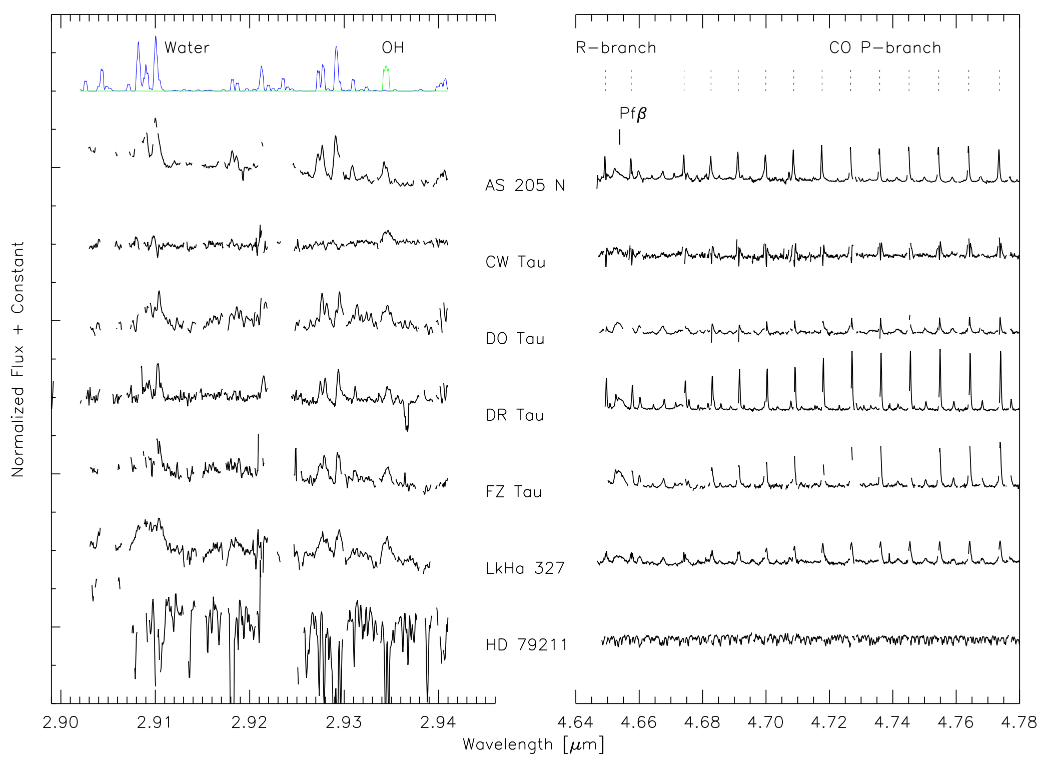

Figure 7.1: Spectra for a sample of circumstellar disks, and a photospheric standard star, in the L- and M-bands. Spectra have been normalized by the continuum, and multiplied by factors of 7 and 0.5 for the L- and M-bands, respectively. Above the spectra are plotted a water + OH emission model, and labels for the CO P- and R-branches.

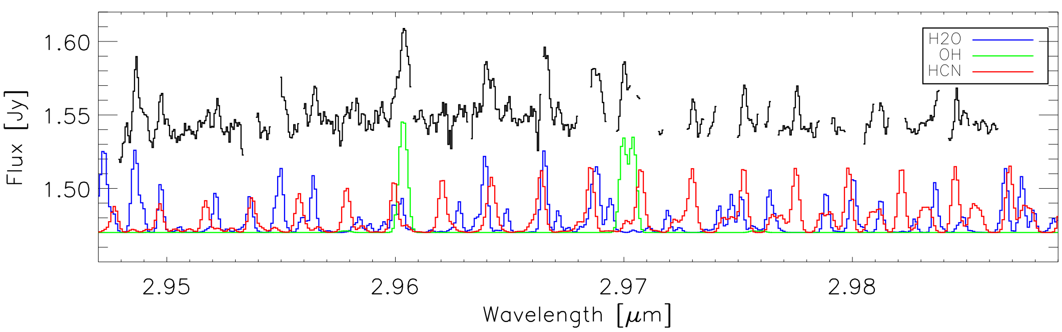

Figure 7.2: NIRSPEC spectrum of a circumstellar disk showing evidence for H_2O, OH, and HCN. Black lines show data, with emission models of H_2O, OH, and HCN shown below.

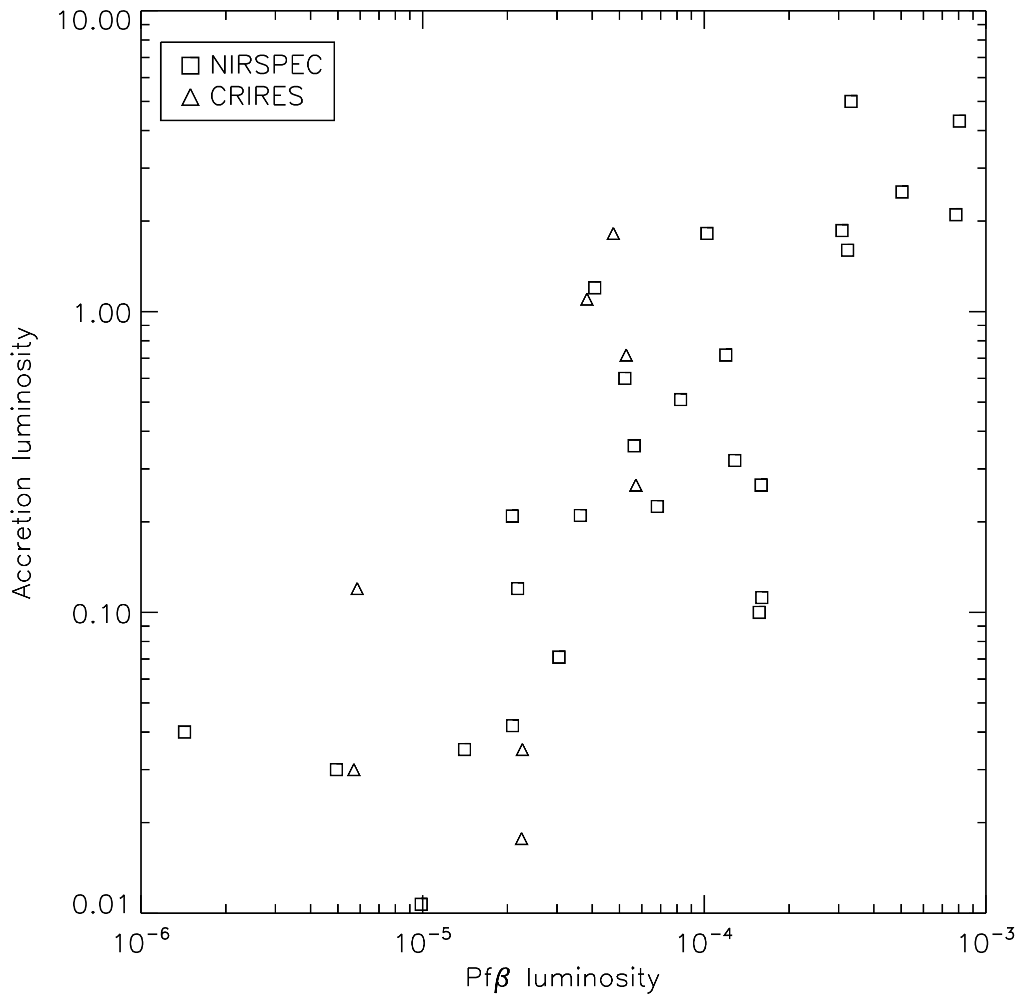

Figure 7.3: Accretion luminosity plotted against Pfβ line luminosity. Pfβ spectra were obtained with Keck-NIRSPEC and VLT-CRIRES.