A NEW PROBE OF THE PLANET-FORMING REGION IN T TAUER DISKS

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ABSTRACT

We present new observations of the far-ultraviolet (FUV; 1100–2200 Å) radiation field and the near- to mid-IR (3–13.5 μm) spectral energy distribution (SED) of a sample of T Tau stars selected on the basis of bright molecular disks (GM Aur, DM Tau, and LkCa 15). In each source we find evidence for Lyα-induced H2 fluorescence and an additional source of FUV continuum emission below 1700 Å. Comparison of the FUV spectra to a model of H2 excitation suggests that the strong continuum emission is due to electron impact excitation of H2. The ultimate source of this excitation is likely X-ray irradiation that creates hot photoelectrons mixed in the molecular layer. Analysis of the SED of each object finds the presence of inner disk gaps with sizes of a few AU in each of these young (~1 Myr) stellar systems. We propose that the presence of strong H2 continuum emission and inner disk clearing are related by the increased penetration power of high-energy photons in gas-rich regions with low grain opacity.

Subject headings: accretion, accretion disks — astrobiology — astrochemistry — circumstellar matter — stars: pre–main-sequence — ultraviolet: stars

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1. INTRODUCTION

In recent years there has been growing evidence for evolution of solid particles in young (≤10 Myr) protoplanetary accretion disks (Beckwith et al. 2000; D’Alessio 2003 and references therein). The onset of this evolution lies in the coagulation of submicron-sized particles into larger grains, a process that continues until the larger grains decouple from the gas and settle to a dusty midplane. In the midplane these solid particles grow in size until they become large enough to gravitationally focus collisions with smaller bodies, eventually making planets (Safonov 1972; Weidenschilling 1997).

Since dust grains within the disk absorb stellar UV and optical photons and reemit at wavelengths longer than ∼2 μm, the dust evolutionary process has direct consequences on disk continuum emission. Thus, at early evolutionary stages the presence of dust in the inner disk (<10 AU) is revealed by optically thick emission at near- and mid-IR wavelengths.

As grains grow the opacity at these wavelengths decreases, revealing stellar photospheric emission. The formation of giant planets can also affect the dust evolution. Gravitational interaction between the disk and the forming planet results in the formation of a gap as the mass of the planet increases (Bryden et al. 1999; Alibert et al. 2004 and references therein), producing a significant decrease in disk flux in the near-IR (Rice et al. 2003, hereafter R03).

What is less recognized, at least in terms of an observational signature, is that the molecular evolution is closely linked with the dust evolution. Disks in a more advanced degree of dust evolution will be more easily permeated by the destructive short-wavelength radiation fields generated in part by accretion. Since grain evolution and planet formation proceed more rapidly in the denser inner disk (Weidenschilling 1997), these effects will be magnified in the very regions that are closest to the source(s) of radiation. In this Letter we suggest that a strong H2 UV emission feature is an observational consequence of grain growth/planet formation in the inner disks of young (~106 yr) accreting T Tauer disks.

2. OBSERVATIONS

The sources chosen for the Space Telescope Imaging Spectrograph (STIS) UV study are DM Tau, GM Aur, and LkCa 15. In Table 1 we provide some basic characteristics for these systems. All sources have relatively similar properties and were selected on the basis of the presence of gas disks with rich molecular complexity (Koerner et al. 1993; Dutrey et al. 1997; Qi et al. 2003). Each are single star systems with no evidence for binary companions (White & Ghez 2001). Hubble Space Telescope (HST) STIS spectra of DM Tau, LkCa 15, and GM Aur were obtained for HST program G09374 on 2003 February 5, February 13, and April 1, respectively. Exposures were taken using the G140L (1150–1730 Å) and G230L (1570–3180 Å) gratings with an aperture size of 2″. The spectral resolution per pixel for G140L is Δλ = 0.6 and 1.58 Å for G230L. With a FWHM of the point-spread function of 1.5 pixels at the far-ultraviolet (FUV) and 2 pixels at the near-ultraviolet (NUV), this results in effective resolutions of 0.9 Å (R ~ 1550) at the FUV and 3 Å in the NUV (R ~ 770). The plate scale is 0″024 pixel⁻¹ in both FUV and NUV, so the aperture size is large enough for spectrophotometry. Exposure times were 10 m (G230L) and ~65 m (G140L) for DM Tau and GM Aur and 189 m.
sources because these sources are embedded within molecular clouds; in contrast TW Hya has no local cloud and little interstellar absorption (Herczeg et al. 2004). Evidence for strong Lyα radiation that penetrates to the molecular layer can be inferred from the presence of numerous emission features coincident with Lyα pumped H₂ emission lines. In Figure 2 some of these coincidences are denoted for LkCa 15, but similar features are seen in all sources shown in our sample. Beyond the clear H₂ emission-line features there also appears a sharp rise in emission below 1700 Å. This feature is likely due to a combination of discrete and continuum emission emitted by H₂ molecules in excited electronic states.

H₂ emission below 1700 Å can result from at least two physical mechanisms (e.g., Herczeg et al. 2004), Lyα-induced fluorescence (solid black line), with strong features identified, the electron impact model spectrum (dotted line), and model of Lyα fluorescence (solid gray line). The model spectra were produced using an excitation model and molecular transition probabilities in the discrete and continuum range (Abgrall et al. 1994, 2000). For ease in comparison, the fluxes from both observation and models are normalized to the flux at 1425 Å.

G140L and 37 m (G230L) for LkCa 15. Standard CALSTIS pipeline procedures were used to reduce the data.¹²

The targets were observed in the mid-IR over the course of three separate observing runs (2003 January and February) that overlapped the HST observations for DM Tau and LkCa 15 (5–6 week difference for GM Aur). Observations were obtained with the Aerospace Corporation’s Broadband Array Spectrograph System (BASS; Sitko et al. 2000) with a 3′4 beam on the NASA Infrared Telescope Facility.

This instrument uses a cold beam splitter to separate the light into two separate wavelength regimes (2.9–6 and 6–13.5 μm). Each beam is dispersed onto a 58 element blocked impurity band linear array, thus allowing for simultaneous coverage from 2.9 to 13.5 μm. The spectral resolution is wavelength dependent, ranging from R ~ 30 to 125 over each wavelength region. Integration times were 40 minutes (GM Aur), 227 minutes (DM Tau), and 143 minutes (LkCa 15). All observations are calibrated relative to α Tau, with typical air masses ~1.07 and calibrator air masses ranging from 1.03 to 1.12.

3. RESULTS

3.1. UV Spectra of T Tauri Stars

Figure 1 shows the FUV dereddened fluxes of the T Tauri stars in our sample including the spectra of TW Hya from Herczeg et al. (2002). In Table 1 we provide the strength of the FUV radiation at 100 AU (estimated by integrating the FUV radiation field from 1100 to 1700 Å normalized to that of the interstellar UV radiation field. This estimate is a lower limit because of the unknown Lyα flux.¹²

Figure 2 shows the spectrum of LkCa 15 with prominent emission features identified. In TW Hya (Fig. 1) there is a strong Lyα emission line that is not as evident in the other

¹¹ There is some overlap in wavelength coverage between the NUV and FUV detectors. No correction was needed to be applied to match flux levels, and the data are presented with overlap included. Some data were not shown at the short-wavelength end of the NUV spectra to better illustrate particular features. However, the NUV data in this spectral region closely mirror the FUV data.

¹² There is little information on the strength of the radiation field below 1100 Å. Far Ultraviolet Spectroscopic Explorer data of TW Hya indicate that the FUV field strength, G FUV = 3400 (including Lyα), does not change appreciably with this radiation included (Herczeg et al. 2004).
cence and electron impact excitation followed by fluorescence (Liu et al. 2002). Ly$\alpha$ excitation involves only the ungerade electronic states ($B \Sigma_u^-$ and $C \Pi_u$), producing a spectrum permeated by discrete emission lines with some continuum emission. However, electron impact excitation can also excite the gerade states ($E, F$, etc.) that cascade toward the $B$ and $C$ states and emit subsequent UV fluorescence. This produces a broader spectrum with greater contribution from the $H_\alpha$ dissociation continuum (Abgrall et al. 1997; Jonin et al. 2000; Liu et al. 2003).

A model spectrum for the 100 eV electron impact spectrum is displayed in Figure 2. A simple comparison of our data to the electron impact model in Figure 2 shows similarities that are suggestive that electron impact excitation may be important. The implications of this result are discussed in § 4.

3.2. Spectral Energy Distributions

The targets, selected on the basis of strong disk molecular emission, show indications of significant dust evolution in their inner disks. For example, the $K - L$ colors of LkCa 15 and GM Aur are bluer than 86\% of the Taurus sample (consisting of 51 classical T Tauri stars with near- and mid-IR observations from Kenyon & Hartmann 1995, hereafter KH95), and the $K - L$ color of DM Tau is bluer than 70\% of the sample. The BASS observations of the targets strengthen these indications. In Figure 3, we compare the mid-IR, optical, and IRAS data of the targets to the median spectral energy distribution (SED) of classical T Tauri stars in Taurus from D'Alessio et al. (1999). The SEDs of the targets show a clear flux deficit in the near-IR relative to the median in Taurus, analogous to that of TW Hya (cf. Fig. 3), for which inner disk clearing due to the action of a planet opening a gap in the disk has been suggested (§ 1; C02; R03).

Attempting to get insight into the structure of the inner region, we use a simple model, following C02 and Uchida et al. (2004). The model consists of (1) a vertical “wall” in the inner edge of the outer disk, representing the far edge of the gap. This wall, located at radius $R_w$, with height $z_w$, is frontally illuminated by the star and emits as a blackbody with temperature $T_w$, where $T_w = T_{\star \text{eff}} R_w^{1/2} z_w^{1/4}$ (cf. C02). We are ignoring the effects of geometry of the gap, inclination, and occultation. In the electron impact model there is an additional strong feature near $\sim 100$ m (Simon et al. 2000; Qi et al. 2003), for which $z_w/R_w$ in GM Aur and DM Tau are consistent with models with very significant grain growth (cf. Fig. 5 in D'Alessio et al. 2001). The much lower value of LkCa 15 cannot be explained by models with well-mixed gas and dust; it probably requires a significant amount of dust settling. (3) The column density of dust required to produce the silicate feature is $n_{SiO} \sim 10^7$ cm$^{-2}$, where $\Sigma_w = \kappa(10 \mu m) \sim 0.001$ g cm$^{-2}$, with $\kappa(10 \mu m) \sim 1$ cm$^{2}$ g$^{-1}$. Using standard expressions for accretion disks (cf. M03), we can estimate the column density of gas in the inner disk from the mass accretion rate $M$. With $M \sim 3 \times 10^{-9}$ $M_\odot$ yr$^{-1}$ as representative of our objects (Table 1), we obtain $\Sigma_{gas} \sim 20$ g cm$^{-2}$ at 1 AU, for $\alpha = 0.01$, $T = 100$ K, and $M = 1$ $M_\odot$, with a corresponding dust column of $\sim 0.2$ g cm$^{-2}$ (using the standard dust-to-gas mass ratio), much higher than detected.

As discussed in C02, one possibility is that the remaining dust is locked up in larger bodies with low near-IR opacities. The location of the outer edge of the gap $R_w$ for GM Aur is larger than that inferred by R03. These authors had only broadband colors and included the silicate emission as emission from the wall. With our better observations, the optically thin emission can be separated from the wall optically thick emission, which is much lower in the $\sim 10$ $\mu$m region.
(4) We can estimate the height $z_{\text{dust}}$ of the rim at the dust destruction radius from the solid angle required to fit the emission, assuming a cylindrical geometry. The radius of this cylinder would be the dust destruction radius, which can be calculated from the stellar and accretion luminosities (M03; Table 1). We find $z_{\text{dust}} \lesssim 0.1 H$ (Table 1), with $H \sim 0.1 R$, which is much lower than the height of the rim previously found in thick inner disks (Dullemond et al. 2001; M03). We note that blackbody emission alone can explain the near-IR excess (Fig. 3). This suggests that the innermost optically thick region has a small radial extent and moreover, may be in the shadow of the rim (Dullemond et al. 2001). Taken together, all these results suggest that the solids in the inner disks of the targets have experienced significant evolution.

4. DISCUSSION

In a small sample of stars selected solely on the basis of strong and diverse disk molecular emission, we have found two striking results: (1) the presence of strong UV continuum emission from H$_2$ molecules and (2) evidence for grain growth and possible inner disk clearing by planetary bodies. Although our sample is limited we suggest that these two results may be related. The process of grain growth and inner disk clearing will certainly enhance the penetration power of both UV and X-ray radiation, perhaps even leading to regions that are optically thin to UV radiation with penetration only weakly limited by molecular opacity. The direct or improved exposure of molecular gas to high-energy radiation can certainly produce the H$_2$ UV emission features seen in our study, which only molecular gas to high-energy radiation can certainly produce. The direct or improved exposure of molecular gas to high-energy radiation can certainly produce the H$_2$ UV emission features seen in our study, which only molecular gas to high-energy radiation can certainly produce. The direct or improved exposure of molecular gas to high-energy radiation can certainly produce.

Electron impact excitation requires the mixture of hot electrons within an undissociated H$_2$ layer (Raymond et al. 1997). For these systems we can assume that the upper layers of the inner disks are mostly cleared of small grains and H$_2$ self-shielding limits photodestruction. Under normal circumstances radiation will erode the H$_2$ layer, but these systems are still accreting, which provides a source term. In the shielded layer some hot photoelectrons will be produced via UV ionization of C$^+$, but these do not have sufficient energy (~2 eV) for H$_2$ excitation. Thus, electron excitation likely requires X-ray photons that have greater penetration power and produce higher energy electrons. In the dust-poor inner disk the opacity for abundant 1 keV X-rays will also be reduced by nearly a factor of 3 (Glassgold et al. 1997), allowing X-rays to penetrate into the self-shielded layer, ionize H$_2$, and produce hot electrons mixed within molecular gas. The radiation produced by electron impact excitation of H$_2$ therefore does not originate from the star (with an oblique angle of incidence on the disk such as Lya) but rather arises from the upper layers of the disk itself. This increases the penetration power of the UV radiation with resulting effects on disk physics (UV clearing of inner disk, accretion, gas temperature structure, etc.) and the chemistry of species sensitive to radiation below 1700 Å.

The reduction of dust opacity inside the planet-forming regions of the inner disk along with the presence of gas (inferred from accretion) suggests that some of the heating mechanisms believed important for the outer disk will not be effective in the inner disk. In particular, the efficiency of photoelectric heating can be expected to be reduced and a greater role must be played by X-ray heating and UV-excited H$_2$ collisional de-excitation. Thus the gas physics of an evolving inner disk will change as a function of dust evolution. UV emission from H$_2$ must trace these changes and provide a direct tracer of the gas conditions within the planet-forming regions of T Tauri disks that are only weakly probed by the dust.

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REFERENCES

Abgrall, H., Roueff, E., & Drina, I. 2000, A&AS, 141, 297
Abgrall, H., Roueff, E., Launay, F., & Roncin, J.-Y. 1994, Canadian J. Phys., 72, 856
Abgrall, H., Roueff, E., Liu, X., & Shenamsky, D. E. 1997, ApJ, 481, 557
Alibert, Y., Mordasini, C., & Benz, W. 2004, A&A, 417, L25
Beckwith, S. V. W., Henning, T., & Nakagawa, Y. 2000, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 533
Bryden, G., Chen, X., Lin, D. N. C., Nelson, R. P., & Papaloizou, J. C. B. 1999, ApJ, 514, 344
Calvet, N., D’Alessio, P., Hartmann, L., Wilner, D., Walsh, A., & S. 2002, ApJ, 568, 1008 (C02)
D’Alessio, P. 2003, Rev. Mexicana Astron. Astrofis. Ser. Conf., 18, 14
D’Alessio, P., Calvet, N., & Hartmann, L. 2001, ApJ, 553, 321
D’Alessio, P., Calvet, N., Hartmann, L., Lizano, S., & Cantó, J. 1999, ApJ, 527, 893
Dullemond, C. P., Dominik, C., & Natta, A. 2001, ApJ, 560, 957
Dutrey, A., Guilloteau, S., & Guélin, M. 1997, A&A, 317, L55
Glassgold, A. E., Najita, J., & Igea, J. 1997, ApJ, 480, 344
Herczeg, G. J., Linsky, J. L., Valenti, J. A., Johns-Krull, C. M., & Wood, B. E. 2002, ApJ, 572, 310
Herczeg, G. J., Wood, B. E., Linsky, J. L., Valenti, J. A., & Johns-Krull, C. M. 2004, ApJ, 607, 369

Jonin, C., Liu, X., Ajello, J. M., James, G. K., & Abgrall, H. 2000, ApJS, 129, 247
Kenyon, S. J., & Hartmann, L. 1995, ApJS, 101, 117 (KH95)
Koerner, D. W., Sargent, A. I., & Beckwith, S. V. W. 1993, Icarus, 106, 2
Liu, X., Shenamsky, D. E., Abgrall, H., Roueff, E., Ahmed, S. M., & Ajello, J. M. 2003, J. Phys. B, 36, 173
Liu, X., Shenamsky, D. E., Abgrall, H., Roueff, E., Dziczek, D., Hansen, D. L., & Ajello, J. M. 2002, ApJ, 138, 229
Muzerolle, J., Calvet, N., Hartmann, L., & D’Alessio, P. 2003, ApJ, 597, L149 (M03)
Qi, C., Kessler, J. E., Koerner, D. W., Sargent, A. I., & Blake, G. A. 2003, ApJ, 597, 986
Raymond, J. C., Blair, W. P., & Long, K. S. 1997, ApJ, 489, 314
Rice, W. K. M., Wood, K., Armitage, P. J., Whitney, B. A., & Bjorkman, J. E. 2003, MNRAS, 342, 79 (R03)
Safonov, V. S. 1972, in Symp. Origin of the Solar System (Paris: CNRS), 89
Simon, M., Dutrey, A., & Guilloteau, S. 2000, ApJ, 545, 1034
Sitko, M. L., Lynch, D. K., & Russell, R. W. 2000, AJ, 120, 2609
Uchida, K. I., et al. 2004, ApJS, 154, 439
Weidenschilling, S. J. 1997, Icarus, 127, 290
White, R. J., & Ghez, A. M. 2001, ApJ, 556, 265