Observations of the Inner Accretion Disk Around Young Stars

Patrick Hartigan

Space Physics and Astronomy Dept.
Rice University
6100 S. Main
Houston TX 77005-1892

Abstract. Many of the spectroscopic signatures characteristic of low mass young stars, including near-infrared, visible, and ultraviolet excess emission, inverse P-Cygni absorption, and a variety of emission lines, originate from the inner regions of accretion disks. The area where the disk interacts with the stellar photosphere is particularly important to understand because it controls how angular momentum transfers between the disk and star, and because stellar jets originate there. This review summarizes some of the recent observational and theoretical work of the inner regions of T Tauri accretion disks.

INTRODUCTION

During the past few decades it has become clear that accretion disks surround a large fraction of the youngest low mass stars in our galaxy. Unfortunately, the closest regions of star formation are too distant to allow us to spatially resolve the region of greatest interest, where material from the disk falls onto the stellar photosphere. Radii of T Tauri stars are $\sim 3R_{\odot}$, or $\sim 10^{-4}$ arcseconds for the closest star formation regions. This angular size is some three orders of magnitude smaller than can currently be resolved with the best telescopes. To date, no eclipsing binaries have been discovered among the sample of young stars with accretion disks. Hence, astronomers have not yet been able to exploit eclipse mapping, which has been so successful in clarifying the structure of CV disks.

In light of the above constraints, we must employ some sort of remote sensing to understand more about T Tauri accretion disks. Studies of T Tauri disks typically focus on either separating the spectral energy distribution (SED) of the disk from that of the photosphere, or observing the kinematics of emission lines produced as material falls onto the star and is ejected into a jet. These approaches are complimentary, as the spectral energy studies give estimates of mass accretion rates, while the emission line work provides some insight into the geometry and dynamics of the accretion process near the star.

In this article I will briefly summarize some of the techniques that have been used by various researchers in the last decade or so to study inner ($\lesssim$ 0.1 AU) accretion disks around young stars, and I will also highlight some recent theoretical work that has been put forth to explain these observations.

SPECTRAL ENERGY DISTRIBUTIONS (SEDS)

It has been known for decades [1,2] that the youngest stars often exhibit excess emission above photospheric levels at both near-infrared, optical, and ultraviolet wavelengths. Though there is some disagreement about the statistics, it seems that at least half of the youngest stars are surrounded by accretion disks (classical T Tauri stars; cTTs) [3]. The fraction of young stars which lack opaque disks (weak-lined T Tauri stars; wTTs) increases substantially at ages $\gtrsim 3 \times 10^6$ yr [4]. The cTTs continuum excesses at near-infrared wavelengths might plausibly arise from either a passive disk, which simply absorbs radiation from the star and re-emits at longer wavelengths characteristic of the disk's cooler temperature [5], or from an accretion disk, where the loss of gravitational potential energy during accretion heats the disk, which then radiates this energy into space [6]. The infrared luminosity of a passive disk is limited to a fraction of the stellar luminosity, while that of an accretion disk is proportional to the mass accretion rate. Both accretion disks and passive disks give rise to similar SEDs in the IR, so it is difficult to distinguish between them unless the accretion rate is large enough to be inconsistent with a reprocessing origin.

A steady accretion disk deposits as much energy in the 'boundary layer' where material falls onto the star as it does throughout the entire disk. Because the boundary layer has a much smaller surface area than does the disk, its temperature is correspondingly higher, and the radiation emerges in the optical and ultraviolet rather than in the IR and sub-mm [7]. The UV/optical excesses add extra continua to the photospheric spectra and thereby reduce the observed equivalent widths of the photospheric absorption lines, a phenomenon called 'veiling' [8,9]. Absorption lines in the blue part of the spectrum are more heavily veiled than those in the red because the excess continuum rises slowly toward the blue, while the photospheric fluxes of K and M stars (the spectral type of low mass $\lesssim 1M_\odot$ stars on the Hayashi track) drop sharply [10].

One can measure the amount of veiling at each wavelength by comparing the depths of the photospheric lines of the object with those of a template star (typically a weak-lined T Tauri star that lacks veiling). For example, if an absorption line in a cTTs is only half as deep as that of a wTTs with the same spectral type, we know that the ratio r_λ of the excess continuum to the photospheric continuum must be ~ 1 at that wavelength. By measuring r_λ at different wavelengths and knowing the true SED of the photosphere (*e.g.*, a K star), we can construct an SED for the excess emission. Because this excess SED is constructed from the relative depth of an absorption line with respect to the adjacent continuum, and any intervening reddening reduces the flux in both the line and the continuum equally, the SED of the veiling measured in this manner is independent of the amount of reddening and of the reddening law. This independence is particularly useful because the reddening toward young stars is difficult to measure accurately.

The total luminosity of the UV/optical excess is proportional to the rate that mass accretes onto the star. Typical accretion rates for classical T Tauri stars range between $\sim 10^{-6} M_\odot \mathrm{yr}^{-1}$, and $10^{-8} M_\odot \mathrm{yr}^{-1}$ [11]. The T Tauri phase lasts $\sim 10^6$ yr, so these stars accrete a significant fraction of their total mass through the disk [10,9]. Some disk accretion rates may be high enough to affect how cTTs evolve in the HR diagram [12].

Temperatures of the UV/optical excesses are high ($\sim 10^4$ K) and the filling factors low ($\sim$ a few percent of the stellar surface area), consistent with the accretion disk scenario [13,14,10,15]. Objects that have veiling also have significant near-IR excesses, as expected. Remarkably, the converse is also true; objects with near-IR excesses all show veiling or inverse P-Cygni profiles indicative of accretion [11]. Hence, any passive disks around young stars must rapidly become optically thin, perhaps as a result of dust coagulation into larger rocky bodies.

The effective temperature of the disk at each radius determines the shape of the SED in the IR and sub-mm [16]. Similarly, the behavior of the near-IR colors is governed by the inner accretion disk. Studies of the near-IR SEDs of intermediate mass (1 – 3 $M_\odot$) young stars have shown that the disk becomes transparent within a few stellar radii [17]. It is more difficult to observe this phenomenon among lower mass stars because the photospheric colors are close to those of the disk for late-type stars, but spectroscopic observations (see below) suggest that gaps also occur close to the star within disks that surround low mass young stars.

EMISSION LINE DIAGNOSTICS

Balmer Lines

Classical T Tauri stars are often discovered because of their strong Balmer emission lines, which typically exhibit linewidths of several hundred $\mathrm{km\,s^{-1}}$ [18,19]. Metallic lines such as Fe, Na, and Ca are also prominent in the spectra of cTTs as are forbidden lines like [O I]λ6300. In contrast, wTTs show only weak, narrow emission lines that can be explained as arising in an active chromosphere, and these stars always lack forbidden lines (*e.g.* [20]).

Hence, it is natural to associate the emission lines of cTTs with the accretion process.

When the emission lines of cTTs are studied at high ($\lesssim 20\ \mathrm{km\,s^{-1}}$) resolution, it is possible to measure the veiling accurately and subtract photospheric absorption lines from the observed spectrum, leaving only residual emission or absorption features. This method has proved to be an extremely powerful way to measure weak emission lines and also weak absorption within emission line profiles [11]. It has been known for some time that a small fraction of cTTs, known as YY Ori stars, exhibit redshifted absorption in their Balmer lines. However, new studies of the line profiles that correct for photospheric absorption have shown that the vast majority of cTTs are, in fact, YY Ori stars [19]. The absorption features are typically redshifted by $100\ \mathrm{km\,s^{-1}}$ – $250\ \mathrm{km\,s^{-1}}$; the orbital velocity at the surface of a typical T Tauri star is $\sim 250\ \mathrm{km\,s^{-1}}$.

To produce an inverse P-Cygni profile, material which flows from the disk to the star must be redshifted by several hundred $\mathrm{km\,s^{-1}}$ along the line of sight, and must lie bewteen the observer and a bright source, either the stellar photosphere or the hot spot where material from the disk impacts the star. These observations rule out a model where a planar accretion disk simply intersects a spherical star, as such geometry would never produce inverse P-Cygni profiles. One way to explain these observations is if a stellar magnetic field funnels material from the disk onto the star [21]. In such a model, emission lines and inverse P-Cygni profiles arise from the accretion columns, and the veiling comes from the hot spots at the base of the column [22]. Recent theoretical models of the accretion columns now include detailed cooling, and predict line profiles like those observed [23]. There is also some evidence for hot spots from analysis of periodic light curves of cTTs [24,25].

Rotational periods have been measured from the light curves of many cTTs and wTTs [26]. One might expect that the accretion of angular momentum from the disk would cause cTTs to rotate more rapidly than their wTTs counterparts; in fact, the *opposite* occurs: rotation periods of cTTs are always $\gtrsim 10$ days, while those for wTTs range from 1.5 – 10 days [27,26]. Equatorial rotational velocities for both cTTs and wTTs are substantially lower than breakup velocity, which occurs for rotational periods $\lesssim 0.7$ days. Hence, it appears that somehow accretion disks regulate the angular momentum of young stars, perhaps by ejecting high angular momentum material in a wind. The means by which accretion disks accelerate and collimate jets is a topic of much current theoretical research [28,29].

Forbidden Lines

There is a one-to-one correspondence between the presence of forbidden line emission and infrared excess among cTTs and wTTs [11]. This remarkable fact ties the presence of an optically thick disk to the heating of cTTs forbidden lines. Forbidden lines in cTTs arise from two very distinct regions. There is a high-velocity component that is typically blueshifted by several hundred $\mathrm{km\,s^{-1}}$ and resembles a stellar jet which is unresolved spatially (the disk probably blocks the receding portion of the jet) [30]. This component is present most often in systems that accrete rapidly, but not all cTTs with high accretion rates have bright high-velocity forbidden line emission. A second low-velocity component appears to be much denser than the high-velocity component, and has a small blueshift of a few $\mathrm{km\,s^{-1}}$. This material may arise in a disk wind, though the method of heating remains unknown. A low-velocity component forbidden line always seems to be present in all cTTs [11].

Studies of the high-velocity component of the [O I] and [S II] lines in cTTs have focussed on estimating mass loss rates from the line luminosities [11,31]. There is a strong correlation between mass loss rates found in this manner and mass accretion rates measured from veiling. Hence, accretion appears to drive outflows from young stars. The spectacular stellar jets that have been discovered within the last two decades are the best examples of such outflows (*e.g.* [32]); jets emanate from very young systems that have high accretion luminosities. In all cases the accretion luminosity exceeds the mechanical luminosity in the jet, though in some objects both these exceed the photospheric luminosity [33].

DISK PHOTOSPHERES

Roughly a dozen objects, known as FU Ori stars, have been discovered in dark clouds that have similar spectral line shapes and SEDs. Some FU Oris have been observed to be eruptive variables, suddenly increasing in brightness by ~ 5 magnitudes in less than a year, and then fading slowly on a timescale of ~ 100 years. These objects are thought to represent accretion disks that undergo a sudden rise in the mass accretion rate, perhaps brought on by an instability in the disk [34].

When the mass accretion rate increases high enough, heating at the disk midplane causes the disk to resemble a photosphere, with a hot layer obscured by a cooler layer. The result of a vertical temperature gradient in an optically thick material is to form absorption lines. These absorption lines should partake of the rotation of the disk, and become broadened or even double-peaked. Also, because the outer parts of the disk are cooler, these regions should dominate the observed spectrum at longer wavelengths and cause the rotational broadening to decrease as one moves from the optical to the infrared. Both the dependence of line broadening with wavelength and double-peaked absorption line profiles have been observed in several FU Ori objects [35].

Theoretical models of FU Ori accretion disks have met with considerable success in reproducing the observed line shapes [36]. Mass accretion rates in FU Oris are as high as $10^{-4}M_{\odot}\mathrm{yr}^{-1}$, which means that $\gtrsim$ 0.01 $\mathrm{M}_{\odot}$ may accrete in a single event [37]. A typical T Tauri star probably experiences at least one, and perhaps several FU Ori events before the disk dissipates. Hence, a significant fraction of the final stellar mass derives from steady and episodic disk accretion. The close connection between accretion and outflow suggests that massive FU Ori accretion events are likely to be responsible for the multiple bow shocks observed in stellar jets [34].

High-resolution emission line profiles of FU Ori objects have been analyzed by subtracting disk models from the data and examining the residuals in much the same manner as has been done for cTTs [38]. The resulting line profiles show a massive outflowing wind which models suggest must have a *rotational* component [39]. This indication of rotation in outflows is particularly important in light of the angular momentum issues discussed in the previous section.

Another potentially powerful means to study the inner disks of T Tauri stars comes from observations and models of the CO emission feature at 2.3μm [40,41]. When convolved with the rotational broadening expected from a disk, the CO emission bandhead matches very well with the observations [41]. These observations indicate the temperature of the molecular gas, and may someday constrain the vertical temperature structure in the disk.

CONCLUDING REMARKS

Though astronomers have made great strides forward in understanding how stars form, the current paradigm will remain fundamentally incomplete until we develop a better idea of how the inner accretion disk operates. Because this region cannot be imaged, models of the interaction region between the disk and the star must connect with observation *via* increasingly sophisticated spectroscopic studies of cTTs. The most obvious extension of the current work is to address accretion disks in binaries. Binaries are common among young stars [42], and studies of these systems could provide some much needed insight into the accretion process. Much could also be learned about the onset of disk instabilities if we could detect and study the early phases of an FU Ori outburst. Any further information about rotation in outflows is clearly of great importance to understanding the angular momentum of accretion disks, though observation of rotation in outflows will likely remain a difficult challenge for the near future.

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