Mid-Infrared Spectroscopy of Disks around Classical T Tauri Stars

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ABSTRACT

We present the first Spitzer Infrared Spectrograph[11] observations of the disks around classical T Tauri stars: spectra in the 5.2-30 μm range of six stars. The spectra are dominated by emission features from amorphous silicate dust, and a continuous component from 5 to 8 μm that in most cases comprises an excess above the photosphere throughout our spectral range. There is considerable variation in the silicate feature/continuum ratio, which implies variations of inclination, disk flaring, and stellar mass accretion rate. In most of our stars,

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structure in the silicate feature suggests the presence of a crystalline component. In one, CoKu Tau/4, no excess above the photosphere appears at wavelengths shortward of the silicate features, similar to 10 Myr old TW Hya, Hen 3-600, and HR 4796A. This indicates the optically thick inner disk is largely absent. The silicate emission features with peaks at 9.7 and 18 μm indicate small dust grains are present. The extremely low 10-20 μm color temperature of the dust excess, 135 K, indicates these grains are located more than 10 AU from the star. These features are suggestive of gravitational influence by planets or close stellar companions and grain growth in the region within 10 AU of the star, somewhat surprising for a star this young (1 Myr).

Subject headings: infrared: stars — circumsteller matter — stars: variables: other — stars: pre-main sequence

1. Introduction

Although Lynden-Bell & Pringle (1974) suggested that T Tauri stars were surrounded by accretion disks, it was not until the advent of IRAS that observations over a wide wavelength range demonstrated that the infrared excesses were due to dust disk emission (Rucinski 1985). Optically-thick models for disk emission powered mostly by accretion (Kenyon & Hartmann 1995) or heated mostly by irradiation by the central star (Adams, Lada, & Shu 1987) were developed to explain the broad features of T Tauri spectral energy distributions (SEDs). Kenyon & Hartmann (1987) pointed out that the overall SEDs could best be explained if the dust was suspended to several scale heights in the gas, resulting in a disk photosphere that is curved away from the midplane, or "flared". Flaring enhances the irradiation heating by the central star, increasing mid- to far- infrared fluxes. The outside-in heating of disks by stellar radiation leads to warmer temperatures in outer layers than near the midplane, which in turn predicts silicate features in emission in optically thick disks (Calvet et al. 1992). Because the disk heating affects its vertical structure, which in turn changes the amount of stellar irradiation, self-consistent models have been developed to predict SEDs in greater detail (D'Alessio et al. 1998, 1999; D'Alessio, Calvet, & Hartmann 2001; Chiang & Goldreich 1997).

The IRS instrument on the Spitzer Space Telescope covers a crucial wavelength range (typically corresponding to disk radii of one to a few AU) for constraining disk structure, and provides an unparalleled opportunity to address particle composition near the disk surface. We present our preliminary findings on a small sample of T Tauri stars in the Taurus-Auriga dark clouds. The 5 – 30 μm spectra are broadly consistent with model expectations. There is typically a strong 10 μm silicate emission feature overlying a continuum well in excess of the stellar photosphere. There is evidence for grain processing in the changing shape of this feature. One of the objects, CoKu Tau/4, shows no detectable excess shortward of 8 μm, but a rapidly rising flux to longer wavelengths with 10 and 18 μm silicate features in emission. The implied dust temperatures are quite low, leading us to interpret this as a disk in transition: the region within 10 AU has been largely cleared of observable, small, dust grains while the outer disk remains.

2. Observations

We observed 20 classical T Tauri stars (SED Class II) in the Taurus dark clouds during the 4 February 2004 Infrared Spectrograph (IRS: Houck et al. 2004) campaign on the Spitzer Space Telescope (Werner et al. 2004). From these we have selected six representative stars (see Table 1). Five of the stars were selected to not have a known close binary companion. GG Tau is in a more complex system. The object we observed, GG Tau Aa, has a close ($0\farcs25$) binary companion, GG Tau Ab, which is also a classical T Tauri star with active accretion (Hartigan & Kenyon 2003). Aa is a factor of 2 brighter than Ab in the K and L bands (2.2 and 3.6 μm; White & Ghez 2001). Our spectrum represents Aa+Ab.
We present observations obtained with the Short-Low (SL; 5.2−14 μm, $\lambda/\Delta\lambda \sim 90$) and Long-Low (LL; 14−38 μm, $\lambda/\Delta\lambda \sim 90$) modules of the IRS. FM Tau, CY Tau, and CoKu Tau/4 were observed in the IRS Staring mode (two nod observations on the slit per target), while FN Tau, GG Tau, and IP Tau were observed using the IRS Spectral Mapping Mode (2×3 steps of the slit across each target). The details of how these modes were used are the same as described by Uchida et al. (2004). For the SL data shown here, the mispointing parallel to the slit was typically of the order of 0.3 pixels; since our spectral reduction method requires that our science targets be placed at precisely the same position on the slit as the calibration star, such small mispointings do not affect the calibration of our spectra.

We reduced our spectra with the IRS team's Spectral Modelling, Analysis, and Reduction Tool (SMART; Higdon et al. 2004) as described by Uchida et al. (2004). α Lac (A1 V) was used to calibrate our SL and LL spectra; the resulting spectra are shown in Figures 1 and 2. The only LL spectra presented here are the ones of FM Tau and CoKu Tau/4. We have compared the fluxes derived in this manner for SL to published fluxes in the literature, primarily N band and IRAS 12 μm fluxes, for about six non-variable objects. The agreement was always better than 10%. We have also compared the IRAC 5.8 and 8 μm observations of TW Hya to the SL spectra in Uchida et al. (2004). The agreement was better than 10%. We conclude that over the flux range 30 mJy to 1.5 Jy the photometric accuracy of our SL calibration is at least as good as 10%. For any undetected, modest mispointing, our reported fluxes would be too low, but the shape of the true spectrum would be preserved. Using the same calibrator star (α Lac), the LL spectrum is typically above the SL spectrum at 14 μm, by factors of $1.2-1.4$. This mismatch is believed to be primarily due to an error in the early pipeline which has been identified and is being corrected. We believe the shape of the LL spectrum is basically correct. The LL spectra in Figure 2 have been multiplied by 0.7 to match SL.

In addition to photometric accuracy, the accuracy of the shape of the spectra is crucial. We have addressed this issue in two ways. Firstly, the SL spectra of several objects reduced using the same hardware, software, and procedures showed no evidence of excess emission. Those spectra were used to assess our photometric accuracy discussed above. The shape of these SL spectra was in agreement, within the spectral errors, to that of the stellar photosphere, which was modelled as a blackbody with the effective temperature of the star (essentially a Rayleigh-Jeans tail here). Secondly, the spectral error in each data point was assessed by comparing the spectra from the two independent nod positions for each object included in this paper. Half the absolute value of the difference is the standard deviation of the mean if the sample distribution is gaussian. We find that these error bars agree with the scatter in the data points shown here. Since we extract two data points per spectral resolution element, neighboring data points are not statistically independent. The scatter in neighboring data points indicates the spectral noise. Only features which significantly exceed this scatter can be considered real.

3. Discussion

The spectra of FM Tau, GG Tau, and IP Tau (Fig. 1) are all similar. From $5-8$ μm, there is a smooth continuum that is shallower than the Rayleigh-Jeans tail of the stellar photosphere. In order to estimate the stellar contribution to these spectra, a simple model for the stellar photosphere was constructed. The effective temperatures were assumed to be those consistent with the spectral class (see Table 1). While the extinction to the stars (Table 1) is small, the contribution of the accretion disk to the flux at wavelengths shortward of 5 μm is not precisely known. Therefore, we have assumed the star provides all of the flux in the K band 2MASS observation (see note for Table 1). This will give an upper limit to the stellar flux in the $5-30$ μm range. The implied star sizes are typically 2 solar radii for an assumed distance of 140 pc. This is consistent with stars $1-3$ Myr old, typical of Taurus members.

For five of the six stars, the $5-8$ μm continuum flux is well above the stellar continuum.

This is a well known characteristic of the accretion disks around young solar mass stars (Kenyon & Hartmann 1987; Calvet et al. 1992). The disk is optically thick and heated by direct and scattered stellar and accretion-shock radiation, re-radiation from the extended disk atmosphere, and conversion of gravitational potential energy to heat. The temperature in the disk increases with decreasing radius; at some point the temperature is high enough ($\sim$ 1500 K) to evaporate the refractory dust. The observed flux represents the sum over many annuli, with many different temperatures.

Beyond 8 μm, there is a prominent emission feature which we identify with emission from small silicate dust grains. This is also a well-known feature of these accretion disks (Calvet et al. 1992; Cohen & Witteborn 1985). The optically thin emission comes from dust suspended in the atmosphere of the flared, optically thick accretion disk. The flaring permits exposure to more nearly direct starlight, promoting heating. Since these small grains absorb starlight more efficiently than they emit in the infrared, the temperatures are elevated above that of a blackbody grain at the same radius (Calvet et al. 1992; Chiang & Goldreich 1997). The grain temperature is well above the temperature in the optically thick accretion disk below, permitting the appearance of emission features in the spectrum. Such "superheating" has been seen in the small silicate dust grains given off by comets in our solar system (Gehrz & Ney 1992).

The smoothest emission feature, which is also among the narrowest of the sample, is seen in FM Tau. It peaks near 9.7 μm, and the shape is similar to that seen in ISM dust as exemplified by the heated dust in the Trapezium (Forrest, Gillett, & Stein 1975; Gillett et al. 1975). There is a slight "knee" at 11.3 μm which is not evident in the Trapezium spectrum. The LL spectrum (Fig. 2) reveals a second emission feature, peaking near 18 μm. We identify this with the bending-mode resonance in small amorphous silicate grains. Its shape is very similar to that seen in the Trapezium (Forrest & Soifer 1976; Forrest, Houck, & Reed 1976). We conclude that the $8-30$ μm emission from the optically thin, superheated, flared disk comes primarily from small silicate grains, similar to those found in the ISM.

The 9.7 μm silicate feature of IP Tau is very similar to FM Tau's. The only noticeable difference is a more definite "knee" at 11.3 μm, perhaps indicating a small amount of crystalline silicates.

The 9.7 μm silicate feature of GG Tau is also similar to FM Tau's. It shows a more distinct "knee" near 11.3 μm than IP Tau. It also has relatively enhanced flux in the $8-9.7$ μm region. Both of these features suggest the presence of a small amount of crystalline silicates (or possibly different grain shapes or sizes) in the flared disk. The "knee" near 11.3 μm was detected by Przygodda et al. (2003). They attribute the changes in the shapes of the 10 μm silicate emission features in T Tauri stars to grain growth. Larger grains can enhance the emissivity longward of the peak, but not shortward of the peak. Thus GG Tau suggests an additional broadening mechanism at work, perhaps an admixture of crystalline silicates or quartz.

The 10 μm silicate feature in FN Tau is quite distinctive. The contrast of the 10 μm feature to the neighboring continuum is less than in the three previous cases. The feature has a flat top from 10 to 11.5 μm. In addition, there is a small emission feature at 9.4 μm. The overall broadening of the silicate feature could be produced by differing shapes and sizes of the dust grains. However, the small peak at 9.4 μm requires a differing chemical composition. The feature appeared equally prominent in both independent nod-position spectra of this object, the spectral noise implied by the scatter of data points is small at these wavelengths, and we have not seen it in any other objects, so we believe this feature is real.

The sequence IP Tau – FM Tau – GG Tau – FN Tau shows a trend of decreasing contrast of the 10 μm silicate feature relative to the $5-8$ μm continuum. This sequence also shows an increasing $5-8$ μm continuum relative to the stellar continuum, while the contrast of the 10 μm silicate feature to the stellar continuum is relatively constant (ranging from 7 to 10). From this we infer that the emission from the superheated flared disk is relatively constant, while the emission from the optically thick accretion disk is increasing, causing the feature contrast to diminish.

The $5-14$ μm spectrum of CY Tau is quite different than the above four stars. The continuum is well elevated from the stellar photosphere, indicating emission from the inner parts of the optically thick accretion disk. There is only a small bump near 10 μm. We believe this arises from silicate grains. The ratio of flux attributable to silicate grains to the stellar continuum at 10 μm is only about 1.7 here. This appears to be a case of the loss of small grains (or growth to large sizes) in the superheated flared disk, while the optically thick accretion disk is still quite prominent; the 8 μm flux is at least 3 times larger than the expected flux from the stellar photosphere.

Similar interesting fine-structure in the 10 μm silicate feature has been seen in Herbig Ae/Be stars (Bouwman et al. 2001; van Boekel et al. 2003) and in T Tauri stars (Przygodda et al. 2003; Alexander et al. 2003; Meeus et al. 2003) and interpreted variously as due to grain growth and the presence of crystalline silicates and crystalline quartz (silica). In a forthcoming paper we will use self-consistent disk models, exploring the effects of grain shape, size, composition and crystallinity, to understand these spectra.

CoKu Tau/4 is unique in this group. There is no evidence at all for excess emission from the optically thick accretion disk in the $5-8$ μm range. In fact, our measured flux is 10-20% below the extrapolated stellar continuum (Figs. 1 & 2). This is greater than our estimated photometric uncertainty. T Tauri stars are notoriously variable; this discrepancy could be explained by variability since the 2MASS observations of this star date back to 1998. The K-band measurement of CoKu Tau/4 reported by Leinert et al. (1993) was 30% lower than the 2MASS measurement, so this degree of variability is quite plausible. Beyond 8 μm, there is increased emission, a broad peak $10-12$ μm, a small dip at 12.5 μm, and a rapid rise at $13-14$ μm which continues up to about 20 μm, where the spectrum flattens to longer wavelengths. We attribute this excess emission above the stellar photosphere to emission from heated dust surrounding the star. The structure in the spectrum described above is indicative of optically thin emission from small silicate grains similar to those found around FM Tau. The shifting of peaks to longer wavelengths and distortion of the spectral shape is primarily due to the much lower temperature of the dust grains here. In addition, there may be a blackbody-like continuum contributing at the longer wavelengths. The $10-20$ μm color temperature of the dust excess here is 135 K, whereas it is 283 K in FM Tau. For an optically thin cloud, the flux will be the mass-weighted average over Planck functions of the various dust temperatures times the silicate emissivity. The silicate emissivity is less at 20 μm than it is at 10 μm, so the implied average dust temperatures are less than 135 K. It is believed that the 20 μm silicate emissivity is less than 0.6 times the 10 μm emissivity (Draine & Lee 1984; Simpson 1991). This means the implied silicate temperature is below 123 K. The extremely low temperature found for CoKu Tau/4 indicates there is very little observable dust at temperatures higher than 123 K. This implies there are very few small grains closer than about 10 AU from the star.

Dividing the CoKu Tau/4 excess by a black body of temperature 123 K reveals the underlying silicate emissivity. The 9.7 and 18 μm silicate peaks are clearly present. The 9.7 μm peak shows no evidence for the 11.3 μm knee; it is the narrowest feature in this group. This feature is narrower than the Trapezium, and matches quite well the excess seen from dust surrounding the supergiant μ Cep (Russell, Soifer & Forrest 1975). This narrow feature indicates the dust grains must be < 1 μm in radius, and they can have no considerable icy coating.

CoKu Tau/4 has a SED of Class II and an age of 1 Myr (Kenyon & Hartmann 1995), but is not a classical T Tauri star since the Hα emission line equivalent width is only 1.8-2.8 Å (Cohen & Kuhi 1979; Kenyon et al. 1998). Thus it appears to not be actively accreting, and the lack of an optically thick inner accretion disk is not surprising. Detectable dust grains are mostly excluded from the central 10 AU of this system. One possibility for this is the dust grains in this inner region have grown to such a large size that they can no longer be seen. In a forthcoming paper we will develop models which can explain this interesting spectrum.

4. Conclusions

The 5 − 30 μm spectra of classical T Tauri stars in the Taurus dark clouds are dominated by three distinct components: the stellar photosphere, usually relatively small, except in the case of CoKu Tau/4; an excess continuum from 5 to 8 μm, associated with the inner parts of the optically thick accretion disk; and emission from optically thin small silicate grains, dominating the spectrum beyond 8 μm (except in the case of CY Tau). These general features are in accord with the theoretical models of these objects (Calvet et al. 1992). The most prominent 10 μm features come from objects with the least continuum excess (i.e. FM and IP Tau). The relatively weak 10 μm feature in CY Tau could indicate a lack of flaring in its disk (or grain growth beyond 4 μm radius).

The detailed structure of the 10 μm silicate feature provides evidence on grain processing in these objects. The 9.7 and 18 μm emission features in FM Tau indicate silicates which are most similar to those found throughout our galaxy in the interstellar medium, while the 11.3 μm "knee" indicates some processing has occurred. IP and GG Tau exhibit more processing, as suggested by a more pronounced "knee" at 11.3 μm and a broader 10 μm feature, most likely explained by an admixture of modified grains. FN Tau has the most complex 10 μm feature; in addition to the broadening noted above, there is a small peak at $\sim$ 9.4 μm.

The spectrum of CoKu Tau/4 is perhaps the most interesting of this sample. The absence of an elevated 5 − 8 μm continuum is consistent with the lack of accretion onto this star. The very cold temperatures implied by the excess emission indicates the absence of observable dust grains closer than $\sim$ 10 AU from the star. We suggest CoKu Tau/4 is a transition object between a classical T Tauri star and a weak-lined T Tauri star. The remains of the optically thick outer disk are still present, while the inner disk has been extensively cleared. Presumably, accretion through the outer disk is still occurring, but something is happening to that material before it reaches the star. The 10 μm silicate feature is the narrowest of this sample. This indicates the dust in the outer parts of the disk has been little modified from its origins in the ISM.

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Table 1. Facts about the T Tauri stars

Name	AOR key	Sp	A_V	T_e	Ω_* $10^{-19} str$	T_{color} $10 - 20\ \mu m$
IP Tau	3535616	M0	0.2	3750	3.8	···
FM Tau	3544832	M0	0.7	3750	2.7	283
GG Tau	3532032	K7	0.8	3900	8.5	···
FN Tau	3534592	M5	1.4	3200	5.6	···
CY Tau	3550208	M1	0.1	3700	3.0	···
CoKu Tau/4	3548416	M1.5	0.9	3600	2.9	135

Note. — The spectral type Sp, the visual extinction A_V and the effective temperature T_e were taken from Kenyon & Hartmann (1995). Ω_* is the solid angle a blackbody of temperature T_e would have to match the 2MASS K-band flux of the system. The AOR key can be used to find details of the observations by consulting the Observing Schedules available at the Spitzer website at http://ssc.spitzer.caltech.edu/.

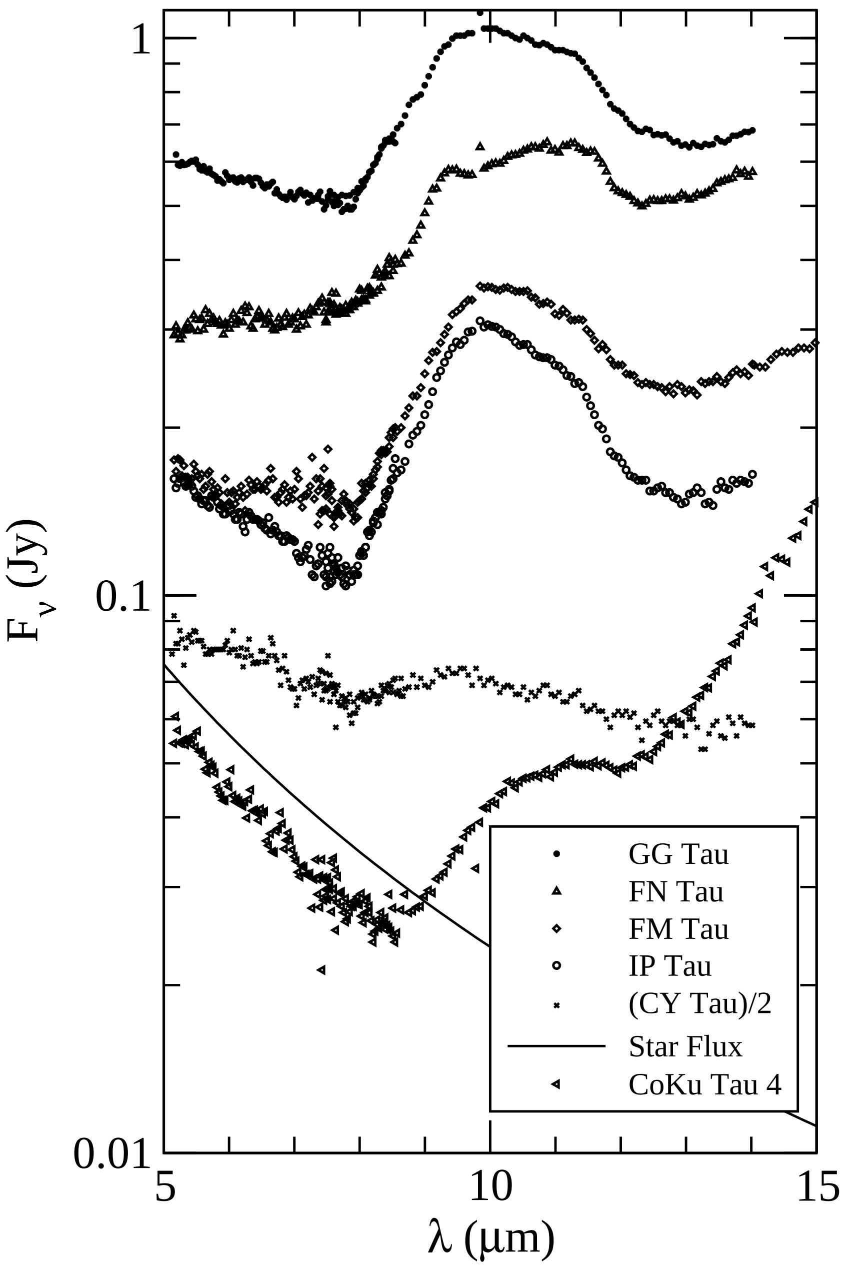

Fig. 1.— IRS spectra of GG Tau, FN Tau, FM Tau, IP Tau, CY Tau, and CoKu Tau/4 (in order, top to bottom). The spectrum of CY Tau has been divided by 2. The smooth curve labelled "Star Flux" represents the stellar photosphere of both CoKu Tau/4 and FM Tau as described in the text.

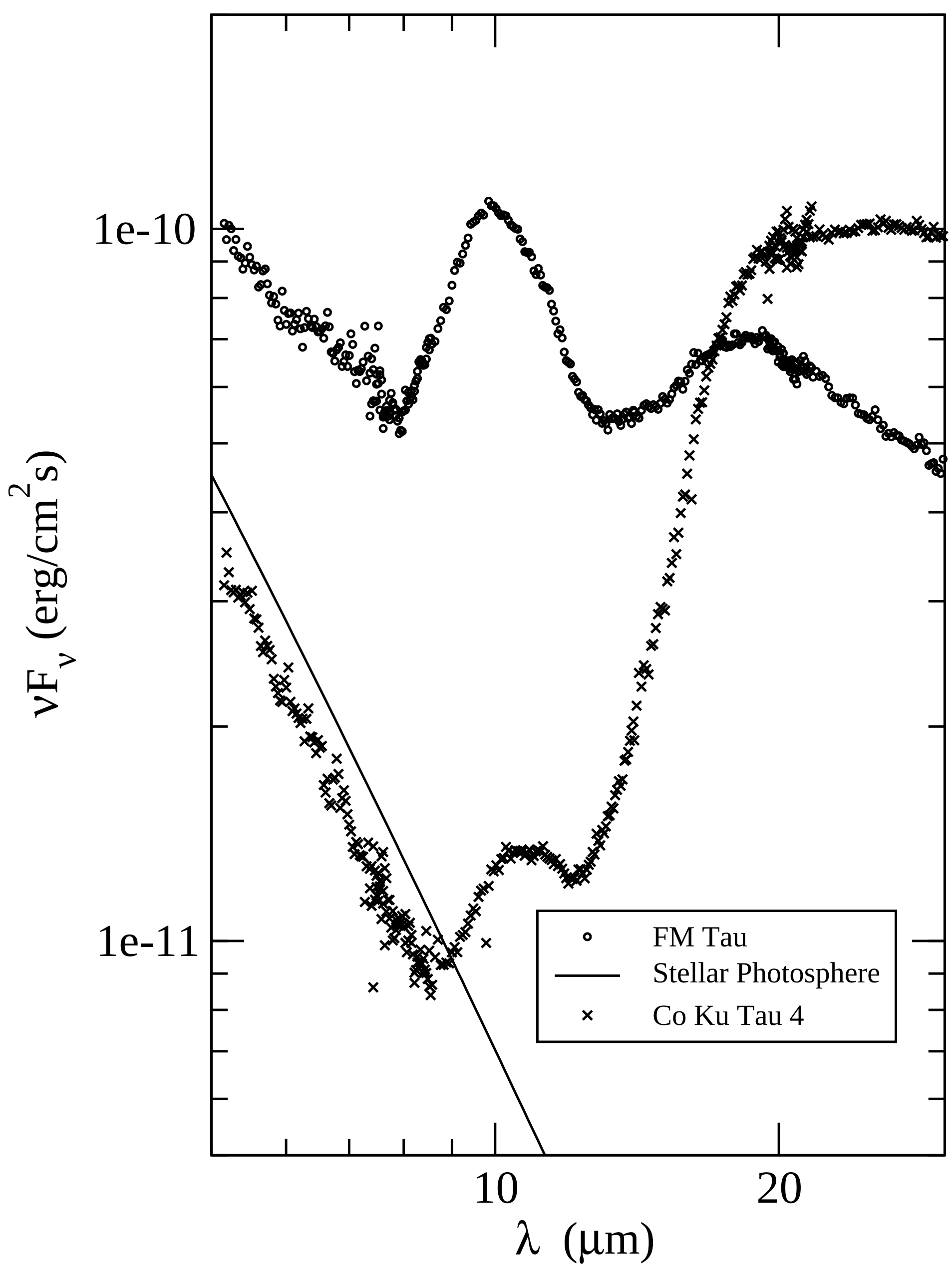

Fig. 2.— IRS spectra of FM Tau and CoKu Tau/4. The smooth curve labelled "Stellar Photosphere" represents the stellar photosphere of both CoKu Tau/4 and FM Tau as described in the text.