Using Multiwavelength Variability to Explore the Connection among X-Ray Emission, the Far-ultraviolet H₂ Bump, and Accretion in T Tauri Stars

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Abstract

The high-energy radiation fields of T Tauri stars (TTS) should affect the surrounding circumstellar disk, having implications for disk transport and heating. Yet observational evidence of the effect of high-energy fields on disks is scarce. Here we investigate the connection between X-ray emission and the innermost gas disk by leveraging the variability of TTS. We obtained multiple epochs of coordinated data (taken either simultaneously or within a few hours) of accreting TTS with the Hubble Space Telescope, the Neil Gehrels Swift Observatory, and the Chandra X-ray Observatory. We measured the far-ultraviolet (FUV) H₂ bump feature at 1600 Å, which traces gas <1 au from the star; the near-ultraviolet emission, from which we extract the accretion luminosity; and also the X-ray luminosity. We do not find a correlation between the FUV H₂ bump and X-ray luminosity. Therefore, an observable tracer of the effect of X-ray ionization in the innermost disk remains elusive. We report a correlation between the FUV H₂ bump and accretion luminosity, linking this feature to the disk surface density. We also see a correlation between the X-ray luminosity and the accretion column density, implying that flaring activity may influence accretion. These results stress the importance of coordinated multiwavelength work to understand TTS.

Key words: accretion, accretion disks – circumstellar matter – protoplanetary disks – stars: formation – stars: pre-main sequence

1. Introduction

Studying the structure and composition of protoplanetary disks is important in order to understand the initial conditions of planet formation. In this vein, many studies have probed the dust and gas content of such disks (e.g., reviews by Henning & Semenov 2013; Andrews 2015), particularly around low-mass (∼1 M⊙) pre-main sequence stars (i.e., T Tauri stars, TTS). Studying the interaction between the disk and its variable young star is crucial, as the star is the dominant heating source of the disk, which may lead to disk structural and compositional changes. In addition, high-energy radiation from the central star has important implications on the fundamentals of physical transport processes. In particular, X-ray photons can partially ionize and heat the gas in the upper atmosphere of the disk to temperatures up to ∼4000–5000 K (Glassgold et al. 2007; Meijerink et al. 2008). Therefore, X-ray irradiation especially should play a crucial role in disk ionization, which is important for disk accretion via magnetorotational instability (e.g., see review by Hartmann et al. 2016). However, robust observational connections between high-energy stellar radiation fields and circumstellar material remain elusive.

In TTS, X-ray emission is thought to arise predominantly from the stellar corona (i.e., originating in stellar magnetic activity; Feigelson et al. 2002; Brickhouse et al. 2010). The effect of X-ray irradiation on the disk has been seen observationally, namely through mid-infrared forbidden line emission. [Ne II] emission lines have been detected in more than 50 TTS (Espaillat et al. 2007, 2013; Lahuis et al. 2007; Pascucci et al. 2007; Flaccomio et al. 2009; Güdel et al. 2010; Baldwin-Saavedra et al. 2011; Szulágyi et al. 2012) and have been attributed to X-ray ionization and heating (Glassgold et al. 2007), although extreme-UV (EUV) photons may also play a role (Hollenbach & Gorti 2009; Espaillat et al. 2013). Recently, variability in X-ray-sensitive millimeter gas lines with the Atacama Large Millimeter Array point to X-ray-driven time-dependent chemistry in the outer disk (Cleeves et al. 2017). A connection between X-ray emission and the innermost disk, where accretion onto the star occurs and terrestrial planets are formed, remains to be seen.

One potential tracer of the connection between the X-ray radiation field and the gas in the innermost disk lies within the broad emission feature at 1600 Å. This feature is a combination of Lyα-fluoresced H₂ emission lines and broad H₂ continuum emission, the latter commonly referred to as the “H₂ bump." The far-ultraviolet (FUV) H₂ bump was first identified by Herczeg et al. (2004) and Bergin et al. (2004) in the spectra of classical TTS (CTTS; i.e., accreting TTS; Hartmann et al. 2016) and has been observed in several disks around CTTS (Ingleby et al. 2009; France et al. 2017). In general, FUV H₂ emission traces gas in roughly the innermost ∼1 au of the disk (Herczeg et al. 2002). Ingleby et al. (2009) found that CTTS display the FUV H₂ bump while weak-lined TTS (WTTS; i.e., non-accreting stars) do not, linking the H₂ bump to the presence of gas in the inner disk. The H₂ bump has been proposed to be due to collisional excitation of H₂ by fast electrons in the inner disk (Weintraub et al. 2000; Bary et al. 2002; Bergin et al. 2004; Herczeg et al. 2004). Collisional excitation occurs when electrons created by X-ray ionization of metals in the inner disk ionize hydrogen and helium and create an abundance of hot electrons. The electrons collisionally excite H₂, and one deexcitation path produces continuum emission. However, more recently, it has been suggested that the H₂ bump is powered by Lyα photons, particularly Lyα-driven dissociation of H₂O in the inner disk (France et al. 2017). Excitation by Lyα photons will populate the upper levels of H₂, and a fluorescent spectrum will be emitted as it deexcites. France et al. (2017) found a strong correlation between
Ly$\alpha$ and the H$_2$ bump luminosity. However, Ly$\alpha$ cannot be observed directly and had to be reconstructed from other H$_2$ lines.

Correlations have been seen between other FUV lines and accretion luminosity, $L_{\text{acc}}$, suggesting these lines are powered by the accretion process (Johns-Krull et al. 2000; Calvet et al. 2004; Ingleby et al. 2011b; Gómez de Castro & Marcos-Arenal 2012; Yang et al. 2012; Robinson & Espaillat 2019, RE19). CTTS have typical dipole field strengths of 0.5–1 kG (e.g., Donati & Landstreet 2009; Johns-Krull et al. 2013) that are thought to be strong enough to truncate the inner disk and lead to the accretion of material onto the star via stellar magnetic field lines (Uchida & Shibata 1985; Koenigl 1991; Shu et al. 1994; Hartmann et al. 2016). The funnel flow and accretion shock on the stellar surface produce near-ultraviolet (NUV), optical, and near-IR (NIR) continuum and line emission along with some X-ray emission. The most direct measurement of $L_{\text{acc}}$ (from which we measure the accretion rate, $\dot{M}$) comes from extracting the excess continuum emission from the accretion shock above the stellar photosphere. This excess is measured best in the NUV, as there is less contribution there from the star (Ingleby et al. 2011a). The excess NUV and optical emission above the stellar photosphere has been fit with accretion-shock models (Calvet & Gullbring 1998; Herczeg & Hillenbrand 2008; Rigliaco et al. 2011; Ingleby et al. 2013; Manara et al. 2014). Most of the X-ray photons emitted by the shock are expected to be absorbed. However, Chandra and XMM-Newton observations detect an additional soft (0.5–1.5 keV) X-ray component ($T \sim 10^6$ K) that is much cooler than the coronal gas emission ($T \sim 10^7$ K) in a few CTTS; this soft X-ray emission has been attributed to the accretion shock (e.g., Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005; Günther et al. 2006; Argiroffi et al. 2007).

Here we aim to search for correlations between $L_{\text{acc}}$, $\dot{M}$, the X-ray luminosity ($L_{\text{X}}$), and the H$_2$ bump luminosity in a sample of seven CTTS using multiple epochs of mostly simultaneous data from the Hubble Space Telescope (HST) and the Neil Gehrels Swift Observatory or the Chandra X-ray Observatory. $M$ (and hence $L_{\text{acc}}$) is known to vary (e.g., Cody et al. 2014; Venuti et al. 2014; Ingleby et al. 2015; Cody & Hillenbrand 2018; Siwak et al. 2018, RE19). X-ray emission from TTS is also known to be quite variable (e.g., Preibisch et al. 2005; Argiroffi et al. 2011; Flaccomio et al. 2012; Principe et al. 2012; Principe et al. 2014; Guacelillo et al. 2017). However, the variability of the H$_2$ bump luminosity and its connection to the variability of both $L_{\text{acc}}$ and $L_{\text{X}}$ has not been explored previously, and this may help us understand the origin of the H$_2$ bump. We also test if there is any correlation in our sample between $L_{\text{X}}$ and accretion properties.

In Section 2, we present the data for our sample and provide a detailed overview of their simultaneity. In Section 3, we search for correlations between $L_{\text{acc}}$, $\dot{M}$, $L_{\text{X}}$, and the H$_2$ bump luminosity. In Section 4, we discuss the implications of the correlations we find and those we do not see.

### Table 1

| Object | Epoch | Proposal ID | Date of Obs. | Start Time (UT) | End Time (UT) |
|--------|-------|-------------|--------------|----------------|--------------|
| CS Cha | E1    | 13775       | 2015 Apr 23  | 01:07:08       | 03:34:10     |
| DM Tau | E1    | 11608       | 2011 Sep 8   | 02:24:15       | 04:48:05     |
| DM Tau | E2    | 11608       | 2011 Sep 15  | 21:20:30       | 23:44:09     |
| DM Tau | E3    | 11608       | 2012 Jan 4   | 11:28:04       | 13:48:51     |
| GM Aur | E1    | 11608       | 2011 Sep 11  | 18:17:51       | 20:39:14     |
| GM Aur | E2    | 11608       | 2011 Sep 17  | 21:19:50       | 23:43:00     |
| GM Aur | E3    | 11608       | 2012 Jan 5   | 06:40:14       | 09:01:56     |
| GM Aur | E4    | 14048       | 2016 Jan 5   | 20:38:03       | 23:00:42     |
| GM Aur | E5    | 14048       | 2016 Jan 9   | 13:40:55       | 16:02:33     |
| GM Aur | E6    | 15165       | 2018 Jan 4   | 06:10:54       | 08:34:18     |
| GM Aur | E7    | 15165       | 2018 Jan 11  | 05:03:19       | 07:26:40     |
| GM Aur | E8    | 15165       | 2018 Jan 19  | 03:43:47       | 06:07:09     |
| SZ Cha | E1    | 13775       | 2015 Mar 15  | 02:18:17       | 04:36:17     |
| Sz 45  | E1    | 14193       | 2016 May 14  | 20:11:30       | 22:35:27     |
| Sz 45  | E2    | 14193       | 2016 May 17  | 02:10:09       | 04:28:48     |
| Sz 45  | E3    | 14193       | 2016 May 18  | 17:50:27       | 19:58:51     |
| Sz 45  | E4    | 14193       | 2016 May 20  | 22:10:50       | 00:27:11$^a$ |
| Sz 45  | E5    | 14193       | 2016 Jul 6   | 01:06:12       | 03:33:04     |
| TW Hya | E1    | 11608       | 2010 Jan 28  | 23:11:40       | 02:38:23$^a$ |
| TW Hya | E2    | 11608       | 2010 Feb 4   | 01:52:28       | 04:07:51     |
| TW Hya | E3    | 11608       | 2010 May 28  | 12:27:38       | 14:49:37     |
| TW Hya | E4    | 13775       | 2015 Apr 18  | 03:39:22       | 06:01:59     |
| VW Cha | E1    | 14193       | 2016 Jan 23  | 05:18:12       | 07:47:10     |
| VW Cha | E2    | 14193       | 2016 Jan 25  | 04:56:07       | 07:25:34     |
| VW Cha | E3    | 14193       | 2016 Jan 27  | 02:58:11       | 05:28:12     |
| VW Cha | E4    | 14193       | 2016 Jan 29  | 02:38:07       | 05:05:27     |
| VW Cha | E5    | 14193       | 2016 Mar 11  | 04:44:55       | 07:13:32     |

Note.

$^a$ Observations for Sz 45 E4 and TW Hya E1 ended on the subsequent UT dates (i.e., 2016 May 21 and 2010 January 29, respectively).
2. Observations and Data Reduction

The goal of our study is to investigate how high-energy radiation fields affect gas in the innermost disk. Most of our sample consists of objects previously identified as transitional or pre-transitional disks (i.e., objects with large holes or gaps in the dust in their inner region; e.g., Espaillat et al. 2014), and it has been seen that the H$_2$ bump is more often detected in transitional disks than full disks (France et al. 2017). We note that VW Cha is the only full disk in our sample, and it was observed with the Space Telescope Imaging Spectrograph (STIS) onboard HST (Table 1). Spectra were obtained from the FUV to the NIR wavelengths (1100 Å–1 μm) using the MAMA detector with the G140L (1150–1730 Å) and G230L (1570–3180 Å) gratings and the CCD detector with the G430L (2900–5700 Å) and G750L (5240–10270 Å) gratings. The spectra were obtained with a 52$''$ × 2$''$ slit, leading to resolutions (R) of ~500–1440 for the G140L and G230L gratings and R ~ 530–1040 for the G430L and G750L gratings. The only exception to that provided is TW Hya, which is too bright in the FUV for the G140L grating. In the case of TW Hya, the E140M (1144–1710 Å) grating was used with a 0.5$''$ × 0.2$''$ slit, for a resolution of about 45,800. We convolve the TW Hya E140M spectra to match the resolution of the G140L data to facilitate comparison.

The HST data for CS Cha and SZ Cha are presented here for the first time. The HST data for the other objects in our sample were presented in RE19. We refer the reader to that paper for further details on the exposure times and data reduction. We note that GM Aur E1, E2, and E3 were also presented previously in Ingleby et al. (2015).

For CS Cha, exposure times with the G140L, G230L, G430L, and G750L gratings were 3315 s, 1178 s, 303 s, and 328 s, respectively. For Sz Cha, exposure times with the gratings were 3315 s, 1491 s, 20 s, and 2 s, respectively. Data were obtained from the STScI calstis reduction pipeline. We corrected the G750L spectra for fringing that typically occurs at wavelengths longer than approximately 7000 Å by following the steps outlined in Goudfrooij & Christensen (1998) using a contemporaneous flat that was taken alongside the science observations. After the fringes were removed, the product was passed through the standard HST STIS pipeline to complete calibration.

2.2. Swift

Swift observations of CS Cha, GM Aur, SZ Cha, Sz 45, TW Hya, and VW Cha were taken with the X-ray Telescope on the dates listed in Table 2. We utilized the High Energy
The Astrophysical Journal, 876:121 (16pp), 2019 May 10

Espaillat et al.

| Object | Epoch | Exp. Time (s) | Net Count Rate (10^{-2} cts s^{-1}) | C-statistic or \( \chi^2 \) Value | Degrees of Freedom | \( kT \) (keV) | Unabsorbed Flux (10^{-12} erg s^{-1} cm^{-2}) |
|--------|-------|---------------|-------------------------------------|----------------------------------|-------------------|----------------|---------------------------------------------|
| CS Cha | E1    | 7052          | 3.47±0.22 0.23                       | 180.56 129                       | 1.00±0.05 0.06    | 0.87±0.10 0.09 |
| GM Aur | E4    | 4900          | 2.11±0.2 0.21                        | 87.73 42                          | 0.45±0.14 0.12    | 1.11±0.29 0.19 |
| GM Aur | E5    | 11910         | 9.7±0.3 0.3                         | 422.92 394                        | 4.2±0.5 0.5       | 5.6±0.4 0.3  |
| GM Aur | E6\(^b\) | 10530         | 3.6±0.2 0.2                         | ... ...                           | ... ...           | 1.45±0.14 0.16 |
| GM Aur | E7\(^b\) | 10490         | 2.9±0.2 0.2                         | 88.5 78                           | 0.17±0.04 0.07    | 1.35±0.14 0.18 |
| GM Aur | E8\(^b\) | 10520         | 3.5±0.2 0.2                         | ... ...                           | ... ...           | 1.55±0.18 0.19 |
| SZ Cha | E1    | 23180         | 0.87±0.06 0.06                       | 385.3 752                         | 2.0±0.5 0.4       | 0.26±0.04 0.04 |
| Sz 45  | E1    | 3279          | 0.63±0.14 0.14                       | 31.21 18                           | 2.7±0.12 0.21     | 0.24±0.10 0.08 |
| Sz 45  | E2    | 6008          | 0.79±0.12 0.12                       | 62.36 42                           | 0.83±0.05 0.18    | 0.19±0.06 0.05 |
| Sz 45  | E3    | 5676          | 0.92±0.13 0.13                       | 62.20 41                           | 1.00±0.22 0.22    | 0.22±0.05 0.05 |
| Sz 45  | E4    | 5983          | 0.63±0.11 0.11                       | 31.79 33                           | 5.40 0.36 0.17    | 0.36±0.07 0.17 |
| Sz 45  | E5    | 7834          | 0.73±0.10 0.10                       | 65.22 48                           | 1.9±0.9 0.22      | 0.22±0.06 0.07 |
| TW Hya | E4    | 1321          | 20.7±1.3 1.3                         | 94.60 11                           | 0.77±0.06 0.06    | 5.0±0.5 0.5   |
| VW Cha | E1    | 7719          | 2.78±0.19 0.19                       | 117.17 130                         | 2.04±0.29 0.19    | 1.00±0.18 0.13 |
| VW Cha | E2    | 3744          | 4.0±0.3 0.3                          | 118.30 118                         | 6.3±0.4 0.4       | 2.1±0.4 0.4   |
| VW Cha | E3    | 4001          | 2.39±0.25 0.25                       | 69.59 78                           | 2.2±0.9 0.23      | 0.82±0.19 0.17 |
| VW Cha | E4    | 3632          | 7.0±0.4 0.4                          | 145.30 193                         | 60±0.60 0.4       | 4.4±0.5 0.4   |
| VW Cha | E5    | 9385          | 2.59±0.17 0.17                       | 158.61 156                         | 3.3±0.17 0.15     | 1.00±0.18 0.14 |

Notes. \( N_H \) was adopted from Kalberla et al. (2005) and can be found in Section 2.2.

\(^a\) For the \Swift\ observations, we list the C-statistic. For the \Chandra\ observations, we list the \( \chi^2 \) value.

\(^b\) We fit all the \Chandra\ spectra with the same two-temperature model. We list the \( \chi^2 \) value, degrees of freedom, and temperatures for the joint fit to all three spectra.

Astrophysics Science Archive Research Center HEASoft software (v. 6.22.1) to analyze the \Swift\ data. We fit our data with the X-ray spectral fitting package XSPEC (Arnaud 1996) using one Astrophysical Plasma Emission Code (APEC) model. Values for neutral hydrogen columns (\( N_H \)) for each of our targets were obtained from the Leiden/Argentine/Bonn survey (Kalberla et al. 2005). We adopted an \( N_H \) for CS Cha, GM Aur, Sz 45, TW Hya, and VW Cha of \( 7.74 \times 10^{20} \text{ cm}^{-2} \), \( 2.51 \times 10^{21} \text{ cm}^{-2} \), \( 7.68 \times 10^{20} \text{ cm}^{-2} \), \( 7.45 \times 10^{20} \text{ cm}^{-2} \), \( 5.43 \times 10^{20} \text{ cm}^{-2} \), and \( 7.83 \times 10^{20} \text{ cm}^{-2} \), respectively, as the input for the modifying absorption component, \textit{phabs}. We used the C-statistic to judge a goodness of fit for the model. We present the exposure times, net count rates, C-statistic, degrees of freedom of the fit, \( kT \), and the unabsorbed X-ray fluxes in Table 3. Uncertainties are reported at the 90% confidence level.

Values reported in Table 3 for GM Aur E4 and SZ Cha E1 were calculated by combining data from multiple observations (Table 2). In the case of GM Aur, the data from Obs. ID 00034249002 overlap with the \HST\ observations, and the data from Obs. ID 00034249003 were taken significantly later (see Section 2.4). However, the flux obtained from combining the two observations is similar to the individual fluxes. Using \textit{addascaspec} to add the data from Obs. ID 00034249002 and Obs. ID 00034249003, we measure a combined X-ray flux of about \( 1.11\pm0.20 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) (Table 3), which is similar to the individual fluxes obtained for Obs. ID 00034249002 and Obs. ID 00034249003 of \( 1.2\pm0.2 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) and \( 0.62\pm0.06 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \), respectively. Therefore, we use the flux from the combined observations for GM Aur E4 moving forward. Similarly, the SZ Cha data from Obs. ID 00033666002 were taken simultaneously with the \HST\ observations, but the data from Obs. ID 00033666001 were taken earlier. We find that the combined X-ray flux of the two observations is \( 0.26\pm0.04 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) (Table 3), which is similar to the individual fluxes for Obs. ID 00033666001 and Obs. ID 00033666002 of \( 0.21\pm0.03 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) and \( 0.38\pm0.05 \times 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \), respectively; we thus use the combined flux for SZ Cha E1 moving forward.

2.3. Chandra

\Chandra\ observations were obtained as part of a joint \HST–\Chandra\ GO program for GM Aur (\HST\ Observation ID 15165, \Chandra\ Observation IDs 20614, 20615, 20616). The \Chandra\ observations were performed with the Advanced CCD Imaging Spectrometer (ACIS). The dates and times of the observations can be found in Table 2. GM Aur was placed on the ACIS-S3 detector at the nominal aimpoint. The detector was operated in VFAINT mode with a one-eighth subarray option in order to mitigate potential pileup due to the known variable X-ray emission from the target (\( \text{radout} = 0.441 \text{s} \)). Spectra and light curves were extracted from the standard pipeline processed level II event files (ASCDSVER = 10.6). Spectra were extracted using the \textit{specextract} task in CIAO 4.8 with CALDB 4.7.4 and were grouped to have a signal-to-noise ratio of 3 per bin. Source counts were extracted from a 5" radius circular region centered on the known position of GM Aur. Background counts were extracted from an annular region centered on the source position with inner and outer radii of 7\" and 14\", respectively.

X-ray light curves were created with \textit{dmextract} using the previous extraction regions. We fit the spectra in XSPEC.
Appendix; luminosity is measured from $z$ (The Astrophysical Journal, 2019 May 10 Espaillat et al.).

We have two 

we refer to our overall sample as mostly simultaneous.

2.4. Simultaneity of the Observations

For this study, we use data from HST, Chandra, and Swift to measure the H$_2$ bump luminosity, $L_{acc}$, and $L_X$. The H$_2$ luminosity is measured from HST data in this work; $L_{acc}$ is calculated using stellar parameters taken from the literature, and $M$ is either adopted from RE19 or measured in the Appendix; $L_X$ is measured in this work from either Swift or Chandra data. Here we review the timing of the HST and X-ray observations in order to assess how much of these data were taken simultaneously (i.e., observed at the same time) as opposed to contemporaneously (i.e., typically taken to mean within a day or so in the literature).

The H$_2$ bump is located in the FUV while $L_{acc}$ is dominated by NUV emission. These are covered by separate gratings that were taken in adjacent HST orbits. The typical length of HST observations is 2.5 hr over two orbits. This is important to note since variability on short timescales of a few minutes has been observed in CTTS and has been associated with accretion (e.g., Cody et al. 2014; Siwak et al. 2018). However, RE19 find that for the HST spectra used in this work, the flux agrees in the wavelength regions that overlap at the edges of the gratings that were taken in different orbits, suggesting minimal discernible variability within the individual sets of observations. Therefore, moving forward, we assume there was no significant variability within the 2.5 hr of the HST observations.

In general, when Chandra data are available, they were taken simultaneously with HST over the length of the HST observations. Most HST and Swift data were simultaneous for some portion. However, given the Target of Opportunity nature of the Swift science program, it was not possible to guarantee strictly simultaneous, uninterrupted observations.

We discuss the timing of the observations in detail for each of the objects below. In sum, the majority of the HST and X-ray data sets used in our analysis are at least partially simultaneous. Of the 18 epochs of coordinated HST and X-ray data here, 4 were entirely simultaneous (GM Aur E6, E7, E8, TW Hya E4), 8 are partially simultaneous with the rest of the data taken within 6 hr (GM Aur E5, Sz 45 E1, E3, E4, VW Cha E2, E3, E4, E5), and 3 are partially simultaneous with the rest of the data taken within 6–21 hr (CS Cha E1, GM Aur E4, VW Cha E1). Only three data sets did not overlap at all with the HST observations: Sz 45 E2 and E5 were taken within 12 hr of the HST observations, and Sz Cha E1 was taken within 24 hr of the HST observations. Moving forward, we refer to our overall sample as mostly simultaneous.

2.4.1. CS Cha

We have one epoch of Swift observations for CS Cha. About 20% of this observation was simultaneous with the HST observations. The rest of the Swift data were taken within 17 hr after the end of the HST observations.

2.4.2. DM Tau

DM Tau does not have coordinated HST and X-ray observations.

2.4.3. GM Aur

GM Aur E1, E2, and E3 do not have coordinated HST and X-ray observations. For GM Aur E4 of the HST observations, the Swift data from 2016 January 5 (Obs. ID 00034249002) were taken entirely within the HST observation time. The Swift data from 2016 January 6 (Obs. ID 00034249003) were taken within 16 hr after the HST observations from E4 ended. In Section 2.2, we show that the fluxes from these Obs. IDs were very similar, and so we use the combined flux in this work. For GM Aur E5, about 40% of the Swift observations were simultaneous with HST. The rest of the Swift data in E5 were taken less than 4.5 hr before the start of the HST observations.

We have Chandra data for GM Aur E6, E7, and E8. Our HST and Chandra data were taken simultaneously over the length of the HST observations. The Chandra data generally began 20–25 minutes before the HST observations and ended about 1 hour after the HST observations. GM Aur is the only target that has Chandra observations.

2.4.4. SZ Cha

We have two Swift observations for SZ Cha. Data from Obs. ID 00033666001 were taken within 24 hr before the start of the HST observations. About 25% of the Obs. ID 00033666002 observations were simultaneous with the HST observations. The rest of the Swift data were taken either 1 hr before the start of or within 13 hr after the end of the HST observations.

2.4.5. Sz 45

We have five Swift observations for Sz 45. For E1, about 40% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within 3 hr
before the start of and 2 hr after the end of the HST observations. For E2, none of these observations were simultaneous with the HST observations. The Swift data were taken within 10 hr after the end of the HST observations. For E3, about 30% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within 1 hr before the start of and 3 hr after the end of the HST observations. For E4, about 10% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within 6 hr before the start of and 3 hr after the end of the HST observations. For E5, none of these observations were simultaneous with the HST observations. The Swift data were taken within 12 hr after the end of the HST observations.

2.4.6. TW Hya

We do not have coordinated HST and X-ray observations for E1, E2, and E3 of TW Hya. For TW Hya E4, the entirety of the Swift observations were simultaneous with the HST observations.

2.4.7. VW Cha

We have five Swift observations for VW Cha. For E1, about 10% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within about 27 hr before the start of the HST observations. For E2, 40% of these observations were simultaneous with the HST observations. The Swift data were taken within 3 hr before the start of and 3 hr after the end of the HST observations. For E3, about 45% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within 2 hr before the start of and 3 hr after the end of the HST observations. For E4, about 70% of these observations were simultaneous with the HST observations. The rest of the Swift data were taken within 2 hr before the start of and 1 hr after the end of the HST observations. For E5, 30% of these observations were simultaneous with the HST observations. The Swift data were taken within 3 hr before the start of and 6 hr after the end of the HST observations.

3. Analysis and Results

Here we present the adopted stellar parameters of our sample (i.e., extinction, distance, stellar luminosity, spectral type, accretion rate). For each epoch of observations, we also provide measurements of $L_{\text{X}}, L_{\text{acc}},$ and the luminosity of the $H_2$ bump as well as two $H_2$ emission lines. These properties are measured using Swift/Chandra, HST NUV, and HST FUV data, respectively. Finally, we search for correlations between the previously mentioned properties, including comparisons between $L_\text{X}$ and UV line luminosities and accretion column properties previously reported by RE19.

3.1. Stellar Properties

We follow RE19 and adopt distances, visual extinctions ($A_V$), spectral types, stellar temperatures, masses, radii, and luminosities from the same literature sources (Table 4). We adopt $M$ (Table 5) from RE19 except for CS Cha and SZ Cha, whose accretion properties are derived in the Appendix following the methods of RE19. We calculate $L_{\text{acc}}$ using

$$L_{\text{acc}} = \frac{GM \dot{M}}{R_\ast} \left(1 - \frac{R_e}{R_\ast}\right),$$

with the values listed in Table 5 and $R_e = 5R_\ast$. Using the X-ray fluxes from Table 3 and distances (Table 4), we calculate X-ray luminosities for our sample (Table 5). The exception is DM Tau, for which we have no new X-ray observations to report.

We note that most of our X-ray fluxes (Table 3) are consistent with previously published literature values within a factor of $\sim 2$ (Güdel et al. 2010; Ingleby et al. 2011b). The exceptions are GM Aur E5 and CS Cha. Our GM Aur E5 flux is $\sim 8$ times higher than that found by Güdel et al. (2010), but all other epochs of GM Aur are consistent within a factor of two; as we discuss later, our findings support that GM Aur was in a flaring state in E5. Our CS Cha flux is $\sim 9$ times higher than previously reported ($1.0 \times 10^{-12} \text{ erg cm}^{-2} \text{s}^{-1}$; Güdel et al. 2010). This suggests that we caught CS Cha in a higher X-ray state. We leave it to future work to explore this further with more epochs of data.

3.2. The FUV $H_2$ Bump

The FUV continuum emission of CTTS can be explained by a combination of accretion-shock emission (e.g., Ingleby et al. 2015) and molecular gas emission that is dominated by $H_2$ (Herczeg et al. 2002, 2004; Bergin et al. 2004; Ingleby et al. 2009; France et al. 2011a, 2011b). Here we focus on the broad molecular and continuum feature at 1600 Å known as the $H_2$ bump (e.g., Bergin et al. 2004; Herczeg et al. 2004) and measure the luminosity of this feature.

In Figure 2, we show the continuum-subtracted FUV emission of all objects in our sample. GM Aur was likely undergoing an accretion burst in E7 (RE19), and we will return to this point in Section 4. We dereddened all the HST FUV data using the $A_V$ values listed in Table 4 and the extinction law toward HD 29647 (Whittet et al. 2004). The underlying FUV continuum emission was removed using a third-degree polynomial fit to hand-selected points representative of the continuum level. The posterior for the fit was found using standard linear regression techniques.
Note. All H₂ bump luminosities have been updated. In addition, for VW Cha, all other parameters have been updated. We add two new columns for two H₂ line luminosity measurements. Accretion rates and luminosities are adopted from RE19 except for CS Cha and SZ Cha, which we measure in the Appendix. As noted by RE19, the uncertainties listed here do not take into account broader systematic uncertainties (e.g., extinction) and reflect only the width of the marginalized posterior from an MCMC analysis. RE19 note that the uncertainties in the M are about 10%, assuming a visual extinction correction error of 0.5. All X-ray, H₂ bump, H₂–7R(3), and H₂-B-X(5-12)P(3) luminosities are measured in this work.

As noted earlier, the feature at 1600 Å is a combination of the H₂ bump and Lyα-fluoresced H₂. There are different methods for measuring the H₂ bump luminosity, depending on the resolution of the data. For example, Ingleby et al. (2009) had low-resolution Advanced Camera for Surveys (ACS) spectra, and so their H₂ bump luminosity measurement was a combination of the H₂ bump and Lyα-fluoresced H₂. Meanwhile, France et al. (2017) had much higher resolution Cosmic Origins Spectrograph (COS) spectra and excluded H₂ lines, leaving behind a more clean measurement of the H₂ bump. While here we have lower resolution than COS, we are able to remove the strongest H₂ lines. Therefore, our STIS-derived H₂ bump luminosities can be compared to those measured with COS with the caveat that there is likely still some Lyα-fluoresced H₂ line emission.

Several of the strongest fluorescent H₂ emission lines were removed by hand using Gaussian line profiles. The lines that were removed (when present) include the following H₂ transitions: 3–9 R(15), 3–9 P(17), 3–10 R(15), 4–11 R(3), 4–11 P(5), 1–8 P(8), 1–9 R(3), 1–9 P(5), 3–10 P(1), 2–8 P(13), 2–9 R(11) (see Herczeg et al. 2006). We then integrated the H₂ bump between 1570 and 1630 Å, avoiding the strong emission lines of CIV, CⅤ, and HeⅡ at 1548 Å, 1560 Å, and 1640 Å, respectively. A posterior for the H₂ bump luminosities was derived using a Markov chain Monte Carlo (MCMC) approach assuming Gaussian measurement uncertainties for the data (following RE19). Measured values (Table 5) are derived from the 50th percentile of the H₂ bump luminosity posterior distribution, while reported uncertainties are 16th and 84th percentile values. We refer the reader to RE19 for analysis of other FUV lines.

Previously reported measurements of the H₂ bump luminosity from high-resolution COS spectra are given by France et al. (2017) for CS Cha ([6.99 ± 1.70] × 10⁻²⁹ erg s⁻¹), DM Tau (8.37 ± 2.33) × 10⁻²⁹ erg s⁻¹), GM Aur ([20.27 ± 5.47] × 10⁻²⁹ erg s⁻¹), and TW Hya ([8.49 ± 1.71] × 10⁻²⁹ erg s⁻¹). (We note that these have been scaled to the Gaia distances listed in Table 4.) Our measured H₂ bump luminosity values are roughly consistent within the measurement uncertainties for GM Aur and TW Hya. Our values for CS Cha and DM Tau are about six to seven times lower than the previous measurements, but still within the uncertainties.
Figure 2. Continuum-subtracted HST FUV spectra of our sample centered on the H$_2$ bump at 1600 Å. The measured H$_2$ bump luminosities are listed in Table 5. Note that the strong lines at 1548 Å and 1640 Å are CIV and HeII, respectively.
seven times higher than those of France et al. (2017). Given the variable nature of these objects, we cannot determine whether this is due to intrinsic variability or whether the STIS resolution leads to overestimating the H$_2$ bump luminosity in some cases but not others. In addition, line luminosity measurements depend on the adopted extinctions and, to some degree, the adopted spectral types. Interestingly, we adopt the same extinction and spectral type AV as France et al. (2017) for CS Cha. For DM Tau, we adopt a different AV (= 1.1) than France et al. (AV = 0; 2017). We leave further exploration of whether this is due to intrinsic variability to future work.

To the best of our knowledge, SZ Cha, Sz 45, and VW Cha have no previously reported H$_2$ bump luminosities. The average H$_2$ bump luminosity in CTTS is $1 \times 10^{32}$ erg s$^{-1}$ (France et al. 2017). SZ Cha and Sz 45 are about 3–6 times higher, while VW Cha is 50–100 times higher. As mentioned previously, these higher-than-average measurements may be due to intrinsic variability or to adoption of an inappropriate AV and/or spectral type.

3.3. Correlations

Here we search for correlations in our data set between the luminosity of the H$_2$ bump and $L_X$ or $L_{acc}$. We also search for correlations between $L_X$ and $L_{acc}$, M, UV emission lines, or accretion column properties. To facilitate comparison with previous works, we report the Pearson correlation coefficient ($\rho_p$) and its p-value ($p_p$), the Spearman correlation coefficient ($\rho_s$) and its p-value ($p_s$), and the Kendall correlation coefficient ($\tau_k$) and its p-value ($p_k$).

We find a positive correlation between the H$_2$ bump luminosity and $L_{acc}$ ($\rho_p = 0.8$, $p_p = 4 e^{-6}$; $\rho_s = 0.7$, $p_s = 1 e^{-5}$; $\tau_k = 0.6$, $p_k = 3 e^{-5}$). In Figure 3 (left), we plot the H$_2$ bump luminosity compared to $L_{acc}$. DM Tau is offset from the rest of the sample, and removing it has an unclear effect on the correlation ($\rho_p = 0.9$, $p_p = 5 e^{-8}$; $\rho_s = 0.6$, $p_s = 8 e^{-4}$; $\tau_k = 0.5$, $p_k = 6 e^{-4}$). In accretion-shock model fitting of DM Tau, RE19 found that DM Tau had more excess at the shortest NUV wavelengths relative to the rest of the sample, and an additional higher-energy ($\mathcal{F} = 3 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$) accretion column best reproduced the data. However, it is unclear how or if this affects the correlation seen here, and we leave it for future work to explore this further. If we remove both DM Tau and the two epochs of VW Cha with the highest $L_{acc}$ (E1 and E2), the correlation between the H$_2$ bump luminosity and $L_{acc}$ is weaker ($\rho_p = 0.6$, $p_p = 5 e^{-3}$; $\rho_s = 0.5$, $p_s = 0.01$; $\tau_k = 0.4$, $p_k = 9 e^{-5}$).

Other works (Ingley et al. 2009; France et al. 2017) have found positive correlations between the H$_2$ bump luminosity and $L_{acc}$. We discuss the implications of this correlation between the H$_2$ bump luminosity and $L_{acc}$ further in Section 4.1.

We find no significant correlations in our sample between $L_X$ and the H$_2$ bump luminosity, $L_{acc}$, or M. There is no correlation between $L_X$ and the H$_2$ bump luminosity ($\rho_p = 0.1$, $p_p = 0.6$; $\rho_s = 0.3$, $p_s = 0.3$; $\tau_k = 0.2$, $p_k = 0.3$). France et al. (2017) also reported the lack of a correlation between $L_X$ and the H$_2$ bump luminosity. We also find no correlation between $L_X$ and $L_{acc}$ ($\rho_p = 0.1$, $p_p = 0.7$; $\rho_s = -0.01$, $p_s = 0.96$; $\tau_k = -0.1$, $p_k = 0.8$; Figure 4, top left) or M ($\rho_p = 0.1$, $p_p = 0.8$; $\rho_s = -0.01$, $p_s = 0.7$; $\tau_k = -0.04$, $p_k = 0.82$; Figure 4, top right). We discuss the implications of the lack of correlation between $L_X$ and the H$_2$ bump luminosity in Section 4.1 and between $L_X$ and $L_{acc}$ or M in Section 4.2.

We also searched for correlations between $L_X$ and emission lines measured in the STIS data by RE19. The lines we investigated from Table 7 of RE19 are as follows: CII 1335 Å, C$_1$ 1463 Å, CIV 1548 Å, HeII 1640 Å, OIII 1666 Å, SiIII 1808 Å, SiIII 1892 Å, CIII 1513 Å, CI 1876 Å, AII 253 Å, M II 2796 Å. We find no correlations with $L_X$. In Figure 4, we show comparisons between $L_X$ and CIV (middle left) and HeII (middle right), the two strongest lines in Figure 2. We find no correlation between CIV and $L_X$ ($\rho_p = 0.04$, $p_p = 0.9$; $\rho_s = 0.3$, $p_s = 0.2$; $\tau_k = 0.2$, $p_k = 0.3$) or HeII and $L_X$ ($\rho_p = 0.1$, $p_p = 0.6$; $\rho_s = 0.05$, $p_s = 0.9$; $\tau_k = 0.0$, $p_k = 1.0$). We note that HeII has been previously linked to X-ray emission (Alexander et al. 2005). We also measure two Lyman-band H$_2$ transition lines (Table 5) from Herczeg et al. (2006) and compare them to $L_X$ in Figure 4. We find no correlation with H$_2$ 1–7R(3) at 1489.5 Å (bottom left, $\rho_p = 0.02$, $p_p = 0.9$; $\rho_s = 0.04$, $p_s = 0.9$; $\tau_k = 0.08$, $p_k = 0.6$) or H$_2$ B-X(5–12)P(3) at 1613 Å (bottom right, $\rho_p = 0.3$, $p_p = 0.2$; $\rho_s = 0.5$, $p_s = 0.1$; $\tau_k = 0.4$, $p_k = 0.04$).

Interestingly, we do see a correlation between the accretion column energy flux and $L_X$ ($\rho_p = 0.8$, $p_p = 9 e^{-5}$; $\rho_s = 0.6$, $p_s = 0.009$; $\tau_k = 0.5$, $p_k = 0.005$). The shock models we used to measure M consist of three columns with an energy flux, $\mathcal{F}$ ($= 1 \times 10^{10}$, $1 \times 10^{11}$, $1 \times 10^{12}$ erg s$^{-1}$ cm$^{-3}$), and a surface filling factor for each column, $f$ (Table 4 of RE19 and Table 6...
in the Appendix). In Figure 5, we plot the average energy flux weighted by the filling factor of each column, $\mathcal{F}_w$, against $L_X$. We did not include VW Cha E5 since in this epoch, the accretion column may have obscured the stellar photosphere leading to optical dimming (RE19). If so, the accretion column may have absorbed some of the X-ray emission as well. If we include VW Cha E5, the correlation between $\mathcal{F}_w$ and $L_X$ is much weaker ($\rho_p = 0.1$, $p_p = 0.7$; $\rho_t = 0.5$, $p_t = 0.03$; $\tau_k = 0.4$, $p_k = 0.02$). We discuss this correlation between $\mathcal{F}_w$ and $L_X$ further in Section 4.2.

Lastly, we investigated the X-ray spectra of objects with multiple epochs of X-ray data (GM Aur, VW Cha, and Sz 45; Figure 6). In GM Aur (top panel), we see that in E4, E6, E7, and E8, the X-ray spectra are very similar. However, in E5, the hard X-ray emission ($1.5$–$8.0$ keV) increases significantly while the soft X-ray emission stays the same. We note that between E4 and E5, $\dot{M}$ did not change significantly (while $L_X$ did change), and in E7, there was a large increase in $\dot{M}$ (while GM Aur E5, the correlation is weaker ($\rho_p = 0.6$, $p_p = 0.01$; $\rho_t = 0.5$, $p_t = 0.03$; $\tau_k = 0.4$, $p_k = 0.02$). We discuss this correlation between $\mathcal{F}_w$ and $L_X$ further in Section 4.2.

Figure 5. Comparison of the X-ray luminosity, $L_X$, to the accretion luminosity, $L_{\text{acc}}$ (top left), the accretion rate, $\dot{M}$ (top right), and the line luminosities of CIV at 1548 Å (middle left), HeII at 1640 Å (middle right), H$_2$ 1–7R(3) at 1489.5 Å (bottom left), and H$_2$ B-X(5–12)P(3) at 1613 Å (bottom right). There are no detected correlations with $L_X$ (see Section 3.3).
L_x did not change). Although not as strong as seen in GM Aur, we see a similar increase in the X-ray emission in E4 of VW Cha (Figure 6, middle panel), while the $\dot{M}$ in this epoch was not significantly higher. In Sz 45, we see no evidence for significant changes in X-ray emission (Figure 6, bottom panel). The increase in the hard X-ray emission of GM Aur and VW Cha is indicative of stellar coronal X-ray flaring activity. We discuss the provided in light of the correlation between $\mathcal{F}_w$ and $L_X$ in Section 4.2.

4. Discussion

In this work, we find a correlation between the FUV H$_2$ bump luminosity and $L_{\text{acc}}$, but not $L_X$. We also see a correlation between $L_X$ and the density of the accretion column. Here we discuss the connection between the variability in the H$_2$ bump luminosity and $L_{\text{acc}}$ and the implications of our results on the connection between X-ray emission and accretion in TTS.

4.1. On the Origin of the FUV H$_2$ Bump

4.1.1. Previously Proposed Mechanisms: X-Ray versus Ly$\alpha$ Emission

Herczeg et al. (2004) and Bergin et al. (2004) proposed that the H$_2$ bump feature was a consequence of collisional excitation of H$_2$ by fast electrons in the inner disk kicked out from heavy elements by X-ray photons. Therefore, one would expect that this would lead to a correlation between the H$_2$ bump and X-ray luminosities. Here we find that the H$_2$ bump luminosity does not increase as $L_X$ increases in our sample (Figure 3). In Figure 7, we present the H$_2$ bump feature in GM Aur and VW Cha, which had stellar flaring in E5 and E4, respectively (Figure 6). The H$_2$ bump feature is not substantially higher in GM Aur E5 and VW Cha E4 relative to other epochs. However, the H$_2$ bump is much higher in GM Aur E7, which we return to below in Section 4.1.2.

We note that a correlation between the H$_2$ bump and X-ray luminosities has not been observed in large samples (France et al. 2017). In addition, using high-resolution COS FUV data, France et al. (2011a, 2011b) noted that the H$_2$ bump is not centered near the expected 1575 Å dissociation peak associated with electron-impact H$_2$. Also, the expected H$_2$ emission spectrum from electron-impact excitation was not seen (France et al. 2017). We do not have the resolution in our STIS data to robustly determine the peak of the H$_2$ bump nor the H$_2$ emission spectrum from electron-impact excitation. However, our results support the interpretation that X-ray ionization cannot be traced with the H$_2$ bump.
There was an accretion burst in GM Aur. Accretion funnel photons would populate the upper levels of H$_2$, and a fraction of H$_2$ would make the H$_2$ bump an FUV spectral signature of H$_2$O fluorescence. This is supported in work by Ingleby et al. (2015) that suggested that this was not coordinated in time. France et al. (2017) also found a clear correlation between the H$_2$ bump and the strength of Ly$\alpha$-driven lines. This is not seen in our GM Aur data. Here we compare the brightest expected Ly$\alpha$-driven lines noted by France et al. (2017) in GM Aur between E7 and E3, the epochs with the highest and lowest $M_{\text{acc}}$, respectively. Figure 8 shows no significant change in the Ly$\alpha$-driven lines. However, the H$_2$ bump luminosity does change between E7 and E3 (Table 5). Ingleby et al. (2015) also saw no correlation between Ly$\alpha$-driven lines and $M_{\text{acc}}$ using the same HST data from GM Aur E1, E2, and E3 as used in this work, as well as two additional HST archival spectra from 2003 (Program 9374; PI: E. Bergin) and 2010 (Program 11616; PI: G. Herczeg). Ingleby et al. (2015) suggested that this was evidence that Ly$\alpha$ is not created in the accretion shock. We do not find evidence that the H$_2$ bump is driven by Ly$\alpha$ photons or that Ly$\alpha$ is generated in the accretion shock.

4.1.2. An Alternative Mechanism: The Disk Surface Density

We find that there is a strong correlation between the H$_2$ bump luminosity and $L_{\text{acc}}$ in our sample (Figure 3) and that the H$_2$ bump is much higher in GM Aur E7 when $M_{\text{acc}}$ was the highest (Figure 7). Ingleby et al. (2009) also found a clear correlation in their study of 32 CTTS with HST STIS and ACS spectra. For the 13 objects in their sample with STIS spectra, $L_{\text{acc}}$ measurements were taken within an hour of the H$_2$ bump measurements (see Section 2.4); $L_{\text{acc}}$ measurements for objects in their sample with ACS data were from the literature and therefore not coordinated in time. France et al. (2017) reported a weaker but positive correlation between the H$_2$ bump and $M_{\text{acc}}$ for 24 objects where the H$_2$ bump was detected. For the majority of the sample, this was not based on coordinated data, and one can speculate that since $M_{\text{acc}}$ is variable, this weakens the correlation seen by France et al. (2017). In our work, we have mostly simultaneous data and see a positive correlation between the H$_2$ bump luminosity and the dust mass in the inner disk (measured from archival spectra from 2003 (Program 9374; PI: E. Bergin) and 2010 (Program 11616; PI: G. Herczeg). Ingleby et al. (2015) suggested that this was evidence that Ly$\alpha$ is not created in the accretion shock. We do not find evidence that the H$_2$ bump is driven by Ly$\alpha$ photons or that Ly$\alpha$ is generated in the accretion shock.

Figure 7. Continuum-subtracted HST FUV spectra of GM Aur and VW Cha from Figure 2 zoomed in on the H$_2$ bump at 1600 Å. We only show those epochs of GM Aur that have coordinated X-ray data. We also note that stellar flaring activity is present in GM Aur E5 and VW Cha E4 (Figure 6) and that there was an accretion burst in GM Aur E7 (Table 5; RE19).

Figure 8. Excess emission in GM Aur E7 relative to E3. We note that the spectra are continuum-subtracted, and we label the wavelengths corresponding to H$_2$ lines created by Ly$\alpha$ fluorescence in gray. There is no significant difference in the emission of these Ly$\alpha$-driven lines between the two epochs.
dust continuum modeling of the NIR data) decreased by the same factor while \( M \) decreased as well. Given that a decrease was seen in the NIR emission tracing the dust content of the inner disk while \( M \) and the H\(_2\) bump luminosity decreased as well, it is plausible this is indicating a decrease of the overall surface density in the inner disk. Changes in the surface density in the inner disk may explain the correlation between \( L_{\text{acc}} \) and the H\(_2\) bump luminosity seen in this work.

France et al. (2017) proposed that the H\(_2\) bump is indirectly correlated to \( M \), as the Ly\(\alpha\) flux is driven by the accretion shock. However, \( M \) also traces the surface density in the inner disk. Therefore, it is not clear if the increase in the H\(_2\) bump luminosity is due to a higher surface density in the inner disk or to more Ly\(\alpha\) photons generated in the accretion shock. We attempt to distinguish between these two scenarios in our data by looking for correlations between Ly\(\alpha\) emission lines, \( M \), and the H\(_2\) bump, which, as noted previously, we do not find (Figure 8). Future work could obtain coordinated HST COS and STIS data in order to measure Ly\(\alpha\)-driven H\(_2\) emission lines and the H\(_2\) bump at high resolution with COS, while acquiring a more direct measure of \( M \) and \( L_{\text{acc}} \) with STIS.

4.2. On the Role of X-Ray Emission in CTTS

4.2.1. Soft X-Ray Emission and the Accretion Column

Most of the X-ray emission from CTTS has been attributed to hot, low-density \((T > 10 \text{ MK}, N_e < 10^{10} \text{ cm}^{-3})\) plasma from coronal emission. However, there is evidence of soft X-ray emission produced by cooler \((T \sim 2–4 \text{ MK})\), high-density \((N_e \sim 10^{12}–10^{13} \text{ cm}^{-3})\) plasma (Kastner et al. 2002; Stelzer & Schmitt 2004; Schmitt et al. 2005; Günther et al. 2006; Argiroffi et al. 2007, 2011; Huemenoeder et al. 2007). This soft X-ray emission is seen in a few CTTS but not in WTTS (e.g., Telleschi et al. 2007b), and so it has been attributed to accretion-related processes. Some works suggest that the high densities indicate this soft X-ray emission is formed in the postshock region at the base of the accretion column (e.g., Kastner et al. 2002; Argiroffi et al. 2017).

However, some observations do not support the interpretation that the soft X-ray emission is formed in the accretion shock. In some objects, soft X-ray emission is present, but the plasma has lower electron densities (e.g., T Tau, AB Aur; Güdel et al. 2007; Telleschi et al. 2007a) than expected if originating in the accretion shock, which should lead to higher densities than the stellar corona. In one case (e.g., DG Tau; Schneider & Schmitt 2008), the soft X-ray component has been spatially separated from the hard X-ray component; these components have been associated with the location of the jet of DG Tau and the star itself, respectively. Also, Brickhouse et al. (2010) could not reproduce the densities and temperatures measured from high-resolution X-ray spectra of TW Hya with a model of plasma heated by the accretion shock. In addition, no correlation has been found between the soft X-ray excess and UV lines known to be accretion indicators (Güdel & Telleschi 2007). An alternative is that the soft X-ray excess is coronal plasma that is modified by the accretion process (Güdel & Telleschi 2007; Brickhouse et al. 2010; Dupree et al. 2012).

In our work, we do not see a correlation between the soft X-ray emission and \( L_{\text{acc}} \). For GM Aur E6, E7, and E8, we have Chandra spectra that trace the soft X-ray wavelengths. While there was a large increase in \( L_{\text{acc}} \) in E7, the soft X-ray emission remained roughly constant throughout the three epochs (Figure 1). This is consistent with predictions that due to the high column densities, the accretion shock is buried in the stellar photosphere and X-ray emission does not escape (Drake 2005). On the other hand, X-ray emission from the accretion shock is expected in some cases, particularly where the column has a lower density and high velocity (Sacco et al. 2010). The change in \( M \) in E7 may not be large enough to lead to an observable change in the continuum of the soft X-ray emission, and instead high-resolution X-ray spectra would be necessary to resolve soft X-ray spectral features attributed to the accretion shock.

4.2.2. Stellar Flares and the Accretion Column

We find a correlation between the weighted accretion column energy flux, \( F_{\nu} \), and \( L_{\text{x}} \) (Figure 5). This correlation is largely driven by GM Aur E5, which had the highest \( F_{\nu} \) and \( L_{\text{x}} \) in our sample. The energy flux \((F = 0.5\rho v^2)\) is proportional to the density, \( \rho \), and the infall velocity, \( v_{\text{in}} \). In our modeling, we keep \( v_{\text{in}} \) fixed at the freefall velocity. This suggests a correlation between \( L_{\text{x}} \) and the density of the accretion column. GM Aur E5 also had the smallest sum of the filling factor, \( f \), for all columns, \( f_{\text{tot}} \) (= 0.06; i.e., the smallest percentage of its surface covered by accretion columns; RE19), which is consistent with narrower, denser columns.

The large increases in \( L_{\text{x}} \) seen in our sample are likely due to X-ray flares from the stellar corona. Most of the increase in the X-ray emission of GM Aur E5 was in the hard X-ray band (Figure 6). The GM Aur E5 spectrum exhibits a prominent hard tail that is consistent with stellar coronal flaring activity (Caramazza et al. 2007). Flaring activity is also supported by the higher temperature found in spectral fitting (Table 3).

The correlation between \( F_{\nu} \) and \( L_{\text{x}} \) may point to a connection between the accretion column and stellar flares. Some theoretical work has found that stellar flaring activity may trigger accretion onto stars. When flaring activity increases, there are more magnetic field lines that link the star to the disk and trigger accretion funnels onto the star (Orlando et al. 2011; Colombo et al. 2019). The predicted timescale for \( M \) to increase after a flare ranges from a few hours to about one day and then the accretion columns themselves last between a few hours to tens of hours (Orlando et al. 2011; Colombo et al. 2019). As the material in the accretion funnel approaches the star, the density increases due to gas compression by the dipolar magnetic field (Orlando et al. 2011). This is consistent with our inference of a narrower, denser column in E5 of GM Aur. However, we do not see an increase in \( M \). This may be attributed to the complexities of mass loading, our viewing angle, or the increase in \( M \) occurring after our observations. Regardless, this connection between the X-ray emission and accretion column properties indicates that more observations to further explore the relationship between stellar flaring and the accretion column density would be fruitful.

5. Summary

Using multiple epochs of mostly simultaneous Swift/Chandra and HST data of TTS, we found that the luminosity of the FUV H\(_2\) bump correlates with \( L_{\text{acc}} \) and not \( L_{\text{x}} \). One mechanism to form the H\(_2\) bump involves collisional excitation by X-ray photons. Specifically, an increase in X-ray emission increases the ionization of the inner disk, which in turn leads to more collisional excitation of H\(_2\). However, we do not see...
evidence of a correlation between the H2 bump and $L_X$. Another mechanism to form the H2 bump involves Lyα-driven dissociation of H2O in the inner disk. A correlation between the H2 bump luminosity and $L_{acc}$ is consistent with this scenario, as the accretion funnel flow is thought to produce Lyα photons. However, we do not see changes in Lyα-driven $H_2$ emission lines between observations where $L_{acc}$ and the H2 bump did change significantly. Given that $M$ is linked to the surface density in the inner disk, we conclude that the correlation of the H2 bump with $L_{acc}$ points to an increase in the surface density of gas in the inner disk.

We found no correlation between $L_X$ and $L_{acc}$ or $M$. In addition, we do not see any changes in the soft X-ray emission in three epochs of Chandra data of GM Aur, while $M$ changed by a factor of $\sim3.5$. This may support that most of the X-ray emission generated by the accretion shock is absorbed. However, high-resolution X-ray spectra would be necessary to explore this further. We also find no correlations between $L_X$ and several FUV and NUV lines, including CIV and He2.

We do see a correlation between the energy flux of the accretion columns, $F_r$, and $L_X$. This trend is dominated by coronal flaring activity. Since $F_r$ traces the density of the accretion column, this may indicate that flaring activity influences accretion onto stars. In particular, we may be seeing evidence that stellar flaring increases the amount of material lifted off the disk and onto the star, and as the material in the accretion funnel approaches the star, the density increases due to gas compression by the dipolar magnetic field. However, we do not see an increase in $M$, which may be due to our viewing angle or time sampling.

In conclusion, our work finds that there is no connection between the X-ray radiation field and the FUV H2 bump in TTS. Therefore, we have yet to identify an observable tracer of the effect of X-ray ionization in the innermost disk. Instead, we find evidence that inhomogeneities in the surface density of the inner gas disk, traced by the FUV H2 bump, propagate through the accretion column as reflected by an increase in $M$. We also find that stellar flares may alter the accretion column density. Further coordinated multiwavelength work is necessary to understand the connection between inhomogeneities in the inner disk, X-ray emission, and mass accretion in TTS.

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Appendix

Mass accretion rates for CS Cha and SZ Cha are measured here following the same methods as RE19. Stellar parameters adopted for CS Cha and SZ Cha are listed in Table 4 and are taken from Manara et al. (2014) and scaled using new Gaia distances (Gaia Collaboration et al. 2016, 2018). For CS Cha, we adopt an $A_V$ of 0.8, a stellar radius of $R_*$ = 1.83 $R_\odot$, and a stellar mass of $M_*$ = 1.32 $M_\odot$. For SZ Cha, we adopt an $A_V$ of 1.3, a stellar radius of $R_*$ = 1.78 $R_\odot$, and a stellar mass of $M_*$ = 1.22 $M_\odot$. We deredden the HST FUV and NUV data using the extinction law toward HD 29647 (Whittet et al. 2004). We deredden the HST optical and IR data with this $A_V$ and the Mathis (1990) extinction law using an $R_V$ of 3.1.

To briefly summarize the methods of RE19, we follow Ingleby et al. (2013) and use the accretion-shock models of Calvet & Gullbring (1998) with multiple accretion columns. The stellar mass, radius, and temperature are input model parameters. The accretion columns are calculated for a variety of energy fluxes, $F = 0.5 \rho v_i^2$. The energy flux depends on the X-ray flux of the accretion column, $\rho$, and the infall velocity, $v_i$. The infall velocity is fixed at the freefall velocity from $\sim5 R_*$ under the assumption that the magnetospheric radius is not changing. The resulting emission is scaled by filling factors, $f_i$, which measure the fraction of the visible stellar surface covered by the column. Finally, we calculate $M$ by adding the contributions of the columns with

$$M = \frac{8\pi R_*^2}{v_i^2} \sum_i f_i \rho_i = \frac{8\pi R_*^2}{v_i^2} F_w \text{f}_{\text{total}}. \quad (2)$$

As our template stellar photosphere, we adopt the WTTS RECX 1, which is in the $\eta$ Chamaeleon star-forming region. RECX 1 has STIS archival spectra obtained as part of HST proposal ID 11616 (PI: G. Herczeg), a measured $A_V$ of 0, and a spectral type of K5 (Luhman & Steeghs 2004). To account for the photospheric emission in order to extract the excess emission due to the accretion shock, we scale the spectrum of our WTTS template to our CS Cha and SZ Cha spectra. To do this properly, we must account for veiling by the excess continuum, which here we assume is due to the accretion shock. Veiling occurs when an excess continuum “fills in” absorption lines, causing them to appear shallower than the spectrum of a standard star of the same spectral type (Hartigan et al. 1991). The veiling (taken to be at 5500 Å) is $\nu_V = F_{V,\text{Veil}}/F_{V,\text{WTTS}}$, where $F_{V,\text{Veil}}$ is the flux of the veiling continuum and $F_{V,\text{WTTS}}$ is the continuum flux of the WTTS. The veiling may change with $M_*$, as it has been shown that there may be some excess at optical wavelengths from accretion (Gullbring et al. 2000; Fischer et al. 2011). We cannot measure veilings from our low-resolution STIS optical spectra, so here we include them as a free parameter in our analysis.

We calculated accretion-shock models with $1 \times 10^{10}$, $1 \times 10^{11}$, and $1 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$. To model our spectra, we combined the veiled WTTS emission with the accretion column emission and left $f_i$ and $r_V$ as free parameters. The fractional uncertainty in the model is also included as a nuisance parameter. To fit these parameters, we used a Bayesian MCMC approach using the ensemble sampler emcee (Foreman-Mackey et al. 2013). Each parameter was fit in log-space, which eliminates the possibility of negative values. A step-function prior excludes the nonphysical cases of $f_i > 1$ and $r_V < 0$. An additional Gaussian prior based on previous modeling efforts by Manara et al. (2014) was placed on $r_V$. In Figure 9, we show the median model from our analysis for each target. The median values for $M_*$, the filling factor per accretion-shock column, and the veiling are listed in Table 6.
Figure 9. Accretion-shock model fits to CS Cha (left) and SZ Cha (right). In each panel, we show the median total model (red) compared with the STIS spectra (black). The total model is composed of the combined emission from three different column energy fluxes (see key) along with the undisturbed photospheric emission, which here is represented with the WTTS template RECX 1 (blue). Parameters for the best-fitting models are listed in Table 6. We note that here we focus on fitting the continuum emission and do not attempt to reproduce the emission lines. The gray shaded regions denote spectral features that were not included in our fitting.

Table 6

Results from Multi-Component Accretion Model Fits to HST Spectra

| Target | $M$ ($10^{-4}$M$_\odot$ yr$^{-1}$) | $f_{\lambda 11}$ | $f_{\lambda 10}$ | $f_{\lambda 8}$ | $f_{\lambda 6}$ |
|--------|-----------------------------------|-----------------|-----------------|---------------|--------------|
| CS Cha | 1.497$^{+0.110}_{-0.099}$         | 0.328$^{+0.007}_{-0.006}$ | 0.0167$^{+0.0006}_{-0.0006}$ | 0.0000217$^{+0.000027}_{-0.000026}$ | 0.072$^{+0.008}_{-0.007}$ |
| SZ Cha | 0.354$^{+0.021}_{-0.019}$         | 0.117$^{+0.004}_{-0.003}$ | 0.00008$^{+0.00008}_{-0.00007}$ | 0.0000462$^{+0.00006}_{-0.00005}$ | 0.005$^{+0.007}_{-0.004}$ |

Note. Accretion columns with energy fluxes ($\mathcal{F}$) of $1 \times 10^{10}$, $1 \times 10^{11}$, and $1 \times 10^{12}$ erg s$^{-1}$ cm$^{-2}$ were calculated and scaled by filling factors ($f_{\lambda}$). Here we list the median values for the accretion rate ($M$), the filling factor for each accretion column, and the veiling factor ($f_v$). The corresponding positive and negative uncertainties listed are the difference between the median and the 16th and 84th percentile, respectively. We note that this is similar to 1σ uncertainties.

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15
