The Evolution of Protoplanetary Disks: Probing the Inner Disk of Very Low Accretors

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Abstract

We report FUV, optical, and NIR observations of three T Tauri stars in the Orion OB1b subassociation with H\textalpha~ equivalent widths consistent with low or absent accretion and various degrees of excess flux in the mid-infrared. We aim to search for evidence of gas in the inner disk in HST Advanced Camera for Surveys/Solar Blind Channel spectra, and to probe the accretion flows onto the star using H\textalpha~ and He I \lambda 10830 in spectra obtained at the Magellan and SOAR telescopes. At the critical age of 5 Myr, the targets are at different stages of disk evolution. One of our targets is clearly accreting, as shown by redshifted absorption at freefall velocities in the He I line and wide wings in H\textalpha~; however, a marginal detection of FUV H2 suggests that little gas is present in the inner disk, although the spectral energy distribution indicates that small dust still remains close to the star. Another target is surrounded by a transitional disk, with an inner cavity in which little sub-micron dust remains. Still, the inner disk shows substantial amounts of gas, accreting onto the star at a probably low but uncertain rate. The third target lacks both a He I line or FUV emission, consistent with no accretion or inner gas disk; its very weak IR excess is consistent with a debris disk. Different processes occurring in targets with ages close to the disk dispersal time suggest that the end of the accretion phase is reached in diverse ways.

Key words: accretion, accretion disk – circumstellar matter – stars: pre-main sequence – stars: variables: T Tauri, Herbig Ae/Be

1. Introduction

While the overall view of the evolution of the disks around low-mass pre-main sequence stars, or T Tauri stars, is fairly well known, the details of this process are still unclear. At an early stage, T Tauri stars host a disk with dust and gas, from which mass is accreting onto the star. At the dust destruction radius, \( \sim 10 R_\star \), the dust in the disk sublimes, creating a dust edge. The gas moves further inward until it reaches the disk truncation radius near the corotation radius, \( \sim 3-4 R_\star \). Inside this radius, the stellar magnetic field channels matter from the disk onto the star. Outside of the corotation radius, the magnetic field lifts the gas and pushes it outward, resulting in winds and jets. These processes, along with photoevaporation and planet formation, disperse the dust and gas from the inner disk. At some point, small dust grains are cleared and all the gas dissipates. This process happens rather quickly (Ingleby et al. 2012). By 5 Myr, less than 10% of the stars are still accreting, and a similar fraction keeps an inner dust disk (Fedele et al. 2010). This suggests that there is a link between the presence of the inner dust disk and accretion. However, it is not quite clear if this is also the case for the inner gas disk. For example, it is unclear whether magnetospheric accretion stops because the disk runs out of gas, or by the action of other processes even before the gas is completely depleted. To address this problem, sensitive diagnostics of gas and accretion must be used to probe the lowest accretors, objects which have very little gas left in the inner disks and/or in which very little accretion goes on.

Gas in the inner disk consists of warm atoms, ions, and molecules. The most abundant molecule in the disk is H2, but its direct observation is difficult because it is a homonuclear molecule lacking a permanent electric dipole component so its rovibrational transitions are very weak. However, the environment in the inner disk, where the temperature is of the order of a few thousand Kelvin, allows direct detection of the molecule in the FUV. The two main mechanisms for exciting and dissociating H2 in the inner disk are Ly\alpha~ fluorescence (Herczeg et al. 2006) and electron-impact excitation (Bergin et al. 2004). H2 molecules excited by Ly\alpha~ photons de-excite back to the electronic ground state, resulting in emission lines in the FUV (1100–1700 Å). At the same time, X-rays from the star partially ionize heavy metals in the disk, and the ejected electrons can excite and dissociate H2. This process results in lines and continuum emission in the FUV, the latter mostly around 1600 Å. The transition probabilities associated with these processes are high, so FUV observations of H2 can be used as a sensitive tool to probe the gas in the inner disk.

We note that a recent study by France et al. (2017) suggests that the 1600 Å feature arises from Ly\alpha-driven H2O dissociation instead of X-ray-driven, electron-impact H2 excitation. In this case, the feature still probes the gas in the inner disk, albeit arising from a different mechanism. Even though throughout this paper we refer to the FUV 1600 Å feature as H2 \( \lambda 1600 \), we acknowledge that the feature may indeed come from H2O.

Ingleby et al. (2009) used the H2 \( \lambda 1600 \) excess feature to probe the inner gas disk of T Tauri stars across an age range of 1–10 Myr; they found that inner disk H2 is only present in...
accreting stars, also known as classical T Tauri Stars (CTTS). Follow-up studies by Ingleby et al. (2012) of non-accreting T Tauri stars, or weak T Tauri stars (WTTS), confirmed the previous result, namely that WTTS have cleared the gas from the inner disk as early as 1–3 Myr. Recently, Doppmann et al. (2017) explored the link between accretion and the inner gas residue using mid-IR CO emission and found that CO is detected only in accreting sources, identified by M-band veiling. These results seem to suggest that the gas is gone as soon as the accretion stops. To test this assumption further, sensitive tools are needed to probe accretion kinematics and measure the very low accretion rate expected at the transition between accreting and non-accreting.

The traditional diagnostics of accretion are the equivalent width (EW) of the Hα line in low-resolution spectra, or the width of the line, or the presence of redshifted absorption, which require high-resolution spectroscopy. However, these diagnostics may fail at very low accretion levels if Hα becomes optically thin.

Being the second most abundant element, helium is a promising alternative to hydrogen. In fact, studies of the He i λ10830 feature in T Tauri stars have shown that the line is a good indicator of accretion and outflows (Edwards et al. 2006; Fischer et al. 2008). Helium atoms in the accretion flow that are ionized by the stellar high-energy radiation (e.g., X-ray) recombine and then cascade down the energy levels until they reach the metastable state 1s2s 3S. The emission line at 10830 Å results from the transition 1s2p 3P → 1s2s 3S (Kwan & Fischer 2011). At the same time, He atoms in the flow capture line and continuum photons at their rest wavelength, resulting in absorption at the velocity of the flow. Depending on the observing geometry, outflow or/and infall of material may produce blueshifted or/and redshifted absorption superimposed on the emission line. Thus, redshifted absorption is a definite probe of accretion; velocities of this feature close to the freefall velocity indicate magnetospheric accretion (Fischer et al. 2008; Kwan & Fischer 2011).

Following studies of the evolution of the inner gas disk by Ingleby et al. (2009, 2012), we report here observations of three T Tauri stars with flux excess over the photosphere in the near or mid-IR, and with EWs of Hα consistent with low or absent accretion. Our targets belong to the Orion OB1b subassociation, thus they have ages of ~5 Myr (Briceno et al. 2005), a critical age for gas dispersal. We aim to probe for accretion using the Hα and the He i λ10830 lines, and for the presence of inner disk gas using H2 λ1600. The details of the observations and data reduction are given in Section 2. Section 3 provides the methods of analysis and the results. Finally, a discussion of the findings and the implications of the results are provided in Section 4.

2. Observations and Data Reduction

2.1. Target Selection

The targets for this study, CVSO 1335, CVSO 114NE, and CVSO 114SW, were selected from the CIDA Variability Survey of Orion (Briceno et al. 2005, 2018). This survey characterizes the population of low-mass stars in the OB1 association with emphasis on the 1a and 1b subsasssociations, which span an age range of 5–10 Myr, a critical timescale for the evolution of protoplanetary disks (Hernández et al. 2008; Fedele et al. 2010). Our targets are in OB1b with an age of ~5 Myr (Briceno et al. 2005) and we use distances calculated from Gaia DR2 parallax measurements (Gaia Collaboration et al. 2018).

The targets were selected as having low Hα EWs for their respective spectral type, consistent with low or no accretion, and excess flux over the photosphere in at least oneWISE band, indicative of the presence of a disk. CVSO 114 was not resolved in the original CVSO photometry (Briceno et al. 2005), but it was later found to be a visual pair with an angular separation of 4″9; we study here each star of the pair. We carried out spectroscopic and photometric observations of the targets. A log of the observations, including instrument specifications and spectral resolutions, is provided in Table 1.

| CVSO  | R.A. (J2000) | Decl. (J2000) | Instrument | Slit/Prism Grating/Filter | Spectral Resolution | UT Start Date | Exp. Timea (s) |
|-------|-------------|--------------|------------|--------------------------|---------------------|--------------|---------------|
| 114NE | 05 33 01.76 | −00 21 01.9 | ACS/SBC | PR130L | ~70° | 2016 Mar 23 | 2586 |
|       |             |              | Goodman  | 2100 l/mm | 14000 | 2014 Nov 11 | 3 × 900 |
|       |             |              | FIRE     | 0°6 | 6000 | 2014 Dec 2 | 201 |
|       |             |              | FIRE     | 0°6 | 6000 | 2017 Jan 5 | 190 |
|       |             |              | SAM      | g, r, i, z | ... | 2014 Jan 23 | 60, 15, 20, 30 |
| 1335  | 05 32 10.16 | −00 37 12.3 | ACS/SBC | PR130L | ~70° | 2016 Mar 22 | 2586 |
|       |             |              | Goodman  | 2100 l/mm | 14000 | 2017 Sep 18 | 3 × 600 |
|       |             |              | MagE     | 1°9 | 4000 | 2017 Nov 30 | 600 + 900 |
|       |             |              | MagE     | 1°9 | 4000 | 2017 Nov 29 | 2 × 900 |
|       |             |              | FIRE     | 0°6 | 6000 | 2017 Jan 5 | 190 |
| 114SW | 05 33 01.97 | −00 20 59.3 | ACS/SBC | PR130L | ~70° | 2016 Mar 23 | 2586 |
|       |             |              | Goodman  | 2100 l/mm | 14000 | 2014 Nov 11 | 3 × 900 |
|       |             |              | M2FS     | HiRes | 44500 | 2012 Dec 10 | 5 × 1200 |
|       |             |              | FIRE     | 0°6 | 6000 | 2014 Dec 2 | 402 |
|       |             |              | SAM      | g, r, i, z | ... | 2014 Jan 23 | 60, 15, 20, 30 |

Notes.

a The listed exposure time for the FIRE observation is for each of the two nod s (A/B).

b The spectral resolution for PR130L ranges from R ~ 220 @ 1250 Å to R ~ 40 @ 1800 Å. The value shown is at 1600 Å.
2.2. FUV Spectroscopy

To investigate the presence of gas in inner disks, we obtained far-ultraviolet spectra of CVSO 114 and CVSO 1335 using the Advanced Camera for Surveys/Solar Blind Channel (ACS/SBC) on board the Hubble Space Telescope (Program GO14190). Since the stars were expected to be faint in the FUV, we took advantage of the high throughput PR130L prism at the cost of resolution. The same system was shown to be a reliable setup in our previous studies (Ingleby et al. 2009, 2012). Each target was observed for one orbit with an exposure time of 40 s for target acquisition and 2586 s for science exposure. The CVSO 114 pair was observed on the same field. The spectrograph was able to resolve each component and the spectra were reduced separately.

The ACS/SBC PR130L prism spectra were reduced with custom-written programs in IDL, following similar reductions in Ingleby et al. (2009) and Yang et al. (2012). The counts were extracted from 9-pixel windows centered on the target, with background counts estimated from nearby regions and subtracted from the spectrum. The wavelength solution was obtained from Larsen et al. (2006) and shifted so that the C IV line occurs at 1549 Å. The counts were then corrected for the extraction aperture and sensitivity, using the detector response function calculated from observations of PG1322+659 in April 2005 by Larsen et al. (2006). Any degradation in the detector sensitivity in the 10 years between those observations and our own observations is unaccounted for and may lead to underestimating the flux.

2.3. Optical Spectroscopy

2.3.1. SOAR Goodman Observations

We used the Goodman High Throughput Spectrograph (Clemens et al. 2004) on the 4.1 m SOAR telescope to obtain high-resolution spectroscopy of the CVSO 114 visual pair. In order to obtain spectra for both components we oriented the slit at PA = 42°.

For determining the velocity width of the Hα line profile, we used 2100 g mm\(^{-1}\) grating in Littrow mode, centered at 650 nm, with the 0°46 slt, and the spectroscopic 1 × 1 region of interest, which provides the native pixel scale of 0.15 pixel\(^{-1}\). This configuration provided a wavelength range of ~630 Å with a resolution R ~ 14,000, equivalent to ~22 km s\(^{-1}\). All the basic data reduction was done with the standard routines in the ccdproc package in IRAF. The processed individual 2D spectra in each mode were then median-combined, and finally extracted to 1D spectra and wavelength-calibrated using the apextract package in IRAF.

2.3.2. MagE Observations

We observed CVSO 1335 using the Magellan Echellette (MagE) instrument (Marshall et al. 2008) on the Magellan Baade Telescope at the Las Campanas Observatory in Chile. The instrument is a medium-resolution spectrograph with wavelength coverage of 3200 Å–1 μm. We used the 1° slit, providing a spectral resolution of R ~ 4100. The data were reduced using the MagE Pipeline in the Carnegie Observatories’ CarPy package (Kelson et al. 2000; Kelson 2003). We calibrated the flux with spectrophotometric standards observed on the same night at comparable airmass. The flux calibration was performed in IRAF. Here, we present two Hα profiles of CVSO 1335 observed 24 hr apart. The full MagE spectra of this and other sources are analyzed in Thanathibodee et al. (in preparation).

2.3.3. M2FS Observations

As part of our program for obtaining Hi-Res observations of a large number of the CVSO stars, we observed CVSO 114SW with the Michigan/Magellan Fiber System (M2FS; Mateo et al. 2012) on the Magellan Clay telescope at Las Campanas Observatory in Chile on the night of 2014 December 10. The instrument was configured in the Hi-Res Echelle mode, with a custom Hα/Li filter that isolates orders 53 and 54, covering a wavelength range from 6528 to 6791 Å. We used the 75 μm slit and 1 × 2 binning, providing a resolution R ~ 44,500 (or ~7 km s\(^{-1}\)). Exposures were processed with a combination of custom Python scripts and an IRAF-based pipeline. The processed individual exposures were median-combined into a final frame, on which the spectral extraction and wavelength calibration was performed.

2.4. NIR Spectroscopy

To probe for magnetospheric accretion using the He I A10830 line, we observed the targets with the FIRE spectrograph (Simcoe et al. 2013) on the Magellan Baade telescope at the Las Campanas Observatory in Chile. The CVSO 114 visual pair was first observed on 2014. Subsequent to the HST observation, the instrument was used again to observe CVSO 114NE and CVSO 1335. For both observing runs, the 0°6 slit was used. This offers a resolution of R ~ 6000 in the NIR and can resolve velocities of ~50 km s\(^{-1}\). We reduced the data using the FIRE reduction pipeline with telluric standard stars and calibration frames taken on the same observing night. Since the wavelength solution of the pipeline is in vacuum wavelength, we converted it to air wavelength using the equations described in Morton (2000).

2.5. SOAR Adaptive Optics Imaging

The CVSO 114 visual pair was not resolved in the original CVSO photometry, so we obtained high angular resolution imaging of the pair using the Southern Astrophysical Research Telescope (SOAR) Adaptive Optics Module (SAM; Tokovinin et al. 2016). SAM contains a 4K × 4K CCD imager covering a 3′ × 3′. We used the standard 2 × 2 binning, yielding a scale of 0.091 pixel\(^{-1}\). We obtained images in the SDSS g, r, i, and z filters. The data were reduced with custom Pyraf routines that do the bias subtraction and flat-field correction, and we used the 2MASS catalog to derive an astrometric solution for each frame. We calibrated the photometric zero-point using photometry for stars in each field from the SDSS DR10. Table 2 shows the derived magnitudes.
3. Analysis and Results

3.1. Stellar Parameters

We took spectral types and reddening corrections for the targets from the CVSO survey (Briceño et al. 2018). All the sources are consistent with $A_V = 0$. We used Table 6 in Pecaut & Mamajek (2013) to get effective temperatures and bolometric corrections, and 2MASS (Skrutskie et al. 2006) $J$ magnitudes to get the stellar luminosities. We determined stellar masses using the Siess et al. (2000) evolutionary tracks. The derived values are shown in Table 3.

| CVSO  | SpT  | $A_V$ (mag) | $J$ (mag) | $L_*$ ($L_\odot$) | $M_*$ ($M_\odot$) | $R_*$ ($R_\odot$) | $d$ (pc) |
|-------|------|-------------|-----------|-------------------|-------------------|------------------|--------|
| 114NE | M1.5 | 0.0         | 12.0      | 0.24              | 0.38              | 1.30             | 314 ± 11 |
| 1335  | K5   | 0.0         | 11.5      | 0.66              | 0.87              | 1.58             | 375 ± 6  |
| 114SW | K7   | 0.0         | 11.2      | 0.61              | 0.68              | 1.65             | 325 ± 5  |

3.2. Spectral Energy Distributions

The spectral energy distribution (SED) gives information about the presence and distribution of dust in the disk. To relate disk properties to the evidence of accretion, we constructed SEDs for the targets, shown in Figure 1. The CVSO, and VISTA photometry are taken from Briceño et al. (2018), the Spitzer IRAC and MIPS photometry comes from J. Hernández et al. (2018, in preparation), and the Herschel PACS photometry is from Maucó et al. (2018). We also include photometry from 2MASS (Skrutskie et al. 2006) and WISE (Wright et al. 2010). We used Pecaut & Mamajek (2013) pre-main sequence stellar colors, scaled at the $J$ magnitude, to construct the photosphere for comparison.

The SED of CVSO 114NE shows excess relative to the photosphere in the near-IR and mid-IR, indicating the presence of optically thick dust emission close to the star. In contrast, CVSO 1335 shows no excess in the near-IR. The SED of this star traces the K5 photosphere up to $\lambda \sim 10 \mu m$, where the emission from the dust starts to appear. The emission is consistent with the median of Taurus at longer wavelengths. This indicates that CVSO 1335 has a transitional disk, in which the inner regions have been mostly cleared of small dust, while still hosting an outer disk (Espaillat et al. 2014). Finally, the SED of CVSO 114SW only shows a small excess over the photosphere at WISE bands 3 and 4.

3.3. Accretion Indicators

3.3.1. Hα

We assessed the accretion state of the targets using the EWs of the Hα line and the profiles of Hα and the He I $\lambda 10830$ line. Table 4 lists the values of the EWs of the Hα line, EW(Hα), of the targets as well as the width at 10% of the height of the Hα emission feature (10%-width; $W_{10}$). The corresponding Hα line profiles are shown in the top row of Figure 2. For comparison, we also show in Table 4 the Hα EWs from Briceño et al. (2018), estimated from low-resolution spectra.

Both the values of the EW(Hα) and the width of the line $W_{10}$ in Table 4 indicate that CVSO 114NE and CVSO 114SW can be classified as CTTS and WTTS, respectively, based on the criteria in White & Basri (2003). The classification is more complicated for CVSO 1335. For its spectral type of K5, the threshold values between CTTS and WTTS in White & Basri (2003) are EW(Hα) $\sim$ 3 Å and $W_{10} \sim$ 270 km s$^{-1}$, although these values are very uncertain since they are based on essentially one veiled star. Nonetheless, the values of EW(Hα) (Table 4) indicate that the star varies between actively accreting to marginally accreting. However, inspection of the line profiles in Figure 2 give a more clear picture of what is happening. The Hα profiles of CVSO 1335 show strong redshifted absorption components, indicating that it was accreting at all the epochs it was observed. The absorption can get to be so strong that it overwhelms the emission, effectively decreasing the EW. The redshifted absorption also complicates the measurement of $W_{10}$. To better define the emission profile, we subtracted the spectrum of 61 Cyg A, a K5V star, from that of CVSO 1335. The standard star spectrum was taken from the Gaia FGK Benchmark Stars library (Blanco-Cuaresma et al. 2014) and is shown on the left panel of Figure 3, together with the spectra of CVSO 1335. The right panel of Figure 3 shows the photosphere-subtracted Hα profiles of CVSO 1335. As shown, the emission beyond the main redshifted absorption is very variable and complex, making the measurement of $W_{10}$ very uncertain. We give two measurements of the $W_{10}$ for CVSO 1335 in Table 4. One corresponds to the measurement of the main blue emission; the other includes the red wing, except for the MagE-20171130 profile, in which the red emission is weaker than 10% of the peak flux (Figure 3).

3.3.2. He I $\lambda 10830$

Evidence for magnetospheric accretion is given by a redshifted absorption superimposed on the bright emission of the He I $\lambda 10830$ line at velocities of the order of the freefall velocity. For comparison, we calculated the freefall velocities of each target using the stellar masses and radii, and a truncation radius of $R_t = 5 R_*$ (Calvet & Gullbring 1998). These velocities are shown in Table 4.

For CVSO 114NE, the He I $\lambda 10830$ profiles show a prominent He I emission at the star’s rest velocity, as well as conspicuous, redshifted absorption components in both epochs of observations. The maximum velocity of the redshifted absorption, $\sim +300$ km s$^{-1}$, is consistent with the freefall velocity of 300 km s$^{-1}$, indicating that magnetospheric accretion is taking place.

The He I $\lambda 10830$ line profiles of CVSO 114NE shown in Figure 2 are remarkably similar, despite being separated by two years. The velocity at the minimum of the redshifted absorption, $v_s \sim 150$ km s$^{-1}$, and the extension of the wing of the redshifted absorption, $v_{\text{max}} \sim 300$ km s$^{-1}$, as well as the velocity of the blueshifted absorption, $v_b \sim -240$ km s$^{-1}$, are similar between the two epochs of observation, indicating a fairly steady accretion flow. Nonetheless, although the strength and the width of the emission features are similar in both epochs, the absorption features have slightly different depths and widths. The depth of the redshifted absorption changes by $\sim 10\%$ between the two epochs, with a slightly smaller change for the blueshifted absorption. As shown in Figure 2, the redshifted absorption is stronger when the blueshifted absorption is weaker. The seesawing behavior seems to preclude stellar continuum changes as the cause of the variability, since if this was the case both lines would change similarly. The
or of the mass accretion rate (Fischer et al. 2013) colors scaled at the J magnitude of the target. The dotted red line is the median SED of Taurus from Maucó et al. (2016). CVSO 114NE shows excess over the photosphere even in the near-IR, indicating optically thick dust emission close to the star. CVSO 1335 has a transitional disk with no NIR excess but conspicuous excess beyond 10 μm. Plotted in light gray along with CVSO 1335 is the SED of GM Aur scaled to the same WISE band 2 flux. The SED of CVSO 1335 does not have a significant flux around ~10 μm, suggesting that it lacks the small grains responsible for the conspicuous silicate feature at ~10 μm in GM Aur. Its optically thin gap may be filled with larger, ~2 μm grains such as that of CS 1335, the mid-IR spectrum of which is scaled and shown here in light green. CVSO 114SW may still have an outer disk, as it shows excess in WISE bands 3 and 4. The SED of CVSO 114NE is also reported by Maucó et al. (2018). The IR spectroscopic data of GM Aur and CS Cha are from the NASA/IPAC Infrared Science Archive.

The He I λ10830 profile of CVSO 1335 shows some emission and an unambiguous redshifted absorption. The absorption component is shallow but broad with a minimum at v_t ~ 240 km s^{-1} and a wing extending to v_{max} ~ 490 km s^{-1}. This extension is ~20% higher than the freefall velocity of 410 km s^{-1} (Table 4). Fischer et al. (2008) found that the He I λ10830 line did not extend beyond the escape velocity for their sample, except in one case that they attributed to incorrect stellar parameters. The discrepancy for CVSO 1335 may be similarly due to uncertainties in the placement of the continuum or in the stellar parameters. The redshifted absorption component seems to be the superposition of two absorption components, one strongest at ~+30 km s^{-1} and another at ~+240 km s^{-1}. Following Fischer et al. (2008), this can be interpreted as a combination of redshifted absorption of stellar continuum at low velocities and of the veiling continuum at high velocities by the diluted accretion flow. The presence of the low-velocity redshifted absorption component may indicate a high inclination, as it is required for viewing the low-velocity flow against the star. This is also seen in the modeling results in Fischer et al. (2008), in which the strong absorption shifts closer to v_t = 0 as the inclination increases.

CVSO 114SW does not show any detectable He I emission nor redshifted absorption. The presence or absence of redshifted absorption of the He I λ10830 line for all the targets is consistent with the accretion classification provided by the profiles of Hα.

### 3.4. Mass Accretion Rates

In addition to the determination of the accretion state, the Hα line can be used to estimate mass accretion rates, using empirical relationships from the literature. We used the relationship between L_{Hα} and M from Ingleby et al. (2013), estimating L_{Hα} from the EW(Hα) and the continuum flux at 6563 Å, which in turn we obtained from the SDSS r magnitude. We also used the relationship between W_{10} and M from Natta et al. (2004). The derived values are shown in Table 4. The values of M determined from the EW(Hα) and W_{10} are consistent for CVSO 114NE. However, they can vary by almost three orders of magnitude in CVSO 1335, depending on the indicator and the value of W_{10} adopted.

### 3.5. H₂ Excess Luminosity

The presence of gas in the inner disk close to the star can be probed using the H₂ features in the FUV. It is difficult to detect these features in the low-resolution ACS/SBC spectra; however, Ingleby et al. (2009) found that the excess around 1600 Å, likely due to electron-impact excitation, could be detected in CTTS, even in SBC spectra. Excess in the 1420–1520 Å region, due to Lyα fluorescence, could be detected in some cases.

In order to determine the presence of excess flux at 1600 Å, we first determined a template spectrum for non-accreting stars, the WTTS, to use as reference. We calculated this template using the ACS/SBC FUV spectra of non-accreting WTTSs from Ingleby et al. (2009) and Ingleby et al. (2012). The spectra were corrected for reddening using A_v from the original papers, smoothed, and finally normalized to the same flux in the range of 1700–1800 Å. The median of the normalized WTTS spectra was then calculated and used as a template. For each of our three stars, we scaled the template to the minimum flux between 1660–1740 Å to avoid an unidentified emission feature at ~1750 Å. The FUV spectra of the targets and the scaled median WTTS spectrum are shown in the bottom row of Figure 2. The spectrum of CVSO 114NE shows only a marginal excess over the median WTTS in the 1575–1625 and 1420–1520 Å region. CVSO 114SW shows even less excess. CVSO 1335 shows a conspicuous excess over the WTTS in both spectral regions.
Table 4
Measured and Derived Properties

| CVSO     | EW(Hα) (Å) | W_0(Hα) (km s$^{-1}$) | M – EW (10$^{-10}$ M$_{\odot}$ yr$^{-1}$) | M – W_0 (10$^{-10}$ M$_{\odot}$ yr$^{-1}$) | L$_{H_\alpha}$ (10$^{-6}$ L$_{\odot}$) | \(\Sigma_H_\alpha\) (10$^{-6}$ g cm$^{-2}$) | \(v^p\) (km s$^{-1}$) | \(v^s\) (km s$^{-1}$) | \(v_{\text{max}}\) (km s$^{-1}$) |
|----------|------------|------------------------|---------------------------------|---------------------------------|-----------------------------|-----------------------------|------------------|------------------|------------------|
| 114NE    |            |                        |                                 |                                 |                             |                             |                  |                  |                  |
| LowRes   | 37.5       | …                      | 2.4                             | …                               | \(\leq 3.79 \pm 0.02\)   | \(\leq 7.4\)                    | 300              | 150              | 300              |
| Goodman  | 35.2       | 350                    | 2.3                             | 3.2                             |                             |                             |                  |                  |                  |
| 1335     |            |                        |                                 |                                 | 23.00 \pm 0.02             | \(> 18.2\)                        | 410              | 238              | 490              |
| LowRes   | 9.1        | …                      | 7.0                             | …                               |                             |                             |                  |                  |                  |
| Goodman  | 5.6        | 277/626                | 4.1                             | 0.63/1500                       |                             |                             |                  |                  |                  |
| MagE$^c$ | 3.8        | 310/531                | 2.7                             | 1.30/180                        |                             |                             |                  |                  |                  |
| MagE$^d$ | 4.3        | 310                    | 3.0                             | 1.30                            |                             |                             |                  |                  |                  |
| 114SW    |            |                        |                                 |                                 |                             |                             |                  |                  |                  |
| LowRes   | 2.5        | …                      | <0.9                           | …                               | \(\leq 0.72 \pm 0.01\)   | \(\leq 3.2\)                        | 354              | …                | …                |
| M2FS     | 1.6        | 158                    | <0.5                           | <0.04                           |                             |                             |                  |                  |                  |
| Goodman  | 1.8        | 187                    | <0.8                           | <0.08                           |                             |                             |                  |                  |                  |

Notes.

$^a$ Two measurements show the ambiguity of the placement of the profile’s red wings.

$^b$ Freefall velocity.

$^c$ Velocity at which the He I \(\lambda 10830\) absorption is strongest.

$^d$ Maximum velocity of the He I \(\lambda 10830\) redshifted absorption.

$^e$ UT2017-11-29.

$^f$ UT2017-11-30.

To quantify our determinations, we calculated, separately, the stellar flux and the template flux from their respective monochromatic fluxes \(f_{\lambda}\) as

\[
F = \int_{1575\,\AA}^{1625\,\AA} f_{\lambda} \, d\lambda. \tag{1}
\]

We then calculated the \(H_2\) excess luminosity as

\[
L_{H_2} = 4\pi d^2 (F_{\text{star}} - F_{\text{wts}}), \tag{2}
\]

where \(F_{\text{wts}}\) is the scaled template and \(d\) is the distance to the star.

The uncertainties in this calculation arise from the placement of the template spectrum relative to the stellar spectrum and from the uncertainty in each data point from the reduction process. To estimate this uncertainty, we assumed that the flux \(f_{\lambda}\) for each data point is an independent random variable with a normal distribution \(N(x, \sigma)\), where \(x\) and \(\sigma\) are the measured flux and the uncertainty from the reduction pipeline, respectively. For each of the 10,000 realizations, the flux for each data point was randomized from the normal distribution, resulting in the spectrum over the FUV range. We then calculated the integrated flux using Equation (1). The mean and the standard deviation of the mean of the stellar flux and the template flux were then used to calculate the \(H_2\) luminosity using Equation (2).

To evaluate the significance of the measurements, we compared the mean stellar flux \(F_{\text{star}}\) with the standard deviation of the calculated template flux \(SD(F_{\text{wts}})\). We found that only the \(H_2\) luminosity measurement of CVSO 1335 is significant at the 3\(\sigma\) level. We report the \(H_2\) luminosity for the targets in Table 4, with the measurements for the CVSO 114 visual pair as upper limits.

Following Ingleby et al. (2009), we calculated the disk \(H_2\) surface density from the \(H_2\) luminosity, assuming that the 1600 Å feature is due to electron-impact excitation. This is given by

\[
\Sigma_{H_2} = \frac{2m_H}{R} \left( \frac{zL_{H_2}}{\pi \hbar \sigma_{1600} \Delta \lambda \chi_e} \right)^{1/2}, \tag{3}
\]

where \(m_H\) is hydrogen mass, \(R\) and \(z\) are the radius and height of \(H_2\) emitting region, respectively, \(\hbar\) is the photon energy at 1600 Å, \(\sigma_{1600}\) is the \(H_2\) cross section to electron impact at this wavelength, \(\Delta \lambda\) is an assumed width of the 1600 Å feature, \(v\) is the impacting electron velocity, and \(\chi_e\) is the electron fraction. As in Ingleby et al. (2009), we adopt \(R = 1\) au, \(z = 0.1\) au, \(\sigma_{1600} = 10^{-20}\) cm$^2$ Å$^{-1}$, \(\chi_e = 5 \times 10^{-3}\), and electron kinetic energy of 12 eV. We take \(\Delta \lambda = 1625\,\AA - 1575\,\AA = 50\,\AA\).

The results are shown in Table 4. Following the discussion in Ingleby et al. (2009), we report the calculated \(\Sigma_{H_2}\) as a lower limit. Since the \(L_{H_2}\) detections of the CVSO 114 pair are not significant, we report their \(\Sigma_{H_2}\) as upper limits.

4. Discussion

We report observations of three \(\sim 5\) Myr old T Tauri stars obtained in ground- and space-based observatories to characterize and evaluate their accretion state. The stars seem to be in different stages of protoplanetary disk evolution at the same age, and we discuss them in detail here.

4.1. CVSO 114NE

Detailed modeling of the SED of CVSO 114NE indicates that the star is surrounded by an accretion disk, with dust as close to the star as 0.07 au (Maucó et al. 2018). Inside this radius, dust sublimates but gas continues moving in until it reaches the magnetospheric radius, from which it falls onto the star along the accretion streams that give rise to the clear signatures of accretion seen in this star. Given the kinematic evidence for accretion, one would reasonably assume that there is still gaseous material in the inner disk feeding the accretion streams. However, the FUV spectrum of
CVSO 114NE shows essentially no excess over the WTTS median either around 1600 Å or shortward of the 1548 Å C IV line. The accretion luminosity of CVSO 114NE, $L_a = GM_a^2/R_a \sim 3 \times 10^{-3}$ yr$^{-1}$, is lower than that of most of the CTTS observed previously with the ACS (Ingleby et al. 2009). Thus, the H$_2$ emission may be below the detection limit.

However, for FP Tau, a star only slightly cooler than CVSO 114NE, with an accretion luminosity of $\sim 1 \times 10^{-3}$ $M_\odot$ yr$^{-1}$, clearly shows excess over the WTTS even at ACS/SBC resolution (Ingleby et al. 2009).

The weakness of the H$_2$ FUV emission may arise from occultation effects. Marginal detection due to occultation could be possible if the gas is distributed asymmetrically. Axial asymmetries have been observed on larger scales ($>15$ au) in

Figure 2. Inner disk gas and accretion indicators for CVSO 1335 (left), CVSO 114NE (center), and CVSO 114SW (right). Top: high- and medium-resolution optical spectra of the H$_\alpha$ feature. CVSO 114NE shows strong emission and wide wings. CVSO 1335 shows weak, but very broad emission, superimposed by a strong redshifted absorption component. CVSO 114SW exhibits a weaker emission profile with narrow wings. The profile seems to change between the Goodman observation (black) and M2FS observation (blue). Middle: ACS/SBC FUV spectra in the 1600 Å region. The median spectrum of non-accreting WTTS from Ingleby et al. (2009, 2012) is also shown (red line). The H$_2$ excesses are calculated over the 1575–1625 Å region (gray shade). CVSO 1335 shows clear excess over the median WTTS in the shaded region and 1420–1520 Å region, whereas CVSO 114NE and CVSO 114SW show only marginal excess. Bottom: FIRE spectra showing the He I 10830 line. The black vertical bar in the left and middle panels shows the freefall velocity of the star. While CVSO 114SW does not exhibit any significant He I feature, CVSO 114NE and CVSO 1335 show conspicuous emission and redshifted absorption. CVSO 114NE shows variability in the redshifted absorption features from two epochs of observations, as well as weak blueshifted absorption.
AB Aur by ALMA using $^{12}$CO $J = 2 - 1$ (Tang et al. 2017), where the disk has spiral arms. However, it is unclear if this is the case on a small scale in this star. In any event, stellar occultation of the H$_2$ emitting region necessitates high inclination. For example, an inclination of 75° is needed to hide the region within ~4 $R_\ast$. Highly inclined disks can also absorb FUV radiation. For instance, Schneider et al. (2015) found that the flux at around 1600 Å can change by a factor of 5 during several epochs in the case of AA Tau ($i \sim 75$°). However, the HeI emission line profiles seem to suggest low inclinations. The peak of the emission is at the stellar rest velocity, suggesting a geometry such that the HeI emission region in accretion flows has low radial velocity. The line profile modeling of Fischer et al. (2008) indicates that the HeI $\lambda$10830 emission peak moves blueward and the absorption minimum moves closer to the stellar rest velocity as inclination to the line of sight increases. This suggests that CVSO 114NE, in which the HeI $\lambda$10830 minimum is at $\sim0.5 v_{\text{ff}}$, is unlikely to be at high inclination.

Finally, we consider the possibility that CVSO 114NE is a spectroscopic binary. If this is the case then it could resemble the AK Sco system, in which a reduction of 10% in the Ly$\alpha$ excited H$_2$ at periastron was interpreted in terms of increased Ly$\alpha$ optical depth in the accretion stream (Gómez de Castro et al. 2016).

To shed some light on the perplexing properties of CVSO 114NE, multi-epoch, higher-resolution FUV spectroscopy is needed to examine the Ly$\alpha$ and X-ray variability via H$_2$ line emission, as well as near-IR spectroscopy to follow the accretion variability. In addition, optical spectroscopy monitoring is required to explore the possibility of the star being a spectroscopic binary.

4.2. CVSO 1335

Both the H$_2$ FUV spectrum and the H$\alpha$ and HeI $\lambda$10830 lines indicate that CVSO 1335 is actively accreting gas from the inner disk onto the star. The main issue with this object is the value of the mass accretion rate. As discussed in Section 3.4, there is a large discrepancy between values of $\dot{M}$ determined from the luminosity and from the 10%-width of the H$\alpha$ line. The latter estimator is generally considered more accurate (White & Basri 2003), but in this case, the actual value of $W_{10}$ is difficult to determine. Nonetheless, analysis of the line profiles shows that the line is very broad at all epochs of observation, despite the variability of the red emission wing of the line (Figure 3), and the 10%-width is of the order of $\sim600$ km s$^{-1}$, which would correspond to an accretion rate of $\sim10^{-7}$ $M_\odot$ yr$^{-1}$ according to the Natta et al. (2004) calibration. However, if this was the case, the accretion luminosity of CVSO 1335 would be of the order of 2.5 $L_\odot$, about four times the stellar luminosity (Table 4), resulting in a heavily veiled spectrum. In contrast, the agreement of the optical and near-IR fluxes of CVSO 1335 with the photospheric fluxes (Figure 1) and the presence of absorption lines consistent with the standard (Figure 3) indicate a very low veiling in CVSO 1335. Moreover, the accretion luminosity expected from the H$_2$ luminosity of CVSO 1335 would be $\sim0.05$ $L_\odot$ from the data of Ingleby et al. (2009), which would correspond to $\dot{M} \sim 3 \times 10^{-9}$ $M_\odot$ yr$^{-1}$. This conflicting evidence is more likely due to the unreliability of the calibration of empirical indicators such as the 10%-width, which is based on higher accretors in which H$\alpha$ profiles are more symmetric and redshifted absorptions are not typically seen. Detailed modeling of the line profiles and the accretion shock emission are required to obtain a more accurate estimate of the mass accretion rate in this object.
In contrast to CVSO 114NE, CVSO 1335 shows no near-IR excess over the photosphere (Figure 1). As discussed in Section 3.2, CVSO 1335 is surrounded by a transitional disk, that is, an optically thick disk truncated at some radius from the star, with a small amount of optically thin dust coexisting with the gas inside the cavity (Espaillat et al. 2014). This is the second transitional disk analyzed in the CVSO survey, after the 10 Myr CVSO 224 in Ori OB1a (Espaillat et al. 2008). Determining the physical properties of the disk is beyond the scope of this paper, but we can get some insight by comparing the SED of CVSO 1335 to that of other transitional disks. For reference, in Figure 1 we have added the IRS spectra of two other stars surrounded by transitional disks, GM Aur and CS Cha, scaled to the same photospheric flux as CVSO 1335. These stars have masses comparable to CVSO 1335, and therefore are expected to have comparable disk dissipation timescales (Hernández et al. 2005; Carpenter et al. 2006; Kennedy & Kenyon 2009; Ribas et al. 2015). GM Aur is located in the 1–2 Myr Taurus association and has a spectral type of K3 and a mass of 1.2 $M_\odot$ (Calvet et al. 2005). CS Cha is in the 2.5 Myr old Cha I association, with a spectral type of K6 and a mass of 0.9 $M_\odot$ (Espaillat et al. 2007). In both stars, the outer disk is truncated at tens of au and the silicate emission arises from dust in an optically thin region inside the cavity (Calvet et al. 2005; Espaillat et al. 2007). Although we lack mid-IR spectroscopy for CVSO 1335, we can compare its fluxes in WISE bands 3 and 4 to those of GM Aur and CS Cha; WISE band 3, which is wide enough to encompass the silicate feature, is particularly informative. We find that the mid-IR fluxes of CVSO 1335 are consistent with the IRS spectrum of CS Cha, and about a factor of 10 lower than that of GM Aur. This is interesting because grains in the optically thin region of CS Cha have grown to a size of $\sim$2 $\mu$m without smaller grains (Espaillat et al. 2007), while in GM Aur the size distribution is similar to the ISM, with grain sizes between 0.005 and 0.25 $\mu$m. The maximum size is also larger than the ISM in CVSO 224, the other transitional disks analyzed in the CVSO survey (Espaillat et al. 2008), leading to the speculation that dust evolution has already taken place in these 5–10 Myr populations. Nevertheless, the absence of sub-$\mu$m dust grains in CVSO 1335, similarly to CS Cha, may suggest a more rapid dust evolution in its mass range, since the smallest grains are still present in older but lower-stellar-mass transitional disks with substantial grain growth, such as TW Hya (Calvet et al. 2002) and CVSO 224 (Espaillat et al. 2008).

### 4.3. CVSO 114SW

CVSO 114SW is a WTTS, as it has a weak and narrow Hα profile. The absence of emission or redshifted absorption of Hα $\lambda$10830 profile strengthens the classification of the star as non-accreting. Although the SED of the star is essentially photospheric in the near-IR, there seems to be some excess in WISE bands 3 and 4 (Figure 1), which could indicate that the star hosts a debris disk. Using the Cieza et al. (2013) criterion, the star can be classified as a warm debris disk since it has mid-IR excess and is not accreting.

### 5. Summary and Conclusions

We probe the inner gas disk and accretion properties of three, 5 Myr, T Tauri stars from the CVSO survey at various stages of dust evolution. We summarize our conclusions as follows:

1. At 5 Myr, diverse states of accretion are found, and they seem to be independent of the state of dust evolution or the stellar mass. This implies that this evolution may be slightly stochastic and proceed in diverse ways.

2. CVSO 114NE shows a very low level of H$_2$ in the inner disk, yet its Hα and He I $\lambda$10830 profiles indicate that it is still actively accreting. A non-axially symmetric geometry for the inner disk and/or highly inhomogeneous accretion flows leading to variability could potentially explain this perplexing situation. Future observations using multi-phase higher-resolution spectroscopy, and more detailed modeling, may shed some light on this peculiar finding.

3. CVSO 1335 has a significant amount of gas in the inner disk, as indicated by the H$_2$ $\lambda$1600 flux. Similarly, the Hα and He I $\lambda$10830 profiles clearly show that it is accreting, although the accretion indicators give inconclusive values for $M$. It hosts a transitional disk, which has cleared the small dust from the inner disk, as shown by weak emission in the NIR. The similarity of the flux in the WISE 3 band between CVSO 1335 and the transitional disk around CS Cha, a star of comparable mass and thus a similar disk dissipation timescale, suggests that as in CS Cha, grains in the inner disk have grown to a single $\sim$$\mu$m size. Comparison with transitional disks of different stellar masses and ages suggests a trend of lack of sub-$\mu$m grains for higher stellar masses, but larger samples need to be studied to confirm this suggestion.

4. CVSO 114SW has no excess of H$_2$ $\lambda$1600 over median WTTS, suggesting that there is essentially no gas left in the inner disk. This agrees with the Hα and He I $\lambda$10830 diagnostic showing that the star is not accreting. The evidence of some IR excess suggests that the star may have a debris disk.

5. Among three accretion indicators discussed in this paper, EW(Hα) is the least sensitive, unable to diagnose a star conclusively as an accretor. While the presence of the redshifted absorption feature of the line conclusively suggests that a star is accreting, it complicates the measurement of $M$ using traditional metrics such as EW and $W_{10}$. Detailed modeling of the origin of the redshifted absorption of Hα is needed to solve this problem.

6. The redshifted absorption in the He I $\lambda$10830 line proves to be a very sensitive probe of accretion. It is a promising accretion indicator to study the low accretors, since veiling and/or filling by emission are less problematic than the profiles in CTTS with high $M$ (Fischer et al. 2008). However, the link between the profile morphology and quantitative estimates of accretion is still incomplete. In many cases, the line profile is also time-dependent (e.g., Fischer et al. 2008). In future studies, a more exhaustive exploration of parameter space, as well as physical modeling (e.g., Kurosawa et al. 2011), are needed.

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