T TAURO STARS AND THEIR ACCRETION DISKS

GIBOR BASRI
University of California, Berkeley

and

CLAUDE BERTOUT
Institut d' Astrophysique de Paris

The T Tauri stars are solar-type stars in their pre-main-sequence phase. The main distinguishing characteristics of the classical T Tauri stars are excess continuum emission from the ultraviolet to the far infrared and strong emission in selected lines, particularly Hα. These characteristics are thought to be due to both mass influx and mass loss in the systems. Such flows are now thought to be due to the presence of an accretion disk around the star—the final phase of star formation and possible precursor to planet formation. The stars themselves are both more rapidly rotating and more convective than their main-sequence counterparts, which leads to increased magnetic activity, a partner in producing the "T Tauri phenomena." This chapter is focused on the evidence for accretion through a disk as the source of the emission excesses, particularly those seen in the continuum between 0.1 and 10 μm and in the strong permitted emission lines. We present a brief overview of the classical T Tauri phenomena, and a detailed discussion of how accretion-disk models can explain them. We explore their relation to the weak-lined T Tauri stars, and mention some effects disk accretion could have on the evolutionary status of young stars. Finally, we suggest some directions that research in this area should take in the near future.

I. INTRODUCTION

Since the realization that the Hα emission stars first studied by Joy (1945) are really solar-type pre-main-sequence stars, we have been presented with the opportunity to directly observe conditions that may have prevailed at the beginning of our own solar system. The principal defining characteristics of T Tauri stars currently in use (besides their late spectral types) are kinematic association with molecular complexes and presence of strong (Wₐ ≥100 mÅ) lithium absorption at 6707 Å. Both characteristics presumably reflect the youth of T Tauri stars. Hα emission, the historical defining criterion (Herbig 1962b), was shown over the last few years to signal only the most active fraction of young low-mass stars, now referred to as classical T Tauri stars (CTTS). Many late-type young stellar objects with Wₑₑ(Hα) ≤10 Å, discovered in X-ray surveys (see Walter et al. 1988; Feigelson et al. 1991), do not stand out at optical wavelengths but are relatively strong X-ray emitters.
\( L_X \approx 10^{-3} L_{\text{bol}} \). They are called weak-emission line T Tauri stars (WTTS) or sometimes naked T Tauri stars (NTTS), and may be several times more numerous than CTTS. The dividing line between these subclasses is somewhat arbitrary and ill defined; we suggest a physical division in Sec. V. The basic properties of WTTS are reviewed in the Chapter by Montmerle et al. Here, we are concerned mainly with properties and models of CTTS. Extensive reviews of these stars have recently appeared by Bertout (1989) and Appenzeller and Mundt (1989).

CTTS exhibit a number of spectral anomalies. In addition to H\( \alpha \) and Ca II lines, the higher Balmer lines are often also seen in emission. In almost half of the CTTS, there is also forbidden line emission of [O I] and, less frequently, of [S II] (Cohen and Kuhi 1979). In extreme T Tauri stars, i.e., in the strongest emission-line cases, many other emission lines of iron, titanium, sodium, helium and calcium are present. Excess continuum emission (over the continuum flux level of main-sequence stars with comparable spectral types) is also quite common, particularly in the ultraviolet and infrared spectral ranges. The infrared excess is discussed in Sec. II. The ultraviolet excess often carries into the optical range, where it "veils" the photospheric absorption lines, sometimes so heavily that their spectral type cannot be determined from low-resolution spectrograms but only from high signal-to-noise, high-resolution data. Compared to their main-sequence counterparts, these stars rotate rapidly (5 to 30 km s\(^{-1}\) or higher), but their rotation is quite slow compared to their breakup velocities (typically 250 km s\(^{-1}\)).

CTTS are irregular photometric variables at all wavelengths. The amplitude of the optical variability can be from a few hundredths of a magnitude to several magnitudes, and the lightcurves vary from star to star. The T Tauri class, as defined from spectroscopic characteristics (Herbig 1962b), indeed includes stars belonging to all three classes of nebular variables (see Glasby 1974).

There is a remarkable variety of unusual phenomena in T Tauri stars, which all fall into three basic categories: magnetic (chromospheric) activity, outflow phenomena, and accretion phenomena.

**A. Magnetic Activity**

From the outset, the superficial similarity of the emission spectrum in T Tauri stars to the solar chromosphere has been noted (Joy 1945). The line profiles, however, are typically much broader and more asymmetric than solar lines. Strong surface magnetic activity is established through a number of different diagnostics. The presence of light modulation with a period of a few days on some stars is thought to be a rotational modulation by sunspot-like concentrations of magnetic field in the photosphere; this interpretation is supported by detailed light-curve models in a few cases which suggest substantial surface coverage (Bouvier and Bertout 1989). The traditional chromospheric diagnostic, Ca II emission, is quite strong in T Tauri stars, and in WTTS the Ca II lines appear very much as they do on magnetically active
main-sequence stars. The amount and characteristics of the X-ray emission in WTTS are also entirely consistent with an origin in hot coronae such as those observed in RS CVn systems (see Chapter by Montmerle et al.). This conclusion is reinforced by evidence that the X-ray luminosity is a function of stellar rotation, accepted as a strong indicator of magnetic dynamo activity (Bouvier 1990). Finally, a technique for direct measurements of the total magnetic flux on T Tauri stars pioneered by Basri and Marcy (1991) indicates that it lies at the high extreme of the total magnetic flux seen on young main-sequence stars. Following a suggestion by Herbig (1970), it has been demonstrated that if the stellar chromosphere occurs deep in the atmosphere (at a continuum optical depth at 5000 Å of, say, 0.1 to 1), the fluxes of some emission lines might be reproduced and even the continuum jumps and veiling (Cram 1979; Calvet et al. 1984). Finkenzeller and Basri (1987) showed that differential filling-in of photospheric lines in WTTS is consistent with the deep-chromosphere explanation. The real difficulty with the hypothesis that the radiative excesses seen in T Tauri stars are caused by the presence of a deep chromosphere comes when one evaluates the total amount of excess energy present in the optical spectrum of CTTS with strong emission features. The true stellar photospheric contribution can be estimated by studying the absorption line spectrum (and the extent of veiling thereof). In some cases, the absorption lines are reduced substantially in depth across the spectrum, implying that major fractions or even multiples of the total photospheric luminosity appear as excess continuum light. These large radiative losses cannot be generated by solar-type magnetic dynamo processes alone even if one assumes complete coverage by active regions of the stellar surface (Calvet and Albarrán 1984).

B. Outflow Phenomena

The evidence for mass loss in young stellar objects is covered in the Chapter by Edwards et al. It suffices to recall here that mass-loss rates in the range $10^{-8}$ to $10^{-7} M_\odot$ yr$^{-1}$ were derived from simple models for the Hα line of a few bright CTTS (Kuhi 1964). DeCampli (1981) was first to emphasize the difficulty for a late-type, low-luminosity star to eject mass at such high rates. He discussed the constraints on outflow models imposed by observations and concluded that although Alfvén-wave-driven winds could conceivably be driving mass losses of a few $10^{-8} M_\odot$ yr$^{-1}$ in T Tauri stars, no known physical mechanism involving the star alone could account for the strongest CTTS winds. Further computations of Hα line profiles as produced by Alfvén-wave-driven winds by Hartmann et al. (1982) demonstrated that turbulent broadening was important in these winds, so that earlier models which neglected this effect systematically overestimated T Tauri mass-loss rates. The fact that only a few CTTS are detected at centimetric wavelengths (see, e.g., Bieging et al. 1984) apparently confirms that their typical mass loss is not greater than, say, a few $10^{-8} M_\odot$ yr$^{-1}$ in the wind's ionized component. But recent analysis of optical forbidden and neutral lines such as those of sodium have led to the belief that T Tauri winds
are mostly made up of atomic, rather than fully ionized gas, and the derived mass-loss rates soared again to much higher values (see Chapter by Edwards et al.). The exact mechanism by which the wind is driven out and collimated thus remains a major outstanding question in research on T Tauri stars and embedded young stellar objects.

C. Accretion Phenomena

First evidence for accretion in CTTS also comes from the shape of hydrogen line profiles. Walker (1972) identified a subclass of CTTS that he named YY Orionis stars after their prototype, which displayed (at times) inverse P Cygni profiles at their Balmer lines. Interestingly, another common property of these objects is their strong ultraviolet excess, which we now know is related to accretion (see Sec. III). Walker proposed that these stars were accreting matter, either through spherical infall or through disk accretion. Some of the work done in the framework of the spherical infall picture is summarized in the first Protostars and Planets book (Bertout and Yorke 1978). High-resolution spectroscopy later demonstrated that matter outflow was prevalent even in YY Orionis stars (see, e.g., Mundt 1984), and the spherical infall picture was abandoned. However, the evidence that mass accretion takes place in a number of CTTS at velocities in the 300 to 500 km s$^{-1}$ range, i.e., comparable to free fall, is clearly established. Simultaneous accretion and outflow of matter is also hard evidence that a successful model must reproduce. These two constraints originate from studies of YY Orionis stars, which thus appear to be primary test objects for realistic models of T Tauri stars.

Plausible explanations for all the different facets of T Tauri activity have appeared, vanished, and been resurrected several times. Most of the early models that were briefly mentioned above focus on one or the other of the above categories. However, a unifying picture has begun to emerge over the last few years. It involves a magnetically active, solar-type star, surrounded by the circumstellar disk that is the natural outcome of the gravitational collapse of a dense molecular core with nonzero angular momentum. In this picture, both CTTS and WTTS display the characteristic properties of the magnetically active central star, and the specific properties of CTTS result from interaction between the disk and the star. WTTS, on the other hand, have either lost their disks or do not interact with one.

The disk hypothesis has proved fairly successful in explaining many properties of T Tauri stars. The next section provides a review of the current observational evidence for disks, and Sec. III discusses existing accretion disk models compared with observed spectral energy distributions. Section IV deals with spectroscopic tests of the accretion disk model. Finally, Sec. V discusses some of the implications of accretion disks to the evolutionary status of young stars, with Sec. VI giving a summary. The obvious successes of simple disk models should not, however, hide the fact that very little is known about the underlying physics of disks, about the nature of the interaction between disk and star, and about the generation of protostellar winds. The

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truly successful paradigm which self-consistently explains all observational facts, particularly the relationship between accretion and outflow, has yet to be worked out. Our aim in the following is merely to point out that the successful model is likely to involve an accretion disk. Whether accretion is driven by viscous torques, as envisioned in current models, or by another mechanism is, in our opinion, still debatable.

II. EVIDENCE FOR CIRCUMSTELLAR DISKS

A primary reason supporting a disk geometry rather than a more isotropic distribution of dust comes from the visual extinction towards T Tauri stars. If the line of sight passed through the amount of dust required to produce the observed infrared luminosity, it would produce much greater extinction than is measured by the optical reddening of the T Tauri stars (Myers et al. 1987). The line of sight therefore must miss most of the dust present, which instead absorbs a fraction of starlight not coming towards the observer and then re-emits it thermally at infrared wavelengths into the line of sight. While for a single system one could be looking through a gap or hole in the dust distribution, the fact that this condition applies to most CTTS leaves little choice but to conclude that the dust distribution is substantially flattened.

A. Direct Imaging

At the distance of the closest star-forming regions such as the Taurus molecular cloud, a solar-system-sized disk (say, 100 AU) subtends an angle of 1.3'. The theoretical resolution of a 4 m telescope at 2 μm is about a tenth of that. Unfortunately, the portion of the disk which emits thermally in the near infrared is much smaller than 1 AU, so one must rely on detection of scattered light from the whole disk. In order to take full advantage of the increased scattering at shorter wavelengths, one should ultimately employ space instruments like HST. Reaching the diffraction limit on the ground is possible today only in the infrared because the coherence length of atmospheric turbulent elements at these wavelengths is large enough to be corrected for by current technologies (e.g., adaptive optics, interferometry).

Both infrared speckle interferometric and imaging techniques have already begun to provide direct images of circumstellar structures (see, e.g., Beckwith et al. 1985; Monin et al. 1990), but distinguishing between disk and other geometries from deconvolution of the data is difficult. Millimeter-wave interferometry currently provides a resolution of a few arcseconds and has the advantage of directly mapping thermal emission without interference from the star. Sargent and Beckwith (1987) mapped a flattened cool circumstellar structure around HL Tau, but it is much more extended than the solar system. The relationship between this structure and the warmer smaller flattened object "seen" at shorter wavelengths is still unclear. In any case, resolving protostellar disks has become a topic of hot international competition which
should bear fascinating results in the next few years. This topic is also dealt with in the Chapter by Beckwith and Sargent.

B. Spectral Energy Distributions

The suggestion that the CTTS might be accretion disk systems was made by Lynden-Bell and Pringle (1974; hereafter LBP), who foresaw and also worked out the main details of the current paradigm. They developed the theory of flat optically thick viscous disks and showed that an infrared continuum distribution ($\lambda F_{\lambda}$) flatter than a single temperature blackbody would result from the disk presence. It arises because the disk will be hotter nearer the star, due both to the increased absorption of stellar radiation by the disk and to the star's increasing gravity which increases the accretion power. The nearby dust contributes near-infrared light and the farther away cooler dust emits at increasingly longer wavelengths. The spectral slope is predicted by the LBP accretion disk model to vary as $\lambda^{-4/3}$. LBP also suggested that if the star were rotating slowly compared to breakup rotation (pure conjecture at the time), a strong ultraviolet excess would be generated in the boundary layer between disk and star. These ideas did not catch on at first, probably because the infrared and ultraviolet evidence that now makes them compelling was not then available. Thus, the previous edition of this volume (Black and Matthews 1984) shows the community feeling that disks may prove a very useful concept, but presents rather little hard evidence for them even at that time. An analysis of IRAS data by Rucinski (1985) then demonstrated that many CTTS had infrared spectral slopes that were more or less compatible with accretion disk models, and detailed analysis of CTTS spectral energy distributions at ultraviolet, optical, and infrared wavelengths confirmed the validity of the disk paradigm.

On the basis of a statistically significant study of the infrared sources in the $\rho$ Ophiuchi star-forming region, Lada and Wilking (1984) suggested the existence of three main classes of young stellar objects according to their near and mid-infrared spectra: Class I stars are optically invisible and their spectra rise steeply to the infrared; Class II stars look basically stellar in the optical but have infrared excesses which decrease more slowly than a blackbody in the infrared; and Class III stars have very little near-infrared excess. Adams et al. (1987) then proposed an interpretation of these classes in evolutionary terms: Class I are protostellar, embedded objects still surrounded by infalling molecular gas; Class II are more evolved objects with circumstellar disks that have expelled their infalling envelopes with the help of their strong winds (i.e., they are the CTTS); and Class III objects are pre-main-sequence objects (the WTTS) that have lost much of their circumstellar material.

All three classes may actually have disks. The presence of a disk in Class I sources is difficult to assess because the infalling cloud is also still present, but spectral energy distributions of these objects have been shown to be consistent with the presence of disks by Adams and Shu (1986). Infrared sources with flat spectra (in the $\log \lambda F_{\lambda}$ vs $\log \lambda$ plane) are intermediate between Classes I
and II. Because many of these are not well extinguished, it is likely that a disk is present. The flatness of the spectrum may come from a nonclassical temperature distribution in the disk (see Chapter by Adams and Lin), or reprocessing from dust out of the disk plane (Kenyon and Hartmann 1987). Alternatively, the overall spectral energy distributions of some of these objects might be composite spectra of several unresolved sources, as demonstrated by Leinert and Haas (1989) for Haro 6–10 and by Maihara and Kataza (1991) for T Tau itself. High-resolution infrared imaging of flat spectra sources will help settle this dispute. Most Class I and II objects, as well as a number of Class III stars (see Chapters by Strom et al. and by Montmerle et al.), are detected in the submillimetric and millimetric continua (see, e.g., Beckwith et al. 1990). This is again consistent with the presence of circumstellar matter but does not imply by itself any given geometry of the dust. Detailed models of spectral energy distributions of Class II sources based on the presence of a disk are presented in Sec. III.

C. Spectroscopic Evidence for Disks

Analysis of the optical and near-infrared line spectra of FU Orionis objects gives evidence for the expected differential rotation in the disk (see Chapter by Hartmann et al.). The cool, molecular disks surrounding CTTS do not allow similar analysis. In these objects, the strongest spectroscopic piece of evidence for the presence of a disk comes from a wind tracer, the [OI] and [S II] forbidden lines that form in low electronic density regions. The shape of these optical forbidden lines is typically asymmetric, with the red wing quite diminished or missing. This has been interpreted by Appenzeller et al. (1984) and Edwards et al. (1987) as the signature of mass loss from the star in which our view of the receding flow is cut off by the presence of a disk (see Chapter by Edwards et al.). With a naive analysis, the size of the disk implied by the emission measure in the forbidden lines is about 100 AU, although it might be substantially smaller if the electron density is smaller due to partial recombination.

D. Polarization Maps

Although the origin of linear polarization in young stellar objects has long been a matter of debate, scattering by dust grains recently emerged as the most likely polarization mechanism. Bastien and Ménard (1990) demonstrated that polarization maps of young stellar objects can be understood in the framework of multiple scattering in a disk/lobe geometry. Both the disk size and its view angle can be determined from a comparison of observed and synthetic maps (Ménard, in preparation). So far, this analysis is restricted to embedded sources surrounded by extensive disks. High-resolution near-infrared polarization maps are, however, becoming possible with the advent of 256×256 detectors and adaptive optics, and will soon make it possible to determine the main physical properties of T Tauri disks independently from other methods.
III. MODELS OF T TAUROI STARS

A. Basic Assumptions of Accretion-Disk Models

The current model of a T Tauri star consists of (i) a central late-type star surrounded by (ii) a geometrically thin, dusty accretion disk that interacts with the star via (iii) a boundary layer. Model spectral energy distributions emitted by such systems can be computed and compared to observations. The accretion-disk model devised by LBP and Shakura and Sunyaev (1973) assumes that local processes induce a viscous coupling between neighboring disk annuli, thereby transporting angular momentum through the disk. Note that there could be other, more global ways of redistributing angular momentum, e.g., through density waves. These are not considered in this model. Once a physical mechanism for transporting angular momentum is specified, the equations governing the disk structure, as well as its evolution in time, can be written down.

The basic angular momentum transport mechanism considered by LBP is kinematic viscosity. In a disk where the gas is rotating differentially, any chaotic motions in the gas will give rise to viscous forces (shear viscosity). Gas particles moving along two neighboring streamlines at \( R \) and \( R + dR \) with angular velocities, respectively, \( \Omega(R) \) and \( \Omega(R + dR) \) have different amounts of angular momentum. Random motions then lead to angular momentum transport resulting in a viscous torque exerted on the outer streamline by the inner streamline. This in turn will result in local dissipation of energy by the gas, and hence to mass accretion at a rate \( \dot{M} \) that is assumed constant throughout the disk. This assumption is made for convenience only; there is no a priori reason why viscosity should adjust itself in such a way as to make a steady-state disk. If one assumes that the disk is not self-gravitating, then its rotation is quasi-Keplerian, i.e., \( \Omega = \sqrt{G M_* / R^3} \), where \( M_* \) is the stellar mass and \( R \) the distance from the star’s center. The hypothesis of a quasi-Keplerian disk can be shown to imply that the disk is geometrically thin. The expression for the energy dissipation rate \( D(R) \) at \( R >> R_* \) is easily derived from first principles (see Adams et al. 1987). It is

\[
D(R) = \frac{\dot{M}}{4\pi} R \Omega \frac{d\Omega}{dR} = \frac{3GM_* \dot{M}}{8\pi R^3}.
\]  

No assumption regarding the physical properties of the kinematic viscosity is necessary to derive the above equation. If a rotation law other than Keplerian was valid as would be the case, e.g., if the viscous torques were of magnetic rather than kinematic origin, then \( D(R) \) would not necessarily be \( \propto R^{-3} \).

In order to determine the disk density, one must, however, assume something about the viscosity because its magnitude determines the angular momentum flow. LBP derive the disk density under the assumption that the kinematic viscosity is constant within the disk. Shakura and Sunyaev (1973) derive another analytical solution based on the same basic assumption but viscosity is assumed to be proportional to the local scale height times the local
sound speed, with the proportionality constant (called $\alpha$) being restricted to values $\leq 1$. Underlying this formulation are the ideas that turbulent eddies cannot be larger than the disk height and that any supersonic turbulence should rapidly become subsonic because of the formation of internal shocks in the disk. Both viscosity prescriptions are ad hoc parameterizations that reflect our ignorance of the nature of kinematic viscosity in disks; they give qualitatively comparable results for the run of density with radius.

The disk’s temperature structure determines the emitted spectrum. To compute it, one must make an assumption about the radiative transfer. LBP presented their hypothesis that viscous energy released in a given disk annulus is radiated away through both faces of that annulus and that the radial radiative flux is zero. While justified for the optically thick, geometrically infinitely thin disks envisioned by LBP, this assumption must be abandoned in the more complex radiative transfer approaches that are now being developed.

Also important for the disk temperature is the heating by stellar photons. Note that there are two ways in which the central star influences disk properties. Its mass and radius determine the potential well seen by the disk, i.e., the viscous energy dissipation rate, and hence the disk temperature. But the local disk temperature also depends upon the stellar effective temperature, which together with geometrical factors determines the local rate of heating by the central star. Adams and Shu (1986) and others computed the resulting disk temperature at the photospheric level. At large distance $R$ from the star, and assuming that the disk is flat and infinitely thin, one finds that the local rate of heating due to reprocessing of photons originating from a star with radius $R_*$ and effective temperature $T_*$ is

$$F(R) = \frac{2\sigma T_*^4 R_*^3}{3\pi R^3}. \quad (2)$$

This equation must be modified when the disk is not flat (Kenyon and Hartmann 1987; Ruden and Pollack 1991), or when a finite disk atmospheric structure is taken into account (Malbet and Bertout 1991). At large distances from the central star, the above assumptions lead to the following equation for the disk effective temperature $T_D(R)$:

$$\sigma T_D^4(R) = \frac{3GM_*/M}{8\pi R^3} + \frac{2\sigma T_*^4 R_*^3}{3\pi R^3} \quad (3)$$

where the first term on the right-hand side represents the viscous energy dissipation rate and the second term takes into account the reprocessing of stellar photons. Note that both terms are proportional to $R^{-3}$ in flat, Keplerian disks. This means that it is difficult to determine whether a disk is passive (purely reprocessing) or active (accreting), from the infrared alone. Only when the infrared luminosity is more that 50% of the stellar luminosity (25% for a flat disk) can one be certain that accretion is taking place (see Hartmann and Kenyon 1987a), but in either case, the presence of a disk is indicated.
Analyses by Strom et al. (1988) and Cohen et al. (1989b) show that at least the most active of the CTTS can be shown to be accreting on that basis.

Equation (3) describes the temperature far away from the central star. When computing the inner disk structure, one must assume something about the inner boundary of the disk, and more specifically about the way angular momentum is transferred from disk to star. LBP imposed the condition that the star exerts no torque on the inner edge of the disk, which also implies the existence of a boundary layer between the slowly rotating T Tauri stars (typically 20 km s\(^{-1}\) at the equator; see Hartmann et al. 1986 and Bouvier et al. 1986a) and the inner edge of the Keplerian disk, where matter is circling the star at about 250 km s\(^{-1}\).

The LBP inner boundary condition assumes that the extent \(b\) of the boundary layer is much smaller than the stellar radius and that the angular velocity at the inner disk edge is comparable to the Keplerian velocity at the star, i.e., \(\Omega(R_* + b) \sim \sqrt{GM_*/R_*^3}\). Energetic properties of the disk/boundary layer system directly follow from this inner boundary condition. One finds for the disk luminosity \(L_D\) and the boundary layer luminosity \(L_{bl}\):

\[
L_D = \frac{GM_*\dot{M}}{2R_*} = \frac{L_{acc}}{2} = L_{bl}.
\]

One thus concludes that half of the total accretion luminosity \(L_{acc}\) is advected from the disk into the boundary layer; this corresponds to the Keplerian kinetic energy rate at the inner disk radius. Now, however, this energy must be dissipated in a small region at the star’s equator instead of over a disk many AU in extent. This means that the temperature of the radiating region will be far higher. While temperatures in the disk range from 10 K far from the star to about 3000 K near the star, the boundary layer’s temperature will be from 7000 to 12000 K (Bertout 1986; Kenyon and Hartmann 1987), and will radiate in the ultraviolet and visible part of the spectrum. As seen below, this is probably the source of the ultraviolet excess and optical veiling observed in many CTTS.

It should, however, be emphasized here that the LBP inner boundary condition maximizes both the boundary layer’s luminosity \(L_{bl}\) and its temperature. \(L_{bl}\) can be reduced in two ways. First, if the star rotates at some angular velocity \(\Omega_*\), then the boundary-layer luminosity is reduced to

\[
L_{bl} = \frac{GM_*\dot{M}}{2R_*} - \frac{MR_*^2\Omega_*^2}{2}.
\]
accretion energy could be released in nonradiative form, e.g., for driving a wind (see Pringle 1989a). One should therefore be aware that all comparisons of observed and computed spectral energy distributions done so far assume that half of the accretion luminosity is radiated away in the boundary layer.

B. Comparisons with Observations

Accretion disks and boundary layers in T Tauri systems have been reviewed several times in the last few years (Basri 1987; Kenyon 1987; Hartmann and Kenyon 1987a; Bertout 1989; Bertout et al. 1991a). Class II infrared sources turn out to be the best examples of “classical” accretion disks. Their infrared spectra are at least as shallow as demanded by the simple flat disk model; most are actually shallower (see Chapter by Beckwith and Sargent). Rydgren and Zak (1987) showed that the average slope of CTTS infrared spectra beyond 5 μm or so is \( \propto \lambda^{-3/4} \) rather than \( \lambda^{-4/3} \), which probably means that the simple model discussed above needs refinement. Two basic suggestions have been made to explain the fact that the observed infrared spectra are flatter than the LBP disk model predicts.

![Figure 1](image.png)

Figure 1. The optical depth distribution in a typical T Tauri accretion-disk model. The heavy-lined contour corresponds to a Rosseland optical depth of 1, and successive contours differ by 0.5 dex. In the case illustrated here, the optically thick disk has a diameter of about 20 AU.

The first of these assumes that the disk flares up out of the plane at large radii, thus intercepting (and thermally re-emitting) more stellar photons in the outer parts than in a thin disk. Some flaring is expected even in classical accretion disks because the local disk height \( H \) determined from hydrostatic equilibrium scales as \( R^{9/8} \). Kenyon and Hartmann (1987) showed that such a geometry would partially explain the infrared discrepancy if the disk remains opaque over its full height. However, flared-up disks do not really do an adequate job of explaining the truly flat infrared spectra. Also, the disks need to subtend a large part of the sky as seen from the star in these extreme cases.
and then one would expect a greater incidence of large extinctions in CTTS. Furthermore, Malbet and Bertout (1991) computed the vertical structure of T Tauri disks in a self-consistent manner and found that the optically thick parts of the disk are confined to regions close to the central plane of the disk even if gas and dust remain mixed together for the required length of time, which is another problem. This result is illustrated by Fig. 1, which displays the optical thickness distribution in a typical T Tauri disk with mass-accretion rate $1 \times 10^{-7} M_\odot$ yr$^{-1}$ as a function of both disk radius and disk height over the midplane. The innermost contour corresponds to Rosseland optical thickness $\log \tau = 1.5$, and successive contours differ by 0.5 dex. The heavy-lined contour corresponds to $\tau = 1$, and thus approximately indicates the physical disk size, here about 20 AU in diameter. In order for the infrared spectrum to steepen up with respect to the usual $\lambda^{-4/3}$ law, the disk should be optically thick all the way out to the outermost contour, which roughly corresponds to $H \sim R^{9/8}$.

The second suggestion, made by Adams et al. (1988), assumes that the temperature distribution in T Tauri disks is flatter than in LBP disks, which implies that the disk’s temperature distribution does not result from kinematic viscosity. Following this suggestion, it has become common practice to parameterize the temperature law index and to use different values of this parameter to model infrared distributions of young stellar objects, particularly those with flat infrared spectra (see, e.g., Beckwith et al. 1990). Using the temperature law as a free parameter is equivalent to implicitly assuming that the energy dissipation mechanism in the disk differs from star to star. A possible physical mechanism to accomplish this has been speculated on by Shu et al. (1990), who invoke a lowest-mode gravitational instability which would operate in disks which are more than 0.24 the mass of the star (see Chapter by Adams and Ruden).

At this point, one must conclude that the far-infrared spectral energy distributions of many T Tauri stars do not fully support the hypothesis that T Tauri disks are really classical accretion disks as proposed by LBP, although there are a few stars, such as DF Tau, which fit the classic model very well. A further problem is that the infrared spectrum alone does not allow one to distinguish between passive reprocessing disks and true accretion disks as long as the accretion luminosity is smaller than or comparable to the reprocessed luminosity, i.e., $\dot{M}_{\text{acc}} \lesssim 5 \times 10^{-8}$ $M_\odot$ yr$^{-1}$.

Why then do we believe that accretion disks actually surround most CTTS even when the infrared luminosity excess is not decisive? The decisive argument comes from the blue and ultraviolet spectral ranges. The excess light there has all the properties expected of boundary-layer emission. At the same time, the accretion only occurs near the equator of the star and so avoids the problems that a strong accretion shock over the entire star posed for spherical accretion models. Even more important, the amount of energy available depends solely on the accretion rate and not on the star’s resources. This resolves the mystery of how the photospheric spectrum can be so veiled in some cases.
The disk paradigm explains naturally the observed correlation between the respective amounts of infrared and ultraviolet excesses. Even the widespread observations of Balmer continuum emission jumps can easily be explained if the boundary layer is optically thin in the Paschen continuum (Basri and Bertout 1989). Of course, there are still questions regarding the actual geometry and extent of the interface region between disk and star, and to what extent it dissipates energy in nonradiative forms (e.g., material motions). For example, the maximum velocities present in the boundary layer are similar to those seen in the broad emission-line components, suggesting that the broad emission lines are partly formed in the boundary layer and connected regions; this is a topic of current work (see Sec. IV).

There are fairly few free parameters in the simple models that have been analysed so far. Some are associated with the star itself: the stellar mass, effective temperature and radius. In principle, these are all known from the comparison of the position of the star in the Hertzsprung-Russell (HR) diagram, with stellar pre-main-sequence evolutionary tracks. In practice, only the stellar temperature is known with reasonable accuracy. Even that is somewhat uncertain because some temperature estimates are based on the optical colors of the system, with no consideration of the boundary layer's effect on them. Other spectral-type estimates based on stellar spectral features should be more reliable. The effect of disk accretion on the luminosity of the system makes it difficult to estimate the stellar radius precisely. An additional constraint on the radius is provided when both the rotation period (through starspots) and the projected rotation velocity (through spectral line broadening) are known. These constrain the radius and inclination jointly. The mass is also uncertain, because the evolutionary tracks themselves are somewhat uncertain (Sec. V), and among the lower mass stars the convective tracks are crowded together. The central star is typically 0.5 to 1.3 $M_\odot$, with a radius from 1.5 to 3.5 $R_\odot$ and luminosity several times that of the Sun.

Another parameter not directly related to the disk is the external extinction to the system. It is difficult to distinguish between circumstellar extinction caused by dust which is near enough to the star to reprocess optical light into the infrared, and true extinction which is due to dust far enough away that the light is fully lost from the beam. A distinction must be made between them, because the latter changes the bolometric flux observed, while the former merely redistributes energy from one wavelength to another. Neither is directly associated with the disk, because a flat disk is unlikely to remove any light coming directly from the star toward the observer. Extinctions are estimated from the reddening of the observed light compared to the expected stellar intrinsic spectral energy distribution. Obviously the presence of the boundary layer makes such determinations uncertain, as its intrinsic spectral energy distribution is now not known \textit{a priori}.

In addition to those, there are several parameters associated with the disk itself. Of these, the mass and size of the disk are not really a concern because it is assumed that the disk is optically thick, and that its size is sufficiently
large not to affect the infrared spectrum. Of course, if one were to consider the spectrum down into the sub-millimetric range these parameters become important, along with details of the grain opacity (see Chapter by Beckwith and Sargent). Another parameter in the disk is the value of the $\alpha$ parameter which is a measure of the strength of turbulent viscosity in the disk. Here there is little theoretical guidance. The largest values derived theoretically are of order $10^{-2}$ from convection (Lin and Papaloizou 1985). Inferred values of $\alpha$ range up to unity, or greater in cataclysmic variables (Lin et al. 1988). Basri and Bertout (1989) found that setting $\alpha$ to unity was acceptable for most cases, although for lower accretion rates it might easily be of order $10^{-1}$ to $10^{-2}$. They adopted the philosophy that it should not be used as a free parameter, but fixed arbitrarily at a certain value. For optically thick disks, this leaves the mass accretion rate as the main free parameter for the disk. The other parameter associated with the disk is the inclination of the disk plane to the line of sight, which acts primarily as a scaling parameter on the observed flux, due to foreshortening.

Bertout et al. (1988) compared quasi-simultaneous sets of data in the ultraviolet/optical and optical/near-infrared ranges to synthetic spectra emitted by models of a T Tauri system made up of a late-type active star, an accretion disk and its boundary layer. They found that typical T Tauri disks are optically thick over most of their surface so long as $\alpha \leq 1$ and that the spectral energy distribution of typical CTTS can be reproduced from about 0.2 to 10 $\mu$m if emission from the (isothermal) boundary layer is confined to an equatorial region with width comparable to the local disk scale height ($\sim$2% of the stellar radius).

Positive aspects of this simple model are its self-consistency and its small number of free disk parameters (essentially the disk mass-accretion rate and view angle), while a major drawback is the assumption of an optically thick boundary layer. Observed Balmer jumps indicate that the Paschen continuum is at least partially optically thin. Basri and Bertout (1989) therefore computed monochromatic gas opacities in the boundary layer, which is again assumed to be isothermal. They made the boundary layer width $\delta_{BL}$ an additional free parameter (rather than $\alpha$) needed to control the optical depth, and computed emergent spectral energy distributions that they compared to observations of the Balmer and Paschen continuum regions. While the head of the Balmer continuum is optically thick in these models, the Paschen continuum is partially optically thin and the Balmer jump consequently appears in emission. A similar analysis by Kenyon and Hartmann (1990) leads to similar results. An example of the observations and fit to them for DF Tau appears in Fig. 2.

Line emission from the Balmer lines with high quantum number appears consistent with optically thick line emission from the boundary layer. The emitting area is at most a few percent of the stellar surface area. There is obviously a more extended region of emission which contributes to the flux in the lowest members of the Balmer series, as these are predicted to have very little emission contrast in the simple boundary-layer model.
Figure 2. Simple disk model fits for the classical T Tauri star DF Tau. Upper panel: The solid lines are spectrophotometry (with a gap in data near log \( \lambda = -4.3 \)) and the composite model fit in the optical range. The dashed lines are flux from the disk (lower right) and an optically thin boundary layer. The lower faint line is a model stellar spectrum by itself. The parameters discussed in the text have been chosen to give a good fit. Lower panel: The same model in the optical and near infrared. The data points are simultaneous photometric fluxes from the star, and the lines are as in the upper panel. Note how the star is not the dominant contributor to the light on either side of the optical range.
C. Derived Disk Parameters

Modeling the spectral energy distributions of T Tauri stars allows one to derive key parameters such as the accretion rate and disk mass. Finding accurate mass-accretion rates from the disk onto the star is important because: (i) if sufficiently high, accretion is expected to affect the evolution of the star in the HR diagram (Kenyon and Hartmann 1990); (ii) one also expects that accretion of disk matter (which possesses high specific angular momentum) will affect the evolution of rotation in CTTS; and (iii) there is growing evidence of a relationship between mass accretion and mass loss (Cohen et al. 1989b; Cabrit et al. 1990; Chapter by Edwards et al.). The efficiency of mass gain/loss conversion is important both for understanding the mass-loss mechanism and for issues (i) and (ii) above. By assuming a classical disk model, mass-accretion rates ranging from a few times $10^{-9}$ to a few times $10^{-7} \, M_\odot \, \text{yr}^{-1}$ can be determined from models of individual stars (Basri and Bertout 1989). Crucial questions remain about the validity of these values: are they highly dependent on the assumed disk model, and are they more or less unique, or can we find several solutions leading to the same spectrum but with very different mass-accretion rates? These questions are discussed in detail by Hartmann and Kenyon (1987a), Basri and Bertout (1989), Bertout and Bouvier (1989) and Bouvier and Bertout (1991).

Bertout and Bouvier (1989) studied the uniqueness problem by constructing maps of the quantity $1/\chi^2$, which measures the goodness of the fit between observed and computed spectral energy distributions, for all possible pairs of parameters. They used 6 computational parameters: the stellar radius $R_*$, the visual extinction in front of the system $A_V$, the inclination angle $i$, the accretion rate $M_{\text{acc}}$, the viscosity parameter $\alpha$, and the width $\delta_{BL}$ of the emission region associated with the boundary layer. In their analysis of DF Tau, for example, the best solutions (with high $1/\chi^2$) span a small range of mass-accretion rates: $M_{\text{acc}} \sim 1$ to $2 \times 10^{-7} M_\odot \, \text{yr}^{-1}$. It thus appears that the mass-accretion rate can be estimated within a factor of 2 from these models. This result stems from the fact that the mass-accretion rate primarily reflects the relatively well-determined quantity of integrated excess flux in the near infrared.

The two parameters $\alpha$ and $\delta_{BL}$ contain most of the assumed physics for the disk and boundary layer. Given the large range of parameter values that the solution spans, it is reassuring that best fits to the overall spectrum (also including the Balmer jump) were obtained for values $\alpha \sim 1$ and $\delta_{BL}/R_* \sim 0.02$. This appears physically reasonable and gives us some confidence both in the validity of the underlying disk physics and in the $\alpha$ parametrization. Even more reassuring, the best fits produce continuum veiling compatible with the observed amount.

Similar computations were made for 10 CTTS (using new simultaneous data sets to be published by Bouvier, Basri and Bertout spanning the ultraviolet to the near infrared) in the spectral-type range K1–M1. They yield an average
mass-accretion rate of \( \langle \dot{M}_{\text{acc}} \rangle = (1.4 \pm 1.2) \times 10^{-7} M_\odot \text{ yr}^{-1} \). Because these systems are rather variable (due to unsteady accretion?), observations from the ultraviolet, optical, and near infrared must be gathered at the same time to make confident determinations of system parameters.

Approximate estimates of the mass and maximum radius of CTTS disks can be made by modeling the spectral energy distribution in the sub-millimeter and millimeter range, using the sharp turnover of the spectrum that occurs in that spectral range because the outer disk becomes optically thin. Adams et al. (1990) and Beckwith et al. (1990) recently presented such computations, based on the assumption discussed above that the temperature distribution in the disk is a free parameter that can be adjusted to get an overall fit to a given spectral energy distribution. While this \textit{ad hoc} assumption introduces some uncertainty in derived disk masses, the main source of uncertainty stems from lack of knowledge of dust opacities in the millimeter range: depending on the assumed opacity law, mass estimates can vary by up to 1 order of magnitude. One thus finds that masses of CTTS disks may range from \(< 10^{-2}\) to perhaps as much as \(1 M_\odot\).

**IV. SPECTROSCOPIC DIAGNOSTICS OF DISK ACCRETION**

It is clear from the last section that further observational constraints on the parameters of the disk models will be very helpful. One clearly relevant accretion diagnostic is the amount of spectral veiling (actually the amount of excess continuum light) in the optical spectral lines. The strong broad optical emission lines are a second such diagnostic; they should in principle reflect the physical properties of the region where the mass loss originates.

**A. Spectral Veiling**

Veiling is defined by

\[
 r(\lambda) = \frac{f_{\text{obs}}(\lambda)}{f_*(\lambda)} - 1
\]

where \( f_{\text{obs}} \) is the observed flux and \( f_* \) the photospheric flux. It can be estimated by comparing the veiled (observed) spectrum with an appropriate spectral standard. One then finds that all the same lines are present and in the same ratios, but all the line depths are reduced in the CTTS. This was done quantitatively at one wavelength by Hartmann and Kenyon (1990), and over a broad spectral range for one star by Hartigan et al. (1989a) and for an extensive sample of stars by Basri and Batalha (1990) and Hartigan et al. (1991). Their efforts yield excess light as expected from accretion disk models, with wavelength dependence as predicted by hot boundary-layer models. The excess light does not show features unexpected for the optically thin emission that has been postulated.

A measurement of veiling is useful for several reasons. It allows one to correct the observed spectrum for nonstellar emission independent of extinction corrections. This allows in turn a proper estimation of the extinction from
the remaining reddened stellar spectrum (Hartigan et al. 1991), and thereby a constraint on the radius of the star (assuming distance is known). It also fixes the level of the boundary-layer emission. Thus, one should demand that disk models produce the observed veiling in detail, constraining the boundary-layer temperature and size along with the extinction, accretion rate and stellar radius. Obviously veiling by itself does not determine all these parameters, but inasmuch as it acts as a further constraint on disk models, it significantly improves the uniqueness of solutions. As veiling is the result of a particular disk model rather than an input parameter, there is no \textit{a priori} guarantee that models which fit the overall spectral energy distribution best will also give the right veiling value.

In their detailed study of DF Tau, Bouvier and Bertout (1991) compare model predictions with empirical average veiling values of $1.6 \pm 0.3$ at 5000 Å and $1.0 \pm 0.3$ at 6500 Å (Basri and Batalha 1990). The acceptable solutions that were found for the disk parameters, after the $\chi^2$ minimization procedure mentioned above, produced veiling values ranging from 1.55 to 1.9 at 5000 Å and from 0.6 to 0.75 at 6500 Å, in fair agreement with the observations although they were not obtained simultaneously with the spectral energy distributions. Veiling varies in time by factors which can be as large as 10 in some stars (Basri and Batalha 1990). In order to take full advantage of this additional constraint on the models, it is thus mandatory to measure veiling at the same time as the spectral energy distribution.

Basri and Batalha (1990) and Hartigan et al. (1990a) showed that the measured veiling has the relation to infrared excess expected if both are due to accretion and also that Hα emission flux is closely related to veiling. Cabrit et al. (1990) and Bertout et al. (1991b) showed that the emission lines in general are correlated with infrared excess, as expected from accretion (and not from a chromospheric origin).

B. Broad Emission Lines

Hα in particular has the breadth and profile expected from a moving extra-stellar region, yet it remains one of the least understood aspects of the T Tauri phenomenon and one of the most fascinating because of the variety of line profiles and their temporal changes. First statistics of line shapes were presented by Kuhn (1978) in the first volume of \textit{Protostars and Planets} (Gehrels 1978) and by Ulrich and Knapp (unpublished catalog). It has recently become possible to monitor emission lines spectroscopically with high resolution and signal to noise, which will hopefully allow clarification of our understanding of the emission lines in the next few years. A first important result of this monitoring is the fact that the Hα line comes in three basic shapes.

1. The most common is broad emission with fairly symmetric far wings extending to 200 to 400 km s$^{-1}$ and a blueshifted absorption feature near 100 km s$^{-1}$ that usually does not go below the continuum. This yields emission peaks with the red usually brighter than the blue.

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2. Less common is a more or less flat-topped emission feature, possibly with central absorption that can be unshifted or shifted to either side.
3. Finally there are fairly symmetric triangular (more sharply peaked than gaussian) shaped emission lines, often with little or no absorption.

These shapes can be seen in the other Balmer lines (although for these, the absorption goes more often below the continuum) and in other strong emission lines. The weakest of these seem to have a preference for the triangular shape with little absorption. The large degree of symmetry seen in broad lines argues for a substantial orbital or turbulent component in the velocity broadening. Although the origin of triangular lines is still controversial, such shapes may well arise due to variable turbulent velocities of comparable brightness (Basri 1990). In some cases (see, e.g., Basri 1987), especially in weaker lines like the Ca II infrared triplet or He I lines, one clearly sees both a low-lying broad component and a narrow, undisplaced emission peak. The less active stars tend to show only the narrow component. It is tempting to associate this component with the chromosphere or with filled magnetic loops on the star.

The variability of broad emission lines is puzzling. The same line can have quite a stable appearance in some objects, while in others it undergoes large intensity changes with little change in its profile (e.g., $\text{H}\alpha$ in DF Tau); and still again in others, it changes its shape dramatically. Figure 3 shows an example of $\text{H}\alpha$ line profile variations seen in twice nightly observations of DR Tau and obtained by Basri with the 24" coudé feed and the Hamilton echelle spectrograph at Lick Observatory. They show that the intensity of the line varies substantially within a few hours, and also that the absorption velocity structure is quite changeable. The appearance of a true P Cygni absorption feature is ephemeral, as is the more usual lower-velocity feature common to T Tauri stars. This means that these features arise in a fairly small region themselves, and the mass outflow is probably very clumpy and changes its structure.

A smooth axisymmetric outflow is probably not a good model, although it may be a useful first approximation. The blue-displaced absorption components do not vary as much as the emission intensity and probably arise in a larger, more distant region. One can look for correlated changes in accretion and outflows in such data, which could establish a direct connection between them. As another example of an extreme case, the same Ca II line in the same star (RW Aur) has shown all three basic shapes discussed above (Bertout et al. 1991b), which may mean that they are compatible with different manifestations of a common underlying structure. The Balmer decrement can be very large, i.e., $\text{H}\alpha$ can be much brighter than the higher Balmer lines relative to the local continuum. This probably means that $\text{H}\alpha$ arises from a substantially larger geometrical area than other Balmer lines. These lines can vary in intensity and shape on time scales down to an hour or less (see, e.g., Mundt and Giampapa 1982; Basri 1990), indicating that they most likely arise in small regions quite near the star.
Figure 3. A time series of Hα profiles from the classical T Tauri star DR Tau. The dotted line in each panel is the preceding profile repeated for comparison. The numbers are the Julian date (without the initial 244), corresponding to 27–31 Oct. 1989 (twice nightly). Each profile is in the same continuum units, and all the abscissas are stellar rest velocities from –500 to 500 km s\(^{-1}\). The profile has both low and high velocity blueshifted absorption for the first half of the run, with the typical simpler T Tauri profile in the latter part. There is a pronounced P Cygni character on 7827.1 JD, and almost no absorption at 7830.6 JD. The red wing is much less variable than the blue side or peak. The total equivalent width is also rather variable, due to changes in both absorption and emission levels.

The boundary layer is an obvious candidate for the line emission region (Basri and Bertout 1989), as it is small, fast moving, turbulent, and energetic. However, inverse P Cygni line profiles seen in YY Orionis stars indicate infall velocities of several hundred km s\(^{-1}\) which cannot arise in the boundary layers of classical disk models, where accretion velocities are restricted to the subsonic. It is our intuition that strong stellar magnetic loops may interrupt the flow of the disk within a few stellar radii of the surface, generating the shocks, turbulence and heating that we have been designating as the boundary layer. Flow down such tubes could reach near free-fall velocities, and a modulation of the accretion (emission intensity or veiling) with the stellar rotation period
would establish that the emitting region was in the interface between star and disk. There have already been a few reports of "hot spot" modulations (see, e.g., Bertout et al. 1988; Simon et al. 1991) which could be interpreted as accretion columns onto magnetic stellar regions.

It may well be the same thing to say that the lines arise in the boundary layer (now being used in the less restrictive sense of the interface region between star and disk) or that they arise in the base of the wind. In this picture, some material would accrete down through the magnetic loops, while other material would be turned back and flung out in the T Tauri wind. Some relevant theoretical ideas on this still controversial view can be found in the Chapter by Königl and Ruden. The development of this picture, where magnetohydrodynamic processes are probably dominant, will be a major task of the coming decade.

V. IMPLICATIONS OF DISKS AND ACCRETION

One must be careful about what is meant by "classical" T Tauri stars and "weak line" T Tauri stars, because there is really a continuum of stars between the two classes as defined by Hα strength. If there is (i) a substantial near-infrared excess (and this is best measured from 2 to 10 μm) compared to the flux expected from a star alone, (ii) Balmer continuum emission, or (iii) strong Hα emission (say more than 10 Å equivalent width in a late K star), then we conclude from the evidence discussed above that an accretion disk is present. Its presence could serve as the (physical) definition of a CTTS. Note that accretion is the crucial part of this definition. Stars without disks or with disks which do not reach their surfaces will appear as WTTS, while a lack of excess emission at any wavelength is required for the star to truly be a naked (and thus diskless) T Tauri star.

The exact relationship between CTTS and WTTS is unclear at present, and work to clarify it should be encouraged as it is one major key for understanding the formation of low-mass stars. A crucial fact is that WTTS are well intermingled with the CTTS both spatially and on the HR diagram (i.e., temporally). Also, the WTTS have lithium lines similar to the CTTS (Strom et al. 1989e; Basri et al. 1991) after correction for continuum veiling. This result also points toward similar ages in the two populations. Furthermore, the distributions of rotational speeds in WTTS and CTTS are similar (see Feigelson et al. 1991). These findings are curious because if steady-state accretion proceeds during a sizable time, then disk accretion could contribute a significant fraction of the stellar mass in CTTS, with noticeable consequences in the star's evolution, and should also alter its angular momentum history. Königl (1991) has suggested that if the stellar magnetic fields are strong enough and stretch well beyond the corotation radius, the disk will not transfer much angular momentum to the star anyway.

Current estimates based on classical convective-radiative evolutionary tracks indicate that accretion disks last up to a few Myr (Strom et al. 1989d;
Chapter by Strom et al.), and are a relatively common phenomenon among young solar-type stars, with perhaps less than one-half and more than one-fifth of them appearing currently as CTTS. This is cause for optimism if one had been hoping that planetary systems are a relatively common phenomenon, although it remains to be seen how many of these “solar nebulae” actually give rise to planets.

Two reasons make it difficult at this point to estimate the actual amount of mass that is ultimately accreted by the star even if we were optimistic enough to believe that the average mass-accretion rates derived from our disk models were representative of accretion during most of the CTTS phase. First, it is becoming increasingly clear that either the disk or the boundary layer is also driving the strong wind that characterizes the CTTS phase (see Chapter by Edwards et al.). Second, disk lifetime estimates depend crucially on the validity of the convective-radiative evolutionary tracks, which may not be relevant for accreting CTTS. The evolution of mass-accreting pre-main-sequence stars was recently computed by Stringfellow (1989), who indeed finds that their paths in the HR diagram bear little resemblance to classical convective-radiative tracks. Furthermore, even if classical tracks are approximately correct, previous determinations of the position of CTTS in the HR diagram (see, e.g., Cohen and Kuhi 1979) did not take into account the presence of the disk and must, therefore, be regarded as uncertain by a factor of 2 or more. These issues have been addressed most directly by Kenyon and Hartmann (1990). For these reasons, age estimates of T Tauri stars based on the HR diagram appear suspect, as do derived disk lifetimes.

Even though the absolute age of T Tauri stars is doubtful, we assume here the conservative point of view that pre-main-sequence stars sharing the same region of the HR diagram have similar masses and ages, i.e., that young stars do not loop through the HR diagram during pre-main-sequence evolution. The observational evidence reviewed above then implies that accretion has little effect on the global stellar properties, perhaps because most of the disk matter is turned into a wind rather than accreted and/or because disk lifetimes are shorter than estimated on the basis of classical evolutionary tracks. Several different possibilities can then be envisioned for the evolutionary status of CTTS and WTTS:

1. WTTS may simply be CTTS which have stopped accreting. Of course, every CTTS must eventually lose its accretion disk because main-sequence stars are never observed to have active disks. But if all WTTS were once surrounded by disks with comparable physical properties, WTTS should be older than CTTS on the average, which is not the case. Thus, data demand a range in disk masses and lifetimes that may represent a variety of initial conditions for star formation.

2. Alternatively, WTTS may be young stars which never had disks. Some of the WTTS are near the “birthline” for optically visible stars and so may never have been CTTS if one believes in the validity of Stahler’s (1983a)
scenario. The existence of Class III radio sources deeply imbedded in the core of the ρ Ophiuchi cloud where the expectation is that they are very young, might also support this possibility (see André et al. 1987).

3. Another possibility is that many T Tauri stars go through CTTS and WTTs phases several times during early pre-main-sequence evolution. In this picture, one could speculate that disk instabilities lead to a large range of recurrent eruptive phenomena from FU Orionis events down to “normal” T Tauri aperiodic variability or even weak-lined phases. Temporal spectroscopic changes seen, e.g., in RY Tau, where the optical spectrum can range from pure absorption to relatively strong emission, perhaps support this hypothesis.

These are probably the three most conservative scenarios for the evolution of CTTS/WTTs. If it turns out that the evolution of T Tauri stars in the HR diagram is very different from what we think today, more radical options follow. Obviously, much remains to be done to test all possibilities. Realistic (magnetohydrodynamic) simulations of T Tauri systems’ evolution would of course be extremely useful, but because of the complexity of this approach, less ambitious projects such as investigations of the stability and evolution of protostellar disks and boundary layers are welcome first steps. An observational approach to these problems based on systematic spectroscopic and photometric monitoring of some T Tauri stars is also possible, and will offer some clues about the basic physical mechanisms of aperiodic variability in pre-main-sequence objects.

VI. CONCLUSIONS

Both direct and indirect evidence that visible young stars are sometimes still surrounded by disks is now available. Disks seem to be found around a substantial fraction of newly born low-mass stars, and apparently are the agents responsible for their continuum excesses in the ultraviolet, optical and infrared, for their strong broad emission lines, and indirectly for their strong winds.

Unified steady-state accretion-disk models have been constructed which self-consistently and simultaneously satisfy many of the observational constraints which differentiate CTTS from normal stars. The disk has dimensions comparable to our solar system and contains perhaps 0.01 to 1.0 M⊙ of dust and gas. The overall continuum shape and observed luminosity between 0.1 and 10 μm, as well as the Balmer jump and some emission-line fluxes, can be accounted for by simple disk models. The disk is optically thick at these wavelengths, but the boundary layer is often partially optically thin. The accretion rates lie between 10⁻⁸ and 5 × 10⁻⁷ M⊙ yr⁻¹ for the CTTS. The models are both very simplified and parameterized, and do not do a good job of matching the slope of the infrared continuum beyond 10 μm without some modification to either the disk geometry or internal heating mechanisms.

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While first results on the stability of the boundary layer and on the detailed structures of both boundary layer and disk are now becoming available, more work is needed on some fundamental aspects of disk theory, particularly on the angular momentum transport mechanism, as well as on details of the interaction between disk and star and on the production of protostellar winds. High-resolution infrared imaging, as well as high-resolution spectroscopy in the ultraviolet, optical and near infrared, will provide major constraints for further work along these lines.

Accretion disks appear responsible in some way (along with the resulting strong mass outflow) for most facets of the “T Tauri phenomena.” None of these characteristics hold for the weak emission-line T Tauri stars, and therefore the presence of an accretion disk delineates the difference between the two classes of young stars. The underlying stars are probably similar in both cases, and both exhibit very strong magnetic activity. The accretion disks may well be examples of “solar nebulae” that hold the exciting potential for allowing current observations relevant to the planetary-formation process.