DEBRIS DISKS AND THE FORMATION OF PLANETS:
A SYMPOSIUM IN MEMORY OF FRED GILLETT
ASP Conference Series, Vol. 324, 2004
L. Caroff, L.J. Moon, D. Backman and E. Praton, eds.

High Resolution Millimeter-Wave to Infrared Spectroscopy of Circumstellar Disks

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Abstract. The role of high spectral and spatial resolution spectroscopy in understanding the evolution of the gaseous component of circumstellar accretion disks is described. Millimeter-wave emission lines from trace constituents such as CO, CN, HCO^+, and HCN can be used to probe the kinematic and physicochemical properties in the near-surface regions of disks beyond 100 AU, but, thanks to extensive molecular depletion in the midplane, they are not a reliable proxy for the disk mass. Mid-infrared observations of the pure rotational transitions of molecular hydrogen would alleviate many of these concerns, and results from the ISO SWS instrument on several "transitional" disks are presented. The measurements of these weak lines used beams substantially larger than the disk angular diameter, and so must be verified or refuted by high angular resolution spectroscopy from the ground. Finally, the high resolution M-band (5 μm) spectroscopy of CO in disks is outlined. Emission lines that are likely optically pumped by hot dust in the inner disk ($R \lesssim 1$ AU) are seen toward inclined systems, while the *absorption* spectra of edge-on disks clearly reveal the molecular depletion inferred at millimeter-wavelengths.

1. Introduction

As the means by which matter and angular momentum are exchanged between molecular clouds and young stars and as the birth sites of planets, circumstellar disks provide the pivotal observational link between star formation and (exo)-planetary science. Though disks must be established very early in the star formation process, these proceedings are concerned primarily with those systems in which the vast majority of accretion has been completed. As the accretion process wanes, reprocessing of the central stellar radiation becomes the dominant source of energy release, and in these so-called passive circumstellar disks an examination of the reradiated longer wavelength photons can be used to learn a great deal about the physical properties of the disk.

The basic geometry is outlined in Figure 1. Material near the star and especially at the disk surface radiates strongly in the infrared, while the more distant and interior portions of the disk can best be probed at longer millimeter-wavelengths where the bulk of the dust is optically thin. Near- and mid-infrared imaging can efficiently search for the presence or absence of such excess emission, and has been used to infer the presence of disks around hundreds of young stars. Infrared surveys also yield time scale estimates of order a few million years for the disappearance of small dust grains in the inner regions of circumstellar disks (Skrutskie et al. 1990, Robberto et al. 1999) – a span similar to that measured

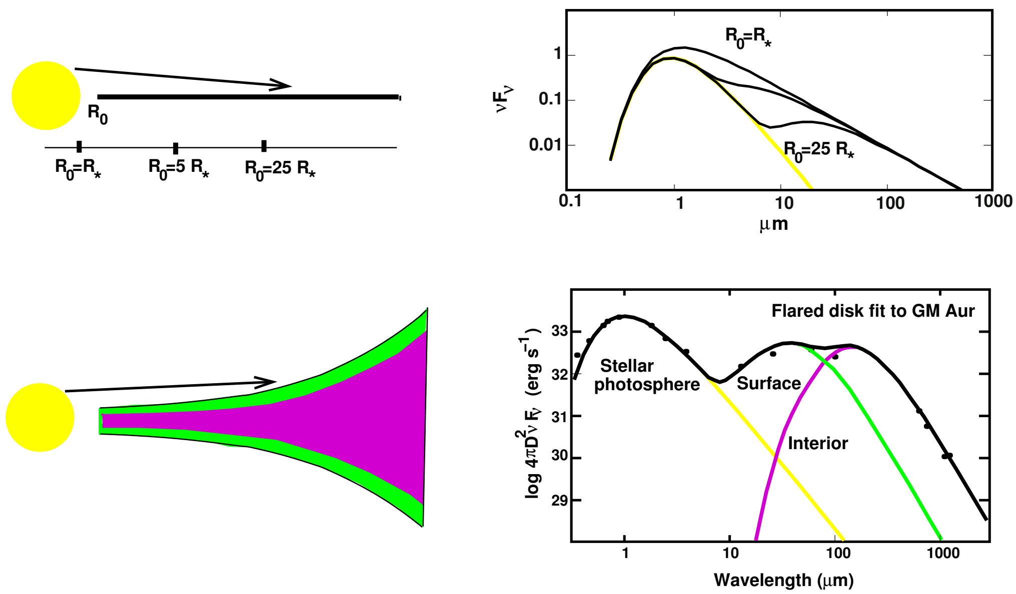

Figure 1. Schematic disk structure cross sections for passive flat vs. flaring (hydrostatic equilibrium) disks, and the spectral energy distributions (SEDs) that result. Conceptual models of the latter predict that the infrared portion of the SED is dominated by optically thin radiation from the disk surface layers exposed to the stellar radiation field, while the millimeter-wave emission is dominated by the cooler disk interior (Chiang & Goldreich 1997). From van Zadelhoff (2002).

for the creation of differentiated planetesimals in the early solar nebula from the absolute ages of chondritic meteorites (Amelin et al. 2002). The time scale and associated mechanism(s) by which individual optically thick disks dissipate to become the optically thin, or debris, disks that are the topic of this meeting are not yet quantitatively known, but exceedingly important to nebular chemistry and to the formation of planetary systems. The more tenuous debris disks themselves are estimated to survive for several tens, perhaps hundreds, of millions of years in at least 15% of young main sequence stars, as judged from mid- and far-infrared continuum excesses (Habing et al. 1999).

The spatio-temporal properties of disks as inferred from SEDs, namely masses of 0.001-0.1 $M_\odot$ and sizes of 10's to 100's of AU, are similar to those inferred for the solar nebula; and have been verified for a *handful* of objects by detailed imaging (see Mundy et al. 2000, McCaughrean et al. 2000). Direct optical/IR imaging and, especially, interferometry (Monnier & Millan-Gabet 2002) has begun to probe closer to the central stars, but cannot directly constrain critical disk properties such as the surface mass density or accretion flows, while millimeter-wave studies can only probe the outer regions of disks, as described below. Similarly, disk dissipation studies based on infrared excesses tell us little about the gas content of such objects. The discovery of extrasolar 'hot Jupiters' some 0.05 AU from their parent stars (Marcy, Cochran & Mayor 2000; Fischer, these proceedings) has highlighted the important role of star-disk-protoplanet interactions and time scales, and demands new tools that can investigate the critical planet-forming zone of disks, but the advent of the next generation of mid-infrared and millimeter-wave arrays lies several years in the future.

High resolution, gas phase molecular spectroscopy with existing telescopes and arrays offers a means of addressing many of these issues, and forms the focus of this overview. The present capabilities will be examined as a function of wavelength; §2 deals with millimeter-wave observations, §3 presents mid-infrared spectroscopy such as that pioneered by ISO and soon to be available with SIRTF (Spitzer), and §4 examines the possibilities of high resolution 2-5 μm spectroscopy with large format echelle spectrographs on 8-10 m class ground-based telescopes.

2. Millimeter-wave Spectroscopy of Circumstellar Disks

At long wavelengths, where the dust emission is largely optically thin, rotational line emission from disks forms a powerful probe of their physics and chemistry. Indeed, disk material at a fiducial radius of 100 AU, with a temperature of 20-30 K, will radiate preferentially at (sub)millimeter wavelengths. The morphology and kinematics of the circumstellar gas, along with an independent estimate of disk mass, can therefore be derived from millimeter-wave spectral lines. The observational challenges of studying isolated accretion and transitional disks in this region are highlighted in Figure 2, in which it can be seen that even the strongest lines from the most optically thick species are strongly beam diluted by the resolution achievable with single telescopes such as the IRAM 30m, the CSO, and the JCMT. These telescopes operate over a wide frequency range, however, and so the combination of millimeter-wave imaging with submillimeter-wave spectroscopy forms a powerful means of constraining the temperature, density, and molecular abundances in disks (van Zadelhoff et al. 2001).

The double peaked nature of the emission lines from LkCa 15 is consistent with Keplerian rotation in an inclined disk, and the separation of the peaks can be used to estimate a disk radius of $R \sim$300 AU for an inclination of 60°. TW Hydra is thought to be viewed face on, hence the narrow lines. These estimates can be directly checked with interferometer maps of the millimeter-wave continuum emission from circumstellar particles to constrain the dust morphology and mass, and high resolution molecular line maps to probe the disk kinematics, temperature and density structure, and chemistry. The age, large size, and mass of the LkCa 15 disk make it an important system for further study since it may represent an important transitional phase in which viscous disk spreading and dispersal competes with planetary formation processes (TW Hya, DM Tau and GM Aur likely present additional examples). Further, only the disk gas beyond $R \sim$100 AU can be studied with present (sub)millimeter-wave arrays and single dish telescopes due to sensitivity limitations and beam dilution (Dutrey, Guilloteau, & Gúelin 2000), and so such large systems provide the only opportunity at present to shed light on the chemical and physical gradients in disks.

As Figure 2 shows, it is now possible to image the emission from several isotopologues of CO and ions such as HCO^+/N_2H^+ in optically thick disks. The combined millimeter-wave images and higher J spectra have been examined with detailed 2D Monte Carlo radiative transfer statistical equilibrium models which reveal that the molecular emission arises from near-surface disk layers

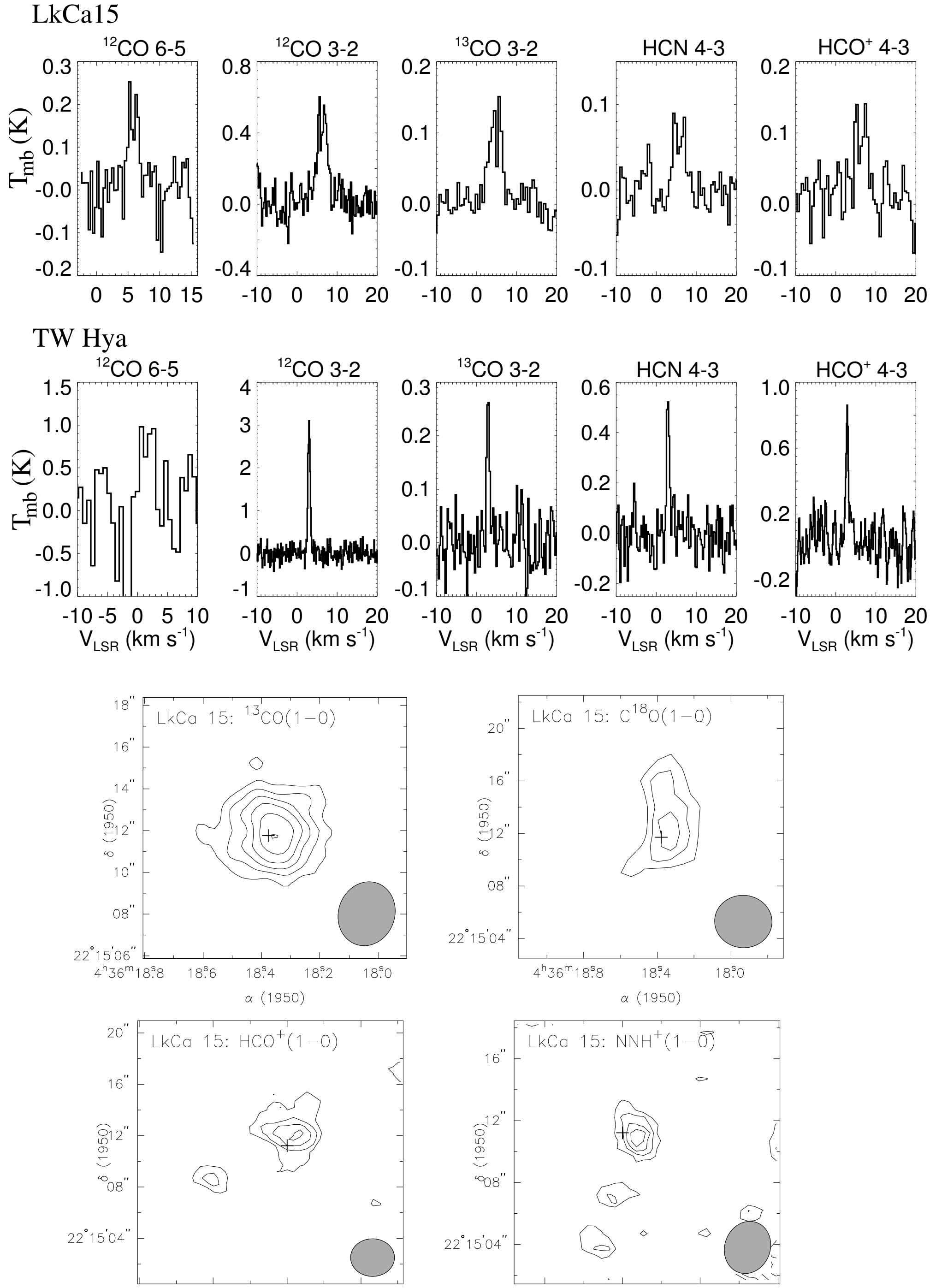

Figure 2. (Top) Submillimeter-wave emission lines from the LkCa 15 and TW Hydra circumstellar disks, observed with the JCMT and CSO (van Zadelhoff et al. 2001). (Bottom) OVRO Millimeter Array interferometric images of the ^{13}CO, C^{18}O, HCO^{+}, and N_2H^+ J = 1–0 emission from the disk encircling LkCa 15 (Qi et al. 2003). Hatched ellipses at lower right present the synthesized beams.

with $n_{H_2} \approx 10^6$-10^8 cm^{-3}, $T \gtrsim 30$ K that are strongly influenced by radiation reprocessing of (inter)stellar optical and UV photons (van Zadelhoff et al. 2001, Aikawa et al. 2002). The strength of the isotopically substituted CO lines indicate $\tau(C^{18}O) < 1$. Still, the estimated disk mass using "standard" dark cloud $C^{18}O$ abundances is nearly two orders of magnitude less than that deduced from millimeter-wave emission from dust (Qi et al. 2003). This discrepancy is most often attributed to the depletion of molecules onto the icy mantles of dust grains near the disk midplane, a topic to which we shall return in §4, and shows that while millimeter-wave rotational line emission is a good tracer of the outer disk velocity field it is not a robust tracer of the mass.

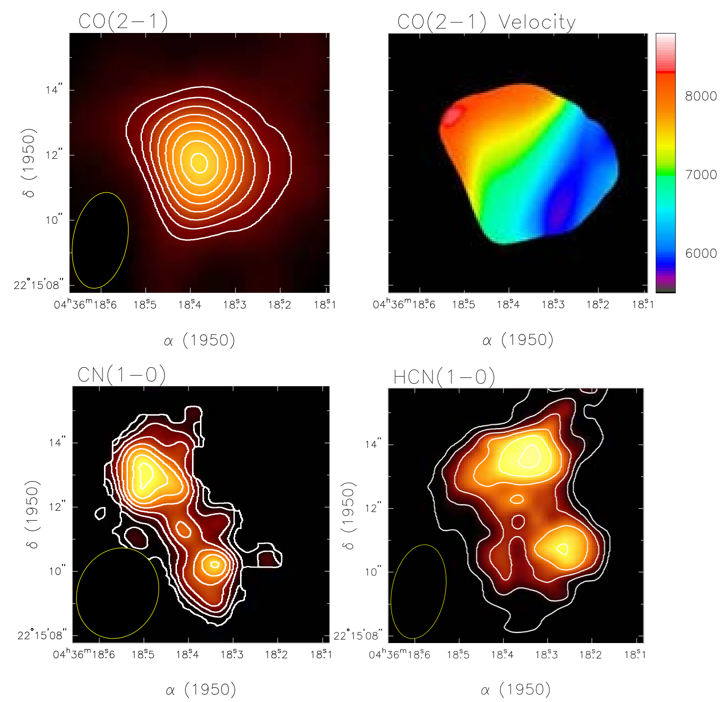

Figure 3. OVRO Millimeter Array maps of the CO J = 2–1 and CN/HCN J= 1–0 emission from the LkCa 15 circumstellar disk, the ellipses in each panel depict the synthesized beams obtained with robust weighting. The disk velocity field as traced by CO is plotted at upper right, receding velocities lie to the NE and approaching velocities to the SW (data kindly provided by D. Koerner and A. Sargent, see also Simon, Dutrey, & Guilloteau 2001). Despite the similar single dish lineshapes, the radial distributions of these species are clearly quite distinct.

That further surprises await the new observational capabilities at millimeter-wavelengths is reinforced by the OVRO LkCa 15 observations of CO, CN, and HCN presented in Figure 3. While the CO is peaked at the stellar position, as expected, the CN and HCN emission show maxima offset from the star along the major axis of the disk as measured by the CO velocity distribution (emission along the minor axis is heavily beam diluted). This offset demands that the

HCN and CN be formed *in situ*. 2D Monte Carlo models with a radial CN/HCN annulus reproduce the observations quite well provided $R_{\rm CN,HCN} \gtrsim 250$ AU.

The location of the maxima may be related to the sublimation behavior of various molecules, for the release of CO from grain mantles can drive a carbon-rich gas phase and grain mantle chemistry in the near-surface regions of certain disk models (Aikawa & Herbst 1999). The sharpness of the inner boundary of the observed morphology should reflect both the temperature profile and radial transport in the disk. Further, CN and HCN appear quite similar at the present resolution. CN is made photochemically from HCN, and for the distributions of these species to be similar there must be sufficient vertical mixing occurring within the disk. At higher resolution and at the appropriate disk orientations, it should be possible to measure the vertical mixing rate directly from the images and the estimated chemical lifetimes of CN and HCN. In more face-on disks, the ratio of CN/HCN itself is a sensitive function of the radiation field and vertical mixing time scale. Such depletion and photochemical processes should also operate in older transitional and debris disks, and may well mean that CO is again not a good tracer of the disk mass (Zuckerman, Forveille, & Kastner 1995; Kamp, van Zadelhoff and co-workers, these proceedings).

3. ISO SWS H_2 Spectroscopy of Circumstellar Disks

High sensitivity mid-infrared observations of the pure rotational lines of H_2 such as those made possible by ISO have a number of advantages over more commonly used indirect tracers for assessing the molecular gas content of optically thick and debris disks. For a gas of solar composition, molecular hydrogen is the overwhelmingly most abundant gaseous species and does not deplete significantly onto grain mantles, obviating the uncertainties associated with the gas phase conversion factors needed for other molecules. Further, the self-shielding nature of molecular hydrogen with respect to photodissociation renders it sufficiently stable at low visual extinctions that it should persist in disks with gas masses as small as several $M_\oplus$.

Because H_2 is a homonuclear diatomic molecule, the intrinsic Δv=0, ΔJ=2 transition strengths are quite small and the optical depths of the mid-infrared lines are therefore low. While this can greatly simplify the radiative transfer analysis, it becomes critical to understand the dust and gas thermal structure in the near-surface regions of disks. Recent models of the disk temperature field predict that the gas temperature will exceed that of the dust, and so the lines are expected to appear in emission and to be optically thin. Except for edge-on disks (§4), nearly any orientation can be studied. Substantially higher temperatures are required for excitation of the H_2 vibration-rotation manifold near 2 μm, while special geometries are needed to conduct either near-infrared or vacuum ultraviolet (electronic) absorption line measurements. Thus, observations of the H_2 mid-infrared lines are the most direct means to directly probe the bulk of the warm molecular gas in the inner ~100 AU of disks.

We have therefore utilized the ISO SWS instrument, which provided the first opportunity to conduct measurements of the H_2 J=2→0 S(0) 28 μm and J=3→1 S(1) 17 μm pure rotational transitions above the Earth's atmosphere. While these are the lowest energy transitions of the H_2 molecule and so the most

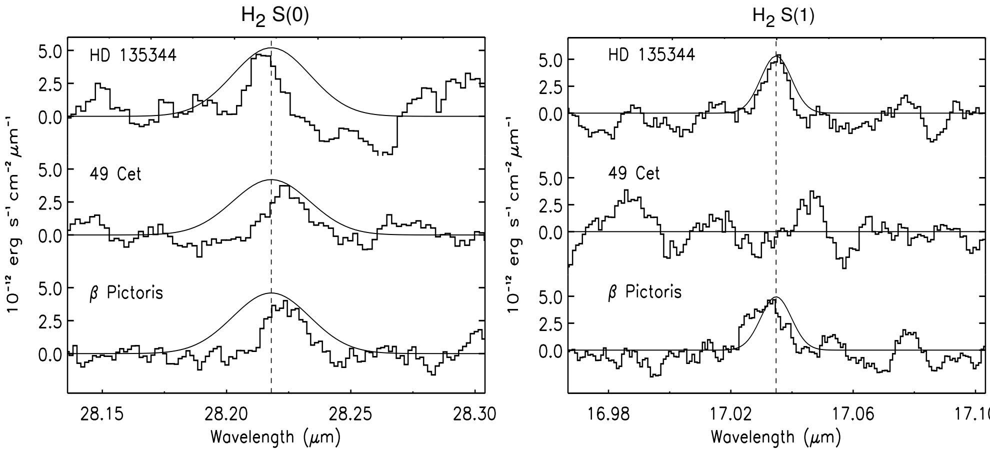

Figure 4. ISO SWS mode 2 spectra of the H_2 S(0) and S(1) pure rotational lines toward the three transitional disk candidates HD 135344, 49 Ceti, and β Pictoris (Thi et al. 2001b). Similar spectra are observed toward the optically thick disks encirling classical T Tauri and Herbig Ae stars (Thi et al. 2001a).

appropriate with which to study disks, they are difficult (17 μm) to impossible (28 μm) to observe with ground based spectrographs due to telluric absorption. A number of classical T Tauri stars, Herbig Ae stars, and young (pre-)main sequence stars with confirmed circumstellar disks have been observed (Thi et al. 2001a), where the emphasis is on three sources previously classified as debris disks; that is, low mass disks with a dust population that is presumed to be dominated by second generation grains, but for which there is also evidence of gas within the disk. These may then be better thought of as "transitional" disks.

It is important to stress that the aperture of the ISO SWS observations is $20'' \times 27''$ at the S(0) line and $14'' \times 27''$ at the S(1) transition, corresponding to 400 AU×540 AU and 280 AU×540 AU, respectively, at the distance of β Pictoris. The dashed vertical line in Figure 4 depicts the rest wavelengths of the H_2 transitions, while the solid curve illustrates the range of potential wavelength shifts induced by grating repositioning errors or pointing offsets of the spacecraft. All line shapes are consistent with the instrumental spectral resolution of $\lambda/\Delta\lambda\sim2000/2400$ at 28.218/17.035 μm. Typical integration times were 600-1000 s per line, in which the 12 SWS detectors were scanned several times over the 28.05-28.40 and 16.96-17.11 μm intervals around the H_2 lines. Individual scans are examined for cosmic ray glitches, dark current drifts, and readout non-linearities before being summed to produce a final spectrum (Valentin & Thi 2000). Off source integrations toward 49 Ceti and HD135344 reveal no H_2 S(1) emission to a limiting flux of 8×10^{-15} ergs s^{-1} cm^{-2} root mean square.

As Figure 4 shows, the measured H_2 intensities lie close to the ISO sensitivity, indeed, their detection required the development of special software to supplement the standard SWS Interactive Analysis Package (see Valentin and Thi 2000 for a thorough discussion of this software). The S(1)/S(0) ratios yield excitation temperature estimates of $T \approx$100 K assuming thermal equilibrium, and so the total gas mass estimates may have large error bars since the transition upper states lie at 510 and 1015 K above ground, respectively. Values range from a minimum of 0.17 M_J (Jupiter mass) for β Pictoris to just over 6.6 M_J for HD135344. Only an upper limit to the S(1) flux is available for 49 Ceti, which constrains the temperature to be less than ∼100 K, corresponding to gas masses of at least 0.35 M_J. The uncertainties in the inferred masses are estimated to be a factor of three, and stem mainly from the weakness of the lines and the unknown molecular hydrogen ortho/para ratio in such disks.

The gas masses for these disks actually enhances the need for the *in situ* generation of 1-100 μm dust grains because such particles can be efficiently ejected from the system in the presence of radial gas gradients (Klahr & Lin 2001). Clearly, massive Jovian planet formation is no longer possible in such systems, and so as noted above they may be better interpreted as tenuous remnants of substantially more massive accretion disks. If so, HD135344 and 49 Ceti could be extremely interesting transition objects in which Jovian planet formation may no longer be possible but for which the residual gas provides the opportunity to image gravitational perturbations in the disks due to existing planets formed at earlier stages. Such observations were, of course, impossible with ISO, but echelle mid-infrared spectrographs on 8-10 m telescopes provide the necessary spectral and spatial resolution. The software used to extract the lines presented in Figure 4 has been carefully checked with observations of low luminosity PDRs, and the agreement with theory is found to be excellent (Thi 2001). Still, the large beam nature of the measurements must be stressed along with the compelling need to verify or refute the ISO observations. The ISO spectrometers were exquisitely sensitive to low-level H_2 emission from extended objects that will be nearly impossible to measure from the ground due to the bright sky at 17/28 μm, and so the detected lines need not arise from the disks themselves if they are surrounded by tenuous envelopes. For initial steps in this regard, see Richter et al. (2002) and Richter et al., these proceedings.

4. M-Band Spectroscopy of Circumstellar Disks

The pure rotational spectroscopy outlined above principally traces the near surface disk regions, and with current capabilities only the disk beyond 100 AU is detectable in pure rotational molecular transitions at millimeter-wavelengths. CARMA (the Combined Array for Research in Millimeter Astronomy, the joining of the OVRO and BIMA Millimeter Arrays) will improve this limit by factors of two to three, and ALMA will be able to examine disks in the nearest star-forming clouds with resolution as fine as 1 AU in continuum and several AU in molecular lines. Similarly, K-band interferometry has now resolved the brightest circumstellar disks (Monnier & Millan-Gabet 2002), and the VLTI and KI systems are targeting the regions of disks with $R <$5–10 AU via 10 μm interferometry, for this is where the bulk of planet formation occurs.

Indeed, recent theoretical studies (Armitage et al. 2002) suggest that a relatively constant rate of planet formation near 5 AU followed by migration is consistent with the presently known distribution of orbits in extraterrestrial planetary systems (Marcy, Cochran & Mayor 2000; Fischer, these proceedings). The models further suggest that giant planets can migrate inward from their formation zones after they have opened gaps in the disk (Lin et al. 2000, Ward &

Hahn 2000), and so the observational characterization of gaps and of the fraction of disks containing Jovian protoplanets therefore forms a pivotal counterpoint to the highly successful radial velocity extrasolar planet searches.

Only high resolution spectroscopy with 8-10 m class telescopes permits robust access to the disk physical conditions and velocity fields on these spatial scales at present (see Najita et al. 2000). Indeed, the potential kinematic signatures are very large. Jupiter induces a stellar velocity wobble of only 13 m s^{-1}, for example, while alterations to the disk kinematics can be a large fraction of the orbital velocity of $\sim$20 km s^{-1} at 5 AU. Gas in and near the $\lesssim$AU gaps opened up by protoplanets can be heated by the star and, if the planet is massive enough, by shocks (Bryden et al. 1999, Kley 1999). The total amount of hot, dense gas is small, but it radiates strongly in the IR since it is adjacent to the low density gap. Abundant species such as H_2, H_2O, and CH_4 are excellent candidate tracers, but they are very difficult to observe from the ground.

CO is widespread through the disk (and any surrounding envelope) thanks to its stability, and while the millimeter-wave pure rotational lines of CO trace the outer disk, the $\Delta v = 2$ overtone emission near 2.3 μm can only arise from the several thousand degree gas immediately adjacent to the young star (Scoville et al. 1983, Najita et al. 1996) – but can only be observed in a handful of stars. CO absorption at 2.3 and 4.6 μm traces cold gas and ice with moderate optical depths, leaving *emission* from the the CO vibrational fundamental near 4.6 μm as a potential gap/protoplanet tracer. In a pioneering study of 8 spectroscopic binary systems, Najita et al. (2000) show that 5 have measurable CO $v = 1 \rightarrow 0$ emission that is proposed to arise from a gap in the *circumbinary* disk, an interpretation consistent with the CO line shapes. In DQ Tau (Carr, Mathieu, & Najita 2001), for example, the 4.6 μm integrated intensities are $\sim 10^{-16}$ W m^{-2} with a FWHM of $\sim$50-55 km s^{-1}. The total amount of radiating material is only 10^{-5} earth masses, with a T$\gtrsim$1100 K. For T$\sim$300 K, the same line strength would correspond to a mass of only $\sim$0.01 $M_\oplus$ at the distance of Taurus!

We have sought to expand upon this work by carrying out an extensive CO M-band spectroscopic survey of T Tauri and Herbig Ae stars in the nearest molecular clouds, which complements the ongoing work of Rettig and co-workers (these proceedings, Brittain & Rettig 2002). As is shown below, the disk inclination is critical in establishing the nature of the CO spectrum, and here we note that infrared spectroscopy has the pivotal advantage over millimeter-wave studies that it can examine *both* the gas phase and solid state.

Figure 5 shows the power of high resolution, high dynamic range IR spectroscopy of isolated disks, where CO *emission* is commonly observed (Brittain & Rettig 2002, Blake & Boogert 2003, Rettig and co-workers, these proceedings). The velocity widths yield characteristic radii of several $\times$ 0.1-1 AU that are well correlated with, but larger than, the 2 μm sizes derived from interferometry (Monnier & Millan-Gabet 2002). The measured linewidths also follow the disk inclination, with face-on systems having the narrowest velocity widths, and so it is unlikely that these lines originate in an outflow or disk wind. A range of excitation temperatures, $\sim$20-500 K, are found even within single disks, but the bulk of the gas lies at temperatures of 300-500 K. The total line emission is typically less than 10% of the 5 μm continuum flux. Neither the continuum nor line emission is resolved at the typical $0''.4$-$0''.5$ seeing conditions at M-band.

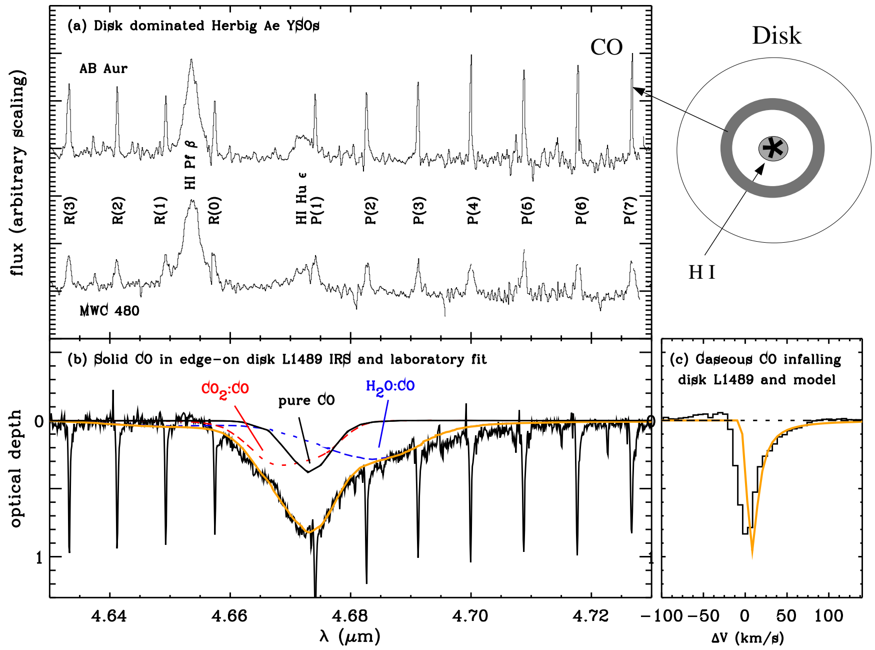

Figure 5. Keck/NIRSPEC R=25,000 spectra of the CO v= 1–0 band toward Herbig Ae star disks (AB Aur, MWC 480) along with the nearly edge on and collapsing disk surrounding L1489 IRS. The two H I lines, Pfund β and Humphries ϵ, arise from the accretion flow onto the star in AB Aur and MWC 480, while the red-shifted wings in the L1489 gas phase lines trace infall to within ∼0.1 AU of the central star (Boogert, Hogerheijde, & Blake 2002). Interestingly, no H I emission is seen in L1489 despite the measured radial inflow from the surrounding disk.

These properties are consistent with the irradiation of a shadowed region of the disk *surface* by a "puffed up" ring of hot dust responsible for the near-IR continuum in these sources (Dullemond, Dominik, & Natta 2001) whose extent has been measured by K-band interferometry. The total amount of radiating material is difficult to estimate since the source is unresolved, but using the slit width (∼0.″45) results in very small masses, typically $\ll M_\oplus$, since IR radiative pumping is very efficient at low optical depths. This same process should occur for any molecule with active vibrations, and the examination of several species would provide exceptional probes of the disk physical conditions at radii near 1 AU. In this regard, the recent detection of H_3^+ emission in HD 141569 by Brittain & Rettig (2002, see also the contribution by Rettig in these proceeding), heralds the advent of an exciting era of discovery in which specific tracers of disk/planetary system evolution (the assembly of proto-Jovian sub-nebulae, gap formation, planet migration, etc.) can be investigated in large samples of objects with spectroscopy. Interferometry could then be used to follow up these surveys with high spatial resolution images.

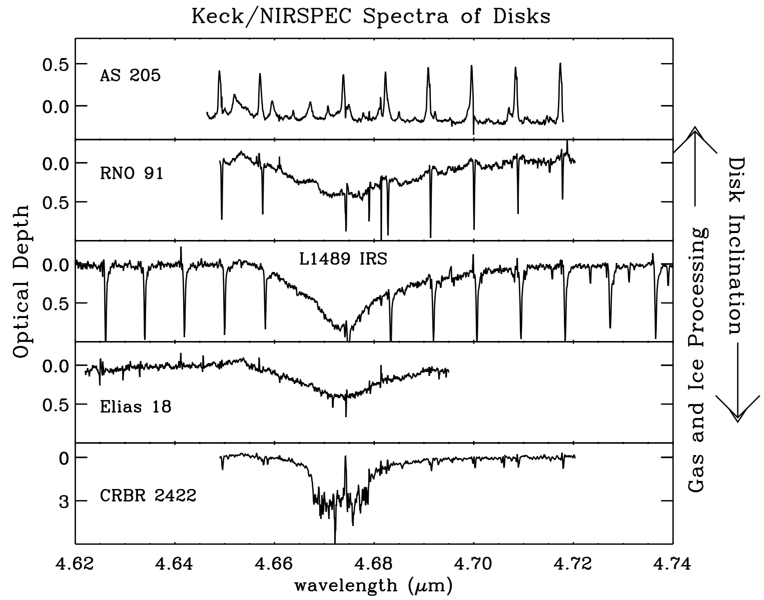

Figure 6. NIRSPEC R=25,000 CO spectra of the edge-on disks RNO91, L1489, Elias 18, and CRBR2422 on an optical depth scale; showing both gas phase and solid state features (the ice/gas ratio increases downward as successively denser regions near the disk mid-plane are probed). RNO91 shows broad emission (inner disk) and narrow absorption (outer disk), while the CO ice band in CRBR2422 is highly saturated (note the large change in the optical depth scale). Depletion estimates for this source are therefore lower limits. Finally, the rich emission line spectrum from the isolated T Tauri star AS205 is plotted at the top for comparison with the spectra observed from disk surfaces.

As the inclination angle of the disk with respect to the observer increases, eventually it will begin to occult the central star and the hot dust near it. Such edge-on orientations, while statistically rare, provide a unique opportunity for several reasons: (1) As Figures 5 and 6 show, the disk can now be probed via *absorption* spectroscopy, which means that both the gas phase and solid state components of the disks can be traced. The depletion of molecules onto grains has long been suspected and is vital to planetesimal growth, but can only be directly tested via observations of edge-on disks. (2) Due to the large filling factor of the inner disk and the high column density at large radii, infrared spectroscopy of edge-on disks is sensitive to all disk regions beyond the hot dust zone. (3) Thanks to the observational geometry, the disk *radial* velocity field can be examined over a wide range of distances, as we have shown for L1489 (Boogert, Hogerheijde, & Blake 2002). Radial mass transport is obviously a critical function of accretion disks, but only absorption spectroscopy of edge-on disks provides access to $R > 0.1$ AU at present. (4) With sufficient sensitivity, regions of the disk much closer to the mid-plane can be probed than are sampled by near-/mid-infrared emission spectroscopy.

Observations of edge-on disks at slightly different inclination angles make it possible to sample different heights within the disk; with slightly tilted disks offering access to near-surface layers and disks nearly perfectly edge-on sampling closer to the mid-plane. Molecular depletion should vary systematically with inclination angle, and as molecules deposit themselves onto grains there should be substantial changes in the gas fractional ionization. This has implications for mass transport in disks via magnetic instabilities (Balbus & Hawley 1991), and so it will be essential to probe both neutral and ionic species in future observations. Of the various edge-on disks discovered over the past decade, only a handful of these can be studied, even with the excellent sensitivity of Keck/Gemini/VLT, thanks to the large extinction provided by the disk itself.

Fortunately, of the edge-on disks amenable to study, a variety of disk heights (inclinations) appear to be probed. The superb resolution available with NIRSPEC (and ISAACS on the VLT) not only permits the detection of gas phase lines, but also enables the shapes of ice bands to be examined in detail. The shape contains important information about the nature of the ices containing CO, and both Keck and VLT studies have shown that the CO ice band profile is remarkably similar in various lines of sight, and can be interpreted in terms of the fundamental molecular interactions within the ice (Boogert, Blake, & Tielens 2002; Pontoppidan et al. in prep.). With more extensive spectral line surveys of edge-on disks, such as will be possible via the combination of ground-based KLM-band ground-based surveys with results from the SIRTF IRS instrument, a detailed comparison of disk and cometary ices will become possible for the first time. Disks such as CRBR2242 (Brander et al. 2000) will be especially interesting in this regard, since the very deep CO ice band (Thi et al. 2002, Figure 6) promises the detection of ice features from a wide suite of minor ice constituents observable in cometary comae.

Acknowledgments. The results outlined here form the thesis and post-doctoral research of several young scientists at Caltech and in Prof. Ewine van Dishoeck's astrochemistry group at Leiden University with whom it has been my great privilege to learn these past several years. Their dedication and camaraderie are gratefully acknowledged. The OVRO Millimeter Array and Caltech Submillimeter Observatory are operated with support from the National Science Foundation, grants AST 99-81546 and AST 99-80846. The NIRSPEC data were obtained at the Keck II telescope of the W.M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W.M. Keck Foundation.

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Meyer: Do you get the H_2 masses from hot gas?

Blake: Yes.

Hollenbach: If you put 10^{-2} $M_{\odot}$ in a 100 AU disk, wouldn't the ^{13}CO be optically thick?

Blake: Yes. Since we don't find it to be optically thick, then it must not be present in the gas phase in that amount. So most of the CO is not in the gas phase.

Becklin: If you do put that much mass into a model, what would you expect to see in H_2?

Blake: If we allow for dust settling from the upper layers, then we do expect strong H_2 emission. But not if the gas and dust are well mixed and at the same temperature.

Davidson: You showed mass estimates in one of your figures. Did those estimates come from assuming gas/dust ratio of 100?

Blake:Yes.

Davidson: OK, this is a standard assumption, but it does not take into account the processes going on in the disk. Right?

Blake: Right.

Becklin: Will SIRTF be able to measure the H_2?

Blake: It will be tough. The line/continuum ratio is still quite faint.