Spectroscopy of Inner Protoplanetary Disks and the Star-Disk Interface

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We review the recent contribution of high resolution spectroscopy to advances in our understanding of the region within a few AU of young low-mass stars. In particular, we describe the role played by strong stellar magnetic fields in the resolution of the angular momentum problem for star formation, and our ability to probe the properties of planet formation environments.

I. INTRODUCTION

The region within a few AU of accreting young stars is of great interest for star and planet formation. Within this region, stars accrete from and interact with their surrounding disks, energetic winds emerge, and planet formation may already be underway. Studying the dynamics and detailed structure of this region is currently restricted to the realm of high resolution spectroscopy due to the small angular scale that the region subtends at the distance of the nearest star-forming regions. In this chapter, we review the contribution of high resolution spectroscopy to advances in our understanding of the star-disk interface and the properties of disks at planet formation distances.

One of the most striking features of accreting young stars is the simultaneous presence of disk accretion and energetic outflows among stars of all masses, a result that was recognized at the time of Protostars and Planets III (Edwards, Ray and Mundt 1993). Since that time results from high resolution spectroscopy have altered and enhanced our understanding of the nature of the interaction between stars and their accretion disks, and the consequences of that interaction for the mass and angular momentum evolution of young stars. In the case of T Tauri stars, which are low mass stars in the final stages of disk accretion, the earlier picture in which accreting disk matter joined the star through an equatorial boundary layer (Lynden-Bell and Pringle 1974), has given way to a new picture with broader explanatory power. A wide array of observational evidence now supports a picture in which a strong, organized stellar magnetic field truncates the inner disk, and disk material from the truncation region accretes onto the star along closed stellar field lines in a funnel flow. The stellar rotation rate is slowed and possibly regulated by the magnetic interaction with the disk so that the star maintains its slow rotation rate even while actively accreting. In at least one version of this picture, mass loss is integral to the whole process, as an energetic wind also emerges from the truncation region along open field lines, contributing significantly to angular momentum loss from the system. The observational evidence from high resolution spectroscopy that supports this paradigm-shift for T Tauri stars is outlined in §II.

Also since PPIII, the advent of sensitive infrared spectrographs with large format arrays has opened up new opportunities to probe the properties of protoplanetary disks within a few AU of the star. The ability to study planet formation environments is of even greater interest today given the discovery of extrasolar planets (see chapter by Marcy et al.). The unexpected presence of giant planets at small orbital radii, and the diversity in their mass and eccentricity, has challenged traditional theories of planet formation and underscored the possibility of significant dynamical evolution in young planetary systems. These results emphasize the need for observational studies of young disk systems in order to better understand the physical and dynamical conditions under which planets form. As we describe in §III, work to date using infrared spectroscopy demonstrates our current capability to study disk dynamics and physical properties within a few AU, the same range of radii currently probed by precision radial velocity searches for extrasolar planets.

II. THE STAR-DISK INTERFACE

The classical T Tauri stars (cTTS) offer an excellent opportunity to probe the star-disk interface. These young, low mass stars undergoing disk accretion are optically revealed, allowing their disk accretion rates to be assessed from the magnitude of their continuum veiling (Gullbring et al. 1998) and the dynamics of the interface region to be probed by spectroscopic study. The first suggestion that disk matter might accrete onto cTTS along stellar magnetic field lines was made by Bertout et al. (1988) who interpreted the observation of rotationally modulated hot "spots" as evidence for non-axisymmetric funnel flows. However, it was the subsequent confrontation of theory with the well-known fact that cTTS rotate much below breakup ($v \sin i \sim 15 \mathrm{km\,s^{-1}}$, e.g., Hartmann and Stauffer 1989) despite ongoing disk accretion that eventually led to an understanding of the importance of star-disk magnetic coupling for stellar mass and angular momentum evolution. A key observational constraint (Edwards et al. 1993; Bouvier et al. 1993; Choi and Herbst 1996) was the discovery that cTTS also rotate more slowly than stars of comparable spectral type and age that show no evidence for disk accretion (weak T Tauri stars; wTTS).

As discussed initially by Königl (1991), and expanded and refined by others (Shu et al. 1994; Cameron and Campbell 1996; Armitage and Clarke 1996), a likely explanation for the slow rotation of accreting young stars is that a strong, organized stellar magnetic field truncates and couples to the inner disk at a few stellar radii, thereby regulating the rotation of the star. Although the proposed models differ in their treatment of the radial extent of the coupling region and the angular momentum redistribution that allows continued slow stellar rotation, all assume the existence of strong (kG), organized fields and the accretion of disk matter from the truncation region in funnel flows that terminate in shocks at the stellar surface. We review in the next section the spectroscopic evidence for strong fields in young low mass stars.

A. Stellar Magnetic Fields

T Tauri stars (TTS) have long been thought to be magnetically active, based on their location on pre-main sequence convective tracks coupled with numerous surrogate diagnostics of magnetic dynamos (X-ray and non-thermal radio emission, photometric evidence for large starspots; see chapter by Glassgold et al.). Direct measurements of TTS field strengths are complicated by rotational broadening which dominates over Zeeman broadening at optical wavelengths. As a result, the first direct indication of strong fields (Basri et al. 1992) ignored line profiles and used a more indirect measure, the correlation of equivalent width enhancement with Zeeman sensitivity (i.e., the number and distribution of Zeeman components for a given line and their Landé g factors), a technique that is sensitive to the average field strength over the stellar surface. To date field strengths in the 1−2.5 kG range have been measured for approximately 3 TTS using this technique (Basri et al. 1992; Guenther et al. 1998). The large uncertainties associated with these values (∼1 kG) stem from the dominance of rotational broadening and the resulting sensitivity to uncertainties in the stellar model.

The detectability of kG fields is much enhanced by going to long wavelengths where Zeeman broadening ($\propto \lambda^2$) dominates over rotational broadening ($\propto \lambda$). In their study of the Zeeman-sensitive Ti I $\lambda 2.2\mu$m line in the cTTS BP Tau, Johns-Krull, Valenti and Koresko (1999) find a line profile with a clear signature of Zeeman broadening and derive an averaged field strength of $Bf = 3.3$ kG, in excellent agreement with values required by theories of magnetospheric accretion. Because Zeeman broadening dominates at 2.2μm, the surface distribution of field strengths and filling factors can be extracted from the line profile. Analysis of the Ti I line implies a distribution of filling factors and field strengths up to 5$-$10 kG.

Insight into the large scale organization of the stellar field is provided in part by Doppler imaging from time-resolved high resolution spectroscopy. Doppler imaging of two wTTS (Hatzes 1995; Joncour et al. 1994) and one cTTS (Johns-Krull and Hatzes 1997) suggests the presence of large cool spots concentrated near the rotational poles, as would be expected from a strong dipole component, although other interpretations are also possible.

Spectropolarimetry contributes additional diagnostic power to the measurement of field strength and geometry. Because the Zeeman σ components in magnetized regions are oppositely polarized, a net field polarity on the stellar surface can be identified by and field strengths measured from the wavelength shift between the right- and left-circularly polarized components of the line profile. Since the measurement is differential in nature, modest line splittings can be detected even in the presence of rapid rotation. While the detection of circular polarization is compromised if regions of opposite polarity are mixed on the visible hemisphere (as in the case of solar-type activity), rapid rotation provides a significant advantage in this case. The detection of net polarization in a given velocity interval of the profile is more likely since the interval probes a restricted region on the stellar surface. In the TTS photospheric spectrum, the polarization is typically weak, reflecting a lack of organization in the photospheric field as a whole (Brown and Landstreet 1981; Johnstone and Penston 1987; Donati et al. 1997). For example, circular polarization has been reported in the optical spectrum of two wTTS (Donati et al. 1997), where rapid rotation and broad spectral coverage were used to detect polarization at 0.2% of the continuum.

In contrast to the situation for the photospheric field, work by Johns-Krull, Valenti, Hatzes, and Kanaan (1999) on the cTTS BP Tau provides clear evidence for a strong, organized field component that is associated with accretion onto the stellar surface. Although in this star circular polarization is not detected in Zeeman sensitive photospheric lines, the He I λ5876 emission line which likely forms in accretion shocks at the base of funnel flows (see §II.B) *is* strongly polarized (at $\sim$10% of the continuum) and the wavelength shift implies a field strength $\geq$ 2.4 kG. The strong polarization of the He I line argues that fields participating in accretion are globally organized, e.g., in a dipole-like configuration, as would be necessary if they are to couple to an inner disk several stellar radii away. The existence of such large–scale fields (magnetic loops extending to several R_*), is also supported by evidence from radio interferometry of wTTS (Phillips 1992; Phillips et al. 1996). The contrasting lack of polarization in the photospheric lines indicates that the organized fields cover a small fraction of the stellar surface. In the rest of this section, we discuss the evidence that the strong, organized field component controls accretion onto the stellar surface and plays an important role in the origin of winds.

B. Kinematic Clues from Permitted Atomic Emission Lines

Spectroscopically, the cTTS are characterized by a rich permitted emission line spectrum, with strong lines of H I and numerous neutral and singly ionized metals in the optical and near infrared and a wide range of ionization states in the ultraviolet. The densities and temperatures required to excite these lines indicate formation within $\sim 10R_*$ of the stellar surface. While profiles of permitted emission lines offer the possibility of probing the dynamics of the star-disk interface, this requires disentangling different kinematic components from profiles of composite origin. The composite nature of the permitted lines are indicated by the variety of shapes found among lines of different optical depth, excitation, and ionization. In Figure 1 we illustrate a sequence of near-simultaneous profiles from 8 lines in the high accretion rate cTTS DF Tau. The profiles consist of multiple emission and absorption components, and display an astonishing range in breadth, symmetry and morphology. Kinematic features indicating outflow within a few stellar radii are seen in lines of Hα, Hβ and Mg II, and the presence of simultaneous outflow and infall is seen in the blueshifted and redshifted absorptions at Na D.

While the profile sequence shown in Figure 1 for DF Tau is typical for a high accretion rate cTTS, the velocities and depths of the blueshifted and redshifted absorption components are particularly time-variable among the high accretion rate stars. There are, however, some systematic trends in profile morphology among the cTTS displayed by stars as a function of accretion rate (Edwards et al. 1994 [EHGA]). In Figure 2 we illustrate the range of profiles among some of the strongest cTTS emission lines, Hα, Hδ and He I λ5876. In the remainder of this section, we use the profiles shown in Figures 1 and 2 to demonstrate that funnel flows, accretion shocks and winds contribute to the composite permitted line profiles in cTTS. We also note that the composite permitted emission line profiles in cTTS almost certainly have additional kinematic components whose origin is as yet unidentified.

Funnel Flows. The most compelling spectroscopic evidence for funnel flows is redshifted "inverse P Cygni" (IPC) absorption features (Walker 1972, EHGA). These are especially prominent in lines of the upper Balmer, Paschen and Brackett series, but are also frequent at Na D and O I λ7773 (e.g., Hamann and Persson 1992, Najita et al. 1996a). The observed infall velocities of several hundred km s^{-1} are readily explained as magnetic accretion from a disk truncated at several stellar radii, and are inconsistent with accretion through an equatorial boundary layer. This interpretation of the line profiles is strengthened by similarities between observed profiles and those predicted by radiative transfer models of idealized funnel flows (Muzerolle, Hartmann and Calvet 1998b; Muzerolle, Calvet and Hartmann 1998a; Hartmann, Hewett and Calvet 1994). The predicted profiles are broad and centrally peaked with a distinct blueward asymmetry. Formation of the redshifted IPC absorption component signifying supersonic infall is found to be sensitive to a variety of factors, including inclination and thermalization effects, and is predicted to be rare in optically thick lines such as Hα. These general characteristics are found to be representative of Balmer and Na D profiles in a snapshot survey of cTTS covering the full range of disk accretion rates (EHGA). Specifically, EHGA find: (1) IPC absorption minima are found in upper Balmer lines and Na D in about 60% of cTTS, independent of accretion rate; (2) blueward asymmetry is found in upper Balmer lines in about 90% of cTTS; (3) IPC and blueward asymmetry are only found at Hα among cTTS of low disk accretion rates. These similarities between observed and model profiles suggest that funnel flows are ubiquitous among cTTS of all disk accretion rates.

The models of Hartmann and collaborators are also able to reproduce the observed luminosities of the Balmer and some metal lines with reasonable estimates for truncation radii and mass accretion rates. This implies that the bulk of the emission in the hydrogen lines arises in accretion flows, not winds, as was previously thought (Hartmann et al. 1994). However, it will be necessary to develop radiative transfer models which include a rigorous treatment of the rotation and thermal structure of funnel flows before we can accurately determine the fraction of the permitted line luminosity that arises in these flows. A first step in this direction has been taken by Martin (1996), who computed the temperature and ionization structure in funnel flows and found that adiabatic compression is a significant heat source. The predicted range of temperatures within the funnel flow (3000−7000 K) is considerably lower than what Hartmann et al. (1994) find is necessary to account for the hydrogen line luminosity, if it arises entirely in a funnel flow. Further study of additional heating processes (e.g., MHD wave heating) and the radiative properties of funnel flows are required before definitive conclusions can be made. At the present, the similarities between theoretical and observed profiles is heartening, but physically self-consistent models are needed in order to establish the uniqueness of the funnel flow interpretation for these permitted line diagnostics.

Accretion Shocks. Although magnetic accretion models successfully describe emission profiles in some permitted lines, the majority of the metallic lines are characterized by a morphology with a symmetric core and a distinctive two-component structure, quite different from the profiles predicted for funnel flows (Basri 1987; Hamann and Persson 1992). Figure 2 illustrates the two-component morphology for representative He I $\lambda5876$ profiles, which are well characterized as the sum of a narrow component (NC) and a broad component (BC). The kinematic properties of the NC are fairly consistent among large samples of cTTs, characterized by halfwidths $\leq$50 km s^{-1}, symmetric structure and velocities close to the stellar rest velocity. In contrast, there is considerable variety in the structure of the BC, characterized by halfwidths from one to several hundred km s^{-1}, often with blueward asymmetries (Batalha et al. 1996; Edwards 1997). There is some indication that BC emission is more prominent in stars with high accretion rates (Muzerolle et al. 1998b), although variations in veiling and line profiles in individual stars show no correlation between the instantaneous accretion rate and the relative proportion of BC to NC emission (Edwards 1997).

A likely interpretation of the two component structure, based largely on the observed kinematics, is that the NC arises in post-shock gas at the base of magnetic accretion columns while the BC arises in infalling gas in the funnel flow. Evidence supporting this interpretation includes: (1) An analysis of Fe I and Fe II lines in the cTTS DR Tau suggests that the NC and BC arise in regions with differing opacities and temperatures (Beristain, Edwards and Kwan 1998); (2) Idealized funnel flow models can account for the strength and morphology of the BC in lines of Na D and the Ca IR triplet (Muzerolle et al. 1998b); and (3) The NC in the highest ionization states seen in the UV from GHRS HST spectra, such as C IV and S IV (see Figure 1), are redshifted compared to lower ionization states as would be expected in immediate post-shock gas, and their line fluxes can be accounted for by emission in the expected post-shock conditions (Calvet et al. 1996). The post-shock gas is also the likely source of the excess continuum veiling of TTS which was formerly attributed to emission from an equatorial boundary layer. In contrast to funnel flows, very little theoretical work has been done to date on magnetic accretion shocks in cTTS. An exploration of the basic shock structure and a prediction of the resulting continuum radiation by Calvet and Gullbring (1998) is a promising first step, and we expect additional significant advances in the near future.

The combination of emission features believed to arise in either the funnel flow or accretion shock also provides important insight into the topology of the magnetic field. In a typical cTTS the spectrum *always* shows evidence for a NC (Batalha et al. 1996; Beristain, Edwards and Kwan 1998), infall (EHGA), and continuum veiling. The continuous presence of all three phenomena in most cTTS suggests a large scale uniformity in the distribution of accretion footpoints. While this could arise from either a dipole geometry or a complex magnetic topology that covers much of the stellar surface, the detection of circular polarization in He I λ5876 in BP Tau (Johns-Krull, Valenti, Hatzes, and Kanaan 1999; §II.A), a line dominated by NC emission from the base of the accretion shock, argues strongly for the former interpretation.

Inner Winds. Spectroscopic evidence for winds emerging from near-stellar regions comes from blueshifted absorption components in profiles of Hα, Na I D, Ca II H & K and Mg II h & k (Kuhi 1964; Giampapa et al. 1981). Evidence for winds on more extended scales is provided by the blueshifted forbidden lines, which trace flows that have been collimated into jets at distances of tens of AU from the star and in some instances are spatially resolved (Hartigan, Edwards and Ghandour 1995 [HEG]; Hirth et al. 1997.) Both the inner and extended wind diagnostics correlate with disk accretion rates in cTTS, and neither are found in non-accreting wTTS. For the inner winds, this trend is demonstrated by a progression in the permitted line absorption features with disk accretion rate, as illustrated in Figures 1 and 2 for Hα. Classic P Cgyni profiles are found among stars with high accretion rates, progressing to less deep and less blueshifted absorption features in stars with average accretion rates, to weak or absent wind signatures among cTTS with the lowest accretion rates. This progression is qualitatively consistent with the correlation found between disk accretion rates and mass loss rates inferred from the forbidden line luminosities (HEG), suggesting that both inner winds and extended winds traced by forbidden lines are powered by accretion.

It is of considerable interest to compare mass loss rates estimated by inner and extended wind diagnostics to ascertain whether they trace the same flow (Calvet 1997) and to compare the mass loss rates of each to disk accretion rates. Of these quantities, the cTTS disk accretion rates are probably the best constrained. The most recent disk accretion rates evaluated from optical continuum veiling average $10^{-8}M_{\odot}yr^{-1}$, but span a wide range of values from $10^{-7} - 10^{-9}$ $M_{\odot}yr^{-1}$ (see chapter by Calvet et al). Mass loss rates from forbidden line luminosities are more uncertain, although average values are estimated to be about $10^{-9}M_{\odot}yr^{-1}$ (HEG). Mass loss rates from inner winds are the least well defined.

Inner wind properties were traditionally estimated from permitted line luminosities and profiles under the assumption that the lines form solely in the wind. For example, Giovanardi et al. (1991) used the hydrogen and Na I D lines to estimate wind mass loss rates, with wind temperature primarily constrained by hydrogen line intensity and column density by Na I absorption strength. They found that inner winds are cool (5000−7000 K) and neutral with mass loss rates $10^{-8} - 10^{-7}M_{\odot}yr^{-1}$ in the most extreme cTTS, comparable to that of associated molecular outflows. The recent realization that the bulk of the hydrogen emission may not form in the wind has loosened the constraints on inner wind properties. The lack of significant emission from the wind coupled with the presence of blueshifted wind features in the Hα and Na I D lines and their absence in the higher Balmer or Brackett lines implies that inner wind temperatures are lower than previous estimates. In the likely event that photoionization is dominant over collisional ionization (i.e., for $T_w < 10^4$K), the lower temperatures imply larger mass loss rates than previously estimated for a given Na I optical depth (e.g., Najita et al. 1996a).

Thus, despite the reinterpretation of hydrogen line luminosities, the indication is that inner winds are dynamically significant components of accreting systems with mass loss rates that are appreciable in comparison to disk accretion rates. Nevertheless, definitive mass loss rates from the inner wind have not yet been established. An improved determination of inner wind mass loss rates will probably require thermal and excitation analyses for specific wind dynamical models. With these, we will be able to make more robust quantitative comparisons to mass loss rates from forbidden lines and disk accretion rates, and thereby potentially distinguish between the various models proposed to explain the existence of jets and winds from accreting young stars.

C. Synoptic Studies

Deeper insight into the composite origin of the emission regions at the star-disk interface can be acquired through variability studies. The spectral features of cTTS can vary on a wide range of time scales, ranging from minutes to years, and thus temporal data can convey information that individual spectra cannot. In particular, synoptic studies provide insight on the size of the region that is changing, on the extent of the changes that can take place in it, and on the timescale of those changes. Ideally, one can even follow events from one region as they have an impact on neighboring regions after some transmittal time. Synoptic observations over many stellar rotation periods can uncover periodic phenomena, thereby providing an additional tool with which to probe the phase relationships between the dynamical components discussed in the previous section. Moreover, synoptic observations of photospheric features can also be used to construct Doppler images of the stellar surface in order to study the properties of hot and cool spots (see §II.A)

An outstanding example of periodic variations in emission line features is demonstrated by the TTS SU Aur. The depths of both a blueshifted absorption component (in Hα and Hβ) and a redshifted absorption component (in Hβ) are observed to vary at the 3-day rotation period of the star but are, remarkably, 180° out of phase (Giampapa et al. 1993; Johns and Basri 1995a). In addition, the velocity of the redshifted component varies at the stellar rotation period, and is at a maximum when the feature is strongest (Petrov et al. 1996). This behavior can be explained by a stellar magnetosphere that is tilted $\sim 15°$ from the rotation axis of the star, which couples to a disk at an X-point (Shu et al. 1994) from which both a funnel flow and a magnetocentrifugal wind emerge. Because the tilt favors inflow in one region of the magnetosphere and outflow $180°$ away in azimuth, the rotation of the magnetosphere at the rotation period of the star can account for the observed period and phase difference (Johns and Basri 1995a).

In a second example, the cTTS Sz 68, an infall feature at $H\alpha$ is found to vary at the stellar rotation period of 4 days, but wind features are not detected (Johns-Krull and Hatzes 1997). As a comment on these studies, it is noteworthy that the large scale symmetry of TTS magnetospheres, as indicated, e.g., by the rough stability of hydrogen line luminosity with rotational phase, implies that the rotationally modulated features detected in the above examples must represent fairly small perturbations on top of the large scale structure. Such small perturbations are consistent with the existence of "hot spots" which represent a small fraction $\sim 1\%$ of the accretion luminosity onto the star (Bertout et al. 1996).

A broader synoptic study with thorough time coverage of seven late-type cTTS did not find further examples of periodic modulation, but did determine that moderately blueshifted absorption components are the least variable part of the line profile, suggesting that winds are more quiescent than the funnel flow region and form well beyond it (Johns and Basri 1995b). This is generally consistent with most wind theories which place the origin of the wind beyond the magnetosphere.

The many spectroscopic monitoring studies of cTTS have opened our eyes to the very time-dependent and complex nature of the star-disk interface. For example, a recent study of ultraviolet spectral features in the cTTS BP Tau reveals that recombination lines vary systematically, possibly with the stellar rotation period, while lines dominated by collisional excitation vary irregularly (Gómez de Castro and Franqueira 1997). These distinctions might arise if the recombination lines form in accretion spots which show rotational modulation while the strong permitted lines might have significant contributions from flares. (See also Johns-Krull and Basri 1997; Hessman and Guenther 1997; and Gullbring et al. 1996). We anticipate that in the future synoptic monitoring programs will play increasingly important roles in unravelling the complex, time-dependent nature of the star-disk interaction region. Synoptic monitoring programs with comprehensive time coverage that include lines with a wide range of optical depths would be of considerable interest.

Recent work on DQ Tau provides a final example of the exciting use of synoptic observations, in this case as a probe of the star-disk interaction and accretion dynamics in close binary systems (Mathieu et al. 1997; Basri et al. 1997). With the tight orbit implied by the 16 day period (8 R_* at periastron), there is little room for disks around each star, and the circumbinary disk is classically expected to be held off by a gap of about 3 times the separation of the 2 stars. In this situation, accretion is perhaps not expected and the fact that DQ Tau is a cTTS system may appear puzzling. However, in the case of DQ Tau, both the broad band flux and emission equivalent widths vary with the orbital period of the system, with the flux and equivalent width reaching maxima near periastron passage. These properties are in excellent agreement with recent dynamical models which suggest that accreting material from the circumbinary disk can cross the gap in streams, thereby perpetuating stellar accretion beyond the stage of gap formation (Artymowicz and Lubow 1996). Spectroscopic evidence for the presence of gas in gaps in close binary systems (including DQ Tau) is discussed in §III.C. These results illustrate the kind of dynamical issues that may prove critical in understanding binary star formation and the role that high resolution spectroscopy may play in resolving these issues.

D. Summary

There is now convincing evidence that during the T Tauri phase accreting disk matter joins the star by infall along stellar magnetic field lines. This picture is based both on direct evidence that young stars possess stellar fields of the requisite strength and geometry to control accretion onto the star, and on the commonly observed dynamical signatures of gas infalling onto stellar surfaces. In addition, there is spectroscopic evidence for outflowing gas in close proximity to the disk truncation region. Moreover, the correlation between inner wind activity and disk accretion rate argues that inner winds are an integral part of the mass accretion process. In the coming decade we anticipate that the study of the star-disk interface in cTTS will progress beyond the cataloging of empirical phenomena which diagnose the presence of funnel flows, accretion shocks, and inner winds and provide a quantitative assessment of the physical conditions and mass flow rates in the region where stellar magnetic fields couple to disks and inner winds are generated.

Although considerable progress has been made in recognizing the role of magnetic accretion in the angular momentum evolution of young stars, consensus has yet to be achieved on the role of winds in this process (see, e.g., chapters by Shu et al. and by Königl and Pudritz; Camenzind 1990; Ferreira et al. 1997). Much theoretical effort has recently been devoted to the origin of collimated flows (bipolar flows, jets) at large distances, but the fact that the same systems also possess dynamically significant inner winds is sometimes overlooked. In the X-wind theory, which addresses the origin of both inner winds and spatially extended collimated flows, disk matter reaching the truncation region is loaded onto stellar field lines which diverge into funnel flows and magnetocentrifugal inner winds. Through the generation of these flows, the stellar field mediates the angular momentum redistribution that allows the star to both spin slowly and grow in mass. Thus, in the context of this theory, the strong stellar fields, funnel flows, and inner winds discussed in this section all play a fundamental role in the mass and angular momentum evolution of young stars.

While much of the work to date has focused on the role of stellar fields in the mass and angular momentum evolution of single, low-mass stars, recent work has begun to expand beyond these boundaries. For example, strong stellar magnetic fields may also be important in various aspects of planet formation. Lin et al. (1996) have suggested that the truncation of disks by a strong stellar field may play a role in halting inward planetary migration. An important issue for the future is the degree to which the current picture for the inner few R_* of cTTS applies to stars at earlier evolutionary phases, of higher masses, or possessing close companions. Remarkably, the spectroscopic diagnostics of the star-disk interface appear to be indistinguishable between stars with and without close companions (see chapter by Mathieu et al.), implying that the isolation of stellar components from the circumbinary disk through gap formation is not an impediment to the emergence of winds and funnel flows. Basri et al. (1997) have hypothesized that accretion streams traverse the gap and are channeled onto the stars via magnetic funnelling when they near the star (see §II.C), but more work is needed to understand how funnel flows and winds can exist in the absence of stable accretion disks.

III. THE INNER DISK

While there is now abundant evidence for the existence of circumstellar disks around young low-mass stars (see chapters by Wilner and Lay.; McCaughrean et al.), our understanding of the detailed properties of disks, especially at planet formation distances $\lesssim 5$AU, is still in its infancy. Early spectroscopic studies of this region in very young low-mass stars undergoing an outburst of mass accretion (i.e., FU Ori objects) focussed on demonstrating the existence of circumstellar disks. As discussed at PPIII, compelling spectroscopic evidence for rotating disks extending close to stellar surfaces had been obtained from high spectral resolution studies of these objects in the optical and near-infrared (Hartmann, Kenyon, and Hartigan 1993; see also Hartmann and Kenyon 1996 for a more recent update).

Since PPIII, it has become apparent that it is possible to carry out spectroscopic studes of circumstellar disks in a broader class of young stars, including the more quiescent T Tauri stars, and over a larger range of disk temperature and radius. This is good news since there is considerable motivation for detailed studies of the dynamics and physical and chemical structure of disks. Theoretical studies of a wide range of problems involving disk physics (e.g., the timescale and physical processes governing planet formation; see chapter by Wuchterl et al.) typically rely on assumed disk properties (e.g., the minimum mass solar nebula). The ability to directly measure disk properties and examine the range of variation among systems would allow us, among other things, to test and distinguish between theories of planet formation in order to better address fundamental questions such as the existence of solar systems like our own.

For example, the formation of stellar or planetary companions out of disk material is predicted to alter the physical structure of the disk, creating gaps through tidal torques and the excitation of spiral density waves (see chapters by Lubow and Artymowicz; Lin et al.). Developing probes of disk physical structure in order to obtain observational evidence in support of this picture is an important step toward confirming this particular aspect of planet formation theories. Measurements of disk molecular abundances are of interest as well since they can provide unique constraints on disk physical conditions and can constrain the extent of chemical processing that occurs in disks. Since measurements of disk chemical abundances would provide an observational context in which to interpret cometary abundances, which carry the fossil record of the conditions in the protosolar nebula, they may also provide important clues to the origin of our own solar system (see chapters by Langer et al. and Irvine et al.).

Due to the small angular sizes involved, the study of the detailed properties and physical structure of disks at $\lesssim 5$AU is currently restricted to the realm of high resolution spectroscopy, and spectroscopy of molecules in the infrared is particularly well-suited to this task. At the high densities and warm temperatures (2000−150 K) characteristic of disks at $\sim$0.1−5AU around low- to intermediate-mass stars, molecules are expected to be abundant in the gas phase, and sufficiently excited to produce a rich vibrational/rotational spectrum at near- and mid-infrared wavelengths. The ability of high spectral resolution studies to resolve individual lines improves the detectability of weak spectral features and provides the kinematic information by which the emitting region can be located in the disk. By measuring multiple resolved profiles, excitation temperatures and column densities can be determined as a function of disk radius.

We are only now beginning to address questions like those described above, due to the advent of sensitive, high resolution infrared spectrographs in the last decade (e.g., CSHELL at the NASA IRTF, CGS4 at UKIRT). In addition to the technological challenge of developing spectrographs with the necessary sensitivity, the study of planet formation environments is intrinsically challenging due to the likelihood that protoplanetary disks are optically thick in the continuum given expected vertical column densities at AU distances (e.g., $N_{\rm H} = 1500\,{\rm g\,cm^{-2}}$ at 1 AU for the minimum mass solar nebula). As a result, it is necessary to target for study optically thick regions with significant vertical temperature structure (a disk atmosphere) in order to detect measurable line emission or absorption. An alternative approach is to focus on regions of low column density that are created, for example, as part of the companion formation process, and search for line emission.

High resolution work to date on inner disks has focused on H_2O and CO, molecules that are likely to be among the most abundant in disks. In the following, we give examples of studies that use these diagnostics to probe both disk atmospheres and low column density regions. While we focus on emission diagnostics in this review, strong absorption in disk atmospheres is also straightforward to measure in disk systems with very high mass accretion rates (e.g., FU Ori objects and stars with associated Herbig-Haro objects; Hartmann and Kenyon 1996; Reipurth and Aspin 1997). The results demonstate the viability of high resolution spectroscopy for the study of inner disk properties, and illustrate the kind of diagnostic information that can currently be extracted from the data.

A. CO Overtone Emission

Due to its high dissociation energy, the CO molecule is expected to be abundant even at fairly high temperatures (< 5000 K). In addition, the excitation temperatures and critical densities of the first overtone bands ($\Delta v = 2$; $\lambda \sim 2.3\mu$m) make these transitions excellent probes of the warm, high density ($n_H = 10^{10-15}{\rm cm}^{-3}$) conditions that characterize inner disks (< 0.1AU).

Following upon the heels of the first detection of CO overtone emission from young stars (Scoville et al. 1983), early low spectral resolution surveys for overtone emission (e.g., Geballe and Persson 1987; Carr 1989) targeted young stars with energetic outflows, detecting a large fraction of sources ($\sim$20%) in emission over a range of stellar masses ($1 - 10{\rm M}_\odot$). The unusual combination of circumstances—*molecular* emission from gas at warm temperatures and high density—restricted possible explanations for the emission, and eventually led to proposals for an origin in circumstellar disks (Scoville et al. 1983; Carr 1989; Calvet et al. 1991) or outflowing winds (e.g., Carr 1989). Since excitation studies based on the low resolution data were unable to distinguish between the two scenarios, higher resolution observations capable of resolving line profiles have been used to obtain a more definitive diagnosis. Such studies are now straightforward with current high resolution (R$\geq$20,000) infrared spectrographs.

High spectral resolution studies generally find a spectral shape that strongly suggests a disk origin (Chandler et al. 1993, Carr et al. 1993, Najita et al. 1996b), particularly in the case of the sources studied in detail (e.g., WL16 and 1548c27). These observations, in fact, currently provide some of the best evidence for the existence of rotating disks around young stars. Excitation and spectral synthesis modeling of the overtone emission in objects covering a range of stellar masses shows that an origin in a vertical temperature inversion region in a Keplerian disk provides an excellent fit to the strength and shape of the emission (Fig. 3; Carr et al. 1993, Najita et al. 1996b, Najita, Greene and Lada 1999).

The model fits also place useful constraints on stellar properties (e.g., masses) and the thermal and physical structure of the inner disk. For low- and intermediate-mass stars, we typically find that the temperature distribution of the emitting gas in the inversion region is $T_d \sim r^{-q}$, where $q = 0.4 - 0.8$, the column density of the emitting gas typically decreases with radius over the range $\sigma_H \sim 0.1 - 1000\,\mathrm{g\,cm^{-2}}$, with the emission originating within $R \simeq 0.4$ AU. The origin of the inversion is presently unclear. Irradiation by the central star has been investigated by Calvet et al. (1991) and D'Alessio et al. (1998), but the importance of irradiation by the magnetospheric accretion shock has yet to be explored in detail. As noted by Carr et al. (1993), the inversion might also be due to hydromagnetic or hydrodynamic wave heating, or turbulent shear and subsequent heating generated by a stellar wind flowing over the disk.

Other proposed explanations for the origin of the emission encounter various difficulties. For example, the scenario in which the emission arises in an optically thin disk (e.g., Carr 1989; Chandler et al. 1995) is less likely since the absence of continuum emission over the range of disk temperatures from which the overtone emission arises cannot explain the strong near-IR excesses that accompany overtone emission. One of the primary difficulties facing the proposal that overtone emission arises in a wind is the likely inability of winds to produce the fairly symmetric emission line profiles that are observed, rather than P Cygni-like profiles with blueshifted absorption components (due to absorption by the wind of the hotter stellar and inner disk continuum), or a global line asymmetry due to the occultation of the receding flow by an optically thick inner disk (see also Najita et al. 1996b). In fact, the inability to detect winds via the overtone bands is somewhat of a puzzle given previous theoretical predictions of abundant CO in warm (~ 2000 K) stellar winds (Glassgold et al. 1991), and the indirect confirmation of low wind temperatures implied by the revised understanding that hydrogen line emission originates in funnel flows rather than winds (see §II and the discussion in Najita et al. 1996a).

The more recent suggestion that overtone emission arises from gas accreting along stellar magnetic field lines (Martin 1997) is interesting since, like winds, funnel flows should originate from a cool region of the disk that is likely to have abundant CO, at least in the case of low-mass T Tauri stars. While funnel flows may certainly produce some emission, the claim that they are solely responsible for the emission, and their relevance to the detection of emission from high mass objects, both require further theoretical study as well as detailed spectral synthesis and comparison to observed line profiles. Unlike the hydrogen emission lines which are produced near the stellar surface, overtone emission is more likely to arise from the cooler outer region of the funnel flow. Since the extent of the CO emitting region will be restricted by thermal and photodissociation processes, thermal models of funnel flows that consider additional heating sources (e.g., MHD wave heating; §II.B), and photodissociation models that include the UV flux of the accretion shock at the stellar surface will be needed to calculate accurate line intensities and profiles. More realistic dynamical models for funnel flows (including rotation) and radiative transfer that treats the background continuum of the star and disk are also required.

Variability studies can also constrain the origin of the overtone emission. Dramatic variations are known to be possible from the comparison of observations that are typically widely-separated in time. For example, at different epochs DG Tau has been observed to be strongly in emission (Carr 1989) and to have nearly zero emission equivalent width (Greene and Lada 1996). However, systematic variability studies are limited. The only synoptic monitoring study to date is the low resolution study of Biscaya et al. (1997) who studied known overtone emission sources of low and high mass. Based on low resolution spectra, these authors find significant variability of the emission equivalent width on timescales as short as a few days. If the variability timescale represents rotational modulation due to azimuthal structure, then this indicates that the overtone emission arises within several stellar radii.

The recent popularity of unbiased, moderate resolution spectroscopic surveys designed primarily for the spectral classification of young stars (e.g., Greene and Lada 1996; Meyer 1996; Luhman and Rieke 1998) has yielded as a by-product, improved statistics on the frequency of CO overtone emission from young stars. Studies of low-mass systems find that, consistent with the early results, CO overtone emission typically arises only in the most energetic low-mass systems, which constitute only a few percent of the sources in a given cluster. The infrequency of the emission is probably due to the high column density needed to produce detectable overtone emission. Since absorption in a late-type stellar photosphere could reduce the unresolved emission equivalent width in some fraction of sources, Carr and Najita carried out a small high resolution survey of sources in Taurus to search for additional overtone emission sources. Only 1 of $\sim$15 sources was detected strongly in emission, but weaker emission cannot be ruled out without further analysis. The incidence rate of emission among young high mass stars is less clear due to the small number of systems studied, but the current indication from studies of rich young clusters is that overtone emission may be more common among young high mass stars than low mass stars (e.g., $\sim$ 10% in M17; Hanson et al. 1997).

B. Hot Water Emission

Water vapor is also expected to be abundant in disks, and an excellent probe of the high density conditions between the thermal dissociation radius ($<$ 0.1 AU; $\sim$2500 K) and the ice condensation radius ($\gtrsim$ 5 AU; $\sim$150 K). In this region, H_2O is a strong molecular coolant, as well as the dominant source of infrared atmospheric opacity in the event of grain settling out of the upper disk atmosphere. Given its high abundance and the large number of radiative transitions capable of sampling a wide range in temperature, H_2O is an excellent diagnostic of the properties of circumstellar disks over a range of disk radii.

Ground-based studies of H_2O are challenging due to strong telluric absorption. However, because the higher excitation states of H_2O have transitions far from the vibrational band centers (e.g., at 1.4μm and 1.9μm), ground-based observations of water that is very much *hotter* than the Earth's atmosphere can be made in the wings of the H_2O bands. Water emission is detectable at low spectral resolution if the emission is very strong. For example, the shape of the $1-2.5\mu$m spectrum of SVS-13, which shows water emission in broad local maxima around the 1.4 and 1.9μm band centers, is a useful probe of physical conditions of the gas (Carr et al. 1999). Preliminary modeling of the low-resolution data confirms that the emission arises from hot ($\sim$2000 K) gas, i.e., at temperatures characteristic of disk radii $<$0.3 AU.

Much weaker water emission can be detected at high spectral resolution by studying individual, resolved lines located far from the vibrational band centers. Using this approach, hot H_2O emission has been detected in a small number of young stellar objects known to be strong CO overtone emission sources (Carr et al. 1999; Fig. 4). High-resolution spectroscopy in the 2μm window reveals that the water lines are consistently narrower than the CO lines, in agreement with a common origin for the CO and water lines in a differentially rotating disk with an outwardly decreasing temperature gradient. In such a situation, molecules with lower dissociation temperatures (e.g., H_2O) will tend to have narrower widths than those with higher dissociation temperatures (e.g., CO). In two sources, the expected double-peaked disk line profiles are observed (e.g., DG Tau; Fig. 4).

Because the water and CO overtone transitions probe similar physical conditions, the water emission is presumed to also originate in a temperature inversion in the disk atmosphere. More detailed modeling is needed to confirm this. At the moment, the primary obstacle to improved spectral synthesis modeling is the lack of complete water line lists in the near-infrared. Ongoing efforts are likely to produce rapid improvement in this area (e.g., Viti et al. 1997). Nevertheless, the ability to study multiple diagnostics (CO, H_2O) that originate from a common region in the disk atmosphere indicates the exciting future possibility of carrying out disk chemical abundances studies.

C. CO Fundamental Emission

The low-J CO fundamental (v=1−0) lines at 4.6μm are good tracers of disk structure at 0.2−2 AU due to their sensitivity to low column densities of gas ($\ll$ 1 g cm^{-2}) at temperatures characteristic of this range of disk radii (1500−300 K). Due to the difficulties of working in the M-band (high thermal background, variable atmospheric transparency), work to date on the fundamental transitions has been limited to only the brightest few low-mass young stars. Work by Carr, Najita, and Mathieu has targeted predominantly known spectroscopic binary systems in order to search for low column density regions (gaps) created by the dynamical interaction of companions with the disk.

The existence of gaps in disks around some young stars has been inferred from their spectral energy distributions (SEDs), both in known spectroscopic binaries (e.g., Mathieu et al. 1991; Jensen and Mathieu 1997) and in systems without known stellar companions (e.g., Marsh and Mahoney 1992). The SEDs in these systems show deficits of continuum emission over a limited range of wavelengths, consistent with a much reduced continuum optical depth over a range of disk radii. In spectroscopic binary systems, the implied gap sizes are generally consistent with those expected for dynamical clearing by the binary. For systems without known stellar companions, the altered disk structure could be due to unseen, perhaps planetary, companions.

Since structure in SEDs can arise for reasons other than disk gaps, it is difficult to use SEDs alone to diagnose the existence and properties of gaps. Less ambiguous studies of disk radial structure are possible with spectroscopy of residual gas in the gap which will appear in emission against the optically thin or absent dust continuum. Since the system parameters of spectroscopic binaries are typically well-known (e.g., stellar masses, sometimes inclination), spectroscopy of disk gas offers the considerable advantage that the radial location and extent of the emitting gas can be pinpointed using the kinematic information in velocity resolved profiles. The viability of this approach is demonstrated by the detection of CO fundamental emission from a number of close binaries, the first detections in low-mass pre-main-sequence stars. The resulting line profiles and relative line strengths are generally consistent with emission from residual gas in a gap created by the binary.

The results for the double-lined spectroscopic binary DQ Tau are representative of the current state of affairs. Figure 5 shows spectra of the v=1−0 R(3) and P(18) and v=2−1 R(10) and R(11) lines from DQ

Tau, along with model disk emission spectra. The line profiles locate the gas at $\sim$0.03$-$0.4AU. Remarkably, this is exactly the radial extent expected for a dynamically cleared gap in this system (Mathieu et al. 1997). The average excitation temperature is 1150 K with a typical disk column density of $5\times10^{-4}\,\mathrm{g\,cm^{-2}}$. Thus, the emission is produced by an extremely small amount of material, a total gas mass of just $10^{-5}\mathrm{M}_\oplus$. Interestingly, DQ Tau is one close binary system in which the expected dip in the SED is not apparent. Mathieu et al. (1997) postulate that a small amount of optically thin dust (corresponding to a total gas mass of $1.6\times10^{-4}\mathrm{M}_\oplus$ at 1000 K) resides in the cleared region. This is remarkably close to the mass required to produce the CO emission. The lower total mass implied by the fundamental observations could be due in part to the assumption of LTE excitation, as sub-thermal excitation is more likely.

Of possible relevance to the origin of the emission in DQ Tau are the observed modulation of the optical continuum veiling and emission line strengths at the orbital period which favors a scenario in which accretion streams from the circumbinary disk cross the gap and accrete onto the stars via magnetic funneling (Basri et al. 1997; see §II.C). Perhaps some of the gas that produces the CO fundamental emission also originates in the accretion streams.

Overall, the detection rate for the CO fundamental lines is very high; 5 of the 8 systems studied have been detected. The high detection rate, compared to that of CO overtone emission, probably reflects the lower column densities needed to produce measurable CO fundamental emission. Most of the detected systems are known spectroscopic binaries, but one is not known to possess stellar companions. These results indicate the potential of applying this technique to search for disk gaps induced by giant protoplanetary companions.

IV. FUTURE PROSPECTS

The results described above illustrate the contribution of high resolution optical and infrared spectroscopy to the exciting developments in our understanding of inner accretion disks. Many of the outstanding issues can be further explored, and potentially resolved, with the next generation of spectrographs on large telescopes. For example, the light gathering power of large telescopes, when coupled with the large wavelength coverage of cross-dispersed echelle spectrographs, is a powerful combination for studies of inner accretion disks. Tremendous progress in our understanding of stellar magnetic field strength and geometry is expected from infrared Zeeman measurements that will made with instruments such as the Keck NIRSPEC. The ability to measure multiple Zeeman-sensitive lines simultaneously will allow the unambiguous detection of Zeeman splitting, and robust determination of the surface distribution of magnetic field strengths and filling factors. Through Doppler imaging of accretion shock diagnostics (e.g., He I λ5876) in polarized light, it will be possible to map out the spatial distribution of accretion footpoints and examine their long-term stability.

Effective, long-term campaigns for spectroscopic monitoring of the star-disk interface will be possible with queue-scheduled telescopes such as the Hobby-Eberly Telescope. The ability to simultaneously monitor large numbers of lines that span a range in optical depth will aid in identifying rotationally modulated phenomena with which to study the dynamical relationship between stellar rotation and inflows and outflows. The same data may also reveal true time-variable phenomena that will probe the time stability of the star-disk interface. Possibly fruitful comparisons may be made with new dynamical models which specifically address the time-dependent nature of accretion and outflow (e.g., Hayashi et al. 1996; Goodson et al. 1997; Miller and Stone 1997).

Dramatic developments are also expected in the study of planet formation environments. The impact of 8-m class ground-based telescopes on this field can be illustrated by considering the possibility of detecting forming protoplanets via their dynamical impact on the parent disk, i.e., through the detection of line emission from a disk gap created by the protoplanet. If the CO fundamental work described in §III is extended to lower companion masses, the sensitivity of large ground-based telescopes translates into the ability to detect protoplanets with masses as low as a Jupiter mass at an orbital radius of 1AU around T Tauri stars 140 pc away. Until the development of milliarcsecond imaging capability in the thermal infrared, this technique offers possibly the best opportunity for detecting forming protoplanets.

Spectroscopic capability in the thermal infrared ($>4\mu$m) will be critical to the study of planet formation environments at large radial distances. Not only does the Planck function for disk material at AU distances peak in the mid-infrared, but this spectral region contains important suites of molecules with transitions that are well-excited at the lower densities and temperatures of disks at several AU (e.g., rotational H_2O lines). Despite its great potential for studies of planetary origins, the mid-infrared has remained largely unexplored due to the severe limitations imposed by large thermal backgrounds and strong telluric absorption. Thus, a large aperture, cooled telescope in space with spectroscopic capability has the potential for significant breakthroughs. Studies of disk structure and physical properties comparable to those possible from the ground could be carried out in star forming regions as distant as Orion, enabling studies of thousands of potentially planet forming systems (Carr and Najita 1997). In addition, the ability to observe above the Earth's atmosphere would allow the study of cool, molecular transitions that are inaccessible from the ground (e.g., H_2O, CH_4), but which are excellent, often unique, probes of the physical and chemical properties of planet formation environments. The large number of 8-m class telescopes to be available at the start of the next millenium offers the exciting opportunity to address these issues, as well as new issues of fundamental importance that have yet to emerge.

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FIGURE CAPTIONS

Figure 1. A series of line profiles taken at virtually the same time for the cTTS DF Tau. The MgII, CIV, and SiIV profiles were obtained by the GHRS on HST and the others were obtained at Lick Observatory with the Hamilton echelle. Note the blueshifted wind component and broad emission wings in the top 3 most opaque diagnostics, the redshifted peak for the next two (high temperature) diagnostics, and the nearly central peak for the next 2 less opaque optical diagnostics. The narrow central absorption in MgII and emission in NaI are probably not associated with the TTS. There is a high velocity redshifted absorption in NaI.

Figure 2. Trends as a function of continuum veiling are shown for representative permitted emission profiles in 4 cTTS. Veiling levels vary from 10 times to 0.5 times the photospheric flux, corresponding roughly to variations in mass accretion rate over 1.5 orders of magnitude. At Hα, blueshifted absorption attributed to formation in an inner wind is seen most prominently in stars with high veiling, while redshifted absorption attributed to magnetic funnel flows is only seen at Hα in cTTS with low veiling levels. Redshifted absorption is common in the the higher Balmer lines such as Hδ, and is found at most all veiling levels. Higher Balmer lines also often show additional absorption components near the stellar velocity that appear to bear no relation to veiling. Strong metallic features such as He I λ5876 are narrower than the Balmer lines and display a two-component emission profile. There is a tendency for stars with high veiling to have a prominent broad component, while stars wiht low veiling have a profile dominated by a narrow component.

Figure 3. (*Left*). Schematic synthesis of bandhead emission from a rotating disk. The rest distribution of CO lines near the v=2-0 bandhead (*a*) is convolved with the double-horned profile of a single isolated line from an inclined Keplerian disk (*b*) to produce the characteristic profile of bandhead emission from a rotating disk (*c*). Actual excitation and spectral synthesis modeling, when compared with spectra for objects such as WL16 (*d*), demonstrates that an origin in a temperature inversion region in a Keplerian disk provides an excellent fit to the data. (*Right*). The signature of bandhead emission from a rotating disk (*c*) is commonly observed in young stars over a range of masses: DG Tau ($\lesssim 1$ M$_\odot$), WL16 (~ 2 M$_\odot$), 1548c27 (~ 4 M$_\odot$), M17 CEN 24 (~ 10 M$_\odot$). In the DG Tau spectrum, the signature is less clear due

to strong stellar CO bandhead absorption.

Figure 4. Hot water emission from young stars. Individual emission lines (positions marked by vertical lines) are detected near the CO bandhead in (*a*) SVS-13 and (*b*) DG Tau. The water lines are narrower than the CO lines, in agreement with a common origin for the CO and water lines in a differentially rotating disk with an outwardly decreasing temperature gradient. In DG Tau, the water spectrum (*histogram*) is dominated by the strongest line (at $\lambda 2.2918\mu$m) which is broad and double-peaked. The rotational broadening of all the lines produces a blend of features that are well reproduced in the synthetic spectrum (*solid line*).

Figure 5. CO fundamental emission from the double-lined spectroscopic binary DQ Tau. Spectra of the v=1−0 R(3) and v=2−1 R(10) and R(11) lines (*Top*) and v=1−0 P(18) lines (*Bottom*) are shown, along with synthetic spectra of emission from an optically thin disk.