Chapter 4

Warm and Hot Disk Structures in Protostellar Envelopes

4.1 Introduction

In Chapter 3 we discussed a special class of envelopes around young stars that have cold disk structures. This chapter describes the study of the warm and hot disks that can exist interior to the cold disks. The hot disks (~ 1000K) are generally extending from 1AU to 10AU and are not spatially resolvable with the existing facilities. Warm disks are known to be Keplerian, of sizes around 150-300AU but extend up to 1000AU in a few cases. The sources discussed here are generally found at the edges of the molecular clouds where the ambient cloud material is very less or totally out of molecular regimes. They generally fall into the category of Class II sources and are T Tauri stars with disks and jets. We utilize the power of near-infrared spectroscopy to study these disks, as it happens to be the only means by which one can study the circumstellar disks even with a 1m class telescope. It is important to understand the hierarchy of the disk structures to form a coherent relation between the hot, warm and cold disks. The data discussed in this chapter forms a subset of a larger sample, the coverage of which is not yet complete. We therefore discuss the individual objects and draw general conclusions from the current data set. We present the first near infrared spectra of the disk candidates that are covered in our sample.
4.2 The Sample Set

The choice of the disk candidates can be made based on several hypotheses and thumb rules. Using Lada's classification of YSO's (see Chapter 1), it is possible to identify the sources at various stages of their evolution. According to their classification Class II sources have circumstellar disks and have expelled their infalling envelopes. Optical polarization studies of the dark cloud regions resulted in the identification of a high degree of electric polarization vectors around the YSO's, aligned in different directions that was attributed to the existence of circumstellar disks (Bastien 1982). Beckwith et al. (1990) showed that the disks can be identified and characterized using the millimeter continuum emission at 1.3mm and 2.7mm from the YSO's. They made an extensive survey of 86 sources in Taurus-Auriga region and showed that 42% of the sample had disks. The main problem in studying these disks lies in their small sizes (100-300AU) that subtends about 1"-2" at a distance of 140pc in the nearest star forming regions of Taurus-Auriga. Adaptive optics can just resolve the disks into elliptical blobs. With the advent of high angular resolution (0.5"-1") imaging in millimeter lines that was possible with the IRAM interferometer, a sample of 33 stars were imaged in the 2.7mm continuum emission by Dutrey et al.(1996) (hereafter D96). These authors detected 2.7mm emission in 12 systems, some of which were later imaged by HST using the Wide Field Planetary Camera (Stapelfeldt et al. 1997, hereafter S97). The physical properties of these disks are fairly well characterized using the millimeter emission data. Our sample consists of 10 out of these 12 stars that showed strong and extended 2.7mm emission. We have also included a few other sources from the catalog of Herbig and Bell (1988), that are suspected disk candidates due to other reasons described above. We started with these sources since they have flattened disk structures whose masses are estimated and shown to be in Keplerian motion. The temperatures determined by millimeter emission, range between 70K and 300K. The near-infrared spectra are expected to trace the inner hot disks that have temperatures of ~ 1000K.
Table 4.1: Observed Sample of YSO's

<table>
<thead>
<tr>
<th>Star</th>
<th>SED</th>
<th>Type</th>
<th>$K_{mag}$</th>
<th>$L_{bol}$</th>
<th>$L_{FIR}$</th>
<th>$T^\circ$ K</th>
</tr>
</thead>
<tbody>
<tr>
<td>CI Tau</td>
<td>II</td>
<td>K7</td>
<td>7.82</td>
<td>1.4</td>
<td>0.23</td>
<td>156</td>
</tr>
<tr>
<td>CY Tau</td>
<td>II</td>
<td>M1</td>
<td>8.49</td>
<td>0.49</td>
<td>0.05</td>
<td>79</td>
</tr>
<tr>
<td>DG Tau</td>
<td>II</td>
<td>K7-M0</td>
<td>6.74</td>
<td>6.36</td>
<td>3.81</td>
<td></td>
</tr>
<tr>
<td>DL Tau</td>
<td>II</td>
<td>K7</td>
<td>7.97</td>
<td>1.12</td>
<td>0.37</td>
<td>158</td>
</tr>
<tr>
<td>DO Tau</td>
<td>II</td>
<td>M0</td>
<td>7.44</td>
<td>2.7</td>
<td>0.64</td>
<td>204</td>
</tr>
<tr>
<td>GM Aur</td>
<td>II</td>
<td>K3</td>
<td>8.48</td>
<td>1.0</td>
<td>0.2</td>
<td>167</td>
</tr>
<tr>
<td>FS Tau</td>
<td>II</td>
<td>M4</td>
<td>9.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>V836 Tau</td>
<td>III</td>
<td>K7</td>
<td>8.87</td>
<td>0.51</td>
<td>0.06</td>
<td>80</td>
</tr>
</tbody>
</table>

We present the first near-infrared spectra of the disk candidates in our sample. Observations were made using PRLNIC with the 1.2m Gurushikhar telescope during two observing runs in the months of Jan-Feb 1999. The Spectrograph has a resolving power of 1000 and the slit width is 2" (Refer Chapter 2 for details on the instrument and data reduction). The stars have been flux calibrated using the photometry provided by Kenyon and Hartmann (1995). The sample set presented in this chapter are listed in Table 4.1 along with some of their known properties. The quoted temperatures refer to that of the disk and are derived by the millimeter data by D96.

4.3 Infrared Spectroscopy of YSO's

Spectroscopic studies have been one of the most important methods of understanding the stellar photospheres. Studies of absorption features in the optical spectra have made it possible to classify the photospheres of different spectral types. Spectroscopic studies of optical emission lines have also been the main tool in understanding the rotation, abundances and classifying spectral types of T Tauri star photospheres. However, embedded objects that are faint in the visible could not be studied until the beginning of this decade since there were no good infrared spectrographs. The advent of NIR focal plane arrays made it possible to obtain
good quality NIR spectra after which such studies have begun. Some of the early workers in the field noticed the important CO overtone bands in the K band spectra (Carr, 1989, Casali and Matthews, 1992). Hodapp and Deane (1993) used the NIR lines in a first attempt to derive spectral types of the embedded objects from NIR spectra. The power of infrared spectroscopy to study the YSO's has been realised more seriously in the last 5 years due to a better understanding of the interpretation of the spectral features. Greene and Meyer (1995) studied a sample of objects in the ρ Ophiuchi cloud using both spectroscopic and photometric techniques to derive the masses, ages and spectral types of several embedded objects. Casali and Eiroa (1996) present an extensive study of the infrared CO absorption bands and showed that these bands originate in the stellar photospheres of the observed low luminosity embedded sources. They arrived at this conclusion based on the Echelle data that showed the broadening of the CO bands by 17 km s⁻¹ which could be attributed to stellar origin rather than a disk. They also showed that the CO absorption depths are correlated with the Spectral Energy Distribution (SED) (see Chapter 1) index and suggested that this correlation could result from veiling produced by continuum emission from a hot circumstellar disk. Greene and Meyer (1995) had also discussed the effects of continuum veiling from the hot disk. Greene and Lada (1996) conducted an extensive survey of sources of various SED spectral classes from different molecular clouds. They also observed a large sample of spectral standards. They show that the strengths of the atomic and CO absorption features are closely related to the evolutionary status of the YSO's and the depths of the features are indicative of the relative amounts of veiling of an underlying photosphere by the continuum emission from the surrounding hot envelope.

To summarize the interpretation of CO features in the K band spectrum; Class I objects are embedded, in the sense that they are optically invisible, have infalling envelopes around them that generally causes heavy extinction. The CO absorption features are not found in Class I objects due to strong veiling from the continuum emission of the infalling envelopes. Class II sources are relatively more evolved objects with revealing photospheres and possess accretion disks. These are
mostly the Classical T Tauri stars (CTTS). The atomic and CO absorption features are found in the spectra of these YSO's but are not intense. The veiled features appear weaker than in similar type stars without IR excesses, causing errors in the determination of the spectral types via equivalent width analysis. However, the equivalent widths of suitable line pairs (at similar wavelengths) can be divided to produce ratios which are independent of this veiling (Greene and Meyer, 1995). Class III sources have expelled most of the material and show the atomic and CO absorption features clearly which allow spectral type determination without much confusion.

Brγ emission is another important spectral feature in the K band wavelength range. It was thought until recently that this emission arises in disk winds from young stars (Natta et al. 1988; Hartmann et al. 1990). Recently Najita et al. (1996) have shown that Brγ emission actually originates in the stellar magnetosphere due to the infalling matter. This assumes an X-wind model (see Chapter 1) with funnel flows from the disk onto the star. Brγ emission from the YSO's have unusually large linewidths at 400-700 km s⁻¹ which is more than one should expect due to free fall from infinity to these low mass stars. These large wing emission is attributed to the large scale turbulence in the infalling material. The broad wings are also believed to be partly due to scattering of photons by electrons (Stahl & Wolf 1980). Adding to these observations, Muzerolle et al. (1998) have shown that Brγ line emission can serve as an important probe to the disk accretion in T Tauri stars and embedded YSO's. They show that the accretion luminosity follows a linear relation with the Brγ line luminosity.

4.4 Results and Discussion

Figure 4.1 displays the 2.1-2.4μm spectra of the sample listed in Table 4.1. Tables 4.2 and 4.3 list the measured equivalent widths of Brγ emission and the CO overtone bands. The negative values indicate emission and positive values indicate absorption. The 1σ levels of the spectra vary from 3-8×10⁻¹⁵ watts m⁻² μm⁻¹
Figure 4.1: K band Spectra of Disk Candidates.
Table 4.2: Brγ Equivalent widths of the sample

<table>
<thead>
<tr>
<th>Star</th>
<th>CI Tau</th>
<th>CY Tau</th>
<th>DG Tau</th>
<th>DL Tau</th>
<th>DO Tau</th>
<th>FS Tau</th>
<th>GM Aur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brγ eqw (in Å)</td>
<td>-8.2</td>
<td>-8</td>
<td>-6.7</td>
<td>-11.6</td>
<td>-8</td>
<td>-</td>
<td>-10</td>
</tr>
</tbody>
</table>

Table 4.3: CO Equivalent widths of the stars with significant features

<table>
<thead>
<tr>
<th></th>
<th>$^{12}$CO v=2-0</th>
<th>v=3-1</th>
<th>v=4-2</th>
<th>v=5-3</th>
<th>$^{13}$CO v=2-0</th>
<th>v=3-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM Aur</td>
<td>-22</td>
<td>-21</td>
<td>-27</td>
<td>-8</td>
<td>-10</td>
<td>-16</td>
</tr>
<tr>
<td>V836 Tau</td>
<td>45</td>
<td>45</td>
<td>59</td>
<td>34</td>
<td>-</td>
<td>12</td>
</tr>
<tr>
<td>DO Tau</td>
<td>-</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

depending upon the magnitudes of the sources. We observed all the sources with almost the same integration time which has resulted in this varying noise level. Out of the observed 7 sources, 4 reveal smooth spectra without any CO features. H₂ emission at 2.122μm is found only in one source namely FS Tau. Discussion of individual objects is given below.

4.4.1 FS Tau

FS Tau or FS Tauri A (Haro 6-5) is the brighter one of the FS Tau pair, the other component being the well known Haro6-5b that has been imaged both in optical and infrared bands by the HST. Lunar occultation observations of this object revealed a binary system with a companion 0.25" away (Chen et al. 1990, Simon et al. 1992). The spectral type is therefore composite and was estimated to be M1 type by Cohen and Kuhi (1979). This is one of the relatively highly polarized (~10%) T Tauri stars indicating the possible presence of a circumstellar disk (Gledhill & Scarrott 1989). HST images in the V, R and I bands have been discussed by Krist
et al. (1998). They also publish the photometry of the individual sources in the FS Tau system.

Our spectrum (Fig 4.1) shows that there are no absorption features of either atomic or molecular origin. However, H$_2$ emission is the only feature seen in this spectrum and this is the only object in our sample that has detectable H$_2$ emission at 2.122$\mu$m. Given that the star is M1 type and has a SED of type II, the absorption features should have been present in the spectrum. The absence of the CO overtone features therefore clearly indicates veiling due to the continuum emission from a hot circumstellar disk. This observation supports the large polarization values measured by Gledhill & Scarrott (1989) in confirming the existence of a disk. The observed H$_2$ emission coming from the unresolved binary system (0.3") strongly indicates the possibility that the companion is an Infrared Companion (IRC) (Herbst et al. 1995, Koresko et al. 1997). The Kinematic data shows the presence of a low velocity component of -5 km s$^{-1}$. However, the detection of [NII] at 6583$\AA$ suggests the presence of a high velocity component (HVC) ($\sim$ 50 - 150 km s$^{-1}$) (see Hilith et al. 1997 and references therein). It is not possible to associate the H$_2$ emission to either of these components since the HVC's dissociate H$_2$ and the low velocity component is not significant enough to excite H$_2$. Further, the interpretation that the binary companion to FS Tau A is an IRC is supported by the photometric observations of this source by HST/WFPC2 observations. K98 report that the fainter companion of FS Tau A which they refer to as FS Tau E is redder than the brighter companion that is refered to as FS Tau W. The flux ratio of the W/E is 18.5 in the V band and 7.3 in the I band. They also note that the flux ratio of the W/E stars is 8.2 obtained by using the photometry provided by Simon et al. (1992). Therefore we believe that the observed H$_2$ emission from the FS Tau binary system must be originating in accretion shocks associated with an IRC, which should be the fainter companion identified as FS Tau E.
4.4.2 DG Tau

DG Tau here is actually referred to as DG Tau A that is the brighter one of the pair. DG Tau A and B. DG Tau B is 1' southwest of DG Tau A and has been imaged by HST. DG Tau B is one of the strongest sources seen in the 2.7mm maps of Dye. The 2.7mm continuum emission contours clearly show a face-on disk. DG Tau A was first identified by Mundt and Fried (1983), as the source of an HH jet. Their Hα CCD frame shows a bright HH knot 8'' SW of DG Tau A, R.A. = 228° 32' apparently connected by a jet. A coude spectrogram shows direct evidence for a stellar wind provided by the NaD lines which show broad blue absorption troughs with velocities up to -200 km s⁻¹. Bastien (1982) presented optical polarization data of this star which shows 6% polarization with the electric vectors oriented at an angle of P.A. = 135° ± 1°. This direction is perpendicular to the direction of the observed jet and therefore Mundt and Fried attribute it to the presence of a disk around DG Tau.

DG Tau is the next spectrum in our sample that is remarkably smooth with no spectral features except for $\text{Br}_7$ emission. The argument of continuum veiling of the
photospheric features holds in this case too, since the star is classified to be of spectral type K7-M0 type where one would expect to see these features. The absence of these CO features therefore confirms the presence of a disk supporting the polarization data of Bastein (1982). A 2.1-2.4 mm spectrum of DG Tau was obtained by Hamann et al. (1988) who reported CO bandheads in emission. The observations of Carr (1989) and Tokunaga (1995) showed the CO in emission whereas Greene and Lada (1996) observed this object during 1993-1994 and found that the CO is in slight absorption. Our spectra do not show any emission of CO bandheads but indicate a possible weak absorption. These observations point to alternate phases of emission and no emission of the CO bands in the spectra. DG Tau is one of the two objects in the survey of D96 that showed detectable CO emission from the disk whereas the other sources had no emission.

The Brγ emission line is clearly broadened and asymmetric. Najita et al. (1996) have presented the Brγ line profiles of DG Tau. The line profile of the Brγ emission of DG Tau from our spectra is presented in Fig 4.2. The asymmetric nature of the profile is clearly seen with a possible second component that is red shifted at ~ 450 km s⁻¹. The FWHM of the lines are ~ 400 km s⁻¹. The broad line wings can be attributed to large scale turbulence in the stellar magnetosphere and can partly be due to scattering of photons by electrons as described in section 4.3.

4.4.3 GM Aurigae

The object is well known since it was one of the first objects to be mapped in the 13CO J=2-1 line at 1.3mm using the IRAM interferometer at 0.6" resolution by Dutrey et al.(1998). These authors demonstrate the Keplerian nature of the disk using CO images and also resolve a dust disk (using 2.7mm continuum) at the center of the CO disk. A 2.7mm image of GM Aur is published by D96. It has been imaged in the optical bands by HST/WFPC2 (S97). There is a remarkable correlation in the morphology of the interferometer image and HST image. The WFPC2 image reveal a flattened circumstellar reflection nebula extending symmetrically
from the star to radial distances of 3" (450AU) along position angle 60°. This nebulosity is attributed to the illuminated upper surface of a flared, optically thick disk observed from ~ 25° above the equatorial plane of the disk (S97). D98 have derived several parameters of the disk from their studies and estimate a dust disk mass of 0.025 M⊙ extending up to ~200AU. Their CO maps, however, show a large Keplerian disk extending up to ~ 525AU from the star.

A near-infrared spectrum of this source has been obtained by us. Our spectrum of GM Aur in Fig 4.1 shows the CO overtone features to be strongly in emission. This result is in support of the presence of CO gas in the disk seen by the HST and mm emission images. Also, the description of the disk as "flared" by S97 is supported by the emission features in our spectrum. The excitation of the CO gas within the optically thick disk can result in the strong emission of these overtone features. Our spectra also show intense Brγ emission that is explained using magnetospheric infall fed through a disk. The atomic absorption features are totally missing in our spectra. This can be accounted for by continuum emission from the central hot disk overfilling the photospheric atomic features.

4.4.4 DL Tau

This is a class II source which has been included in many surveys as a sample source from the Taurus-Auriga molecular cloud. However, to the best of our knowledge it has been studied as an individual object only by D96 through their millimeter continuum maps. The 2.7mm dust emission from an associated Keplerian disk is prominent and extended. The morphology suggests a face-on disk. Our spectrum shows intense Brγ emission and the CaII absorption feature at a 2σ level. The Brγ emission profile is asymmetric towards the red, suggesting infall signatures in a magnetosphere. The CO overtone features are missing in this object too, suggesting the presence of a disk and thus conforming to the millimeter images of D96.
4.4.5 DO Tau

This classical T Tauri star is associated with an arc-like reflection nebula. The 2.7mm continuum images of D96 shows a face-on Keplerian disk with an estimated dust disk mass of 0.019 $M_\odot$. Hirth et al. (1997) have studied the forbidden line emission in visible from this object and demonstrated the existence of an outflow with the blue shifted lobe oriented at PA. = 250° ± 10°. This is nearly perpendicular to the optical polarization angle of PA. = 175° ± 2° found by Bastien (1982). Our spectra of DO Tau reveal shallow $^{12}$CO absorption features. This maybe due to the fact that the CO features are not veiled sufficiently owing to the inclination angle (face-on) of the disk. It also shows Br$\gamma$ in emission with a broadened profile at 400 km s$^{-1}$.

4.4.6 CY Tau

CY Tau is a class II source and a CTTS. The 2.7mm continuum emission images of D96 show a tilted disk with intense emission. The tilt appears to be about 30° to the line of sight. Our spectrum shows Br$\gamma$ emission and the photospheric absorption features are at the 1σ level. The Br$\gamma$ line profile is broad with FWHM of ~ 400 km s$^{-1}$.

4.4.7 V836 Tau

This is the only SED class III source and a weak-line T Tauri star in our sample. This is a single star which shows very faint 2.7mm continuum emission (that too, not in a disk pattern) in comparison with the other strong sources discussed above. Our spectra display strong absorption features of CO bands and also those of NaI and CaI. The features are in accordance with the K7-M0 type photosphere of this star. This verifies the anti-correlation result of the association of CO features with the dust emission in disks. As a Class III source it is expected that this star has expelled most of the circumstellar material. Hence the photospheres are revealed,
the features of which are clearly seen in our spectrum.

4.5 Conclusions

We obtained near-infrared spectra of stars that are known to have Keplerian disks by direct imaging in the millimeter by IRAM interferometer or those which had strong observational evidences for having disks. In this process we provide direct verifications of the interpretations of the spectral features in the 2.1-2.4μm band with regard to the presence of disks and flows in the near environments of the YSO's. The hot inner disks and warm outer disks appear to co-exist and are in Keplerian motion. The presence of Brγ line emission in almost all cases suggests ongoing accretion through funnel flow in the magnetosphere of the young star. Some specific results on individual objects have been obtained. We identify that one of the companions in the FS Tau binary to be an Infrared Companion, since we find molecular hydrogen emission at 2.122μm from this unresolved pair. We point out that HST/WFPC2 results provide supporting proof to the characterization of the FS Tau companion as an IRC. We note that DG Tau, which is known to show CO overtone bands in phases of emission and absorption during the last several years is currently showing neither absorption nor emission. The existence of CO in the disk of GM Aur is confirmed by the presence of CO overtone emission bands in our near-IR spectra.
4.6 References

• Tokunaga, A. T., 1995, Private Communication to Greene & Lada