Gaseous Inner Disks

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As the likely birthplaces of planets and an essential conduit for the buildup of stellar masses, inner disks are of fundamental interest in star and planet formation. Studies of the gaseous component of inner disks are of interest because of their ability to probe the dynamics, physical and chemical structure, and gas content of this region. We review the observational and theoretical developments in this field, highlighting the potential of such studies to, e.g., measure inner disk truncation radii, probe the nature of the disk accretion process, and chart the evolution in the gas content of disks. Measurements of this kind have the potential to provide unique insights on the physical processes governing star and planet formation.

1. INTRODUCTION

Circumstellar disks play a fundamental role in the formation of stars and planets. A significant fraction of the mass of a star is thought to be built up by accretion through the disk. The gas and dust in the inner disk (r <10 AU) also constitute the likely material from which planets form. As a result, observations of the gaseous component of inner disks have the potential to provide critical clues to the physical processes governing star and planet formation.

From the planet formation perspective, probing the structure, gas content, and dynamics of inner disks is of interest, since they all play important roles in establishing the architectures of planetary systems (i.e., planetary masses, orbital radii, and eccentricities). For example, the lifetime of gas in the inner disk (limited by accretion onto the star, photoevaporation, and other processes) places an upper limit on the timescale for giant planet formation (e.g., *Zuckerman et al.*, 1995).

The evolution of gaseous inner disks may also bear on the efficiency of orbital migration and the eccentricity evolution of giant and terrestrial planets. Significant inward orbital migration, induced by the interaction of planets with a gaseous disk, is implied by the small orbital radii of extrasolar giant planets compared to their likely formation distances (e.g., *Ida and Lin*, 2004). The spread in the orbital radii of the planets (0.05–5 AU) has been further taken to indicate that the timing of the dissipation of the inner disk sets the final orbital radius of the planet (*Trilling et al.*, 2002). Thus, understanding how inner disks dissipate may impact our understanding of the origin of planetary orbital radii. Similarly, residual gas in the terrestrial planet region may play a role in defining the final masses and eccentricities of terrestrial planets. Such issues have a strong connection to the question of the likelihood of solar systems like our own.

An important issue from the perspective of both star and planet formation is the nature of the physical mechanism that is responsible for disk accretion. Among the proposed mechanisms, perhaps the foremost is the magnetorotational instability (*Balbus and Hawley*, 1991) although other possibilities exist. Despite the significant theoretical progress that has been made in identifying plausible accretion mechanisms (e.g., *Stone et al.*, 2000), there is little observational evidence that any of these processes are active in disks. Studies of the gas in inner disks offer opportunities to probe the nature of the accretion process.

For these reasons, it is of interest to probe the dynamical state, physical and chemical structure, and the evolution of the gas content of inner disks. We begin this Chapter with a brief review of the development of this field and an overview of how high resolution spectroscopy can be used to study the properties of inner disks (Section 1). Previous reviews provide additional background on these topics (e.g., *Najita et al.*, 2000). In Sections 2 and 3, we review recent observational and theoretical developments in this field, first describing observational work to date on the gas in inner disks, and then describing theoretical models for the surface and interior regions of disks. In Section 4, we look to the future, highlighting several topics that can be explored using the tools discussed in Sections 2 and 3.

1.1 Historical Perspective

One of the earliest studies of gaseous inner disks was the work by Kenyon and Hartmann on FU Orionis objects. They showed that many of the peculiarities of these systems could be explained in terms of an accretion outburst in a disk surrounding a low-mass young stellar object (YSO; cf. *Hartmann and Kenyon*, 1996). In particular, the varying spectral type of FU Ori objects in optical to near-infrared spectra, evidence for double-peaked absorption line profiles, and the decreasing widths of absorption lines from the optical to the near-infrared argued for an origin in an optically thick gaseous atmosphere in the inner region of a rotating disk. Around the same time, observations of CO vibrational overtone emission, first in the BN object (*Scoville et al.*, 1983) and later in other high and low mass objects (*Thompson*, 1985; *Geballe and Persson*, 1987; *Carr*, 1989), revealed the existence of hot, dense molecular gas plausibly located in a disk. One of the first models for the CO overtone emission (*Carr*, 1989) placed the emitting gas in an optically-thin inner region of an accretion disk. However, only the observations of the BN object had sufficient spectral resolution to constrain the kinematics of the emitting gas.

The circumstances under which a disk would produce emission or absorption lines of this kind were explored in early models of the atmospheres of gaseous accretion disks under the influence of external irradiation (e.g., *Calvet et al.*, 1991). The models interpreted the FU Ori absorption features as a consequence of midplane accretion rates high enough to overwhelm external irradiation in establishing a temperature profile that decreases with disk height. At lower accretion rates, the external irradiation of the disk was expected to induce a temperature inversion in the disk atmosphere, producing emission rather than absorption features from the disk atmosphere. Thus the models potentially provided an explanation for the FU Ori absorption features and CO emission lines that had been detected.

By PPIV (*Najita et al.*, 2000), high-resolution spectroscopy had demonstrated that CO overtone emission shows the dynamical signature of a rotating disk (*Carr et al.*, 1993; *Chandler et al.*, 1993), thus confirming theoretical expectations and opening the door to the detailed study of gaseous inner disks in a larger number of YSOs. The detection of CO fundamental emission (Section 2.3) and emission lines of hot H_2O (Section 2.2) had also added new probes of the inner disk gas.

Seven years later, at PPV, we find both a growing number of diagnostics available to probe gaseous inner disks as well as increasingly detailed information that can be gleaned from these diagnostics. Disk diagnostics familiar from PPIV have been used to infer the intrinsic line broadening of disk gas, possibly indicating evidence for turbulence in disks (Section 2.1). They also demonstrate the differential rotation of disks, provide evidence for non-equilibrium molecular abundances (Section 2.2), probe the inner radii of gaseous disks (Section 2.3), and are being used to probe the gas dissipation timescale in the terrestrial planet region (Section 4.1). Along with these developments, new spectral line diagnostics have been used as probes of the gas in inner disks. These include transitions of molecular hydrogen at UV, near-infrared, and mid-infrared wavelengths (Sections 2.4, 2.5) and the fundamental ro-vibrational transitions of the OH molecule (Section 2.2). Additional potential diagnostics are discussed in Section 2.6.

1.2 High Resolution Spectroscopy of Inner Disks

The growing suite of diagnostics can be used to probe inner disks using standard high resolution spectroscopic techniques. Although inner disks are typically too small to resolve spatially at the distance of the nearest star forming regions, we can utilize the likely differential rotation of the disk along with high spectral resolution to separate disk radii in velocity. At the warm temperatures ($\sim$100 K–5000 K) and high densities of inner disks, molecules are expected to be abundant in the gas phase and sufficiently excited to produce rovibrational features in the infrared. Complementary atomic transitions are likely to be good probes of the hot inner disk and the photodissociated surface layers at larger radii. By measuring multiple transitions of different species, we should therefore be able to probe the temperatures, column densities, and abundances of gaseous disks as a function of radius.

With high spectral resolution we can resolve individual lines, which facilitates the detection of weak spectral features. We can also work around telluric absorption features, using the radial velocity of the source to shift its spectral features out of telluric absorption cores. This approach makes it possible to study a variety of atomic and molecular species, including those present in the Earth's atmosphere.

Gaseous spectral features are expected in a variety of situations. As already mentioned, significant vertical variation in the temperature of the disk atmosphere will produce emission (absorption) features if the temperature increases (decreases) with height (*Calvet et al.*, 1991; *Malbet and Bertout*, 1991). In the general case, when the disk is optically thick, observed spectral features measure only the atmosphere of the disk and are unable to probe directly the entire disk column density, a situation familiar from the study of stellar atmospheres.

Gaseous emission features are also expected from regions of the disk that are optically thin in the continuum. Such regions might arise as a result of dust sublimation (e.g., *Carr*, 1989) or as a consequence of grain growth and planetesimal formation. In these scenarios, the disk would have a low continuum opacity despite a potentially large gas column density. Optically thin regions can also be produced by a significant reduction in the total column density of the disk. This situation might occur as a consequence of giant planet formation, in which the orbiting giant planet carves out a "gap" in the disk. Low column densities would also be characteristic of a dissipating disk. Thus, we should be able to use gaseous emission lines to probe the properties of inner disks in a variety of interesting evolutionary phases.

2. OBSERVATIONS OF GASEOUS INNER DISKS

2.1 CO Overtone Emission

The CO molecule is expected to be abundant in the gas phase over a wide range of temperatures, from the temperature at which it condenses on grains (∼20 K) up to its thermal dissociation temperature (∼4000 K at the densities of inner disks). As a result, CO transitions are expected to probe disks from their cool outer reaches (>100 AU) to their innermost radii. Among these, the overtone transitions of CO (Δv=2, λ=2.3μm) were the emission line diagnostics first recognized to probe the gaseous inner disk.

CO overtone emission is detected in both low and high mass young stellar objects, but only in a small fraction of the objects observed. It appears more commonly among higher luminosity objects. Among the lower luminosity stars, it is detected from embedded protostars or sources with energetic outflows (*Geballe and Persson*, 1987; *Carr*, 1989; *Greene and Lada*, 1996; *Hanson et al.*, 1997; *Luhman et al.*, 1998; *Ishii et al.*, 2001; *Figueredo et al.*, 2002; *Doppmann et al.*, 2005). The conditions required to excite the overtone emission, warm temperatures ($\gtrsim 2000$ K) and high densities ($>10^{10}\,\mathrm{cm}^{-3}$), may be met in disks (*Scoville et al.*, 1983; *Carr*, 1989; *Calvet et al.*, 1991), inner winds (*Carr*, 1989), or funnel flows (*Martin*, 1997).

High resolution spectroscopy can be used to distinguish among these possibilities. The observations typically find strong evidence for the disk interpretation. The emission line profiles of the v=2–0 bandhead in most cases show the characteristic signature of bandhead emission from symmetric, double-peaked line profiles originating in a rotating disk (e.g., *Carr et al.*, 1993; *Chandler et al.*, 1993; *Najita et al.*, 1996; *Blum et al.*, 2004). The symmetry of the observed line profiles argues against the likelihood that the emission arises in a wind or funnel flow, since inflowing or outflowing gas is expected to produce line profiles with red- or blue-shifted absorption components (alternatively line asymmetries) of the kind that are seen in the hydrogen Balmer lines of T Tauri stars (TTS). Thus high resolution spectra provide strong evidence for rotating inner disks.

The velocity profiles of the CO overtone emission are normally very broad ($>100\,\mathrm{km\,s^{-1}}$). In lower mass stars ($\sim 1 M_\odot$), the emission profiles show that the emission extends from very close to the star, ∼0.05 AU, out to ∼0.3 AU (e.g., *Chandler et al.*, 1993; *Najita et al.*, 2000). The small radii are consistent with the high excitation temperatures measured for the emission (∼1500–4000 K). Velocity resolved spectra have also been modeled in a number of high mass stars (*Blum et al.*, 2004; *Bik and Thi*, 2004), where the CO emission is found to arise at radii ~ 3 AU.

The large near-infrared excesses of the sources in which CO overtone emission is detected imply that the warm emitting gas is located in a vertical temperature inversion region in the disk atmosphere. Possible heating sources for the temperature inversion include: external irradiation by the star at optical through UV wavelengths (e.g., *Calvet et al.*, 1991; *D'Alessio et al.*, 1998) or by stellar X-rays (*Glassgold et al.*, 2004; henceforth GNI04); turbulent heating in the disk atmosphere generated by a stellar wind flowing over the disk surface (*Carr et al.*, 1993); or the dissipation of turbulence generated by disk accretion (GNI04). Detailed predictions of how these mechanisms heat the gaseous atmosphere are needed in order to use the observed bandhead emission strengths and profiles to investigate the origin of the temperature inversion.

The overtone emission provides an additional clue that suggests a role for turbulent dissipation in heating disk atmospheres. Since the CO overtone bandhead is made up of closely spaced lines with varying inter-line spacing and optical depth, the emission is sensitive to the intrinsic line broadening of the emitting gas (as long as the gas is not optically thin). It is therefore possible to distinguish intrinsic line broadening from macroscopic motions such as rotation. In this way, one can deduce from spectral synthesis modeling that the lines are suprathermally broadened, with line widths approximately Mach 2 (*Carr et al.*, 2004; *Najita et al.*, 1996). *Hartmann et al.* (2004) find further evidence for turbulent motions in disks based on high resolution spectroscopy of CO overtone absorption in FU Ori objects.

Thus disk atmospheres appear to be turbulent. The turbulence may arise as a consequence of turbulent angular momentum transport in disks, as in the magnetorotational instability (MRI; *Balbus and Hawley*, 1991) or the global baroclinic instability (*Klahr and Bodenheimer*, 2003). Turbulence in the upper disk atmosphere may also be generated by a wind blowing over the disk surface.

2.2 Hot Water and OH Fundamental Emission

Water molecules are also expected to be abundant in disks over a range of disk radii, from the temperature at which water condenses on grains (∼150 K) up to its thermal dissociation temperature (∼2500 K). Like the CO overtone transitions, the rovibrational transitions of water are also expected to probe the high density conditions in disks. While the strong telluric absorption produced by water vapor in the Earth's atmosphere will restrict the study of cool water to space or airborne platforms, it is possible to observe from the ground water that is much hotter than the Earth's atmosphere. Very strong emission from hot water can be detected in the near-infrared even at low spectral resolution (e.g., SVS-13; *Carr et al.*, 2004). More typically, high resolution spectroscopy of individual lines is required to detect much weaker emission lines.

For example, emission from individual lines of water in the K- and L-bands have been detected in a few stars (both low and high mass) that also show CO overtone emission (*Carr et al.*, 2004; *Najita et al.*, 2000; *Thi and Bik*, 2005). Velocity resolved spectra show that the widths of the water lines are consistently narrower than those of the CO emission lines. Spectral synthesis modeling further shows that the excitation temperature of the water emission (typically ∼1500 K), is less than that of the CO emission. These results are consistent with both the water and CO originating in a differentially rotating disk with an outwardly decreasing temperature profile. That is, given the lower dissociation temperature of water (∼2500 K) compared to CO (∼4000 K), CO is expected to extend inward to smaller radii than water, i.e., to higher velocities and temperatures.

The Δv=1 OH fundamental transitions at 3.6μm have also been detected in the spectra of two actively accreting sources, SVS-13 and V1331 Cyg, that also show CO overtone and hot water emission (Carr et al., in preparation). As shown in Fig. 1, these features arise in a region that is crowded with spectral lines of water and perhaps other species. Determining the strengths of the OH lines will, therefore, require making corrections for spectral features that overlap closely in wavelength.

Spectral synthesis modeling of the detected CO, H_2O and OH features reveals relative abundances that depart significantly from chemical equilibrium (cf. *Prinn*, 1993), with the relative abundances of H_2O and OH a factor of 2–10 below that of CO in the region of the disk probed by both diagnostics (*Carr et al.*, 2004; Carr et al., in preparation; see also *Thi and Bik*, 2005). These abundance ratios may arise from strong vertical abundance gradients produced by the external irradiation of the disk (see Section 3.4).

2.3 CO Fundamental Emission

The fundamental (Δv=1) transitions of CO at 4.6μm are an important probe of inner disk gas in part because of their broader applicability compared, e.g., to the CO overtone lines. As a result of their comparatively small A-values, the CO overtone transitions require large column densities of warm gas (typically in a disk temperature inversion region) in order to produce detectable emission. Such large column densities of warm gas may be rare except in sources with the largest accretion rates, i.e., those best able to tap a large

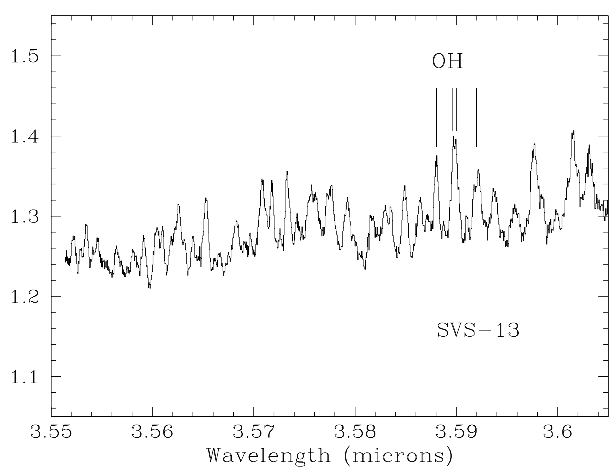

Fig. 1.— OH fundamental ro-vibrational emission from SVS-13 on a relative flux scale.

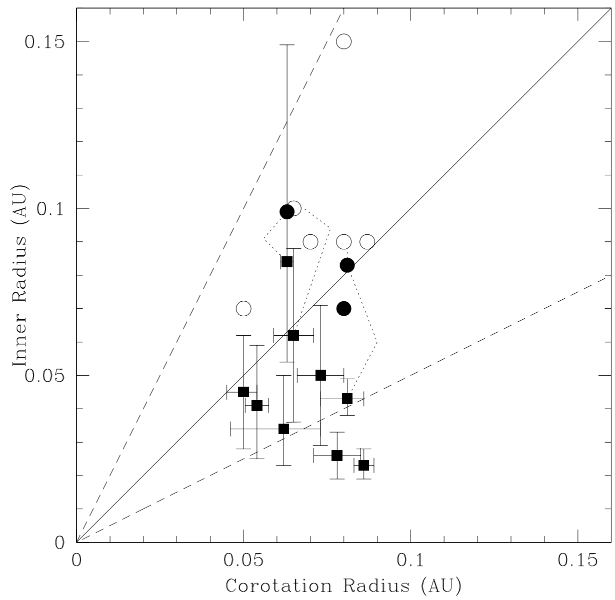

Fig. 2.— Gaseous inner disk radii for TTS from CO fundamental emission (filled squares) compared with corotation radii for the same sources. Also shown are dust inner radii from near-infrared interferometry (filled circles; *Akeson et al.*, 2005a,b) or spectral energy distributions (open circles; *Muzerolle et al.*, 2003). The solid and dashed lines indicate an inner radius equal to, twice, and 1/2 the corotation radius. The points for the three stars with measured inner radii for both the gas and dust are connected by dotted lines. Gas is observed to extend inward of the dust inner radius and typically inward of the corotation radius.

accretion energy budget and heat a large column density of the disk atmosphere. In contrast, the CO fundamental transitions, with their much larger A-values, should be detectable in systems with more modest column densities of warm gas, i.e., in a broader range of sources. This is borne out in high resolution spectroscopic surveys for CO fundamental emission from TTS (*Najita et al.*, 2003) and Herbig AeBe stars (*Blake and Boogert*, 2004) which detect emission from essentially all sources with accretion rates typical of these classes of objects.

In addition, the lower temperatures required to excite the CO v=1–0 transitions make these transitions sensitive to cooler gas at larger disk radii, beyond the region probed by the CO overtone lines. Indeed, the measured line profiles for the CO fundamental emission are broad (typically 50–100 $\mathrm{km\,s^{-1}}$ FWHM) and centrally peaked, in contrast to the CO overtone lines which are typically double-peaked. These velocity profiles suggest that the CO fundamental emission arises from a wide range of radii, from $\lesssim$0.1 AU out to 1–2 AU in disks around low mass stars, i.e., the terrestrial planet region of the disk (*Najita et al.*, 2003).

CO fundamental emission spectra typically show symmetric emission lines from multiple vibrational states (e.g., v=1–0, 2–1, 3–2); lines of ^{13}CO can also be detected when the emission is strong and optically thick. The ability to study multiple vibrational states as well as isotopic species within a limited spectral range makes the CO fundamental lines an appealing choice to probe gas in the inner disk over a range of temperatures and column densities. The relative strengths of the lines also provide insight into the excitation mechanism for the emission.

In one source, the Herbig AeBe star HD141569, the excitation temperature of the rotational levels (∼200 K) is much lower than the excitation temperature of the vibrational levels (v=6 is populated), which is suggestive of UV pumping of cold gas (*Brittain et al.*, 2003). The emission lines from the source are narrow, indicating an origin at $\gtrsim$17 AU. The lack of fluorescent emission from smaller radii strongly suggests that the region within 17 AU is depleted of gaseous CO. Thus detailed models of the fluorescence process can be used to constrain the gas content in the inner disk region (S. Brittain, personal communication).

Thus far HD141569 appears to be an unusual case. For the majority of sources from which CO fundamental is detected, the relative line strengths are consistent with emission from thermally excited gas. They indicate typical excitation temperatures of 1000–1500 K and CO column densities of $\sim 10^{18}\,\mathrm{cm}^{-2}$ for low mass stars. These temperatures are much warmer than the dust temperatures at the same radii implied by spectral energy distributions (SEDs) and the expectations of some disk atmosphere models (e.g., *D'Alessio et al.*, 1998). The temperature difference can be accounted for by disk atmosphere models that allow for the thermal decoupling of the gas and dust (Section 3.2).

For CTTS systems in which the inclination is known, we can convert a measured HWZI velocity for the emission to an inner radius. The CO inner radii, thus derived, are typically ∼0.04 AU for TTS (*Najita et al.*, 2003; *Carr et al.*, in preparation), smaller than the inner radii that are measured for the dust component either through interferometry (e.g., *Eisner et al.*, 2005; *Akeson et al.*, 2005a; *Colavita et al.*, 2003; see chapter by *Millan-Gabet et al.*) or through the interpretation of SEDs (e.g., *Muzerolle et al.*, 2003). This shows that gaseous disks extend inward to smaller radii than dust disks, a result that is not surprising given the relatively low sublimation temperature of dust grains (∼1500–2000 K) compared to the CO dissociation temperature (∼4000 K). These results are consistent with the suggestion that the inner radius of the dust disk is defined by dust sublimation rather than by physical truncation (*Muzerolle et al.*, 2003; *Eisner et al.*, 2005).

Perhaps more interestingly, the inner radius of the CO emission appears to extend up to and usually within the corotation radius (i.e., the radius at which the disk rotates at the same angular velocity as the star; Fig. 2). In the current paradigm for TTS, a strong stellar magnetic field truncates the disk near the corotation radius. The coupling between the stellar magnetic field and the gaseous inner disk regulates the rotation of the star, bringing the star into corotation with the disk at the coupling radius. From this region emerge both energetic (X-)winds and magnetospheric accretion flows (funnel flows; *Shu et al.*, 1994). The velocity extent of the CO fundamental emission shows that gaseous circumstellar disks indeed extend inward beyond the dust destruction radius to the corotation radius (and beyond), providing the material that feeds both X-winds and funnel flows. Such small coupling radii are consistent with the rotational rates of young stars.

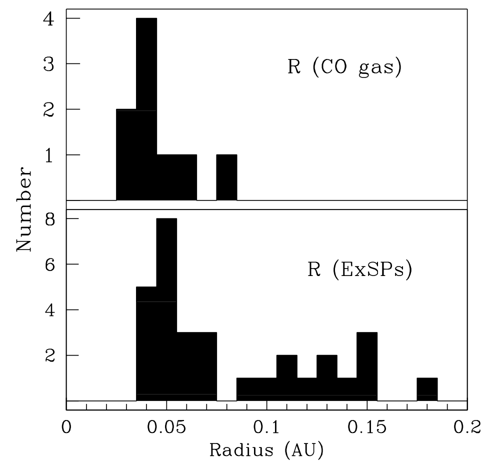

Fig. 3.— The distribution of gaseous inner radii, measured with the CO fundamental transitions, compared to the distribution of orbital radii of short-period extrasolar planets. A minimum planetary orbital radius of ∼0.04 AU is similar to the minimum gaseous inner radius inferred from the CO emission line profiles.

It is also interesting to compare the distribution of inner radii for the CO emission with the orbital radii of the "close-in" extrasolar giant planets (Fig. 3). Extra-solar planets discovered by radial velocity surveys are known to pile-up near a minimum radius of 0.04 AU. The similarity between these distributions is roughly consistent with the idea that the truncation of the inner disk can halt the inward orbital migration of a giant planet (*Lin et al.*, 1996). In detail, however, the planet is expected to migrate slightly inward of the truncation radius, to the 2:1 resonance, an effect that is not seen in the present data. A possible caveat is that the wings of the CO lines may not trace Keplerian motion or that the innermost gas is not dynamically significant. It would be interesting to explore this issue further since the results impact our understanding of planet formation and the origin of planetary architectures. In particular, the existence of a stopping mechanism implies a lower efficiency for giant planet formation, e.g., compared to a scenario in which multiple generations of planets form and only the last generation survives (e.g., *Trilling et al.*, 2002).

2.4 UV Transitions of Molecular Hydrogen

Among the diagnostics of inner disk gas developed since PPIV, perhaps the most interesting are those of H_2. H_2 is presumably the dominant gaseous species in disks, due to high elemental abundance, low depletion onto grains, and robustness against dissociation. Despite its expected ubiquity, H_2 is difficult to detect because permitted electronic transitions are in the far ultraviolet (FUV) and accessible only from space. Optical and rovibrational IR transitions have radiative rates that are 14 orders of magnitude smaller.

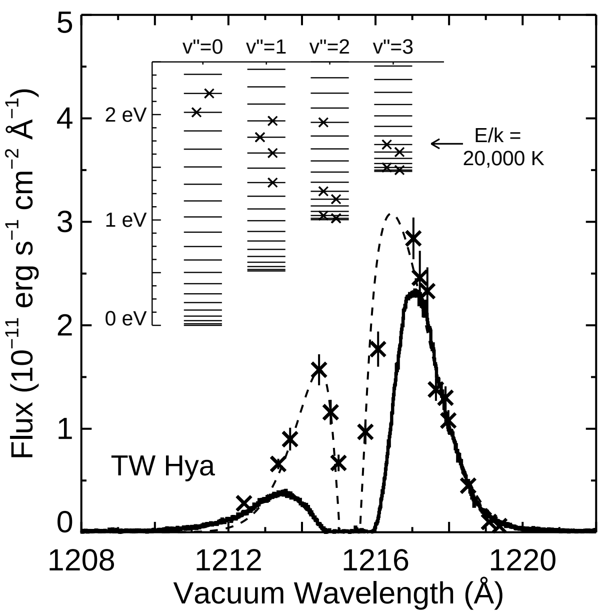

Fig. 4.— Ly α emission from TW Hya, an accreting T Tauri star, and a reconstruction of the Ly α profile seen by the circumstellar H_2. Each observed H_2 progression (with a common excited state) yields a single point in the reconstructed Ly α profile. The wavelength of each point in the reconstructed Ly α profile corresponds to the wavelength of the upward transition that pumps the progression. The required excitation energies for the H_2 *before* the pumping is indicated in the inset energy level diagram. There are no low excitation states of H_2 with strong transitions that overlap Ly α. Thus, the H_2 must be very warm to be preconditioned for pumping and subsequent fluorescence.

Considering only radiative transitions with spontaneous rates above 10^7 s^{-1}, H_2 has about 9000 possible Lyman-band (B-X) transitions from 850-1650 Å and about 5000 possible Werner-band (C-X) transitions from 850-1300 Å (*Abgrall et al.*, 1993a,b). However, only about 200 FUV transitions have actually been detected in spectra of accreting TTS. Detected H_2 emission lines in the FUV all originate from about two dozen radiatively pumped states, each more than 11 eV above ground. These pumped states of H_2 are the only ones connected to the ground electronic configuration by strong radiative transitions that overlap the broad Ly α emission that is characteristic of accreting TTS (see Fig. 4). Evidently, absorption of broad Ly α emission pumps the H_2 fluorescence. The two dozen strong H_2 transitions that happen to overlap the broad Ly α emission are all pumped out of high v and/or high J states at least 1 eV above ground (see inset in Fig. 4). This means some mechanism must excite H_2 in the ground electronic configuration, before Ly α pumping can be effective. If the excitation mechanism is thermal, then the gas must be roughly 10^3 K to obtain a significant H_2 population in excited states.

H_2 emission is a ubiquitous feature of accreting TTS. Fluoresced H_2 is detected in the spectra of 22 out of 24 accreting TTS observed in the FUV by HST/STIS (*Herczeg et al.*, 2002; *Walter et al.*, 2003; *Calvet et al.*, 2004; *Bergin et al.*, 2004; *Gizis et al.*, 2005; *Herczeg et al.*, 2005; unpublished archival data). Similarly, H_2 is detected in all 8 accreting TTS observed by HST/GHRS (*Ardila et al.*, 2002) and all 4 published FUSE spectra (*Wilkinson et al.*, 2002; *Herczeg et al.*, 2002; 2004; 2005). Fluoresced H_2 was even detected in 13 out of 39 accreting TTS observed by IUE, despite poor sensitivity (*Brown et al.*, 1981; *Valenti et al.*, 2000). Fluoresced H_2 has not been detected in FUV spectra of non-accreting TTS, despite observations of 14 stars with STIS (*Calvet et al.*, 2004; unpublished archival data), 1 star with GHRS (*Ardila et al.*, 2002), and 19 stars with IUE (*Valenti et al.*, 2000). However, the existing observations are not sensitive enough to prove that the circumstellar H_2 column decreases contemporaneously with the dust continuum of the inner disk. When accretion onto the stellar surface stops, fluorescent pumping becomes less efficient because the strength and breadth of Ly α decreases significantly and the H_2 excitation needed to prime the pumping mechanism may become less efficient. COS, if installed on HST, will have the sensitivity to set interesting limits on H_2 around non-accreting TTS in the TW Hya association.

The intrinsic Ly α profile of a TTS is not observable at Earth, except possibly in the far wings, due to absorption by neutral hydrogen along the line of sight. However, observations of H_2 line fluxes constrain the Ly α profile seen by the fluoresced H_2. The rate at which a particular H_2 upward transition absorbs Ly α photons is equal to the total rate of observed downward transitions out of the pumped state, corrected for missing lines, dissociation losses, and propagation losses. If the total number of excited H_2 molecules before pumping is known (e.g., by assuming a temperature), then the inferred pumping rate yields a Ly α flux point at the wavelength of each pumping transition (Fig. 4).

Herczeg et al. (2004) applied this type of analysis to TW Hya, treating the circumstellar H_2 as an isothermal, self-absorbing slab. Fig. 4 shows reconstructed Ly α flux points for the upward pumping transitions, assuming the fluoresced H_2 is at 2500 K. The smoothness of the reconstructed Ly α flux points implies that the H_2 level populations are consistent with thermal excitation. Assuming an H_2 temperature warmer or cooler by a few hundred degrees leads to unrealistic discontinuities in the reconstructed Ly α flux points. The reconstructed Ly α profile has a narrow absorption component that is blueshifted by $-90\ \mathrm{km\,s^{-1}}$, presumably due to an intervening flow.

The spatial morphology of fluoresced H_2 around TTS is diverse. *Herczeg et al.* (2002) used STIS to observe TW Hya with 50 mas angular resolution, corresponding to a spatial resolution of 2.8 AU at a distance of 56 pc, finding no evidence that the fluoresced H_2 is extended. At the other extreme, *Walter et al.* (2003) detected fluoresced H_2 up to 9 arcsec from T Tau N, but only in progressions pumped by H_2 transitions near the core of Ly α. Fluoresced H_2 lines have a main velocity component at or near the stellar radial velocity and perhaps a weaker component that is blueshifted by tens of $\mathrm{km\,s^{-1}}$ (*Herczeg et al.*, 2006). These two components are attributed to the disk and the outflow, respectively. TW Hya has H_2 lines with no net velocity shift, consistent with formation in the face-on disk (*Herczeg et al.*, 2002). On the other hand, RU Lup has H_2 lines that are blueshifted by $12\ \mathrm{km\,s^{-1}}$, suggesting formation in an outflow. In both of these stars, absorption in the blue wing of the C II 1335 Å wind feature strongly attenuates H_2 lines that happen to overlap in wavelength, so in either case H_2 forms inside the warm atomic wind (*Herczeg et al.*, 2002; 2005).

The velocity widths of fluoresced H_2 lines (after removing instrumental broadening) range from $18\ \mathrm{km\,s^{-1}}$ to $28\ \mathrm{km\,s^{-1}}$ for the 7 accreting TTS observed at high spectral resolution with STIS (*Herczeg et al.*, 2006). Line width does not correlate well with inclination. For example, TW Hya (nearly face-on disk) and DF Tau (nearly edge-on disk) both have line widths of $18\ \mathrm{km\,s^{-1}}$. Thermal broadening is negligible, even at 2000 K. Keplerian motion, enforced corotation, and outflow may all contribute to H_2 line width in different systems. More data are needed to understand how velocity widths (and shifts) depend on disk inclination, accretion rate, and other factors.

2.5 Infrared Transitions of Molecular Hydrogen

Transitions of molecular hydrogen have also been studied at longer wavelengths, in the near- and mid-infrared. The v=1–0 S(1) transition of H_2 (at 2μm) has been detected in emission in a small sample of classical T Tauri stars (CTTS) and one weak T Tauri star (WTTS; *Bary et al.*, 2003 and references therein). The narrow emission lines ($\lesssim 10\mathrm{km\,s^{-1}}$), if arising in a disk, indicate an origin at large radii, probably beyond 10 AU. The high temperatures required to excite these transitions thermally (1000s K), in contrast to the low temperatures expected for the outer disk, suggest that the emission is non-thermally excited, possibly by X-rays (*Bary et al.*, 2003). The measurement of other rovibrational transitions of H_2 is needed to confirm this.

The gas mass detectable by this technique depends on the depth to which the exciting radiation can penetrate the disk. Thus, the emission strength may be limited either by the strength of the radiation field, if the gas column density is high, or by the mass of gas present, if the gas column density is low. While it is therefore difficult to measure total gas masses with this approach, clearly non-thermal processes can light up cold gas, making it easier to detect.

Emission from a WTTS is surprising since WTTS are thought to be largely devoid of circumstellar dust and gas, given the lack of infrared excesses and the low accretion rates for these systems. The Bary et al. results call this assumption into question and suggest that longer lived gaseous reservoirs may be present in systems with low accretion rates. We return to this issue in Section 4.1.

At longer wavelengths, the pure rotational transitions of H_2 are of considerable interest because molecular hydrogen carries most of the mass of the disk, and these mid-infrared transitions are capable of probing the $\sim$100 K temperatures that are expected for the giant planet region of the disk. These transitions present both advantages and challenges as probes of gaseous disks. On the one hand, their small A-values make them sensitive, in principle, to very large gas masses (i.e., the transitions do not become optically thick until large gas column densities N_H=$10^{23}-10^{24}\,\mathrm{cm^{-2}}$ are reached). On the other hand, the small A-values also imply small critical densities, which allows the possibility of contaminating emission from gas at lower densities not associated with the disk, including shocks in outflows and UV excitation of ambient gas.

In considering the detectability of H_2 emission from gaseous disks mixed with dust, one issue is that the dust continuum can become optically thick over column densities $N_H \ll 10^{23}-10^{24}\,\mathrm{cm^{-2}}$. Therefore, in a disk that is optically thick in the continuum (i.e., in CTTS), H_2 emission may probe smaller column densities. In this case, the line-to-continuum contrast may be low unless there is a strong temperature inversion in the disk atmosphere, and high signal-to-noise observations may be required to detect the emission. In comparison, in disk systems that are optically thin in the continuum (e.g., WTTS), H_2 could be a powerful probe as long as there are sufficient heating mechanisms (e.g., beyond gas-grain coupling) to heat the H_2.

A thought-provoking result from ISO was the report of approximately Jupiter-masses of warm gas residing in $\sim$20 Myr old debris disk systems (*Thi et al.*, 2001) based on the detection of the 28 μm and 17 μm lines of H_2. This result was surprising because of the advanced age of the sources in which the emission was detected; gaseous reservoirs are expected to dissipate on much shorter timescales (Section 4.1). This intriguing result is, thus far, unconfirmed by either ground-based studies (*Richter et al.*, 2002; *Sheret et al.*, 2003; *Sako et al.*, 2005) or studies with Spitzer (e.g., *Chen et al.*, 2004).

Nevertheless, ground-based studies have detected pure rotational H_2 emission from some sources. Detections to date include AB Aur (*Richter et al.*, 2002). The narrow width of the emission in AB Aur ($\sim 10\ \mathrm{km\,s^{-1}}$ FWHM), if arising in a disk, locates the emission beyond the giant planet region. Thus, an important future direction for these studies is to search for H_2 emission in a larger number of sources and at higher velocities, in the giant planet region of the disk. High resolution mid-IR spectrographs on $>$3-m telescopes will provide the greater sensitivity needed for such studies.

2.6 Potential Disk Diagnostics

In a recent development, *Acke et al.* (2005) have reported high resolution spectroscopy of the [OI] 6300 Å line in Herbig AeBe stars. The majority of the sources show a narrow ($<50\ \mathrm{km\,s^{-1}}$ FWHM), fairly symmetric emission component centered at the radial velocity of the star. In some cases, double-peaked lines are detected. These features are interpreted as arising in a surface layer of the disk that is irradiated by the star. UV photons incident on the disk surface are thought to photodissociate OH and H_2O, producing a non-thermal population of excited neutral oxygen that decays radiatively, producing the observed emission lines.

Fractional OH abundances of $\sim 10^{-7} - 10^{-6}$ are needed to account for the observed line luminosities.

Another recent development is the report of strong absorption in the rovibrational bands of C_2H_2, HCN, and CO_2 in the 13–15 μm spectrum of a low-mass class I source in Ophiuchus, IRS 46 (*Lahuis et al.*, 2006). The high excitation temperature of the absorbing gas (400-900 K) suggests an origin close to the star, an interpretation that is consistent with millimeter observations of HCN which indicate a source size $\ll$100 AU. Surprisingly, high dispersion observations of rovibrational CO (4.7 μm) and HCN (3.0 μm) show that the molecular absorption is *blueshifted* relative to the molecular cloud. If IRS 46 is similarly blueshifted relative to the cloud, the absorption may arise in the atmosphere of a nearly edge-on disk. A disk origin for the absorption is consistent with the observed relative abundances of C_2H_2, HCN, and CO_2 (10^{-6}–10^{-5}), which are close to those predicted by *Markwick et al.* (2002) for the inner region of gaseous disks ($\lesssim$2 AU; see Section 3). Alternatively, if IRS 46 has approximately the same velocity as the cloud, then the absorbing gas is blueshifted with respect to the star and the absorption may arise in an outflowing wind. Winds launched from the disk, at AU distances, may have molecular abundances similar to those observed if the chemical properties of the wind change slowly as the wind is launched. Detailed calculations of the chemistry of disk winds are needed to explore this possibility. The molecular abundances in the inner disk midplane (Section 3.3) provide the initial conditions for such studies.

3. THERMAL-CHEMICAL MODELING

3.1 General Discussion

The results discussed in the previous section illustrate the growing potential for observations to probe gaseous inner disks. While, as already indicated, some conclusions can be drawn directly from the data coupled with simple spectral synthesis modeling, harnessing the full diagnostic potential of the observations will likely rely on detailed models of the thermal-chemical structure (and dynamics) of disks. Fortunately, the development of such models has been an active area of recent research. Although much of the effort has been devoted to understanding the outer regions of disks ($\sim$100 AU; e.g., *Langer et al.*, 2000; chapters by *Bergin et al.* and *Dullemond et al.*), recent work has begun to focus on the region within 10 AU.

Because disks are intrinsically complex structures, the models include a wide array of processes. These encompass heating sources such as stellar irradiation (including far UV and X-rays) and viscous accretion; chemical processes such as photochemistry and grain surface reactions; and mass transport via magnetocentrifugal winds, surface evaporative flows, turbulent mixing, and accretion onto the star. The basic goal of the models is to calculate the density, temperature, and chemical abundance structures that result from these processes. Ideally, the calculation would be fully self-consistent, although approximations are made to simplify the problem.

A common simplification is to adopt a specified density distribution and then solve the rate equations that define the chemical model. This is justifiable where the thermal and chemical timescales are short compared to the dynamical timescale. A popular choice is the α-disk model (*Shakura and Sunyaev*, 1973; *Lynden-Bell and Pringle*, 1974) in which a phenomenological parameter α characterizes the efficiency of angular momentum transport; its vertically averaged value is estimated to be $\sim 10^{-2}$ for T Tauri disks on the basis of measured accretion rates (*Hartmann et al.*, 1998). Both vertically isothermal α-disk models and the Hayashi minimum mass solar nebula (e.g., *Aikawa et al.*, 1999) were adopted in early studies.

An improved method removes the assumption of vertical isothermality and calculates the vertical thermal structure of the disk including viscous accretion heating at the midplane (specified by α) and stellar radiative heating under the assumption that the gas and dust temperatures are the same (*Calvet et al.*, 1991; *D'Alessio et al.*, 1999). Several chemical models have been built using the D'Alessio density distribution (e.g., *Aikawa and Herbst*, 1999; GNI04; *Jonkheid et al.*, 2004).

Starting about 2001, theoretical models showed that the gas temperature can become much larger than the dust temperature in the atmospheres of outer (*Kamp and van Zadelhoff*, 2001) and inner (*Glassgold and Najita*, 2001) disks. This suggested the need to treat the gas and dust as two independent but coupled thermodynamic systems. As an example of this approach, *Gorti and Hollenbach* (2004) have iteratively solved a system of chemical rate equations along with the equations of hydrostatic equilibrium and thermal balance for both the gas and the dust.

The chemical models developed so far are characterized by diversity as well as uncertainty. There is diversity in the adopted density distribution and external radiation field (UV, X-rays, and cosmic rays; the relative importance of these depends on the evolutionary stage) and in the thermal and chemical processes considered. The relevant heating processes are less well understood than line cooling. One issue is how UV, X-ray, and cosmic rays heat the gas. Another is the role of mechanical heating associated with various flows in the disk, especially accretion (GNI04). The chemical processes are also less certain. Our understanding of astrochemistry is based mainly on the interstellar medium, where densities and temperatures are low compared to those of inner disks, except perhaps in shocks and photon-dominated regions. New reaction pathways or processes may be important at the higher densities ($> 10^7\,\mathrm{cm}^{-3}$) and higher radiation fields of inner disks. A basic challenge is to understand the thermal-chemical role of dust grains and PAHs. Indeed, perhaps the most significant difference between models is the treatment of grain chemistry. The more sophisticated models include adsorption of gas onto grains in cold regions and desorption

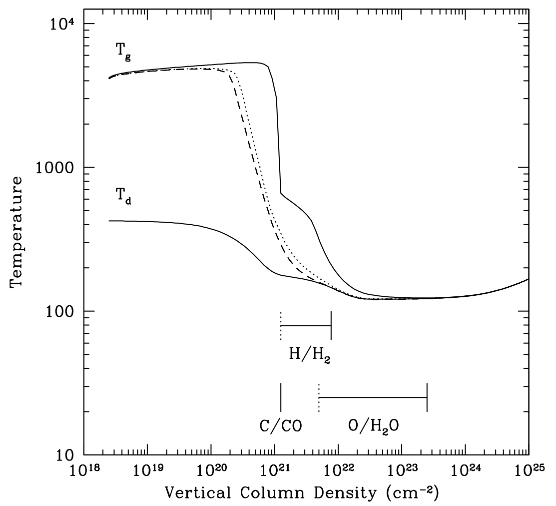

Fig. 5.— Temperature profiles from GNI04 for a protoplanetary disk atmosphere. The lower solid line shows the dust temperature of *D'Alessio et al.* (1999) at a radius of 1 AU and a mass accretion rate of $10^{-8} M_{\odot}$ yr^{-1}. The upper curves show the corresponding gas temperature as a function of the phenomenological mechanical heating parameter defined by Equation 1, α_h = 1 (solid line), 0.1 (dotted line), and 0.01 (dashed line). The $\alpha_h = 0.01$ curve closely follows the limiting case of pure X-ray heating. The lower vertical lines indicate the major chemical transitions, specifically CO forming at $\sim 10^{21}\mathrm{cm}^{-2}$, H_2 forming at $\sim 6 \times 10^{21}\mathrm{cm}^{-2}$, and water forming at higher column densities.

in warm regions. Yet another level of complexity is introduced by transport processes which can affect the chemistry through vertical or radial mixing.

An important practical issue in thermal-chemical modeling is that self-consistent calculations become increasingly difficult as the density, temperature, and the number of species increase. Almost all models employ truncated chemistries with with somewhere from 25 to 215 species, compared with 396 in the UMIST data base (*Le Teuff et al.*, 2000). The truncation process is arbitrary, determined largely by the goals of the calculations. *Wiebe et al.*, (2003) have an objective method for selecting the most important reactions from large data bases. Additional insights into disk chemistry are offered in the chapter by *Bergin et al.*

3.2 The Disk Atmosphere

As noted above, *Kamp and van Zadelhoff* (2001) concluded in their model of debris disks that the gas and dust temperature can differ, as did *Glassgold and Najita* (2001) for T Tauri disks. The former authors developed a comprehensive thermal-chemical model where the heating is primarily from the dissipation of the drift velocity of the dust through the gas. For T Tauri disks, stellar X-rays, known to be a universal property of low-mass YSOs, heat the gas to temperatures thousands of degrees hotter than the dust temperature.

Fig. 5 shows the vertical temperature profile obtained by *Glassgold et al.* (2004) with a thermal-chemical model based on the dust model of *D'Alessio et al.* (1999) for a generic T Tauri disk. Near the midplane, the densities are high enough to strongly couple the dust and gas. At higher altitudes, the disk becomes optically thin to the stellar optical and infrared radiation, and the temperature of the (small) grains rises, as does the still closely-coupled gas temperature. However, at still higher altitudes, the gas responds strongly to the less attenuated X-ray flux, and its temperature rises much above the dust temperature. The presence of a hot X-ray heated layer above a cold midplane layer was obtained independently by *Alexander et al.* (2004).

GNI04 also considered the possibility that the surface layers of protoplanetary disks are heated by the dissipation of mechanical energy. This might arise through the interaction of a wind with the upper layers of the disk or through disk angular momentum transport. Since the theoretical understanding of such processes is incomplete, a phenomenological treatment is required. In the case of angular momentum transport, the most widely accepted mechanism is the MRI (*Balbus and Hawley*, 1991; *Stone et al.*, 2000), which leads to the local heating formula,

$$\Gamma_{\rm acc} = \frac{9}{4}\alpha_h \rho c^2 \Omega, \qquad (1)$$

where ρ is the mass density, c is the isothermal sound speed, Ω is the angular rotation speed, and α_h is a phenomenological parameter that depends on how the turbulence dissipates. One can argue, on the basis of simulations by *Miller and Stone* (2000), that midplane turbulence generates Alfvén waves which, on reaching the diffuse surface regions, produce shocks and heating. Wind-disk heating can be represented by a similar expression on the basis of dimensional arguments. Equation 1 is essentially an adaptation of the expression for volumetric heating in an α-disk model, where α can in general depend on position. GNI04 used the notation α_h to distinguish its value in the disk atmosphere from the usual midplane value.

In the top layers fully exposed to X-rays, the gas temperature at 1 AU is ~5000 K. Further down, there is a warm transition region (500–2000 K) composed mainly of atomic hydrogen but with carbon fully associated into CO. The conversion from atomic H to H_2 is reached at a column density of $\sim 6 \times 10^{21}\,\mathrm{cm}^{-2}$, with more complex molecules such as water forming deeper in the disk. The location and thickness of the warm molecular region depends on the strength of the surface heating. The curves in Fig. 5 illustrate this dependence for a T Tauri disk at $r = 1$ AU. With $\alpha_h = 0.01$, X-ray heating dominates this region, whereas with $\alpha_h > 0.1$, mechanical heating dominates.

Gas temperature inversions can also be produced by UV radiation operating on small dust grains and PAHs, as demonstrated by the thermal-chemical models of *Jonkheid et al.* (2004) and *Kamp and Dullemond* (2004). *Jonkheid et al.* use the *D'Alessio et al.* (1999) model and focus on the disk beyond 50 AU. At this radius, the gas temperature can rise to 800 K or 200 K, depending on whether small grains are well mixed or settled. For a thin disk and a high stellar UV flux, *Kamp and Dullemond* obtain temperatures that asymptote to several 1000 K inside 50 AU. Of course these results are subject to various assumptions that have been made about the stellar UV, the abundance of PAHs, and the growth and settling of dust grains.

Many of the earlier chemical models, oriented towards outer disks (e.g., *Willacy and Langer*, 2000; *Aikawa and Herbst*, 1999; 2001; *Markwick et al.*, 2002), adopt a value for the *stellar* UV radiation field that is 10^4 times larger than Galactic at a distance of 100 AU. This choice can be traced back to early IUE measurements of the stellar UV beyond 1400 Å for several TTS (*Herbig and Goodrich*, 1986). Although the UV flux from TTS covers a range of values and is undoubtedly time-variable, detailed studies with IUE (e.g., *Valenti et al.*, 2000; *Johns-Krull et al.*, 2000) and FUSE (e.g., *Wilkinson et al.*, 2002; *Bergin et al.*, 2003) indicate that it decreases into the FUV domain with a typical value $\sim 10^{-15} \mathrm{erg\,cm^{-2} s^{-1}\,Å^{-1}}$, much smaller than earlier estimates. A flux of $\sim 10^{-15} \mathrm{erg\,cm^{-2} s^{-1}\,Å^{-1}}$ at Earth translates into a value at 100 AU of ∼100 times the traditional Habing value for the interstellar medium. The data in the FUV range are sparse, unfortunately, as a function of age or the evolutionary state of the system. More measurements of this kind are needed since it is obviously important to use realistic fluxes in the crucial FUV band between 912 and 1100 Å where atomic C can be photoionized and H_2 and CO photodissociated (*Bergin et al.*, 2003 and the chapter by *Bergin et al.*).

Whether stellar FUV or X-ray radiation dominates the ionization, chemistry, and heating of protoplanetary disks is important because of the vast difference in photon energy. The most direct physical consequence is that FUV photons cannot ionize H, and thus the abundance of carbon provides an upper limit to the ionization level produced by the photoionization of heavy atoms, $x_e \sim 10^{-4}$–10^{-3}. Next, FUV photons are absorbed much more readily than X-rays, although this depends on the size and spatial distribution of the dust grains, i.e, on grain growth and sedimentation. Using realistic numbers for the FUV and X-ray luminosities of TTS, we estimate that $L_{\rm FUV} \sim L_{\rm X}$. The rates used in many early chemical models correspond to $L_{\rm X} \ll L_{\rm FUV}$. This suggests that future chemical modeling of protoplanetary disks should consider both X-rays and FUV in their treatment of ionization, heating, and chemistry.

3.3 The Midplane Region

Unlike the warm upper atmosphere of the disk, which is accessible to observation, the optically thick midplane is much more difficult to study. Nonetheless, it is extremely important for understanding the dynamics of the basic flows in star formation such as accretion and outflow. The important role of the ionization level for disk accretion via the MRI was pointed out by *Gammie* (1996). The physical reason is that collisional coupling between electrons and neutrals is required to transfer the turbulence in the magnetic field to the neutral material of the disk. Gammie found that Galactic cosmic rays cannot penetrate beyond a surface layer of the disk. He suggested that accretion only occurs in the surface of the inner disk (the "active region") and not in the much thicker midplane region (the "dead zone") where the ionization level is too small to mediate the MRI.

Glassgold et al. (1997) argued that the Galactic cosmic rays never reach the inner disk because they are blown away by the stellar wind, much as the solar wind excludes Galactic cosmic rays. They showed that YSO X-rays do almost as good a job as cosmic rays in ionizing surface regions, thus preserving the layered accretion model of the MRI for YSOs. *Igea and Glassgold* (1999) supported this conclusion with a Monte Carlo calculation of X-ray transport through disks, demonstrating that scattering plays an important role in the MRI by extending the active surface layer to column densities greater than $10^{25}\,\mathrm{cm^{-2}}$, approaching the Galactic cosmic ray range used by *Gammie* (1996). This early work showed that the theory of disk ionization and chemistry is crucial for understanding the role of the MRI for YSO disk accretion and possibly for planet formation. Indeed, *Glassgold, Najita, and Igea* suggested that Gammie's dead zone might provide a good environment for the formation of planets.

These challenges have been taken up by several groups (e.g., *Sano et al.*, 2000; *Fromang et al.*, 2002; *Semenov et al.*, 2004; *Kunz and Balbus*, 2004; *Desch*, 2004; *Matsumura and Pudritz*, 2003, 2005; and *Ilgner and Nelson*, 2006a,b). *Fromang et al.* discussed many of the issues that affect the size of the dead zone: differences in the disk model, such as a Hayashi disk or a standard α-disk; temporal evolution of the disk; the role of a small abundance of heavy atoms that recombine mainly radiatively; and the value of the magnetic Reynolds number. *Sano et al.* (2000) explored the role played by small dust grains in reducing the electron fraction when it becomes as small as the abundance of dust grains. They showed that the dead zone decreases and eventually vanishes as the grain size increases or as sedimentation towards the midplane proceeds. More recently, *Inutsuka and Sano* (2005) have suggested that a small fraction of the energy dissipated by the MRI leads to the production of fast electrons with energies sufficient to ionize H_2. When coupled with vertical mixing of highly ionized surface regions, Inutsuka and Sano argue that the MRI can self generate the ionization it needs to be operative throughout the entire disk.

Recent chemical modeling (*Semenov et al.*, 2004; *Ilgner and Nelson*, 2006a,b) confirms that the level of ionization in the midplane is affected by many microphysical processes. These include the abundances of radiatively-recombining atomic ions, molecular ions, small grains, and PAHs. The proper treatment of the ions represents a great challenge for disk chemistry, one made particularly difficult by the lack of observations of the dense gas at the midplane of the inner disk. Thus the uncertainties in inner disk chemistry preclude definitive quantitative conclusions about the midplane ionization of protoplanetary disks. Perhaps the biggest wild card is the issue of grain growth, emphasized anew by *Semenov et al.*, (2004). If the disk grain size distribution were close to interstellar, then the small grains would be effective in reducing the electron fraction and producing dead zones. But significant grain growth is expected *and* observed in the disks of YSOs, limiting the extent of dead zones (e.g., *Sano et al.*, 2002).

The broader chemical properties of the *inner* midplane region are also of great interest since most of the gas in the disk is within one or two scale heights. The chemical composition of the inner midplane gas is important because it provides the initial conditions for outflows and for the formation of planets and other small bodies; it also determines whether the MRI operates. Relatively little work has been done on the midplane chemistry of the inner disk. For example, GNI04 excluded N and S species and restricted the carbon chemistry to species closely related to CO. However, *Willacy et al.* (1998), *Markwick et al.* (2002), and *Ilgner et al.* (2004) have carried out interesting calculations that shed light on a possible rich organic chemistry in the inner disk.

Using essentially the same chemical model, these authors follow mass elements in time as they travel in a steady accretion flow towards the star. At large distances, the gas is subject to adsorption, and at small distances to thermal desorption. In between it reacts on the surface of the dust grains; on being liberated from the dust, it is processed by gas phase chemical reactions. The gas and dust are assumed to have the same temperature, and all effects of stellar radiation are ignored. The ionizing sources are cosmic rays and ^{26}Al. Since the collisional ionization of low ionization potential atoms is ignored, a very low ionization level results. *Markwick et al.* improve on *Willacy et al.* by calculating the vertical variation of the temperature, and *Ilgner et al.* consider the effects of mixing. Near 1 AU, H_2O and CO are very abundant, as predicted by simpler models, but *Markwick et al.* find that CH_4 and CO have roughly equal abundances. Nitrogen-bearing molecules, such as NH_3, HCN, and HNC are also predicted to be abundant, as are a variety of hydrocarbons such as CH_4, C_2H_2, C_2H_3, C_2H_4, etc. *Markwick et al.* also simulate the presence of penetrating X-rays and find increased column densities of CN and HCO^+. Despite many uncertainties, these predictions are of interest for our future understanding of the midplane region.

Infrared spectroscopic searches for hydrocarbons in disks may be able to test these predictions. For example, *Gibb et al.* (2004) searched for CH_4 in absorption toward HL Tau. The upper limit on the abundance of CH_4 relative to CO (<1%) in the absorbing gas may contradict the predictions of *Markwick et al.* (2002) if the absorption arises in the disk atmosphere. However, some support for the *Markwick et al.* (2002) model comes from a recent report by *Lahuis et al.* (2006) of a rare detection by *Spitzer* of C_2H_2 and HCN in absorption towards a YSO, with ratios close to those predicted for the inner disk (Section 2.6).

3.4 Modeling Implications

An interesting implication of the irradiated disk atmosphere models discussed above is that the region of the atmosphere over which the gas and dust temperatures differ includes the region that is accessible to observational study. Indeed, the models have interesting implications for some of the observations presented in Section 2. They can account roughly for the unexpectedly warm gas temperatures that have been found for the inner disk region based on the CO fundamental (Section 2.3) and UV fluorescent H_2 transitions (Section 2.4). In essence, the warm gas temperatures arise from the direct heating of the gaseous component and the poor thermal coupling between the gas and dust components at the low densities characteristic of upper disk atmospheres. The role of X-rays in heating disk atmospheres has some support from the results of *Bergin et al.* (2004); they suggested that some of the UV H_2 emission from TTS arises from excitation by fast electrons produced by X-rays.

In the models, CO is found to form at a column density $N_H \simeq 10^{21}\,\mathrm{cm}^{-2}$ and temperature $\sim$1000 K in the radial range 0.5–2 AU (GNI04; Fig. 5), conditions similar to those deduced for the emitting gas from the CO fundamental lines (*Najita et al.*, 2003). Moreover, CO is abundant in a region of the disk that is predominantly atomic hydrogen, a situation that is favorable for exciting the rovibrational transitions because of the large collisional excitation cross section for H + CO inelastic scattering. Interestingly, X-ray irradiation alone is probably insufficient to explain the strength of the CO emission observed in actively-accreting TTS. This suggests that other processes may be important in heating disk atmospheres. GNI04 have explored the role of mechanical heating. Other possible heating processes are FUV irradiation of grains and or PAHs.

Molecular hydrogen column densities comparable to the UV fluorescent column of $\sim 5 \times 10^{18} \mathrm{cm}^{-2}$ observed from TW Hya are reached at 1 AU at a total vertical hydrogen column density of $\sim 5 \times 10^{21} \mathrm{cm}^{-2}$, where the fractional abundance of H_2 is $\sim 10^{-3}$ (GNI04; Fig. 5). Since Lyα photons must traverse the entire $\sim 5 \times 10^{21} \mathrm{cm}^{-2}$ in order to excite the emission, the line-of-sight dust opacity through this column must be relatively low. Observations of this kind, when combined with atmosphere models, may be able to constrain the gas-to-dust ratio in disk atmospheres, with consequent implications for grain growth and settling.

Work in this direction has been carried out by *Nomura and Millar* (2005). They have made a detailed thermal model of a disk that includes the formation of H_2 on grains, destruction via FUV lines, and excitation by Lyα photons. The gas at the surface is heated primarily by the photoelectric effect on dust grains and PAHs, with a dust model appropriate for interstellar clouds, i.e., one that reflects little grain growth. Both interstellar and stellar UV radiation are included, the latter based on observations of TW Hya. The gas temperature at the surface of their flaring disk model reaches 1500 K at 1 AU. They are partially successful in accounting for the measurements of *Herczeg et al.* (2002), but their model fluxes fall short by a factor of five or so. A likely defect in their model is that the calculated temperature of the disk surface is too low, a problem that might be remedied by reducing the UV attenuation by dust and by including X-ray or other surface heating processes.

The relative molecular abundances that are predicted by these non-turbulent, layered model atmospheres are also of interest. At a distance of 1 AU, the calculations of GNI04 indicate that the relative abundance of H_2O to CO is $\sim 10^{-2}$ in the disk atmosphere for column densities $<10^{22}\,\mathrm{cm}^{-2}$; only at column densities $>10^{23}\,\mathrm{cm}^{-2}$ are H_2O and CO comparably abundant. The abundance ratio in the atmosphere is significantly lower than the few relative abundances measurements to date (0.1–0.5) at $<$0.3 AU (*Carr et al.*, 2004; Section 2.2). Perhaps layered model atmospheres, when extended to these small radii, will be able to account for the abundant water that is detected. If not, the large water abundance may be evidence of strong vertical (turbulent) mixing that carries abundant water from deeper in the disk up to the surface. Thus, it would be of great interest to develop the modeling for the sources and regions where water is observed in the context of both layered models and those with vertical mixing. Work in this direction has the potential to place unique constraints on the dynamical state of the disk.

4. CURRENT AND FUTURE DIRECTIONS

As described in the previous sections, significant progress has been made in developing both observational probes of gaseous inner disks as well as the theoretical models that are needed to interpret the observations. In this section, we describe some areas of current interest as well as future directions for studies of gaseous inner disks.

4.1 Gas Dissipation Timescale

The lifetime of gas in the inner disk is of interest in the context of both giant and terrestrial planet formation. Since significant gas must be present in the disk in order for a gas giant to form, the gas dissipation timescale in the giant planet region of the disk can help to identify dominant pathways for the formation of giant planets. A short dissipation time scale favors processes such as gravitational instabilities which can form giant planets on short time scales (<1000 yr; *Boss*, 1997; *Mayer et al.*, 2002). A longer dissipation time scale accommodates the more leisurely formation of planets in the core accretion scenario (few–10 Myr; *Bodenheimer and Lin*, 2002).

Similarly, the outcome of terrestrial planet formation (the masses and eccentricities of the planets and their consequent habitability) may depend sensitively on the residual gas in the terrestrial planet region of the disk at ages of a few Myr. For example, in the picture of terrestrial planet formation described by *Kominami and Ida* (2002), if the gas column density in this region is $\gg 1\,\mathrm{g\,cm}^{-2}$ at the epoch when protoplanets assemble to form terrestrial planets, gravitational gas drag is strong enough to circularize the orbits of the protoplanets, making it difficult for them to collide and build Earth-mass planets. In contrast, if the gas column density is $\ll 1\,\mathrm{g\,cm}^{-2}$, Earth-mass planets can be produced, but gravitational gas drag is too weak to recircularize their orbits. As a result, only a narrow range of gas column densities around $\sim 1\,\mathrm{g\,cm}^{-2}$ is expected to lead to planets with the Earth-like masses and low eccentricities that we associate with habitability on Earth.

From an observational perspective, relatively little is known about the evolution of the gaseous component. Disk lifetmes are typically inferred from infrared excesses that probe the dust component of the disk, although processes such as grain growth, planetesimal formation, and rapid grain inspiraling produced by gas drag (*Takeuchi and Lin*, 2005) can compromise dust as a tracer of the gas. Our understanding of disk lifetimes can be improved by directly probing the gas content of disks and using indirect probes of disk gas content such as stellar accretion rates (see *Najita*, 2006 for a review of this topic).

Several of the diagnostics decribed in Section 2 may be suitable as direct probes of disk gas content. For example, transitions of H_2 and other molecules and atoms at mid-through far-infrared wavelengths are thought to be promising probes of the giant planet region of the disk (*Gorti and Hollenbach*, 2004). This is a important area of investigation currently for the Spitzer Space Telescope and, in the future, for Herschel and 8- to 30-m ground-based telescopes.

Studies of the lifetime of gas in the terrestrial planet region are also in progress. The CO transitions are well suited for this purpose because the transitions of CO and its isotopes probe gas column densities in the range of interest ($10^{-4} - 1\,\mathrm{g\,cm}^{-2}$). A current study by Najita, Carr, and Mathieu, which explores the residual gas content of optically thin disks (*Najita*, 2004), illustrates some of the challenges in probing the residual gas content of disks. Firstly, given the well-known correlation between IR excess and accretion rate in young stars (e.g., *Kenyon and Hartmann*, 1995), CO emission from sources with optically thin inner disks may be intrinsically weak if accretion contributes significantly to heating disk atmospheres. Thus, high signal-to-noise spectra may be needed to detect this emission. Secondly, since the line emission may be intrinsically weak, structure in the stellar photosphere may complicate the identification of emission features. Fig. 6 shows an example in which CO absorption in the stellar photosphere of TW Hya likely veils weak emission from the disk. Correcting for the stellar photosphere would not only amplify the strong v=1–0 emission that is clearly present (cf. *Rettig et al.*, 2004), it would also uncover weak emission in the higher vibrational lines, confirming the presence of the warmer gas probed by the UV fluorescent lines of H_2 (*Herczeg et al.*, 2002).

Stellar accretion rates provide a complementary probe of the gas content of inner disks. In a steady accretion disk, the column density Σ is related to the disk accretion rate $\dot{M}$ by a relation of the form $\Sigma \propto \dot{M}/\alpha T$, where T is the disk temperature. A relation of this form allows us to infer Σ from $\dot{M}$ given a value for the viscosity parameter α. Alternatively, the relation could be calibrated empirically using measured disk column densities.

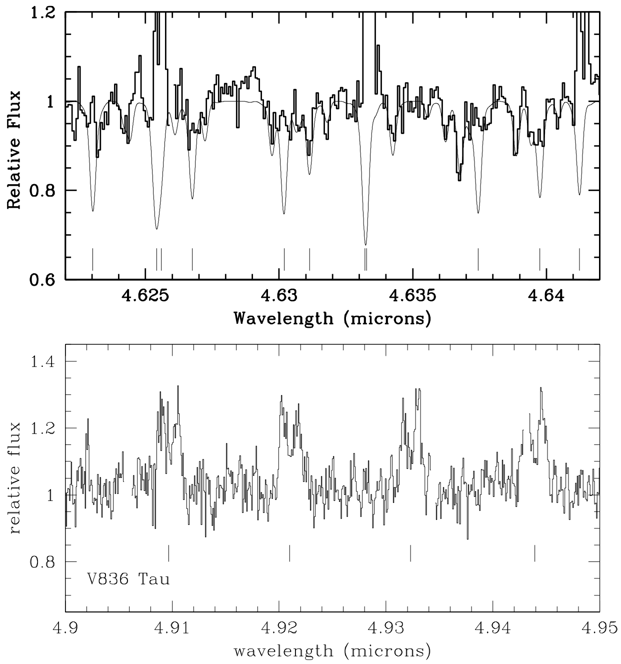

Fig. 6.— (Top) Spectrum of the transitional disk system TW Hya at 4.6 μm (histogram). The strong emission in the v=1–0 CO fundamental lines extend above the plotted region. Although the model stellar photospheric spectrum (light solid line) fits the weaker features in the TW Hya spectrum, it predicts stronger absorption in the low vibrational CO transitions (indicated by the lower vertical lines) than is observed. This suggests that the stellar photosphere is veiled by CO emission from warm disk gas. (Bottom) CO fundamental emission from the transitional disk system V836 Tau. Vertical lines mark the approximate line centers at the velocity of the star. The velocity widths of the lines locate the emission within a few AU of the star, and the relative strengths of the lines suggest optically thick emission. Thus, a large reservoir of gas may be present in the inner disk despite the weak infrared excess from this portion of the disk.

Accretion rates are available for many sources in the age range 0.5–10 Myr (e.g., *Gullbring et al.*, 1998; *Hartmann et al.*, 1998; *Muzerolle et al.*, 1998, 2000). A typical value of $10^{-8} M_\odot\,\mathrm{yr}^{-1}$ for TTS corresponds to a(n active) disk column density of $\sim 100\,\mathrm{g\,cm^{-2}}$ at 1 AU for α=0.01 (*D'Alessio et al.*, 1998). The accretion rates show an overall decline with time with a large dispersion at any given age. The existence of 10 Myr old sources with accretion rates as large as $10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$ (*Sicilia-Aguilar et al.*, 2005) suggests that gaseous disks may be long lived in some systems.

Even the lowest measured accretion rates may be dynamically significant. For a system like V836 Tau (Fig. 6), a $\sim$3 Myr old (*Siess et al.*, 1999) system with an optically thin inner disk, the stellar accretion rate of $4 \times 10^{-10} M_\odot\,\mathrm{yr}^{-1}$ (*Hartigan et al.*, 1995; *Gullbring et al.*, 1998) would correspond to $\sim 4\,\mathrm{g\,cm^{-2}}$ at 1 AU. Although the accretion rate is irrelevant for the buildup of the stellar mass, it corresponds to a column density that would favorably impact terrestrial planet formation. More interesting perhaps is St34, a TTS with a Li depletion age of 25 Myr; its stellar accretion rate of $2 \times 10^{-10} M_\odot\,\mathrm{yr}^{-1}$ (*White and Hillenbrand*, 2005) suggests a dynamically significant reservoir of gas in the inner disk region. These examples suggest that dynamically significant reservoirs of gas may persist even after inner disks become optically thin and over the timescales needed to influence the outcome of terrestrial planet formation.

The possibility of long lived gaseous reservoirs can be confirmed by using the diagnostics described in Section 2 to measure total disk column densities. Equally important, a measured the disk column density, combined with the stellar accretion rate, would allow us to infer a value for viscosity parameter α for the system. This would be another way of constraining the disk accretion mechanism.

4.2 Nature of Transitional Disk Systems

Measurements of the gas content and distribution in inner disks can help us to identify systems in various states of planet formation. Among the most interesting objects to study in this context are the transitional disk systems, which possess optically thin inner and optically thick outer disks. Examples of this class of objects include TW Hya, GM Aur, DM Tau, and CoKu Tau/4 (*Calvet et al.*, 2002; *Rice et al.*, 2003; *Bergin et al.*, 2004; *D'Alessio et al.*, 2005; *Calvet et al.*, 2005). It was suggested early on that optically thin inner disks might be produced by the dynamical sculpting of the disk by orbiting giant planets (*Skrutskie et al.*, 1990; see also *Marsh and Mahoney*, 1992).

Indeed, optically thin disks may arise in multiple phases of disk evolution. For example, as a first step in planet formation (via core accretion), grains are expected to grow into planetesimals and eventually rocky planetary cores, producing a region of the disk that has reduced continuum opacity but is gas-rich. These regions of the disk may therefore show strong line emission. Determining the fraction of sources in this phase of evolution may help to establish the relative time scales for planetary core formation and the accretion of gaseous envelope.

If a planetary core accretes enough gas to produce a low mass giant planet ($\sim 1 M_J$), it is expected to carve out a gap in its vicinity (e.g., *Takeuchi et al.*, 1996). Gap crossing streams can replenish an inner disk and allow further accretion onto both the star and planet (*Lubow et al.*, 1999). The small solid angle subtended by the accretion streams would produce a deficit in the emission from both gas and dust in the vicinity of the planet's orbit. We would also expect to detect the presence of an inner disk. Possible examples of systems in this phase of evolution include GM Aur and TW Hya in which hot gas is detected close to the star as is accretion onto the star (*Bergin et al.*, 2004; *Herczeg et al.*, 2002; *Muzerolle et al.*, 2000). The absence of gas in the vicinity of the planet's orbit would help to confirm this interpretation.

Once the planet accretes enough mass via the accretion streams to reach a mass $\sim$5–10M_J, it is expected to cut off further accretion (e.g., *Lubow et al.*, 1999). The inner disk will accrete onto the star, leaving a large inner hole and no trace of stellar accretion. CoKu Tau/4 is a possible example of a system in this phase of evolution (cf. *Quillen et al.*,

2004) since it appears to have a large inner hole and a low to negligible accretion rate ($<$few $\times 10^{-10} M_\odot\,\mathrm{yr}^{-1}$). This interpretation predicts little gas anywhere within the orbit of the planet.

At late times, when the disk column density around 10 AU has decreased sufficiently that the outer disk is being photoevaporated away faster than it can resupply material to the inner disk via accretion, the outer disk will decouple from the inner disk, which will accrete onto the star, leaving an inner hole that is devoid of gas and dust (the "UV Switch" model; *Clarke et al.*, 2001). Measurements of the disk gas column density and the stellar accretion rate can be used to test this possibility. As an example, TW Hya is in the age range ($\sim$10 Myr) where photoevaporation is likely to be significant. However, the accretion rate onto star, gas content of the inner disk (Sections 2 and 4), as well as the column density inferred for the outer disk ($32\,\mathrm{g\,cm}^{-2}$ at 20 AU based on the dust SED; *Calvet et al.*, 2002) are all much larger than is expected in the UV switch model. Although this mechanism is, therefore, unlikely to explain the SED for TW Hya, it may explain the presence of inner holes in less massive disk systems of comparable age.

4.3 Turbulence in Disks

Future studies of gaseous inner disks may also help to clarify the nature of the disk accretion process. As indicated in Section 2.1, evidence for suprathermal line broadening in disks supports the idea of a turbulent accretion process. A turbulent inner disk may have important consequences for the survival of terrestrial planets and the cores of giant planets. An intriguing puzzle is how these objects avoid Type-I migration, which is expected to cause the object to lose angular momentum and spiral into the star on short timescales (e.g., *Ward*, 1997). A recent suggestion is that if disk accretion is turbulent, terrestral planets will scatter off turbulent fluctuations, executing a "random walk" which greatly increases the migration time as well as the chances of survival (*Nelson et al.*, 2000; see chapter by *Nelson et al.*).

It would be interesting to explore this possible connection further by extending the approach used for the CO overtone lines to a wider range of diagnostics to probe the intrinsic line width as a function of radius and disk height. By comparing the results to the detailed predictions of theoretical models, it may be possible to distinguish between the turbulent signature, produced e.g., by the MRI instability, from the turbulence that might be produced by, e.g., a wind blowing over the disk.

A complementary probe of turbulence may come from exploring the relative molecular abundances in disks. As noted in Section 3.4, if relative abundances cannot be explained by model predictions for non-turbulent, layered accretion flows, a significant role for strong vertical mixing produced by turbulence may be implied. Although model-dependent, this approach toward diagnosing turbulent accretion appears to be less sensitive to confusion from wind-induced turbulence, especially if one can identify diagnostics that require vertical mixing from deep down in the disk. Another complementary approach toward probing the accretion process, discussed in Section 4.1, is to measure total gas column densities in low column density, dissipating disks in order to infer values for the viscosity parameter α.

5. SUMMARY AND CONCLUSIONS

Recent work has lent new insights on the structure, dynamics, and gas content of inner disks surrounding young stars. Gaseous atmospheres appear to be hotter than the dust in inner disks. This is a consequence of irradiative (and possibly mechanical) heating of the gas as well as the poor thermal coupling between the gas and dust at the low densities of disk atmospheres. In accreting systems, the gaseous disk appears to be turbulent and extends inward beyond the dust sublimation radius to the vicinity of the corotation radius. There is also evidence that dynamically significant reservoirs of gas can persist even after the inner disk becomes optically thin in the continuum. These results bear on important star and planet formation issues such as the origin of winds, funnel flows, and the rotation rates of young stars; the mechanism(s) responsible for disk accretion; and the role of gas in the determining the architectures of terrestrial and giant planets. Although significant future work is needed to reach any conclusions on these issues, the future for such studies is bright. Increasingly detailed studies of the inner disk region should be possible with the advent of powerful spectrographs and interferometers (infrared and submillimeter) as well as sophisticated models that describe the coupled thermal, chemical, and dynamical state of the disk.

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